Hydrologic and Chemical Interaction of the Arkansas River and the *Equus* Beds Aquifer Between Hutchinson and Wichita, South-Central Kansas

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
acre	4,047	square meter
inch per hour (in/hr)	25.4	millimeter per hour
inch per year (in/yr)	25.4	millimeter per year
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
ton per day (ton/d)	907.2	kilogram per day
ton per day	370.78/(ft^3/s)	milligram per liter (mg/L)
foot squared per day[1] (ft^2/d)	0.09290	meter squared per day
degree Fahrenheit (°F)	°C = (°F-32)5/9	degree Celsius (°C)

[1]The standard unit for transmissivity (T) is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. To avoid confusion to the nontechnical reader, the mathematical expression has been reduced to foot squared per day (ft^2/d).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

DEFINITION OF TERMS

Aquifer. A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Equipotential line. A line in a two-dimensional ground-water flow field such that the total **hydraulic head** is the same for all points along the line.

Evapotranspiration. Water withdrawn from a land area by evaporation from water surfaces and moist soil, and by plant transpiration.

Hydraulic conductivity. The volume of water at the existing kinematic viscosity that will move in unit time under a unit **hydraulic gradient** through a unit area measured at right angles to the direction of flow. Units of **hydraulic conductivity** are:

$$\frac{(\text{length}^3/\text{time})}{(\text{length}^2)\ (\text{length/length})}\left(\text{for example, }\frac{(\text{feet}^3/\text{day})}{(\text{feet}^2)\ (\text{feet/feet})}\right)$$

but, as in this report, are commonly simplified and reported as length/time (for example, feet per day).

Hydraulic gradient. Change in total **hydraulic head** per unit of distance in a given direction.

Hydraulic head. Height above a standard datum of the surface of a water column that can be supported by the static pressure at a given point.

Phreatophyte. A plant that can live with its roots in and obtains water from the saturated zone.

Porosity. The ratio of the volume of void spaces in sediment or rock to its total volume.

Potentiometric surface A surface that represents the level to which water will rise in a tightly cased well. More than one **potentiometric surface** may be required to describe the distribution of **hydraulic head** if **hydraulic head** varies appreciably with depth in the **aquifer**.

Recharge. The processes involved in the addition of water to the zone of saturation.

Saturated thickness. The thickness of the saturated zone in an **aquifer**.

Specific storage. The volume of water released from or taken into ground-water storage per unit volume of the porous medium per unit change in **hydraulic head**.

Specific yield. The ratio of the volume of water that saturated rock or sediment will yield by gravity to the volume of the rock or sediment.

Steady state. Condition under which the magnitude and direction of ground-water flow velocities are constant with time.

Storage coefficient. The volume of water an **aquifer** releases from or takes into storage per unit surface area of the **aquifer** per unit change in head.

Subcrop. The areal extent of a truncated rock unit at a buried surface of unconformity. The subcrop would be the surface outcrop if overlying beds were removed.

Transient. Condition under which the magnitude and direction of ground-water flow velocities vary with time.

Transmissivity. The volume of water of the existing kinematic viscosity that will move in unit time through a unit width of the **aquifer** under a unit **hydraulic gradient**. Units of **transmissivity** are:

$$\frac{(\text{length}^3/\text{time})}{(\text{length})\ (\text{length/length})}\left(\text{for example, }\frac{(\text{feet}^3/\text{day})}{(\text{feet})\ (\text{feet/feet})}\right)$$

but, as in this report, are commonly simplified and reported as length^2/time (for example, feet squared per day).

Water table. That surface in a ground-water body at which the water pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water.

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Abstract

Large chloride concentrations in Arkansas River water have the potential to degrade water quality in the adjacent *Equus* beds aquifer between Hutchinson and Wichita, Kansas. The aquifer is an important source of water for municipal, industrial, agricultural, and domestic uses.

A three-dimensional, finite-difference, ground-water flow-model program (MODFLOW) was used with data from past studies and data collected during 1988–91 to simulate aquifer and stream conditions during the late 1930's, during 1940–89, and during 1990–2019. Results of ground-water flow-model simulations indicated that declining water levels in the *Equus* beds aquifer since the 1940's have caused base flow in the Arkansas and Little Arkansas Rivers to decrease. In 1940, the Arkansas and Little Arkansas Rivers had simulated net base-flow gains within the model area of about 21 and about 67 ft^3/s (cubic feet per second), respectively. By the end of 1989, the Arkansas River had a simulated net base-flow loss of about 52 ft^3/s, and the Little Arkansas River had a net base-flow gain of about 27 ft^3/s. Simulations for 1990–2019 showed that the water-level changes in a selected model cell located in the central part of the Wichita well field could range from -0.2 to -78 feet. Water-level changes in a selected model cell located near the Arkansas River could range from +1.3 to -1.2 feet. In model simulations where only pumpage varied, net base-flow loss from the Arkansas River to the aquifer ranged from about 59 ft^3/s (no increase in pumpage since 1989) to 117 ft^3/s (a 3-percent per year increase in pumpage since 1989) by 2019.

Assuming a chloride concentration of 630 milligrams per liter, the median concentration in Arkansas River water collected during 1988–91, the quantity of chloride discharged from the Arkansas River to the aquifer was estimated to have increased from about 21 tons per day in 1940 to about 100 tons per day in 1989. By 2019, chloride discharge was indicated to range from about 110 tons per day (associated with no increase in pumpage since 1989) to 200 tons per day (associated with a 3-percent per year increase in pumpage since 1989).

A particle-tracking program (MODPATH), which used the results from the flow model, was used to simulate the distribution in the aquifer of chloride from the river during the same time periods. Particle-tracking simulations show that, during 1940–89, the simulated distribution of particles representing chloride from the Arkansas River expanded from relatively narrow bands near the river to a wider distribution within the aquifer and the Wichita well field. Particle-tracking simulations indicate that chloride discharge from the Arkansas River may have reached the edge of the Wichita well field as early as 1963.

INTRODUCTION

Background

Large chloride concentrations in Arkansas River water have the potential to degrade water quality in the adjacent *Equus* beds aquifer. Since 1940, total ground-water withdrawals from the *Equus* beds aquifer in the study area for municipal, industrial, and agricultural uses have increased from about 15,270 to as much as 138,630 acre-ft/yr in 1988 (Spinazola and others, 1985; data on file with the U.S. Geological Survey, Lawrence, Kans.). Many of the wells near the Arkansas River have poorer water quality than wells farther away from the river. Further development of the aquifer could increase infiltration of Arkansas River water to the aquifer, thereby increasing chloride concentrations in the aquifer and decreasing streamflows in the Arkansas River. An understanding of how the stream-aquifer system responds to various system stresses (such as ground-water withdrawals from wells, drought, large or small river flows) could lead to improved management of the available water resources near the Arkansas River. A 4-year study to evaluate the hydrologic and chemical interaction between the river and the aquifer was begun in 1988 as a joint effort of the Kansas Water Office; the Equus Beds Groundwater Management District No. 2 (Halstead, Kansas); the Bureau of Reclamation, U.S. Department of the Interior; and the U.S. Geological Survey (USGS).

The purpose of the 4-year study was to improve understanding of the hydrologic and chemical interaction of the Arkansas River and *Equus* beds (stream-aquifer system) so that water-management agencies can develop strategies to minimize aquifer water-quality degradation and streamflow declines. In this study, "hydrologic interaction" includes the effect of water levels in the *Equus* beds aquifer on flow in the Arkansas and Little Arkansas Rivers, the effect of the Arkansas River on water levels in the aquifer, and the quantity of water exchanged between these rivers and the aquifer. "Chemical interaction" includes the quantity of chloride being discharged from the Arkansas River to the aquifer and the distribution of chloride from the river in the aquifer.

Specific objectives of this study were to develop a detailed understanding of the geology, hydrology, and chloride concentration near the Arkansas River; to use this information to develop a three-dimensional ground-water flow model; to use the ground-water flow model as a tool to help understand the flow between the river and aquifer and horizontal and vertical flow in the aquifer near the river; and to use the ground-water flow model and a particle-tracking program to estimate the horizontal and vertical distribution of chloride from the Arkansas River in the aquifer. It is the intent of the Bureau of Reclamation to use the ground-water flow model developed by the USGS to develop a solute-transport model to simulate chloride transport in the aquifer (Shirley Shadix, Bureau of Reclamation, written commun., 1993).

Purpose and Scope

This report presents the results of a hydrologic and chemical-interaction study of the Arkansas River and *Equus* beds aquifer, and flow-model and particle-tracking simulations of the stream-aquifer system between Hutchinson and Wichita in south-central Kansas. The primary geologic section considered consists of unconsolidated sediments of Pliocene and Pleistocene age (*Equus* bed sediment) that underlie and border the Arkansas River. The *Equus* beds aquifer, which consists of *Equus* beds sediment, is the primary aquifer that is considered. The Permian-age Wellington Formation and Ninnescah Shale, which underlie the unconsolidated sediments, are discussed relative to their effect on ground-water flow and ground-water quality in the unconsolidated sediments. Most of the water-level measurements and water-quality samples for this study were collected from 1986 to 1990; however, model-calibration simulations of ground-water flow cover 1940–89. In addition, model simulations are used to estimate the effects of natural and human-induced stresses on the stream-aquifer system. The sources of chloride and movement of chloride from the Arkansas River into the *Equus* beds aquifer are discussed.

Description of Study Area

The study area is located in south-central Kansas in parts of Reno, Harvey, McPherson, and Sedgwick Counties (fig. 1). The reach of the Arkansas River between Hutchinson and Wichita and the associated unconsolidated sediment (part of the *Equus* beds aquifer) are the focus of this study. However, use of a ground-water flow model necessitated the inclusion of major aquifer stresses, such as the Wichita well field and the Little Arkansas River (fig. 2), and boundaries, such as the contact between Permian-age bedrock and *Equus* beds sediment, in the study area. Principal cities in the area are Hutchinson, Newton, and Wichita. Other towns in the area are shown in figure 2.

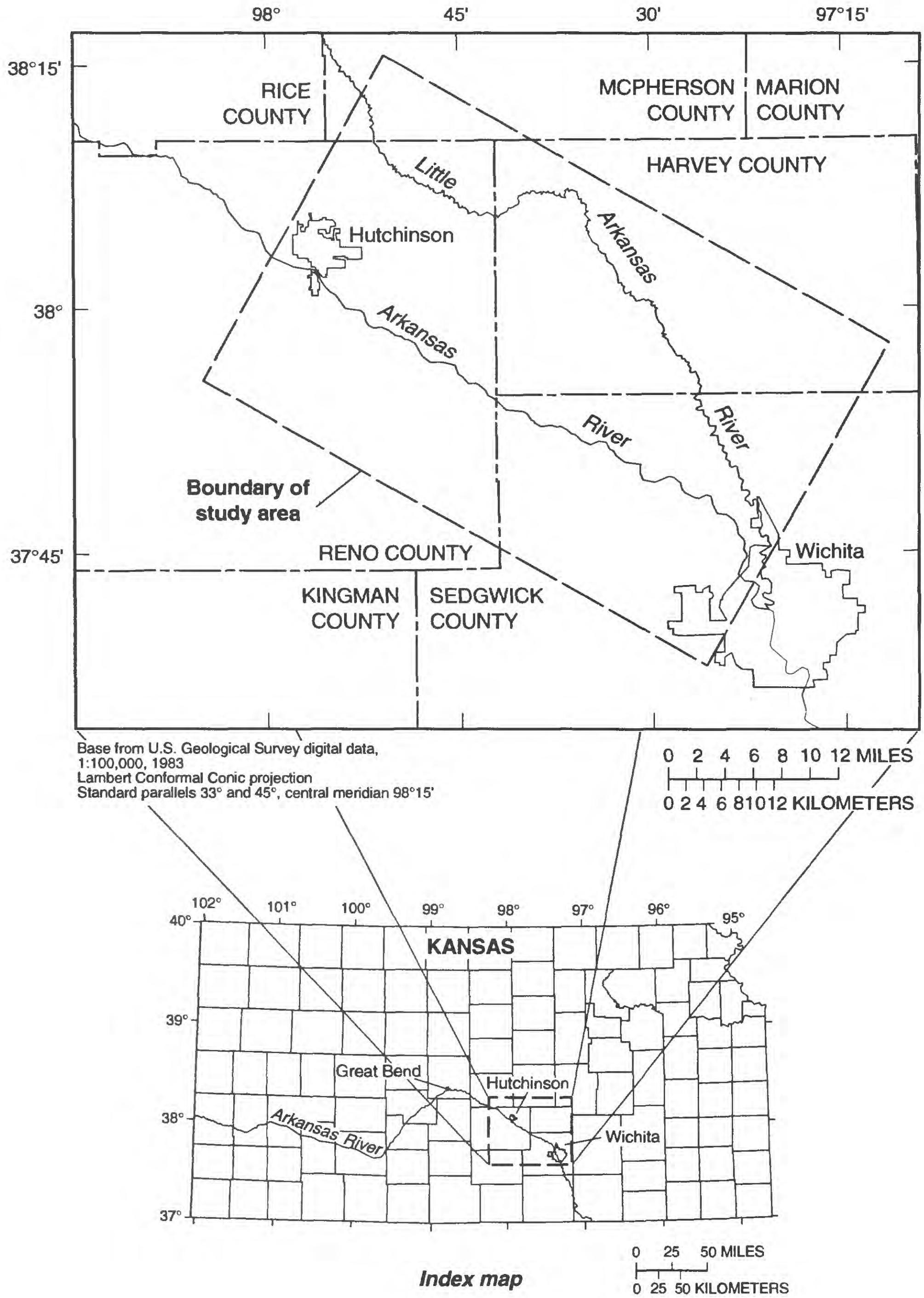


Figure 1. Location of study area.

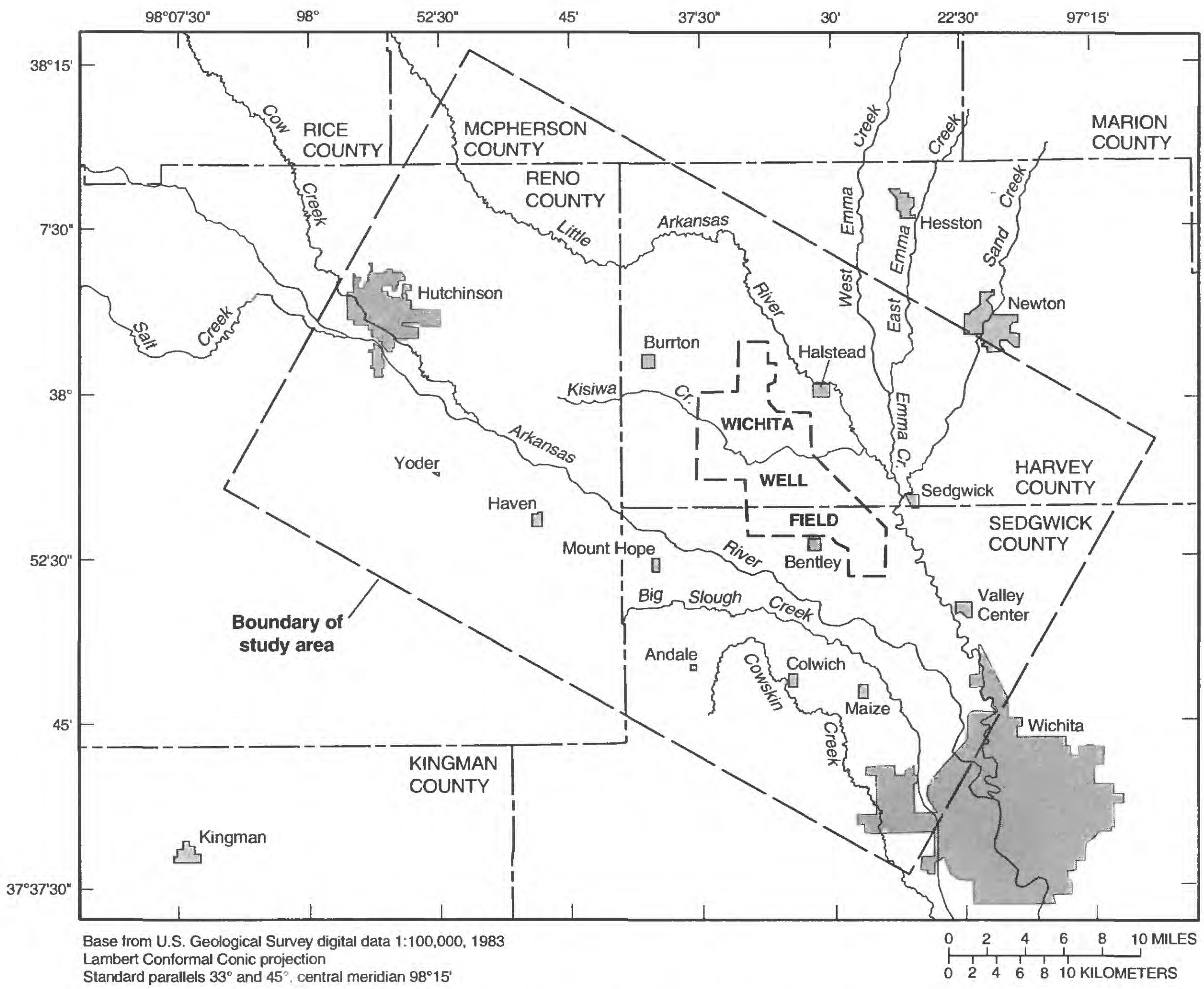


Figure 2. Location of study area, streams, Wichita well field, cities, and towns.

South-central Kansas has a continental climate and is characterized by large variations in seasonal temperatures, moderate precipitation, and windy conditions. Seasonal temperatures range from daily averages of 29.6 °F in January to 81.4 °F in July (National Oceanic and Atmospheric Administration, 1935–89). Temperatures may range from more than 100 °F in the summer to less than -20 °F in the winter. Mean annual precipitation at weather stations near Hutchinson, Mount Hope, and Wichita is 29.88, 31.65, and 30.48 in., respectively, for 1940–89 (National Oceanic and Atmospheric Administration, 1935–89) or about 30.67 in. for the study area. Most of this precipitation occurs during spring and summer.

The study area lies in the Arkansas River section of the Central Lowland physiographic province (Schoewe, 1949). There is very little topographic relief in the study area except for an area of sand dunes (fig. 3) north and northeast of Hutchinson. For the most part, the land surface slopes gently toward the major streams in the area.

The Arkansas River and the Little Arkansas River are the major streams in the study area (fig. 2). The Arkansas River flows southeast in a fairly straight, slightly braided channel. The Arkansas River channel is entrenched 5 to 10 ft below the general land surface. In contrast, the Little Arkansas River meanders as it flows east and southeast to its confluence with the Arkansas River in Wichita. The channel of the Little Arkansas River is entrenched 15 to 25 ft below the general land surface. Cow Creek and smaller creeks are tributaries to the Arkansas River. Emma and Sand Creeks and smaller creeks are tributaries to the Little Arkansas River.

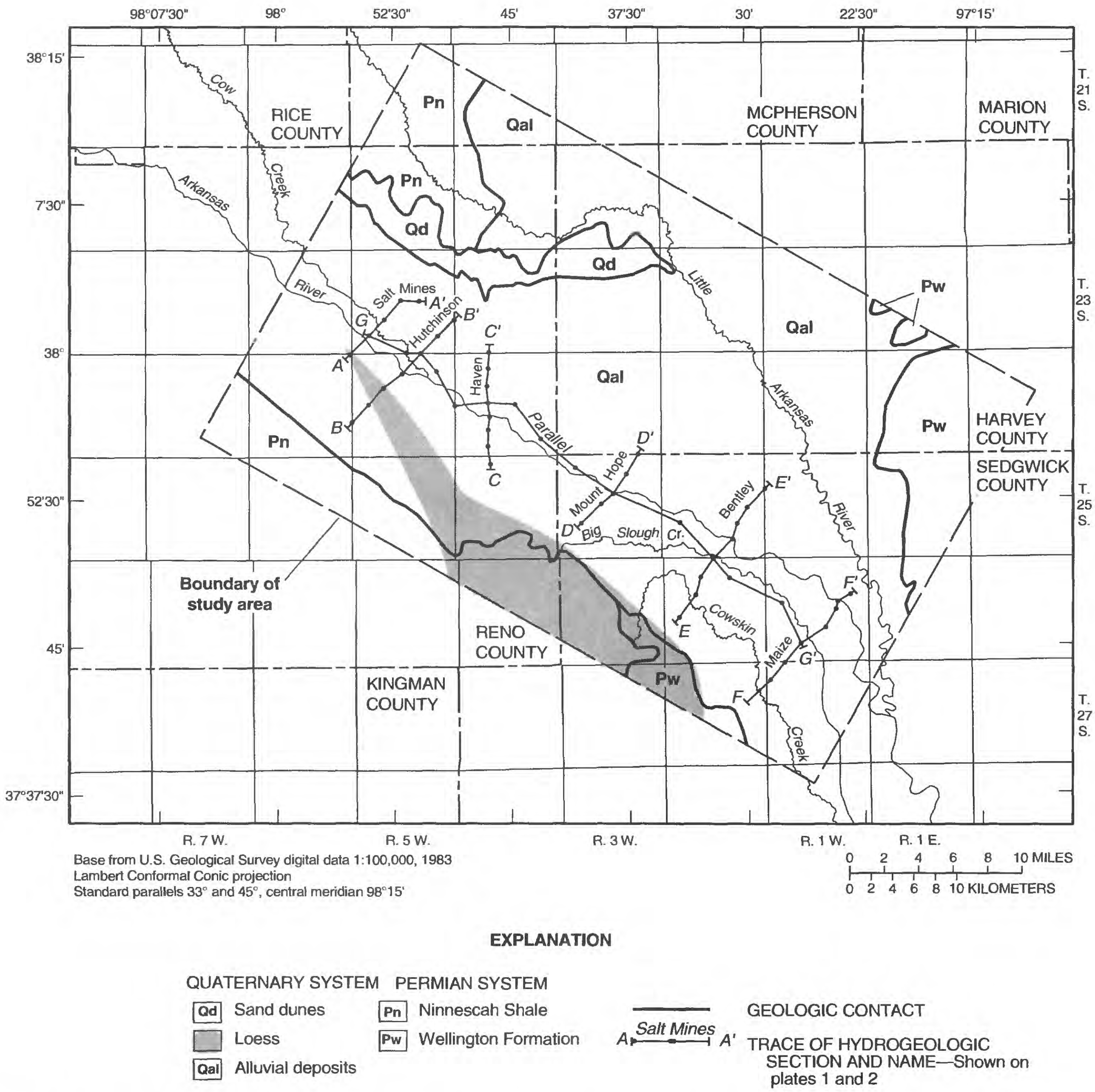


Figure 3. Areal geology, traces of hydrogeologic sections, and section names (geology modified from Kansas Geological Survey, 1964).

Site- and Well-Numbering System

In this report, wells installed during this study or utilized in a well network near the Arkansas River are designated as L-###-I, where L may be EB (*Equus* beds), NAS (North American Salt Company), or USGS-H (U.S. Geological Survey wells drilled near Hutchinson); ### is a site number; and I is a letter or letters designating the relative depth of the well. For example, EB-240-AA, EB-240-A, EB-240-B, and EB-240-C are four wells located at site 240 and have well screens that are shallow (AA), intermediate (A or B), and deep (C). Wells with relative depth designations of A (or any multiple of A's) through C have their screens in *Equus* beds sediment. One well with a depth designation of D (EB-237-D) has its well screen in Permian-age bedrock.

The numbering system for other wells, from which data were used in this study, is based on a modification of the Bureau of Land Management's

(U.S. Department of the Interior) system of land subdivision (fig. 4). The first number indicates the township south (S) of the Kansas-Nebraska State line; the second indicates the range east or west (E or W) of the sixth principal meridian; and the third indicates the section in which the well is located. The first letter following the section number denotes the quarter section or 160-acre tract; a second letter, the quarter-quarter section or 40-acre tract; a third letter, the quarter-quarter-quarter section or 10-acre tract. The 160-acre, 40-acre, and 10-acre tracts are designated A, B, C, and D in a counterclockwise direction beginning in the northeast quarter of the section. Wells or sampling sites in a tract are

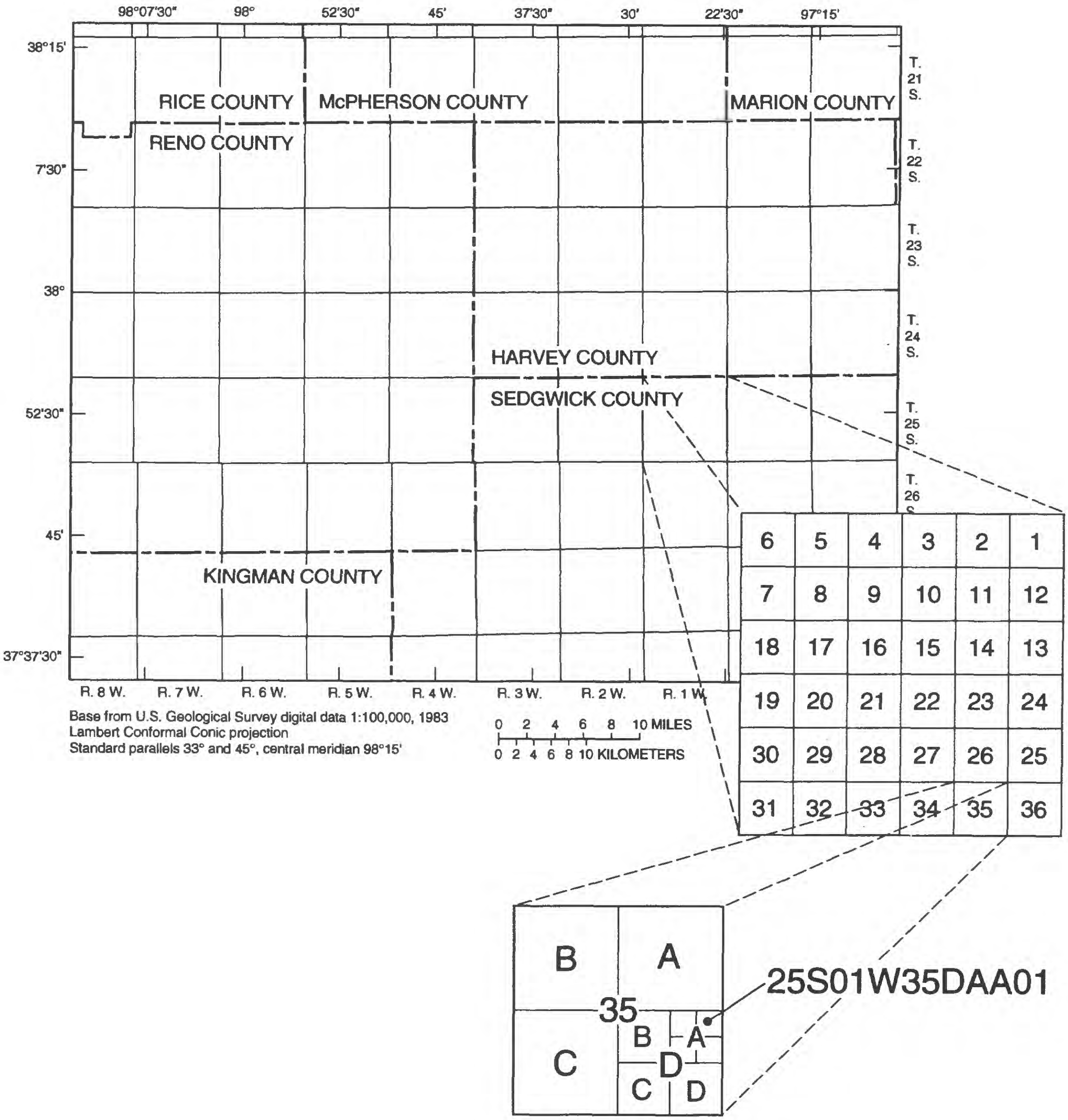


Figure 4. Modified Bureau of Land Management land subdivision system used for numbering well or site locations.

numbered consecutively, beginning with 1, in the order in which the wells or sites were inventoried. For example, 25S01W35DAA01 indicates the first well inventoried in the northeast quarter of the northeast quarter of the southeast quarter of sec. 35, T. 25S., R. 1W. (fig. 4).

Methods of Investigation

Results from previous investigations were used to guide data-collection efforts during this study. A network of 155 clustered (well screens at different depths) observation wells at 55 sites was established by the Bureau of Reclamation, the Kansas Geological Survey, and the USGS along the Arkansas River (fig. 5) during this and previous studies. Four wells at two sites (NAS-1-A, NAS-1-C, NAS-2-A, NAS-2-C) were drilled by the North American Salt Company (Hutchinson, Kansas) and were included in the network. Lithologic logs for the network wells are presented in the "Supplemental Information" section of this report. A streamflow-gaging station was installed on the Arkansas River near Maize, and water-level recorders were placed in five shallow wells (20–35 ft deep) that were drilled near the river (wells EB-204-AA, EB-210-AA, EB-216-AA, EB-221-AA, and EB-232-AA). Two pumping tests (fig. 6) were performed to help refine estimates of aquifer characteristics. Water samples from the observation-well network were collected annually by personnel of the Equus Beds Groundwater Management District No. 2 (GMD2) and were analyzed for major ions by the Kansas Department of Health and Environment (Topeka). During most of the study

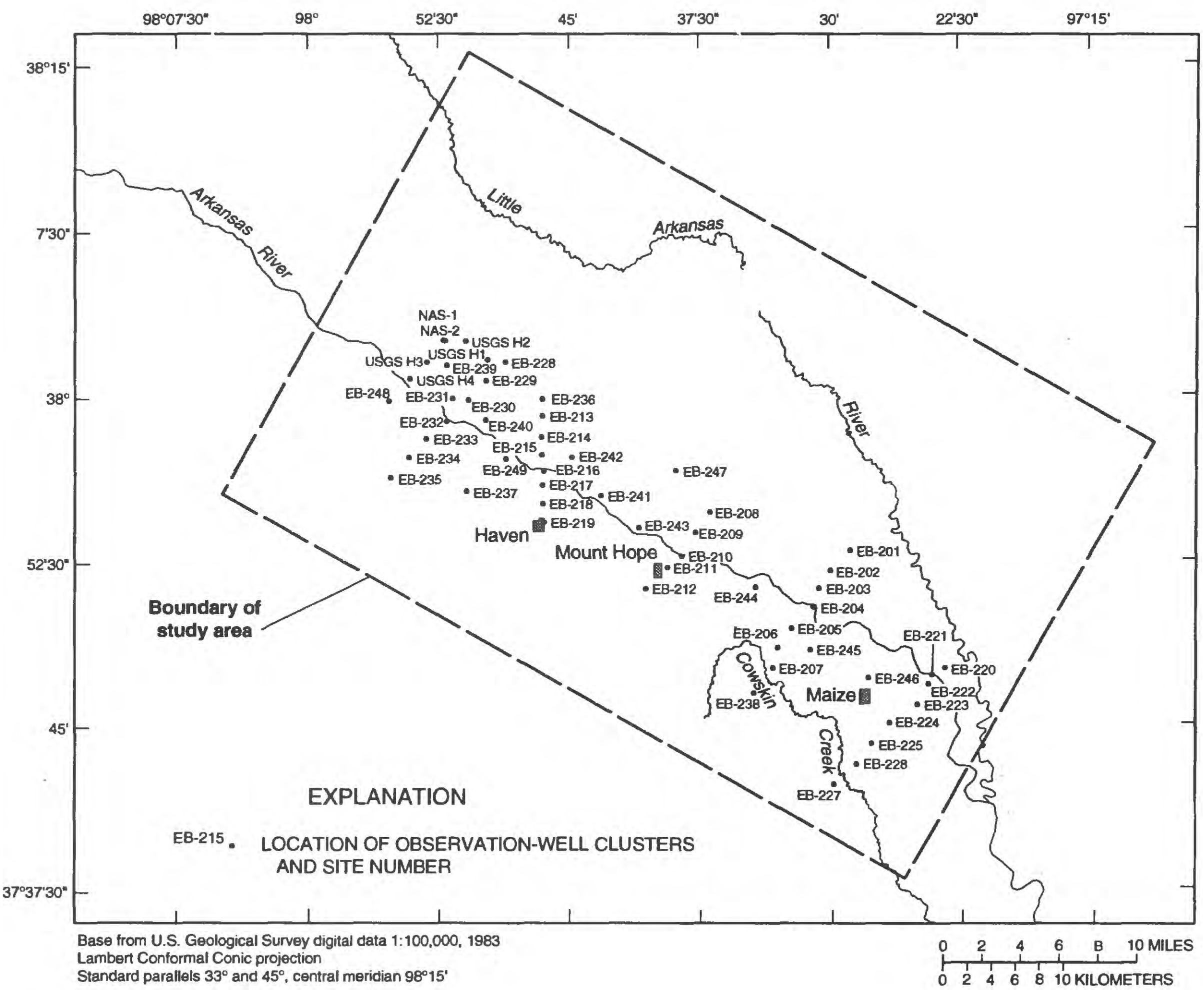


Figure 5. Location of observation-well clusters.

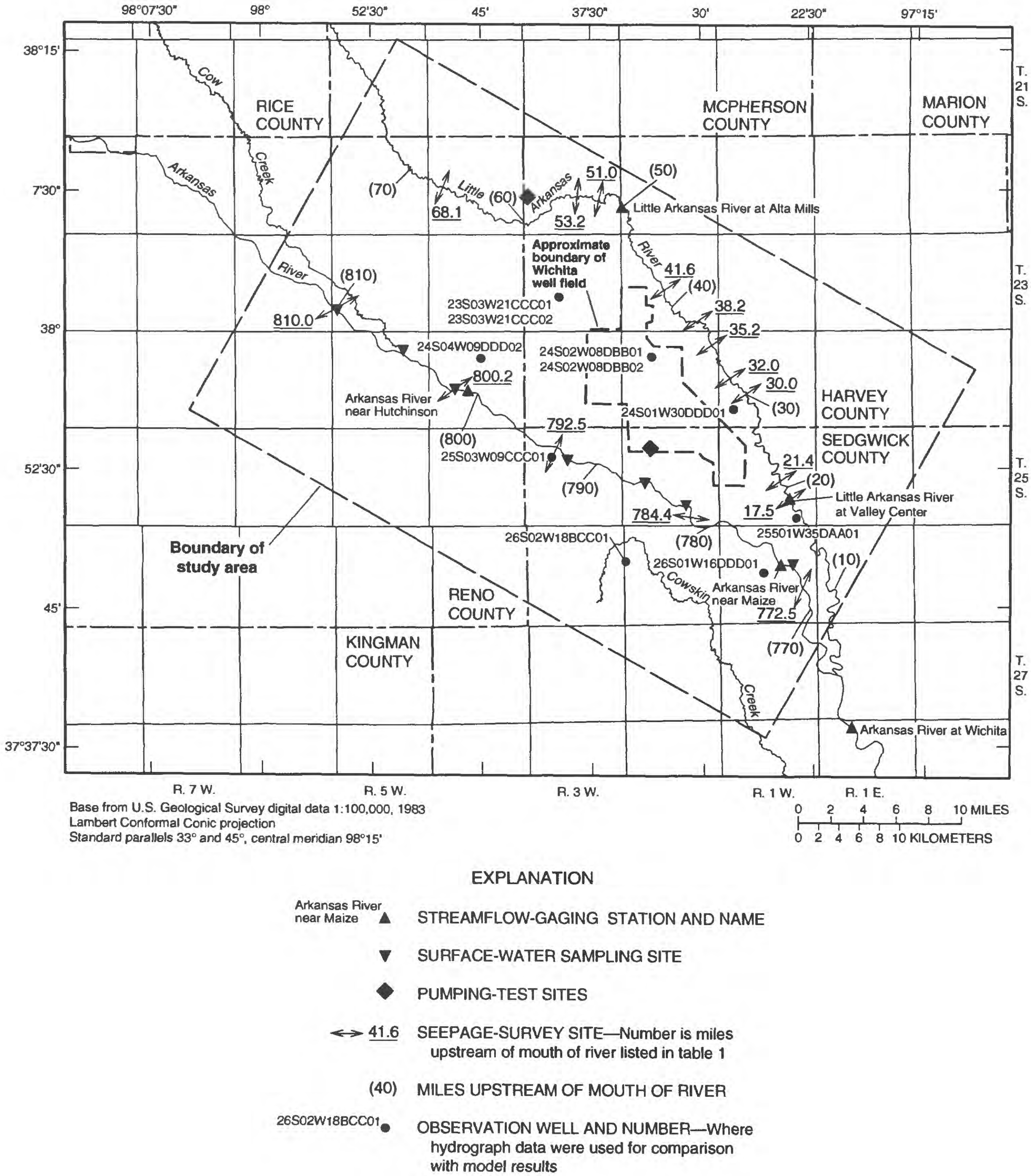


Figure 6. Location of streamflow-gaging stations, surface-water sampling sites, seepage-survey sites, pumping-test sites, and wells for which hydrographs were used to compare measured and simulated hydraulic heads.

period, GMD2 personnel measured, on a monthly basis, water levels in network observation wells and stream stage at selected bridges along the Arkansas River.

Seepage data for the Arkansas and Little Arkansas Rivers were obtained from USGS files in Lawrence, Kansas, for the years prior to this study (before 1988). Two seepage surveys were completed on the Arkansas River for this study during April 1989 and September 1990. The seepage surveys were done using USGS methods for the measurement and computation of streamflow (Rantz and others, 1982).

Hydraulic-conductivity, recharge, evapotranspiration, and pumpage data for the ground-water flow model were obtained, in large part, from data sets of a single-layer ground-water flow model developed by Spinazola and others (1985). Water-level data collected during 1938–42 and reported in studies by Williams (1946) and Williams and Lohman (1949), and potentiometric-surface maps published by Williams and Lohman (1949) and Spinazola and others (1985) were modified to construct a circa-1940 potentiometric-surface map. A steady-state model was developed to simulate conditions that existed during the late 1930's (pre-1940) (Spinazola and others, 1985). Three model layers were defined on the basis of lithologic data from the observation-well network along the Arkansas River and lithologic logs published by Williams (1946) and Williams and Lohman (1949). Steady-state flow-model data were adjusted during the calibration process to approximate the pre-1940 potentiometric surface. Then, a transient model was developed to simulate conditions in the aquifer from 1940 to 1989. Flow-model aquifer properties and stresses were refined during calibration of the transient model to approximate streamflows; 1971, 1980, and 1989 potentiometric surfaces; and water-level changes for 10 observation wells in the study area.

Previous Studies

The *Equus* beds aquifer is an important source of water to cities, industries, and farms. Because of the importance of this source of water and because of the occurrence of large chloride concentrations in parts of the aquifer, in streams, and in adjacent rocks, the *Equus* beds aquifer has been the subject of many studies. Williams and Lohman (1949) extensively described the geology and ground-water resources of the *Equus* beds. Williams (1946) described ground-water conditions near Hutchinson. Williams and Lohman (1947), Stramel (1956, 1962a, 1962b, 1967), and Petri and others (1964) have studied the aquifer in the Wichita well field area. Bayne (1956) and Lane and Miller (1965a) described the geology and hydrology of Reno and Sedgwick Counties, respectively. Bevans (1988) described the water resources of Sedgwick County.

Chloride concentrations in the *Equus* beds aquifer have been the subject of several studies. Leonard and Kleinschmidt (1976) studied the occurrence of saline water in the Little Arkansas River Basin, Hathaway and others (1981) studied the chemical quality of irrigation water in the *Equus* beds area, Williams (1946) discussed the origin of large concentrations of chloride in the aquifer near Hutchinson, and Gogel (1981) discussed the potential for discharge of saltwater from Permian-age rocks to the *Equus* beds. Whittemore (1982, 1990) and Whittemore and Basel (1982) identified sources of saltwater brines in the *Equus* beds using chloride-iodide and chloride-bromide ratios.

Investigators in previous ground-water flow and solute-transport modeling studies have simulated the *Equus* beds aquifer as one layer. These studies focused on the overall or specific aspects of the ground-water flow system and on the movement of chloride derived from concentrated sources such as oil-field brine or natural brine from the Wellington Formation. None, however, focused on the interaction between the Arkansas River and *Equus* beds aquifer.

Ground-water flow models of all or part of the *Equus* beds have been developed to determine the long-term safe yield of the aquifer (Green and Pogge, 1977; McElwee and others, 1979) and to describe the ground-water flow in the *Equus* beds aquifer (Spinazola and others, 1985) and between the *Equus* beds aquifer and the underlying Wellington aquifer (Gogel, 1981; Spinazola and others, 1985). Solute-transport models have been used to simulate the movement of chloride in the *Equus* beds aquifer (Sophcleous, 1983; Spinazola, 1985) and to develop water-use management strategies for aquifer reclamation and restoration (Heidari and others, 1986).

Acknowledgments

The authors wish to thank Shirley Shaddix, Bureau of Reclamation, for her time and effort in coordinating this study with the participating agencies. Most of the wells in the observation-well network installed along the Arkansas River were drilled by the Bureau of Reclamation. Mike Dealy and Don Koci, Equus Beds Groundwater Management District No. 2, measured a large number of water levels and collected water samples.

GEOLOGY

The oldest rocks that either crop out in the study area or subcrop beneath the *Equus* beds are the

Wellington Formation and Ninnescah Shale of Permian age (fig. 3). The Wellington Formation and Ninnescah Shale together make up the Sumner Group. The Sumner Group is underlain by rocks of the Chase Group. The Wellington Formation and the Ninnescah Shale rocks dip gently to the west. The Wellington Formation underlies the *Equus* beds in most of the study area.

The Wellington Formation is about 700 ft thick (Bayne, 1956) and is divided into the lower anhydrite member, Hutchinson Salt Member, and the upper shale member. The lower anhydrite member consists of about 200 ft of gray shale and silty shale with some carbonate lenses and thin anhydrite beds. The Hutchinson Salt Member consists of salt beds, interbedded halite, anhydrite, and shale that lie about 650 ft below land surface at Hutchinson (Bayne, 1956) and is mined at that location. The salt beds are about 300 ft thick at Hutchinson and reach a maximum thickness of 450 ft to the southwest, but thin rapidly to the northeast (fig. 7) due to dissolution of the salt by freshwater (Gogel, 1981). The upper shale member of the Wellington Formation consists of gray, green, and maroon shale interbedded with thin layers of limestone, dolomite, anhydrite, and gypsum (Bayne, 1956). The upper shale member is about 200 ft thick. The upper shale member is overlain by sediment of Quaternary age in about the eastern two-thirds of the study area. In this area, the upper surface of the upper shale member forms the bedrock surface. In about the western one-third of the study area, the upper shale member is overlain by the Ninnescah Shale.

The Ninnescah Shale crops out (fig. 3) or subcrops in the western part of the study area. It consists of red silty shale, siltstone, and fine-grained sandstone (Bayne, 1956). Gray-green streaks and spots are common in the unit. The maximum thickness is estimated to be 300 ft (Bayne, 1956). Southwest of the study area, the Ninnescah Shale contains a salt bed, but this salt bed has not been identified in the study area. The Ninnescah Shale is overlain by sediment of Quaternary age in about the western one-third of the study area. In this area, the upper surface of the Ninnescah Shale forms the bedrock surface.

Dissolution of the Hutchinson Salt Member and subsequent subsidence and collapse of overlying rock caused as much as 350 ft of Quaternary sediment to accumulate in subsiding areas. Areas of present-day subsidence are indicated by a linear trend of water-filled depressions and sinkholes at land surface (Williams and Lohman, 1949). Because of salt dissolution and pre-Quaternary erosion, the bedrock surface is irregular and is generally lowest where the greatest thickness of salt has been dissolved (fig. 8). The lowest part of the bedrock surface forms a depression, which lies near the present-day course of the Arkansas River. This bedrock-surface map has been updated with data obtained during this study and so may not match exactly the bedrock surface shown in figure 7.

Quaternary deposits occur throughout the study area as alluvial deposits, sand dunes, and loess deposits (fig. 3). The alluvial deposits, known as the *Equus* beds, are from 0 to about 350 ft thick in the study area. For the purposes of this study, the *Equus* beds sediment was divided into lower, middle, and upper units on the basis of gamma logs and lithologic descriptions; refer to the "Supplemental Information" section, plates 1 and 2, Williams (1946), Williams and Lohman (1949), and Lane and Miller (1965b). The lower and upper units primarily consist of sand and gravel interbedded with clay or silt but may consist primarily of clay with thin sand and gravel layers. Sand in the lower unit, in general, is finer grained than sand in the upper unit. The middle unit primarily consists of clay or silty clay interbedded with sand and gravel but may consist primarily of sand and gravel with thin clay layers. The middle unit generally has more fine-grained material than the lower and upper units.

Sand dunes overlie the Ninnescah Shale near Hutchinson and overlie *Equus* beds sediment east of Hutchinson (fig. 3). Dune deposits consist of fine-grained tan sand with interbedded buried soil layers of silt, clay, and organic-material mixtures (Williams, 1946). The maximum thickness of dune sand is about 150 ft, but in most areas, dune sands do not exceed 30 to 50 ft in thickness.

Loess deposits occur primarily on uplands southwest of the Arkansas River (fig. 3). These windblown silt deposits are about 30 ft thick on uplands but thin rapidly towards the Arkansas River (Lane and Miller, 1965b).

HYDROLOGY

Surface Water

The Arkansas River, the Little Arkansas River, and their tributaries constitute the stream-drainage system in the study area. Flow in these streams is maintained primarily by base flow from the adjacent

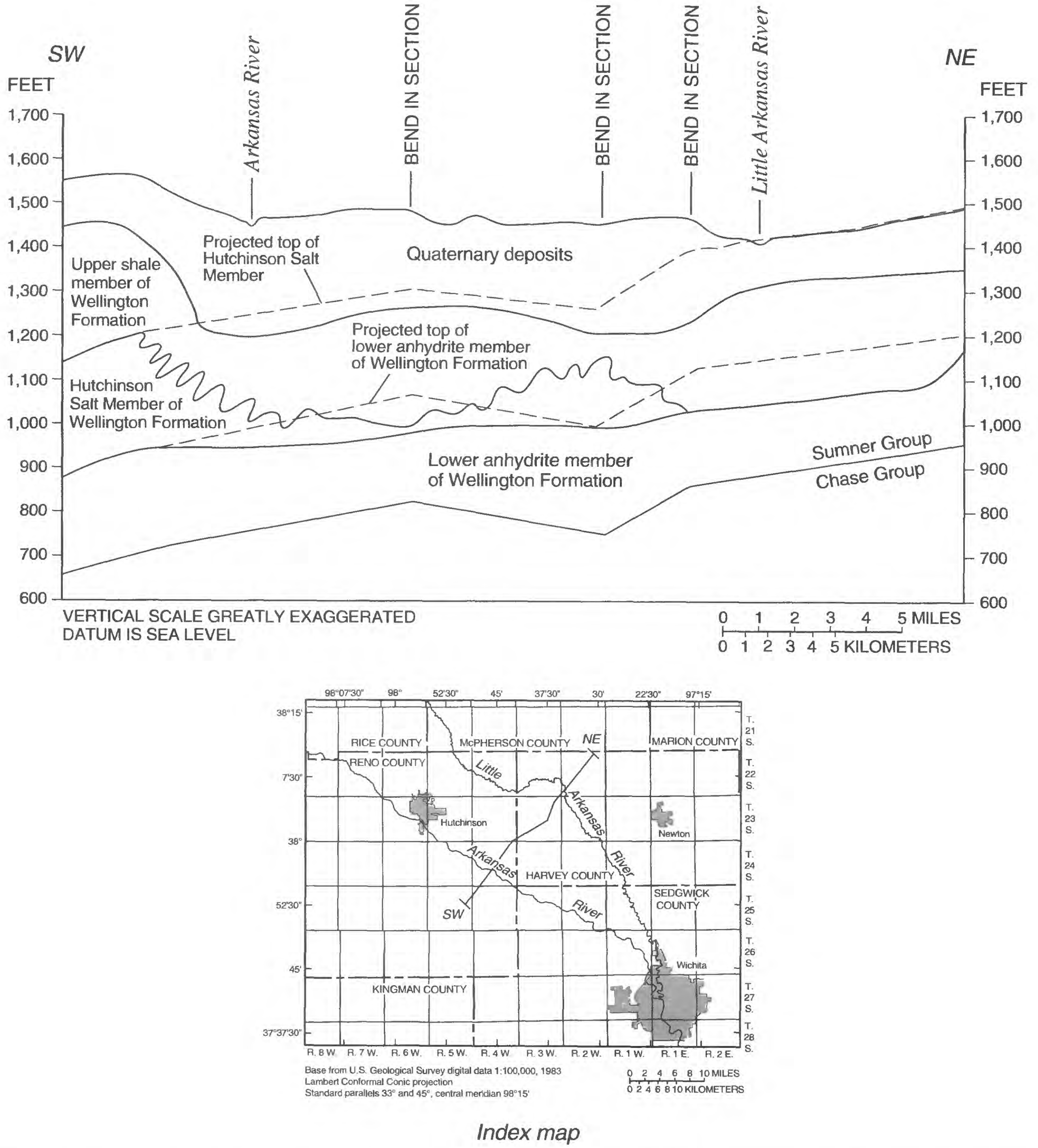


Figure 7. Generalized geologic section showing present and projected past extent of the Hutchinson Salt Member (modified from Leonard and Kleinschmidt, 1976).

aquifer. Most of the base flow ultimately is derived from precipitation that recharges this aquifer (Bevans, 1988).

Seepage data collected during this study and from files at the USGS (Lawrence, Kans.) for the Arkansas River (table 1, fig. 9) for the 1980's and

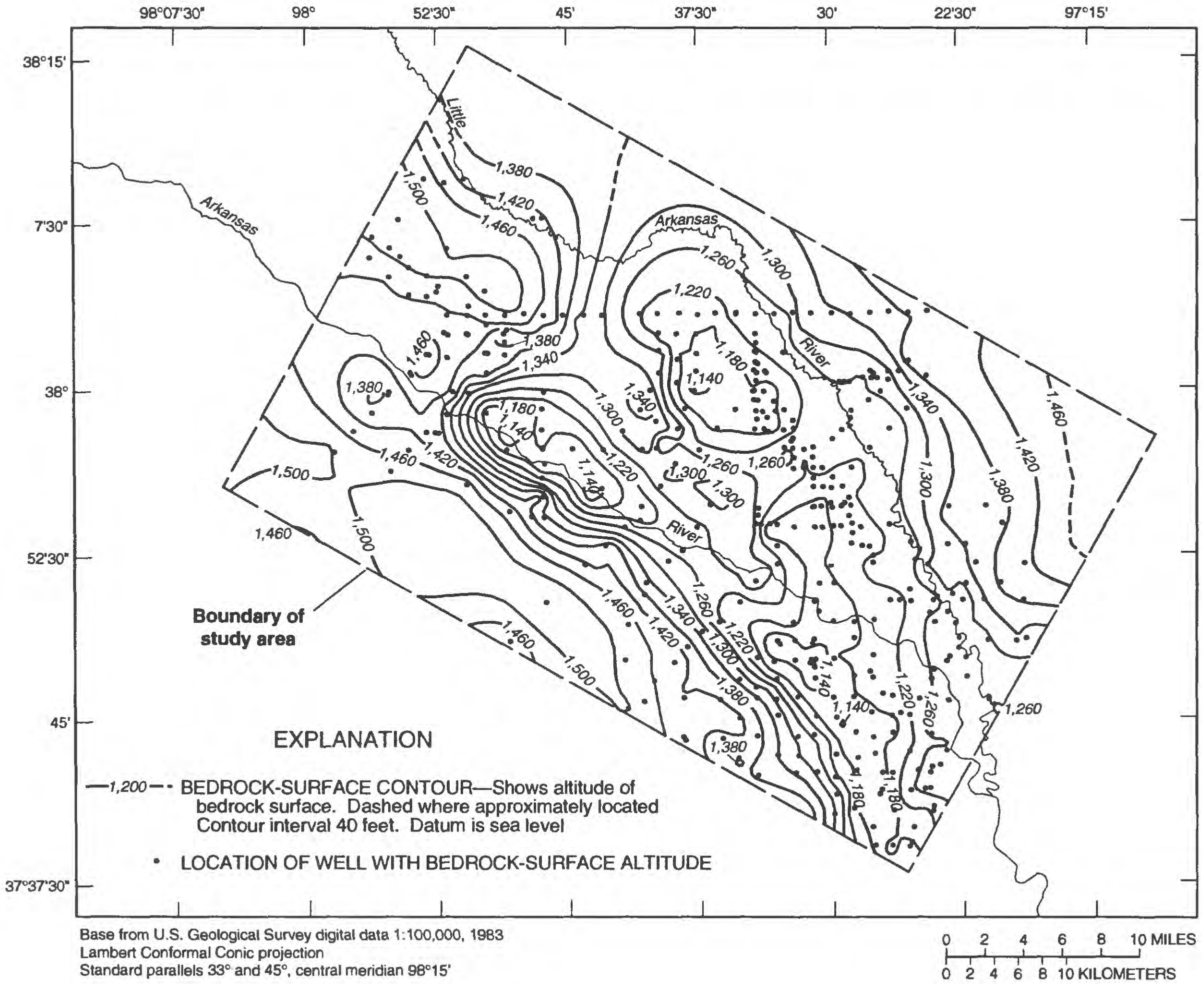


Figure 8. Altitude of bedrock surface (modified from Williams and Lohman, 1949; Lane and Miller, 1965a; and Spinazola and others, 1985).

1990 show that the river gains or loses water in the upper reach and loses water in the lower reach. When the upper reach of the river is gaining, the point at which the river changes from a gaining stream to a losing stream is between the Haven (*C–C'*) and Bentley (*E–E'*) hydrogeologic sections; this point probably moves upstream or downstream with changes in river stage and aquifer stresses.

The Little Arkansas River is primarily a gaining stream within the study area. Seepage data from files of the USGS (Lawrence, Kans.) (table 1, fig. 10) for the 1960's and 1970's show that the rate of gain is largest downstream of river mile 53.2. Some of this gain may be due to contributions from tributaries.

Streamflow hydrographs for the Arkansas River near Hutchinson, the Arkansas River near Maize, the Arkansas River at Wichita, the Little Arkansas River at Alta Mills, and the Little Arkansas River at Valley Center show seasonal streamflow patterns (figs. 11 and 12). Figures 11*A* and 12*A* show the monthly mean streamflow for the period for which there is contemporaneous streamflow data—March 1987–December 1991 for the three gaging stations on the Arkansas River and July 1973–December 1991 for the two gaging stations on the Little Arkansas River. In general, the largest streamflows in both rivers occur during the spring and summer months when most of the annual precipitation occurs. Smaller streamflows occur during the dryer fall and winter months.

Streamflow of the Arkansas River at Maize was less than streamflow of the Arkansas River near Hutchinson about one-half of the time for the

Table 1. Seepage-survey data available for the Arkansas and Little Arkansas Rivers

[Data collected during this study and from files of the U.S. Geological Survey, Lawrence, Kans.]

River mile upstream of mouth (fig. 6)	Date (month/day/year)	Streamflow (cubic feet per second)	Gain (+) or loss (-) between measuring sites (cubic feet per second)
Arkansas River			
800.2	03/17/81	80	--
792.5	03/17/81	72	-8.0
772.5	03/17/81	67	-5.0
800.2	12/03/87	261	--
792.5	12/03/87	268	+7.0
784.4	12/03/87	282	+14
772.5	12/03/87	261	-21
800.2	04/20/89	81	--
792.5	04/20/89	66	-15
784.4	04/20/89	85	+19
772.5	04/20/89	59	-26
810.0	09/11/90	95	--
800.2	09/11/90	120	+25
792.5	09/11/90	107	-13
784.4	09/12/90	94	-13
772.5	09/12/90	84	-10
Little Arkansas River			
68.1	11/21/68	7.4	--
41.6	11/21/68	29	+21.6
35.2	11/21/68	32	+3.0
17.5	11/21/68	84	+52
68.1	11/13/69	2.6	--
53.2	11/13/69	3.6	+1.0
41.6	11/13/69	15	+11.4
35.2	11/13/69	18	+3.0
17.5	11/13/69	55	+37
68.1	02/20/70	2.9	--
41.6	02/18/70	21	+18.1
35.2	02/19/70	20	-1.0
68.1	09/10/70	.06	--
53.2	09/10/70	.18	+.12
41.6	09/10/70	5.8	+5.62
35.2	09/10/70	6.2	+.40
Little Arkansas River—Continued			
53.2	04/15/71	6.1	--
51.0	04/15/71	13	+6.9
38.2	04/15/71	18	+5.0
32.0	04/15/71	21	+3.0
30.0	04/15/71	22	+1.0
21.4	04/15/71	41	+19
17.5	04/15/71	46	+5.0
68.1	09/29/71	.55	--
53.2	09/30/71	1.4	+.85
41.6	09/30/71	10	+8.6
35.2	09/30/71	11	+1.0
17.5	10/01/71	24	+13
68.1	12/09/71	5.2	--
53.2	12/09/71	7.5	+2.3
41.6	12/10/71	22	+14.5
35.2	12/10/71	24	+2.0
68.1	11/07/72	4.9	--
41.6	11/08/72	7.0	+2.1
38.2	11/08/72	15	+8.0
35.2	11/08/72	16	+1.0
17.5	11/08/72	51	+35

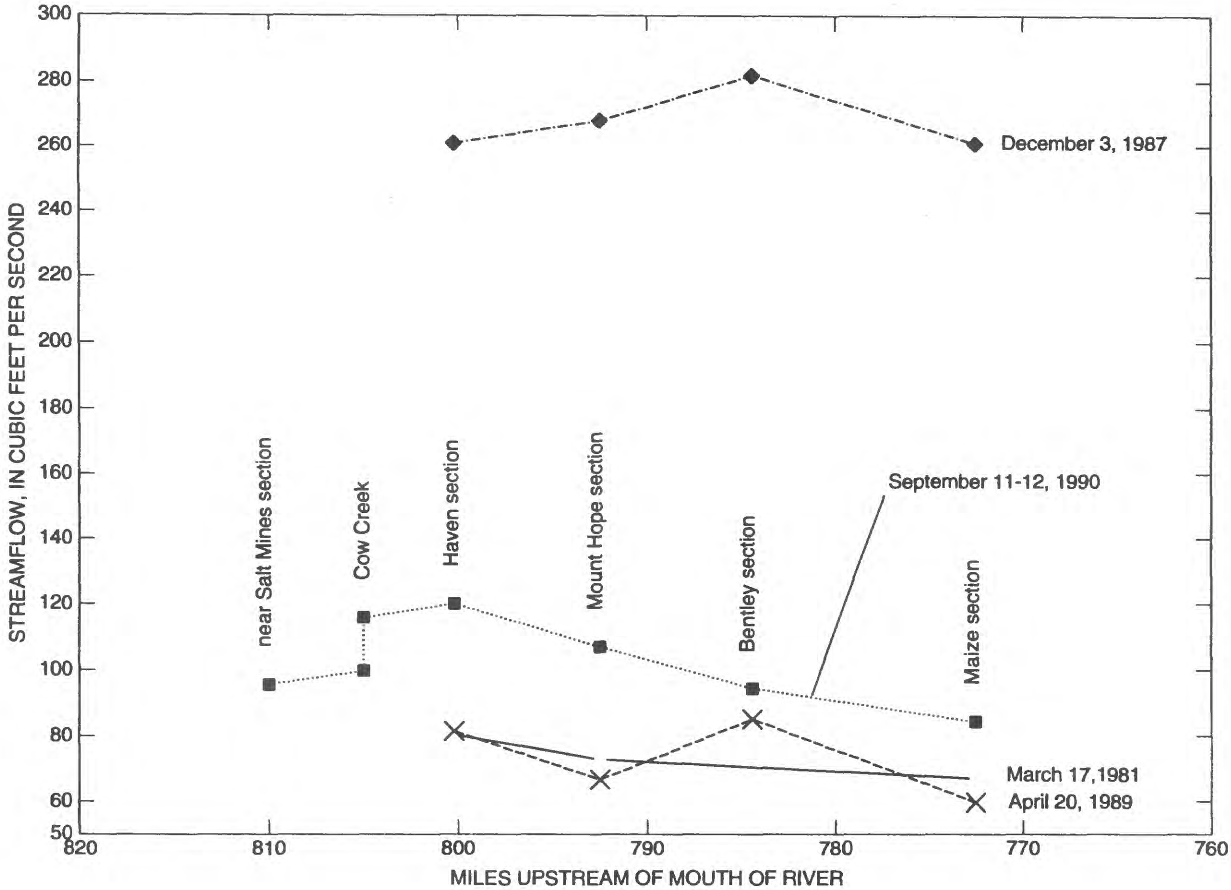


Figure 9. Measured streamflow in the Arkansas River during seepage surveys (seepage-survey sites shown in figure 6; hydrogeologic-section locations shown in figure 3; seepage data collected during this study and from files of the U.S. Geological Survey, Lawrence, Kans.).

contemporaneous period of record (fig. 11*B*). This relation usually occurs during the late-summer to early-spring months when small streamflows occur but may persist into late spring and summer during periods of less-than-normal rainfall, such as occurred in 1991 (fig. 11*B*). Streamflow of the Arkansas River at Wichita usually exceeds the streamflow at Maize or near Hutchinson (fig. 11*A*) because of the additional streamflow from the Little Arkansas River and other tributary streams. Streamflow of the Little Arkansas River at Valley Center rarely was less than streamflow of the Little Arkansas River at Alta Mills for the contemporaneous period of record (fig. 12*B*). The smallest differences in streamflow usually occur during the late-summer to early-spring months.

Ground Water

Equus beds sediment is an important source of ground water because of the generally shallow depth to the water table and the large saturated thickness. Near the Arkansas River, the water table may be as little as 10 ft below land surface. Farther from the river and near the Little Arkansas River, the water table may be at a greater depth below land surface, depending on the altitude of land surface and the amount of water-table decline that has been caused by long-term pumping. Data collected during this study indicate that the maximum saturated thickness within the study area, about 300 ft, is near the course of the Arkansas River and corresponds to the lowest areas of the bedrock surface (fig. 8).

The potentiometric-surface maps for 1940 and 1989 represent the composite potentiometric surface for all three units of the *Equus* beds aquifer. There were insufficient water-level data for some parts of the study area to construct separate potentiometric-surface maps for all three units. In areas where water-level data are available for all three units, such as near the Arkansas River, water-level altitudes in the three units

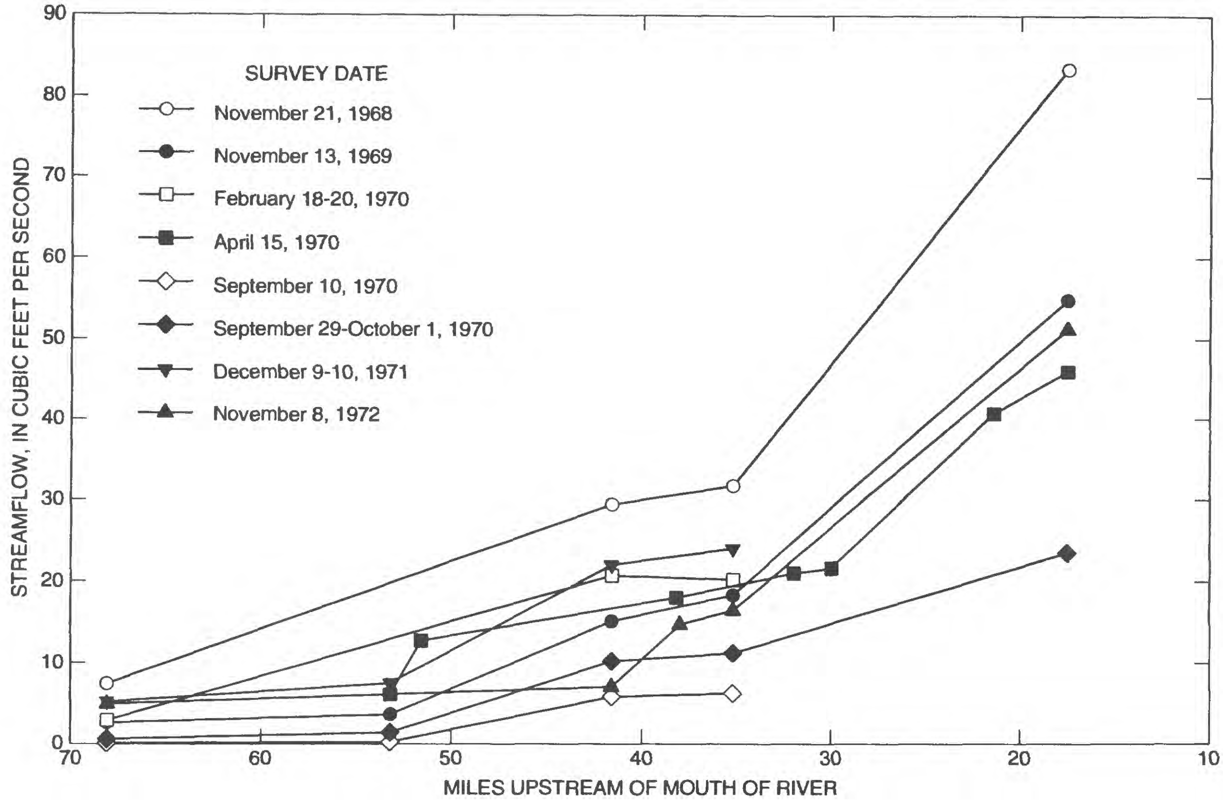


Figure 10. Measured streamflow in the Little Arkansas River during seepage surveys (seepage-survey sites shown in figure 6; seepage data from files of the U.S. Geological Survey, Lawrence, Kans.).

are similar (plates 1 and 2) except in the area of well sites EB-203 and EB-204 (plate 2).

Potentiometric-surface maps for 1940 and 1989 (figs. 13 and 14) indicate that the Arkansas and Little Arkansas Rivers control the direction of ground-water flow in the study area to a large extent. Near the Arkansas River, ground water flows southeast and generally parallels the direction of river flow (figs. 13 and 14). Near the Little Arkansas River, ground water flows towards the river (figs. 13 and 14). Northeasterly flow of ground water occurs southwest of the Arkansas River near Hutchinson (fig. 13). Except for the Wichita well field area, the direction of ground-water flow in 1989 generally is similar to that for 1940. In the Wichita well field area continuous pumping of municipal wells since the early 1940's and seasonal pumping of irrigation wells since the late 1950's have caused ground-water levels to decline as much as 30 ft or more (Lane and Miller, 1965a). Consequently the direction of ground-water flow in 1989 in the Wichita well field area is variable (fig. 14). Water-level data from clustered observation wells along the Arkansas River show that the overall direction of ground-water flow is similar in the upper, middle, and lower units (plates 1 and 2) except in the area of well sites EB-203 and EB-204 (plate 2).

The sand-dune area near Hutchinson contains layers of silt and clay that retard the downward movement of water, as shown by water levels in closely spaced wells that differ by as much as 27 ft (Williams and Lohman, 1949, table 37, wells 375 and 376), and by the presence of interdune ponds (Williams, 1946) and springs (Williams and Lohman, 1949). Nevertheless, the sand dunes are an effective precipitation-capture area and probably recharge the aquifer with a larger percentage of precipitation than other areas in the study area (Williams, 1946). A "ridge" of ground water in *Equus* beds sediment under and near the southern edge of the sand dunes (figs. 13 and 14) indicates that recharge in the sand dunes is larger than in surrounding areas.

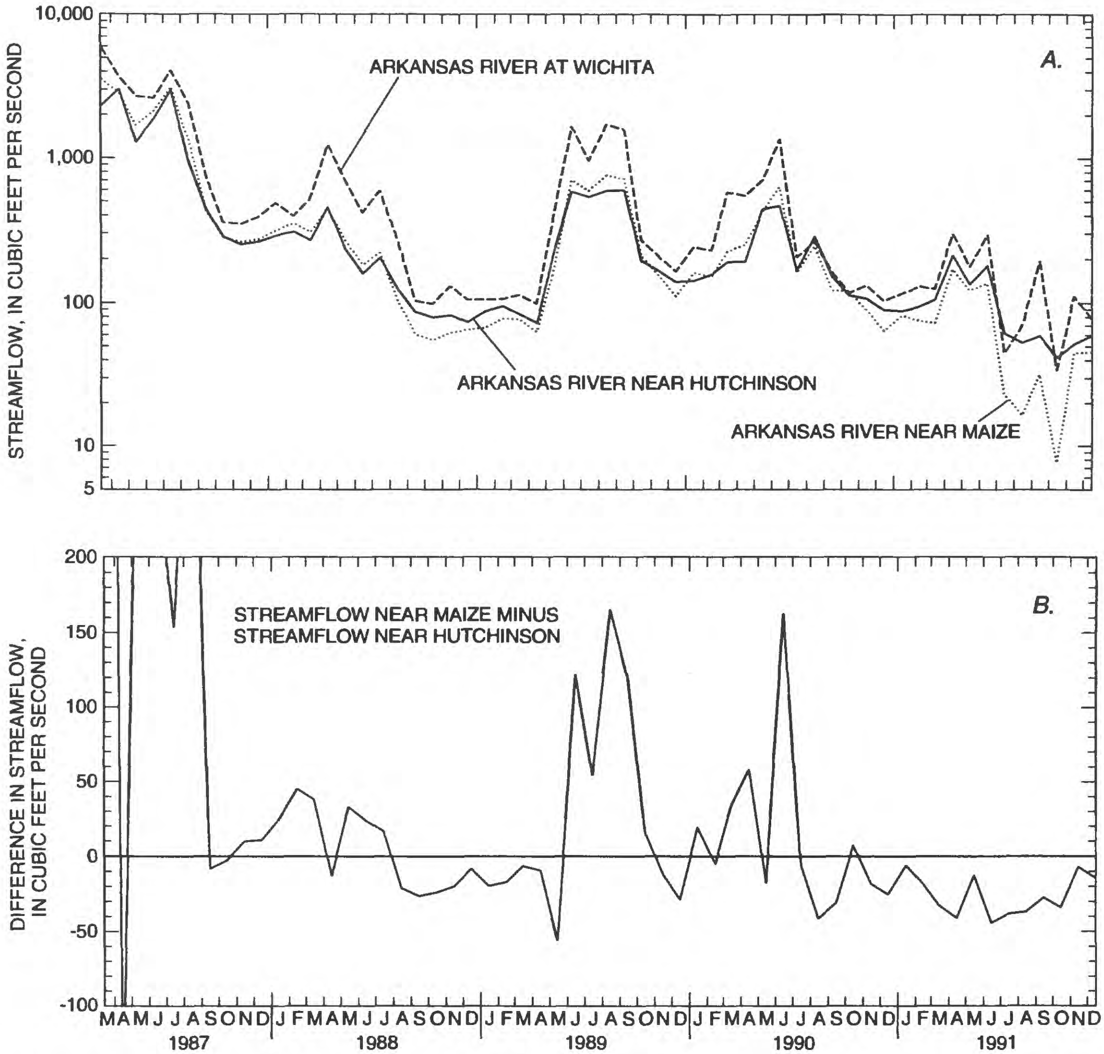


Figure 11. Monthly mean (*A*) streamflow for the Arkansas River near Hutchinson, near Maize, and at Wichita, and (*B*) difference between streamflow near Maize and near Hutchinson.

Hydraulic Relation Between Rivers and Aquifer

The relation of the potentiometric surface to the Arkansas and Little Arkansas Rivers is indicative of the hydraulic conductivity of the sediment near the rivers. Potentiometric-surface contours cross the Arkansas River nearly perpendicular to the channel (figs. 13 and 14). River stage and ground-water levels are very nearly the same because nearby aquifer sediment consists of coarse material that transmits water-level changes readily. Hydrographs from a streamflow-gaging station (Arkansas River near Hutchinson) and a well about 300 ft downstream (well EB-216-AA) show that water-level changes in the river are transmitted very quickly to the nearby well (fig. 15). Water-level changes in the river also are reflected by changes in the water levels in deeper wells at the same site (fig. 16). In contrast, potentiometric-surface contours bend upstream before they cross the Little Arkansas River (figs. 13 and 14). The water level in the aquifer is higher than the water level in the river because nearby aquifer sediment is finer grained and less transmissive than the sediment near the Arkansas River.

Water Use

Withdrawal of water by wells is a significant source of discharge from the *Equus* beds aquifer. Prior to 1940, water withdrawals from the *Equus* beds, which were relatively insignificant in terms of their effects on the aquifer, were mainly for municipal and

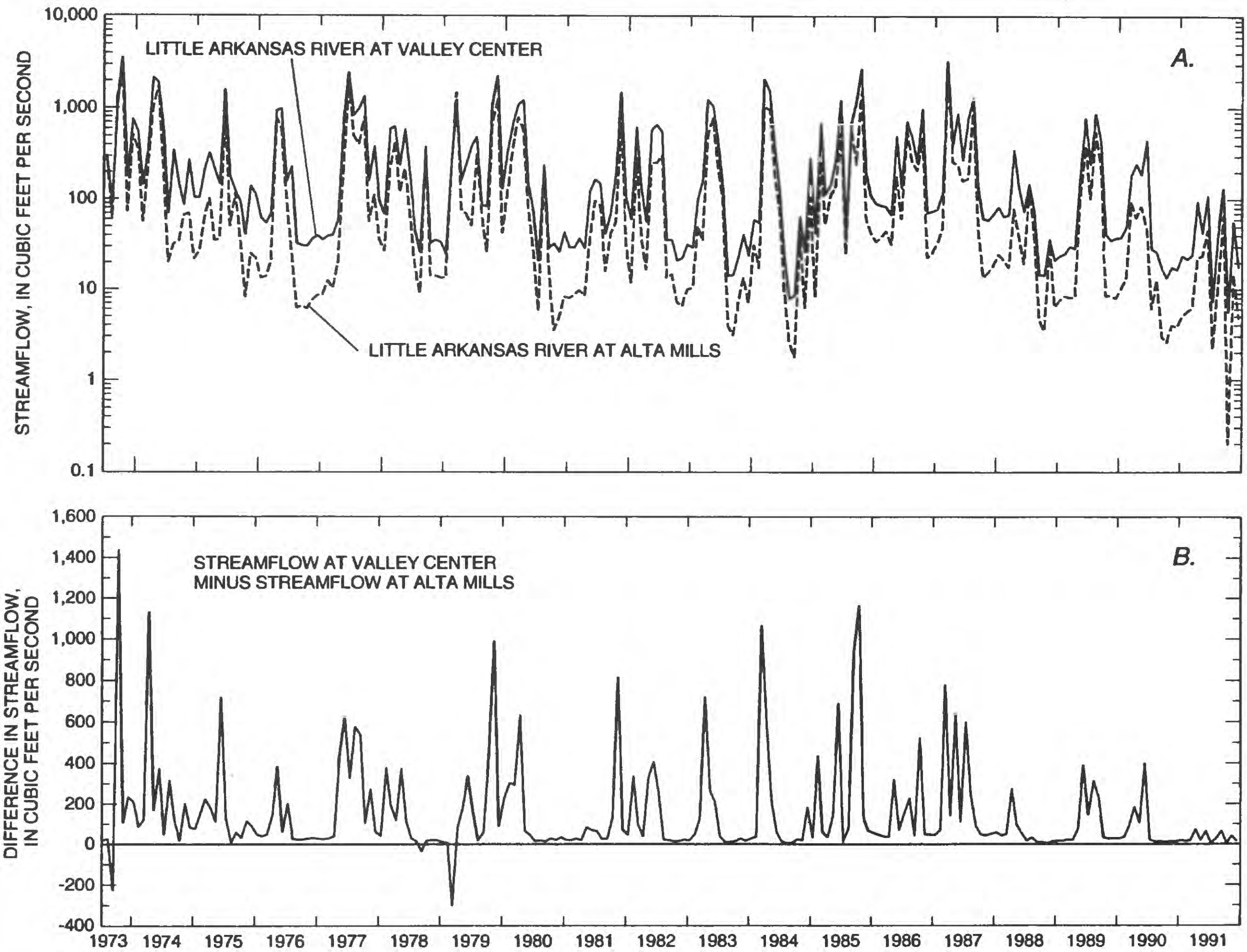


Figure 12. Monthly mean (*A*) streamflow for the Little Arkansas River at Alta Mills and at Valley Center, and (*B*) difference between streamflow at Valley Center and at Alta Mills.

industrial use and occurred near the cities of Hutchinson and Wichita (Spinazola and others, 1985). With the development of 25 wells in the Wichita well field in 1940, municipal water use increased rapidly from 1940 to about 1952 (fig. 17). In 1992, there were 55 municipal wells in the Wichita well field. Water withdrawals from the aquifer were fairly constant throughout the 1950's, but in the late 1950's and early 1960's, agricultural and industrial water uses began increasing. Agricultural water use (primarily irrigation) was fairly uniform in distribution throughout the study area, including the area of the Wichita well field. Industrial water use was limited to local areas. In the mid-1970's agricultural water use increased substantially and has been the single largest use of water since the early 1980's (fig. 17).

Most of the municipal wells in the Wichita well field obtain water from the middle and lower units of the *Equus* beds aquifer. Irrigation wells near the Arkansas River usually obtain water from the upper and middle units because of the large chloride concentrations found in the buried bedrock depression near the course of the river. Irrigation wells farther from the river may obtain water from all three layers. Some industrial wells also may obtain water from all three layers.

CHLORIDE IN WATER

Large concentrations of chloride make water unsuitable for uses such as human and livestock consumption and crop irrigation. The Kansas Department of Health and Environment (1986) has established a Secondary Maximum Contaminant Level (SMCL) of 250 mg/L (milligrams per liter) for

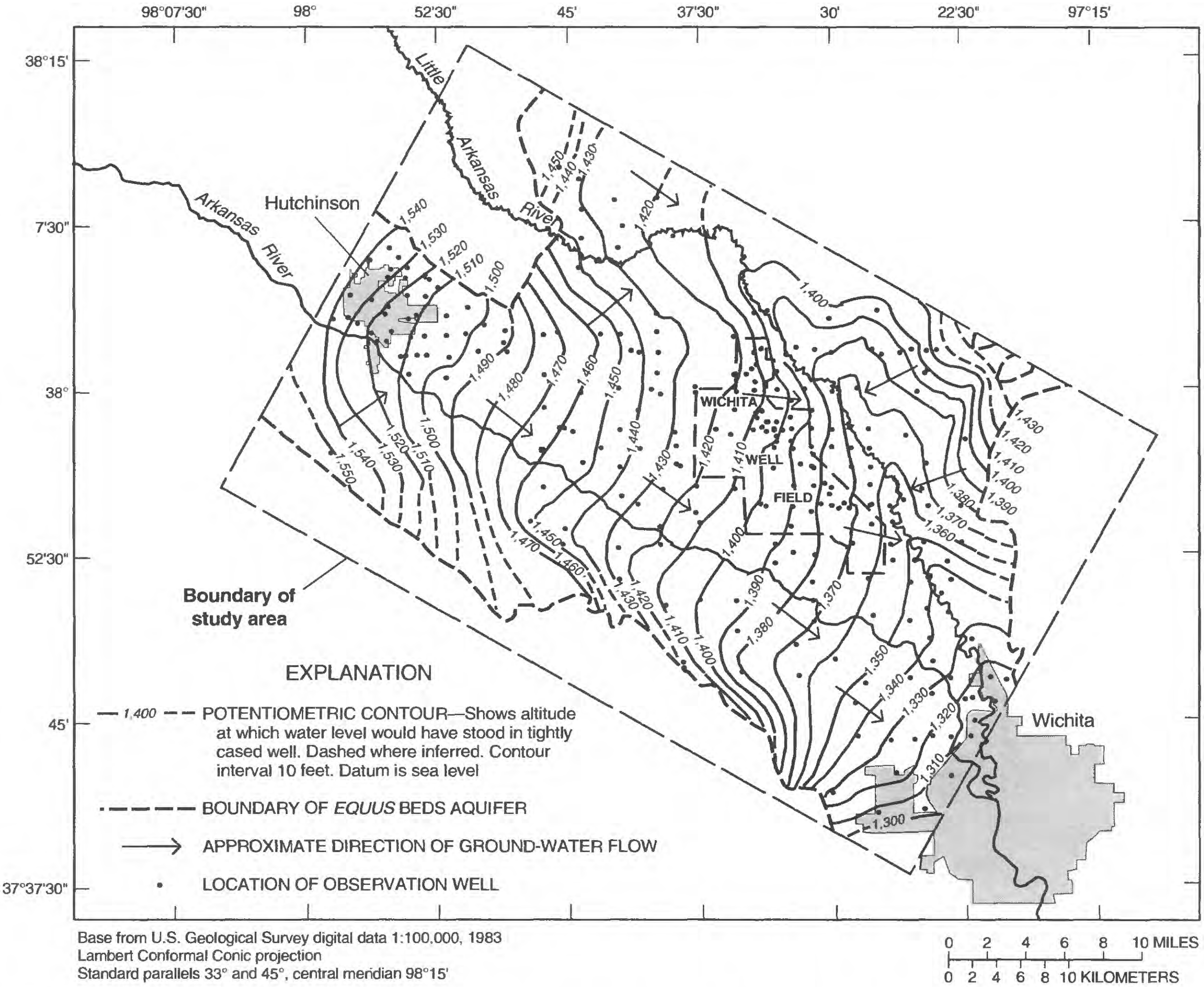


Figure 13. Potentiometric surface in the *Equus* beds aquifer, 1940 (composite of water levels from all three units) (modified from Spinazola and others, 1985).

chloride in drinking water. SMCL's have been established for constituents of water that affect the aesthetic qualities of the water, such as taste, color, or smell. SMCL's are not enforceable.

Sources of Chloride

Two natural sources of chloride and three artificial sources, resulting from human activities, affect ground-water quality in the study area. The two natural sources of chloride are Arkansas River water and saline ground water from the Wellington Formation (Gogel, 1981). The three artificial sources of chloride are brine from oil-field activities, brine from salt-mining activities, and evaporation-pan brine from salt-refining activities. In addition, Williams and Lohman (1949) noted large chloride concentrations in Arkansas River water downstream of a sewage outlet near Hutchinson, probably derived from salt-mining and salt-refining activities.

Because of the multiple sources of the chloride, it was useful to distinguish the naturally derived chloride from the artificially derived chloride. In this way chloride in ground water that came from the Arkansas River could be identified more easily and tracked. During this study, samples of water from the observation-well network along the Arkansas River were analyzed by Whittemore (1990) who used chloride-iodide and chloride-bromide ratios to distinguish chloride from oil-field, salt-refining, and natural sources. Chloride from salt-mining activities was indistinguishable from chloride from natural

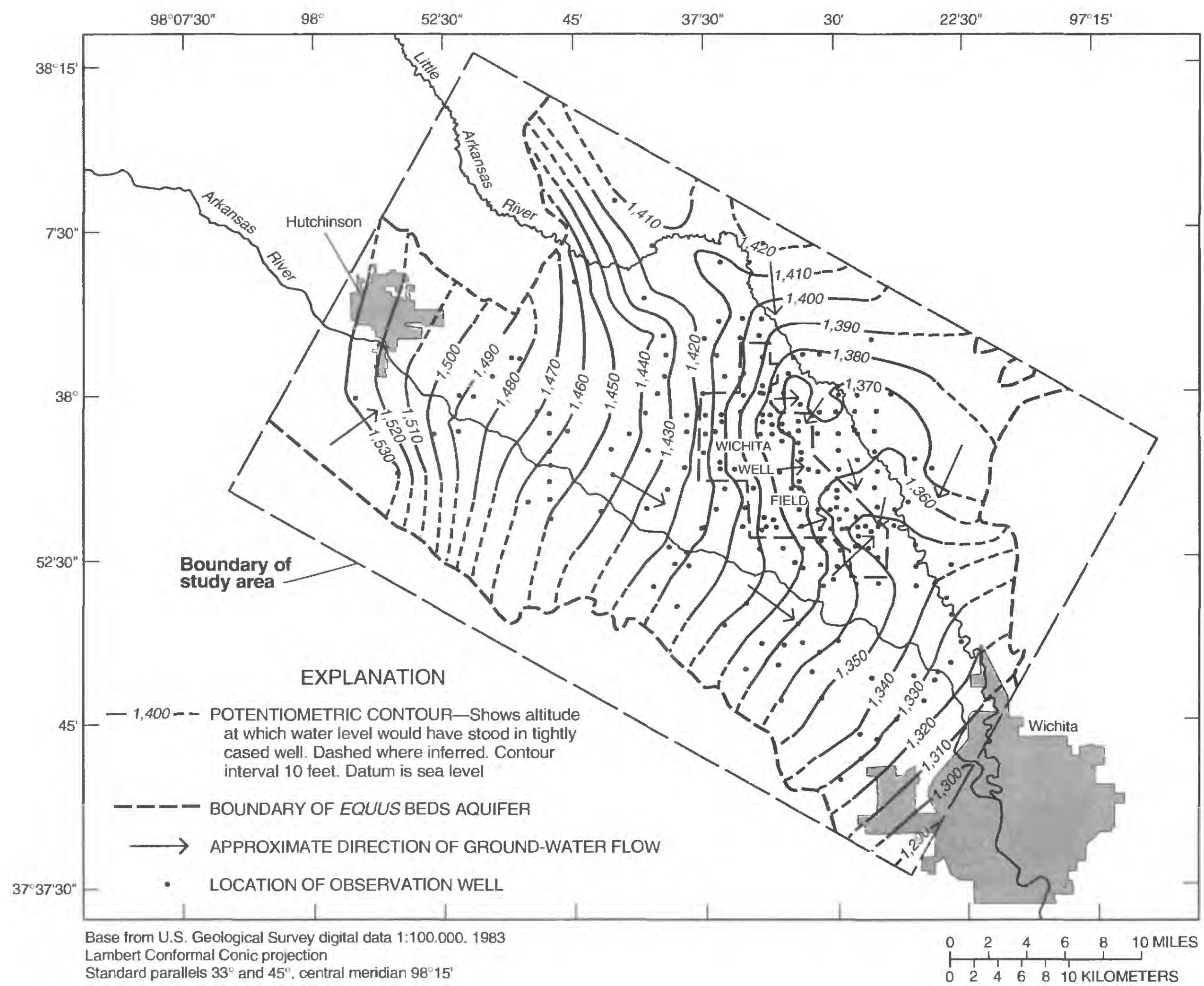


Figure 14. Potentiometric surface in the *Equus* beds aquifer, 1989 (composite of water levels from all three units) (data from the U.S. Geological Survey WATSTORE data base).

sources. However, chloride from mining activities most likely would be found in the vicinity of the salt mines near Hutchinson. Using mixing curves, Whittemore (1990) also determined the concentrations of chloride in samples that were derived from oil-field, salt-refining, and natural sources.

Chloride in Surface Water

Chloride concentrations in Arkansas River water increase downstream of Great Bend, Kans. (fig. 1). Much of the chloride probably comes from salt marshes on tributaries to the Arkansas River upstream of Hutchinson (Williams, 1946). Within the study area, water from the Arkansas River is classified as brackish or salty (Williams, 1946). Williams and Lohman (1949) reported that concentrations of chloride in Arkansas River water samples collected during the winter of 1934–35 at two sampling sites near Hutchinson ranged from 392 to 460 and 750 to 1,895 mg/L. The largest chloride concentrations were downstream of the sewage outlet near Hutchinson (Williams and Lohman, 1949). Chloride concentrations were as large as 1,400 mg/L and were generally larger than 1,000 mg/L during low river flows in the fall of 1937 (Williams and Lohman, 1949).

Samples of Arkansas River water were collected during this study at sampling sites along the river (fig. 6) near Hutchinson, Haven, Mount Hope, Bentley, and Maize. Median chloride concentrations for each of the five sites ranged from 620 to 640 mg/L (table 2). The median chloride concentration for all

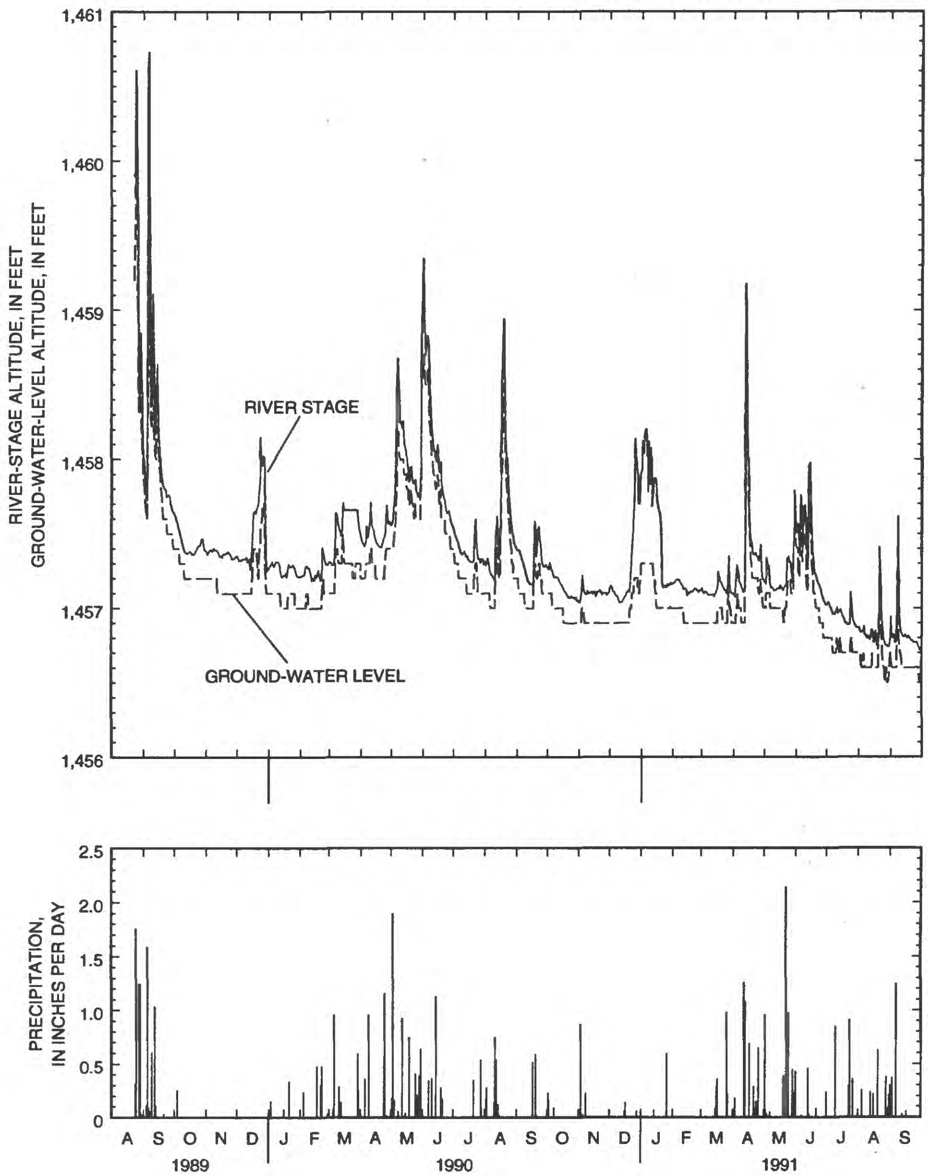


Figure 15. Daily mean river-stage altitude of the Arkansas River near Hutchinson (gaging station 07143330), daily mean water-level altitude in nearby well EB-216-AA, and daily precipitation rate at streamflow-gaging station, August 1989–September 1991. Well EB-216-AA was completed in the upper unit of the *Equus* beds aquifer and is perforated from 20 to 30 feet below land surface.

175 samples was 630 mg/L (table 2). Figures 18*A* and 18*B* show that generally there is an inverse relation between flow in the river and chloride concentration. Chloride loads in the river (fig. 18*C*) are a function of flow and concentration, and fluctuate depending primarily on streamflow but also on the chloride concentration of the stream water.

The Little Arkansas River also is known to have had salty water although generally not in as large concentrations as in the Arkansas River. Leonard and Kleinschmidt (1976) reported that chloride concentrations in water samples collected during 1960–72 at Valley Center ranged from 56 to 220 mg/L. The maximum chloride concentrations in the Little

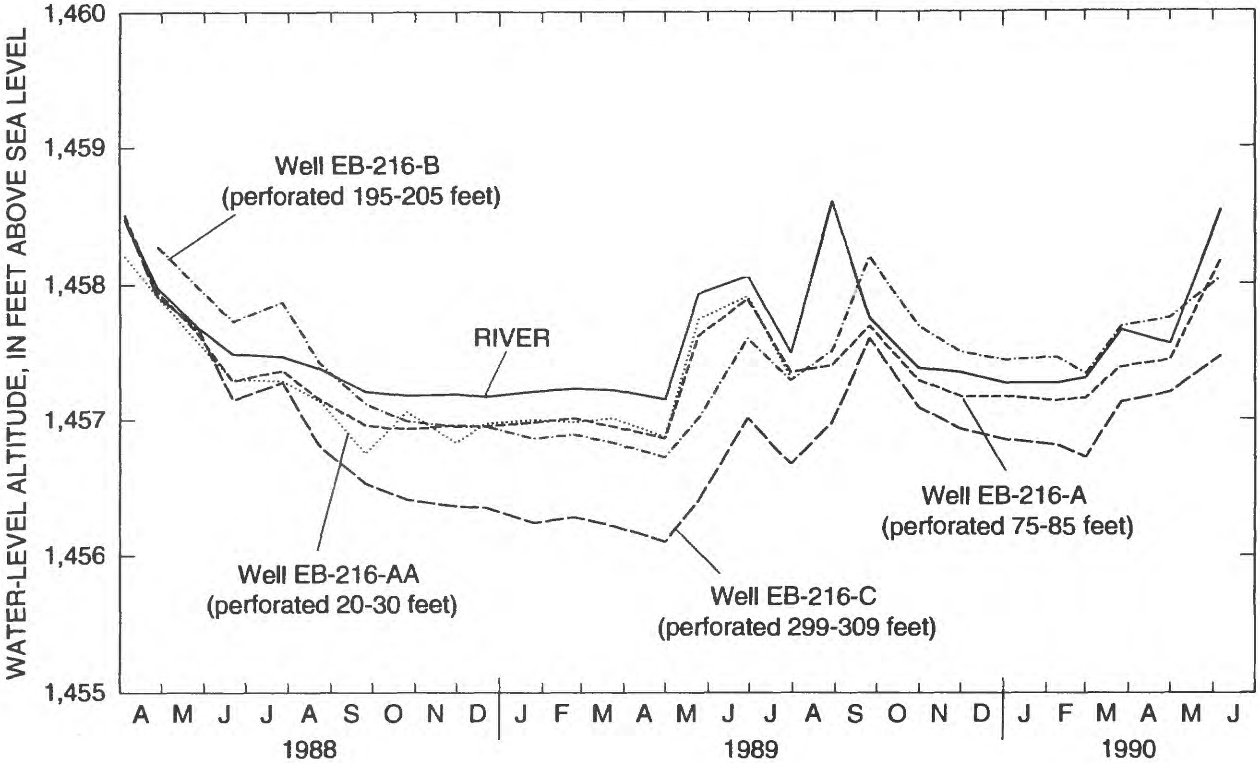


Figure 16. Monthly instantaneous ground-water levels in wells EB-216-AA, EB-216-A, EB-216-B, and EB-216-C and the daily mean river stage of the Arkansas River near Hutchinson for those days when ground-water levels were measured, April 1988–May 1990.

Arkansas River occurred near the mouths of tributaries draining oil-field areas (Leonard and Kleinschmidt, 1976).

Chloride in Ground Water

Williams (1946) found that chloride concentrations in wells within 1 mi of the Arkansas River in the vicinity of Hutchinson ranged from "... a few hundred..." to 1,200 mg/L. He also found that, with the exception of ground-water wells in oil fields, the chloride concentrations in ground water were progressively smaller farther from the river. In general, this is the pattern for the entire river reach from Hutchinson to Wichita. Hathaway and others (1981, fig. 9) showed that chloride concentrations generally ranged from 75 to 250 mg/L in an area along the Arkansas River, and concentrations exceeded 250 mg/L at some locations. Hathaway and others (1981) also stated that a comparison of data from Williams and Lohman (1949) and data from their study "...suggests that pumpage of wells in the Wichita well field area has produced little apparent change in chloride concentration levels of waters in this region."

Chloride analyses of water samples collected during this study (fig. 19) show a pattern similar to that found by Hathaway and others (1981). The concentrations shown in figure 19 represent the concentrations of natural chloride in ground water based on geochemical identifications by Whittemore (1990). Thus, in areas where chloride from oil-field and salt-refining brines is present, the chloride concentration shown in figure 19, which represents the natural chloride concentration, is some fraction of the total concentration of dissolved chloride. The largest concentrations of natural chloride were found in the lower unit of the *Equus* beds aquifer (fig. 19*C*). These large concentrations may result from subsurface flow

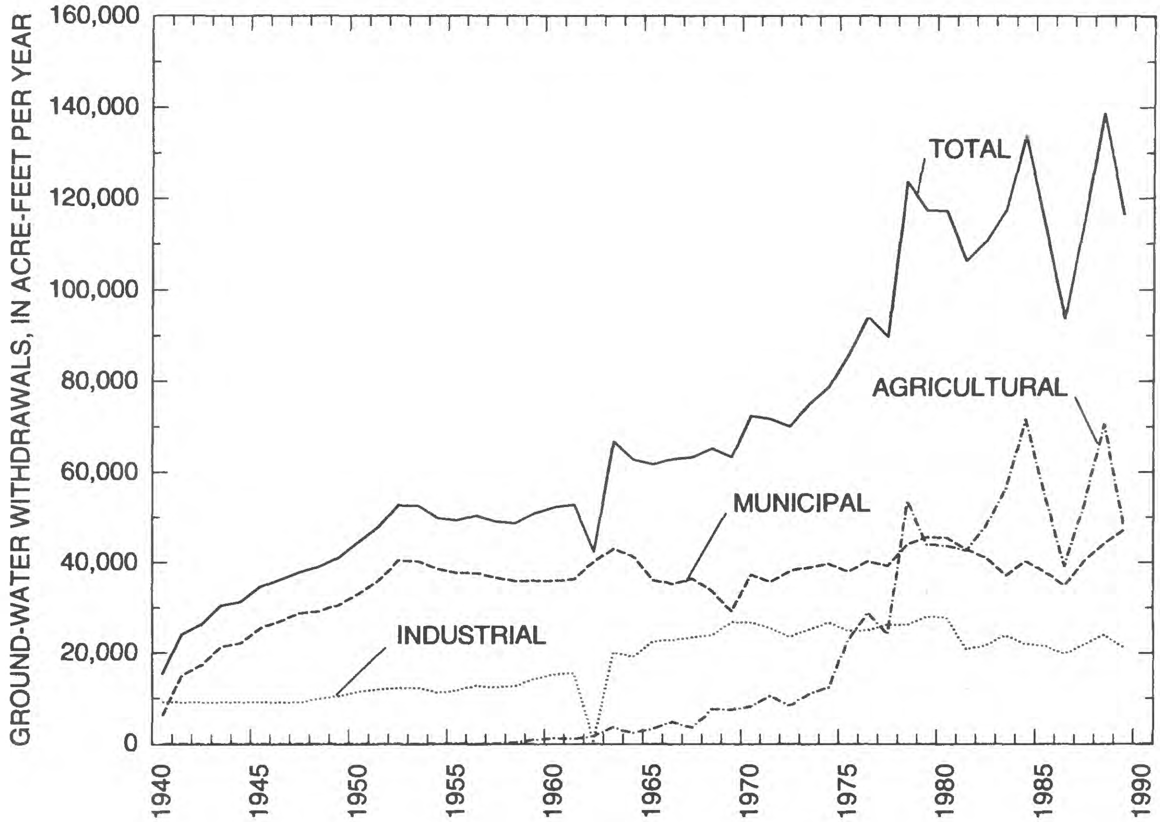


Figure 17. Industrial, municipal, agricultural, and total pumpage from the *Equus* beds aquifer in study area for 1940–89 (modified from Spinazola and others, 1985). Data for 1980–89 were estimated from records of pumpage in Harvey, Reno, and Sedgwick Counties (data obtained from Kansas Department of Agriculture, Division of Water Resources, Topeka, Kans.).

of saline water from zones of active salt dissolution in the Wellington Formation. Concentrations of natural chloride in the upper and middle units are similar to each other (figs. 19*A* and 19*B*). The primary source of this natural chloride probably is the Arkansas River. Other sources could be mined-salt brine (indistinguishable from other natural sources) that has not been concentrated by evaporation or saline water from the Wellington Formation. In the upper unit, the areal distribution of natural chloride concentrations reflects the gaining and losing reaches of the Arkansas River. During periods of base flow, the upstream part of the reach between Hutchinson and Wichita may be gaining or losing water and the downstream part is losing water. Thus, in the upper unit, water from the river has penetrated a greater distance into the aquifer (fig. 19*A*) in the downstream part of the reach. Some of the natural chloride in the upper unit near Hutchinson may have originated from saline water in Cow Creek (table 2).

CONCEPTUAL MODEL OF THE *EQUUS* BEDS AQUIFER

A conceptual model of the *Equus* beds aquifer, including boundaries, aquifer properties, ground-water recharge, and ground-water discharge, was useful to guide the development of the ground-water flow model and for later evaluation of results from the ground-water flow model.

Boundaries

Within the study area, shale of the Wellington Formation and Ninnescah Shale acts as a low-permeability barrier to ground-water flow. This shale exists beneath all of the study area and crops out on the southwest side and in the northwest and northeast corners of the study area. The sediments that comprise the *Equus* beds aquifer extend beyond the study area along the Little Arkansas and Arkansas River Valleys.

Table 2. Summary of chloride-concentration data collected from Cow Creek and the Arkansas River, August 1988–July 1991

Sampling-site name and number (fig. 6)	Number of samples	Chloride concentration, in milligrams per liter			
		Mean	Median	Minimum	Maximum
Cow Creek near confluence with Arkansas River 375906097503900	22	533	495	380	740
Arkansas River at Hutchinson 375903097515700	27	621	640	340	1,100
Arkansas River near Hutchinson 07143330	40	634	640	190	1,100
Arkansas River near Mount Hope 375343097394000	29	610	620	380	1,000
Arkansas River 4 miles northeast of Colwich 375032097305500	30	619	635	240	1,100
Arkansas River near Maize 07143375	49	590	620	140	1,100
Arkansas River, all sites	**175**	**613**	**630**	**140**	**1,100**

Aquifer Properties

Aquifer properties include horizontal and vertical hydraulic conductivity and specific yield. Horizontal hydraulic-conductivity values calculated from transmissivities reported by Reed and Burnett (1985) ranged from 55 to 1,000 ft/d. Hydraulic conductivities calculated from two pumping tests done during this study were 50 and 1,200 ft/d. Vertical-to-horizontal hydraulic-conductivity ratios from aquifer tests reported by Reed and Burnett (1985) and from two pumping tests done during this study ranged from 0.0006 to 0.22. Specific yield of fine- to coarse-grained materials, which comprise the *Equus* beds alluvial sediments, typically range from 0.1 to 0.35 (Fetter, 1988) and were calculated to range from 0.08 to 0.34 for aquifer tests reported by Williams and Lohman (1949) and Reed and Burnett (1985). Spinazola and others (1985) used a specific yield of 0.15 in their gound-water flow model of the *Equus* beds. Storage coefficients calculated by Reed and Burnett (1985) and from two pumping tests done during this study ranged from 0.0004 to 0.16.

Recharge

Recharge to the *Equus* beds aquifer is from subsurface inflow, precipitation, streamflow losses, and irrigation return flow. On the basis of the 1989 potentiometric surface (fig. 14), subsurface inflow probably occurs along parts of the northwest and northeast sides of the study area. An estimate of the inflow across the northwest side, assuming a hydraulic gradient of 0.0011, a hydraulic conductivity of 450 ft/d, and an inflow area of 3,836,000 ft^2, is about 22 ft^3/s. Estimated inflow across the northeast side of the study area, assuming a hydraulic gradient perpendicular to the study-area boundary of about

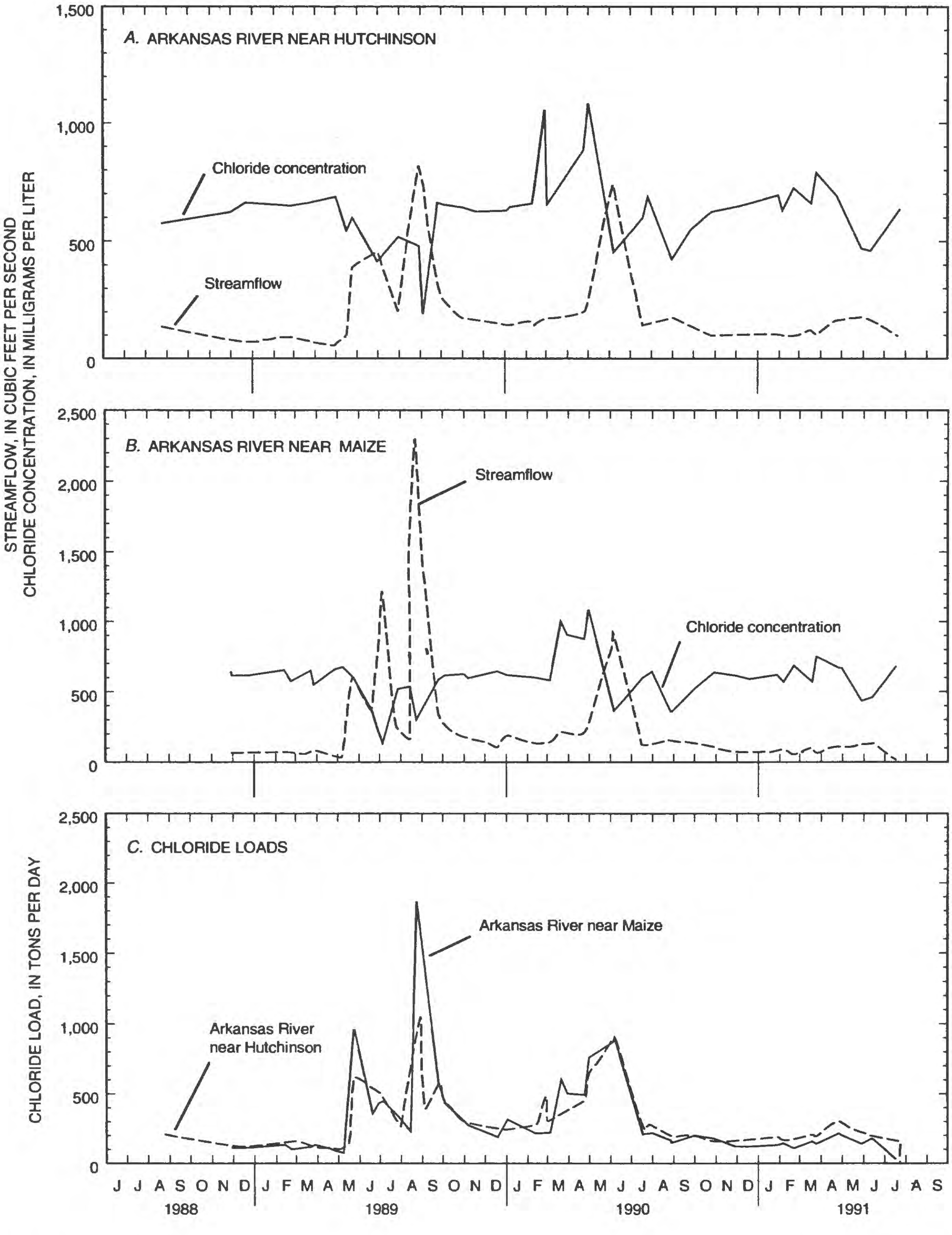


Figure 18. Streamflow and chloride concentrations in (*A*) the Arkansas River near Hutchinson, August 1988–July 1991, and (*B*) in the Arkansas River near Maize, November 1988–July 1991, and (*C*) chloride loads in the Arkansas River near Hutchinson, August 1988–July 1991, and the Arkansas River near Maize, November 1988–July 1991. Load calculated from streamflow and chloride-concentration data (chloride-concentration data from Equus Beds Groundwater Management District No. 2, Kansas Geological Survey, and USGS; data on file with the U.S. Geological Survey, Lawrence, Kans.).

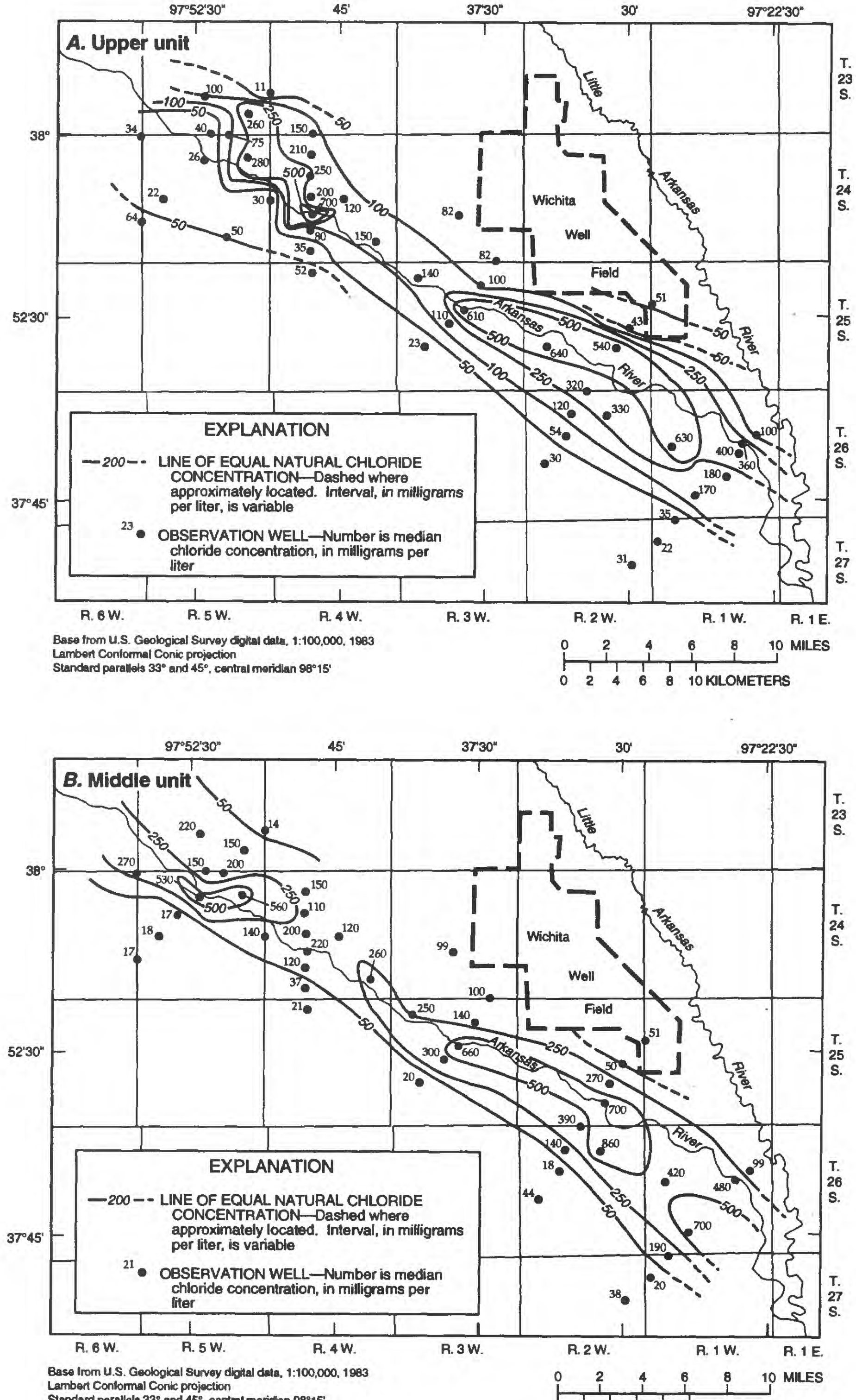


Figure 19. Natural chloride concentrations and lines of equal concentration in (*A*) upper, (*B*) middle, and (*C*) lower units of the *Equus* beds aquifer, 1989–90 [data from Whittemore (1990) and on file with the U.S. Geological Survey, Lawrence, Kans.].

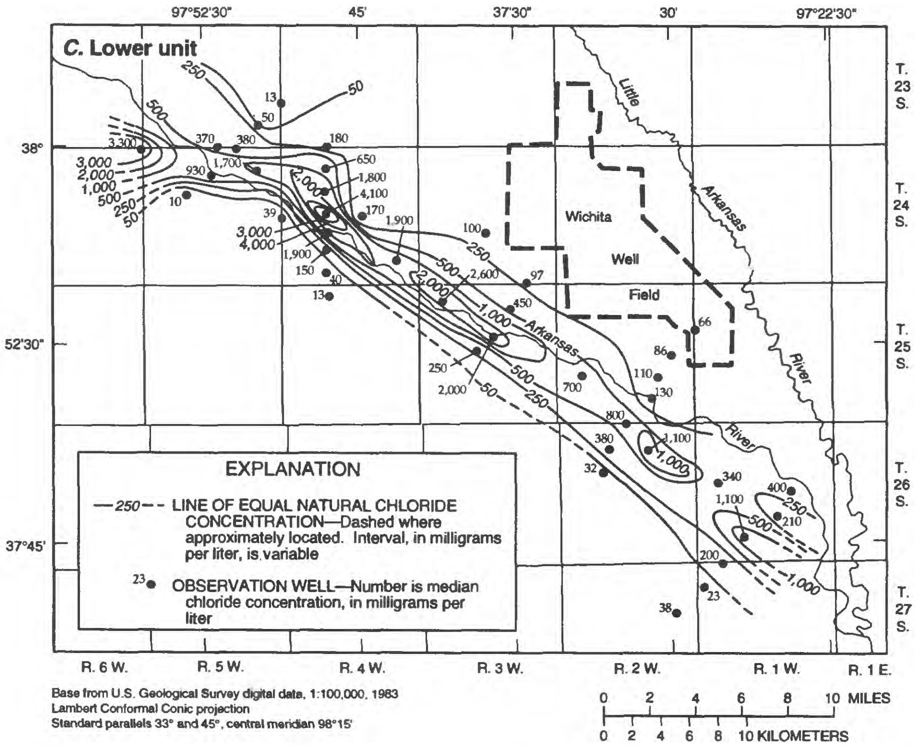


Figure 19. Natural chloride concentrations and lines of equal concentration in (*A*) upper, (*B*) middle, and (*C*) lower units of the *Equus* beds aquifer, 1989–90 [data from Whittemore (1990) and on file with the U.S. Geological Survey, Lawrence, Kans.]—Continued.

0.0012, a hydraulic conductivity of 100 ft/d, and an inflow area of 6,595,000 ft^2, is about 9 ft^3/s. Total subsurface inflow for 1989 conditions thus is estimated to have been about 31 ft^3/s.

Recharge from precipitation occurs over all of the study area except where shale crops out. The amount of water reaching the saturated zone of the aquifer over the long term would be the total amount of precipitation minus the sum of surface runoff and evapotranspiration from the unsaturated zone, assuming no net change in subsurface storage. Results of soil-moisture water-balance computations for an area near Newton indicate that the mean annual recharge to the aquifer ranges from 0.44 to 6.02 in. (about 1.4 to 20 percent of the 1940–89 mean annual precipitation for the study area), depending on the type of vegetative cover (Dugan and Peckenpaugh, 1985, table 3). Assuming a recharge area within the study area of about 438,300 acres, the mean annual recharge thus could range from about 22 to 304 ft^3/s.

Recharge from streams occurs primarily along the Arkansas River. Results of seepage surveys (table 1) show that streamflow losses for the Arkansas River between river mile 800.2 and river mile 772.5 ranged from 0 to 36 ft^3/s, or an average per mile streamflow loss of 0 to 1.3 ft^3/s. Extrapolating this rate of loss to the entire reach of the Arkansas River within the study area, 48.2 river miles, estimated losses could range from 0 to about 63 ft^3/s. Losses probably are less than the maximum of 63 ft^3/s because some reaches of the Arkansas River gain streamflow. Estimates of streamflow loss prior to 1988 would be difficult to make because the gaging station near Maize was installed in 1988 and because of changing ground-water withdrawal patterns and amounts.

Irrigation water would recharge the aquifer if the amount of water applied exceeded the consumptive irrigation requirements of crops. During 1989 and 1990, the mean depth of irrigation water applied to crops within the study area was 10.8 and 13.6 in., respectively, for a 2-year mean of 12.2 in. (Kansas Department of Agriculture and Kansas Water Office, 1990). Assuming that some of this water would evaporate before infiltrating the ground, less than 12.2 in. of water actually would be available to the irrigated crops. Consumptive irrigation requirements of row crops and alfalfa near Newton were calculated to be 11.41 and 13.68 in/yr, respectively (Dugan and Peckenpaugh, 1985, table 3). On the basis of this data and assuming appropriate timing of applications, the amount of irrigation return flow to the aquifer would be negligible.

Discharge

Discharge from the aquifer is from subsurface outflow, evapotranspiration, streamflow gains, and ground-water withdrawals from wells. On the basis of the 1989 potentiometric surface (fig. 14), subsurface outflow probably occurs along parts of the northeast and southeast sides of the study area. Estimated outflow along the northeast side, assuming a hydraulic gradient perpendicular to the study-area boundary of 0.0011, a hydraulic conductivity of 150 ft/d, and an outflow area of 5,240,000 ft^2, is about 10 ft^3/s. Estimated outflow along the southeast side, assuming a hydraulic gradient of 0.0012, a hydraulic conductivity of 500 ft/d, and an outflow area of 4,371,000 ft^2, is about 30 ft^3/s. Total subsurface outflow for 1989 conditions thus is estimated to have been about 40 ft^3/s.

Discharge by evapotranspiration occurs over all the study area. Evapotranspiration discharge may be separated into two components—that which comes from the unsaturated zone and that which comes from the saturated zone by phreatophytic consumption. Evapotranspiration from the unsaturated zone, although strictly speaking not a discharge from the aquifer, intercepts water that might have otherwise percolated down to the saturated zone. In this conceptual model, evapotranspiration from the unsaturated zone is accounted for in the recharge amount (see preceding "Recharge" section). No information on phreatophyte evapotranspiration rates is available for the study area. However, phreatophytic consumption probably occurs near streams and lakes where the water table is close to the land surface. Evapotranspiration discharges from both the saturated and unsaturated zones vary seasonally due to climate and plant demands.

Discharge to streams occurs primarily along the Little Arkansas River. Results of seepage surveys of the Little Arkansas River completed during the late 1960's and early 1970's (table 1) show that streamflow gains between river mile 68.1 and river mile 17.5 ranged from 23.45 to 76.6 ft^3/s, or an average per mile of 0.46 to 1.5 ft^3/s. By extrapolating this rate of gain to the entire reach of the Little Arkansas River within the study area, 54.0 river miles, estimated gains could range from about 25 to 81 ft^3/s. The range in streamflow gain in 1989 probably was less because ground-water withdrawals from the aquifer near the Little Arkansas River have increased since the early 1970's, consequently causing a decrease in the hydraulic gradient towards the river and a decrease in streamflow gain.

Discharge from the aquifer by ground-water withdrawals from wells occurs throughout the study area. Municipal and industrial ground-water withdrawals occur in localized areas, whereas irrigation ground-water withdrawals in 1989 were distributed fairly uniformly over the study area. Total ground-water withdrawals during 1989 in the model area were about 116,265 acre-ft/yr or about 160.6 ft^3/s.

SIMULATION OF STREAM-AQUIFER INTERACTION

A three-dimensional, finite-difference, flow-model program, MODFLOW (McDonald and Harbaugh, 1988), was used to simulate ground-water flow, surface-water flow, and stream-aquifer interaction. It is common to speak of both the computer program and the data sets that represent the stream-aquifer system as "models." In this report, the computer program will be referred to as the flow-model program or flow-model modules, and the data sets, which represent the stream-aquifer system, will be referred to as the ground-water flow model or model.

Ground-water flow models, by definition, are simplifications of the actual stream-aquifer system and embody certain assumptions. Assumptions for MODFLOW are:

(1) The density of water is uniform, is that of freshwater, and is not affected by temperature; the solute-concentration effect is neglible.

(2) Aquifer properties and stresses are distributed uniformly within a model cell and are constant during a stress period.

(3) The effects of aquifer stresses beyond the model boundaries are neglible.

(4) Tops and bottoms of model cells are horizontal, and the sides of cells are vertical.

(5) Stream leakage to and from the aquifer is vertical.

McDonald and Harbaugh (1988) discuss model theory, mathematical treatment of simulated conditions, and solution techniques used in the MODFLOW program.

The ground-water flow model was developed in two stages. First, a steady-state flow model was developed to simulate aquifer conditions existing in the study area during the late 1930's. (Prior to 1940, there were no major pumpage centers in the study area.) Second, a transient model was developed to simulate aquifer conditions for 1940–89. The hydraulic-head distribution generated by the steady-state model was used as the initial hydraulic-head distribution for the transient model. The transient model also was used for simulations using hypothetical conditions for 1990–2019. Data sets for the steady-state and transient (1940–89) models are available on magnetic tape or disk from the USGS in Lawrence, Kans.

Steady-State Ground-Water Flow Model

The steady-state ground-water flow model can be described in terms of its geometry, simulated aquifer properties, and simulated stresses. The steady-state model was assigned one stress period during which the geometry, aquifer properties, and stresses were held constant, and the aquifer-storage change was assumed to be zero.

Model Geometry

Model geometry was determined by the focus of the study, the area of interest, natural boundaries, aquifer thickness, and aquifer stratigraphy. Because the focus of this study was the Arkansas River and the adjacent *Equus* beds aquifer in the area between Hutchinson and Wichita, a model grid was laid out with rows parallel to the river, and with a small grid spacing near the river (fig. 20). The model consists of 34 rows, 42 columns, and three layers for a total of 4,284 model cells. The upper, middle, and lower model layers correspond to the upper, middle, and lower units of the *Equus* beds aquifer. The row and column spacings for all three model layers were identical. The model grid was made large enough to take advantage of natural barriers to ground-water flow, such as the contact between shale and *Equus* beds sediment, and to encompass the Wichita well field and the Little Arkansas River, which are major stresses in the ground-water flow system. Row spacing was varied to provide detail near the river and yet to minimize the total number of grid cells in the model. Northeast from the Arkansas River, row spacings were 1,000, 2,000, 5,000, and 10,000 ft. Southwest from the river, row spacings were 1,000, 2,000, and 5,000 ft. Column spacing was 5,000 ft.

Various boundaries affect the geometry of the three model layers. No-flow boundaries were simulated, with no-flow cells, where shale provides a natural boundary to ground-water flow southwest of the river from near Hutchinson to near Wichita, northeast of Hutchinson, and north of Wichita (fig. 20). A no-flow boundary also was simulated beneath the *Equus* beds aquifer where shale is considered a relatively impermeable boundary to ground-water flow. Stream cells in the model are where the flux of water to or from the stream is dependent on the difference between hydraulic head in the stream and aquifer and the vertical hydraulic conductivity of the streambed. Stream cells were used to simulate perennial streams (fig. 20*A*). Constant-head cells (constant-head boundaries) were used to simulate ground-water flow into or out of the model area where the *Equus* beds aquifer extends laterally beyond model limits (fig. 20). Water-level data collected during this study indicate that there is little vertical hydraulic-head gradient near the constant-head boundaries. Accordingly, constant-head values used in model simulations were the same in all three layers for a given row-and-column location in the model. The saturated thickness of the aquifer determined the overall thickness simulated by the model, and the stratigraphy determined the thickness simulated for each of the three model layers.

Aquifer Properties

Aquifer properties defined for the steady-state flow model were horizontal and vertical hydraulic conductivity. Specific yield and storage coefficient were assumed to be zero in the steady-state simulation. The model developed by Spinazola and others (1985), which represented the *Equus* beds aquifer with a single layer, was the primary source of aquifer-property data. Aquifer-test data from Reed and Burnett (1985) and from this study were used to refine aquifer properties for the three model layers. The distribution of horizontal hydraulic conductivity in the model layers is shown in figure 21.

Vertical hydraulic conductivity was specified in the model in terms of a vertical conductance. First, vertical hydraulic conductivity was calculated by

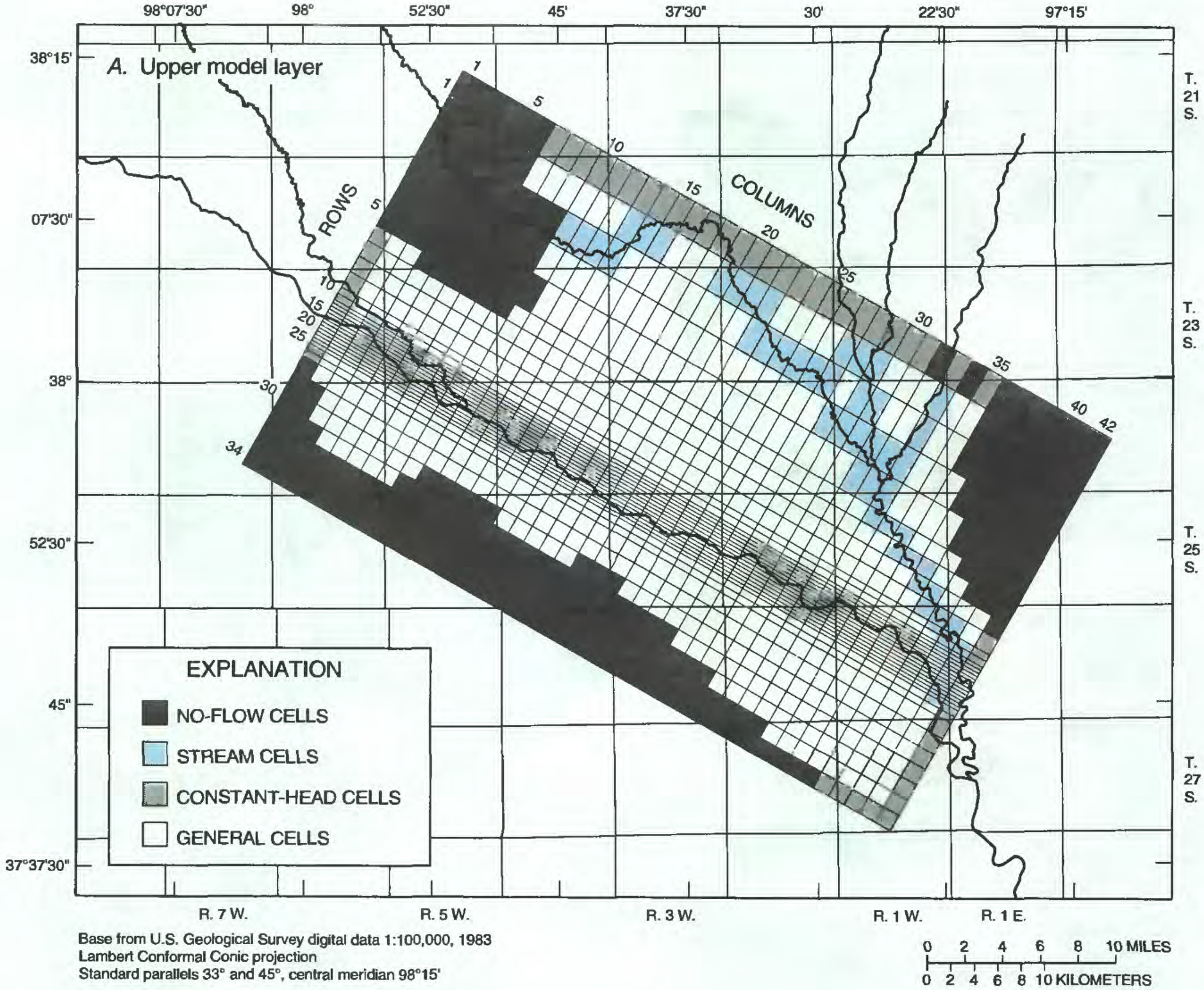


Figure 20. Model grid, row and column numbers, and boundary conditions for (*A*) upper, (*B*) middle, and (*C*) lower model layers.

multiplying an assumed vertical-to-horizontal hydraulic-conductivity ratio (K_v/K_h) of 0.005 times the horizontal hydraulic conductivity for each model cell. Vertical hydraulic conductivity then was used to calculate the vertical conductance between model cells using the formula (McDonald and Harbaugh, 1988, p. 5–13):

$$vcont = \frac{1}{\left(\frac{0.5 x z_k}{K_{v_k}}\right) + \left(\frac{0.5 x z_{k+1}}{K_{v_{k+1}}}\right)}, \quad (1)$$

where

$vcont$ = vertical conductance, in day^{-1};

k = 1, 2, 3 for upper, middle, or lower model layer, respectively;

z_k = thickness of model cell in layer K, in feet;

z_{k+1} = thickness of model cell in layer k+1, in feet;

K_{v_k} = vertical hydraulic conductivity of model cell in layer K, in feet per day; and

$K_{v_{k+1}}$ = vertical hydraulic conductivity of model cell in layer k+1, in feet per day.

Stresses

Stresses simulated in the steady-state ground-water flow model include recharge, evapotranspiration, streamflow, stream leakage, and pumpage by

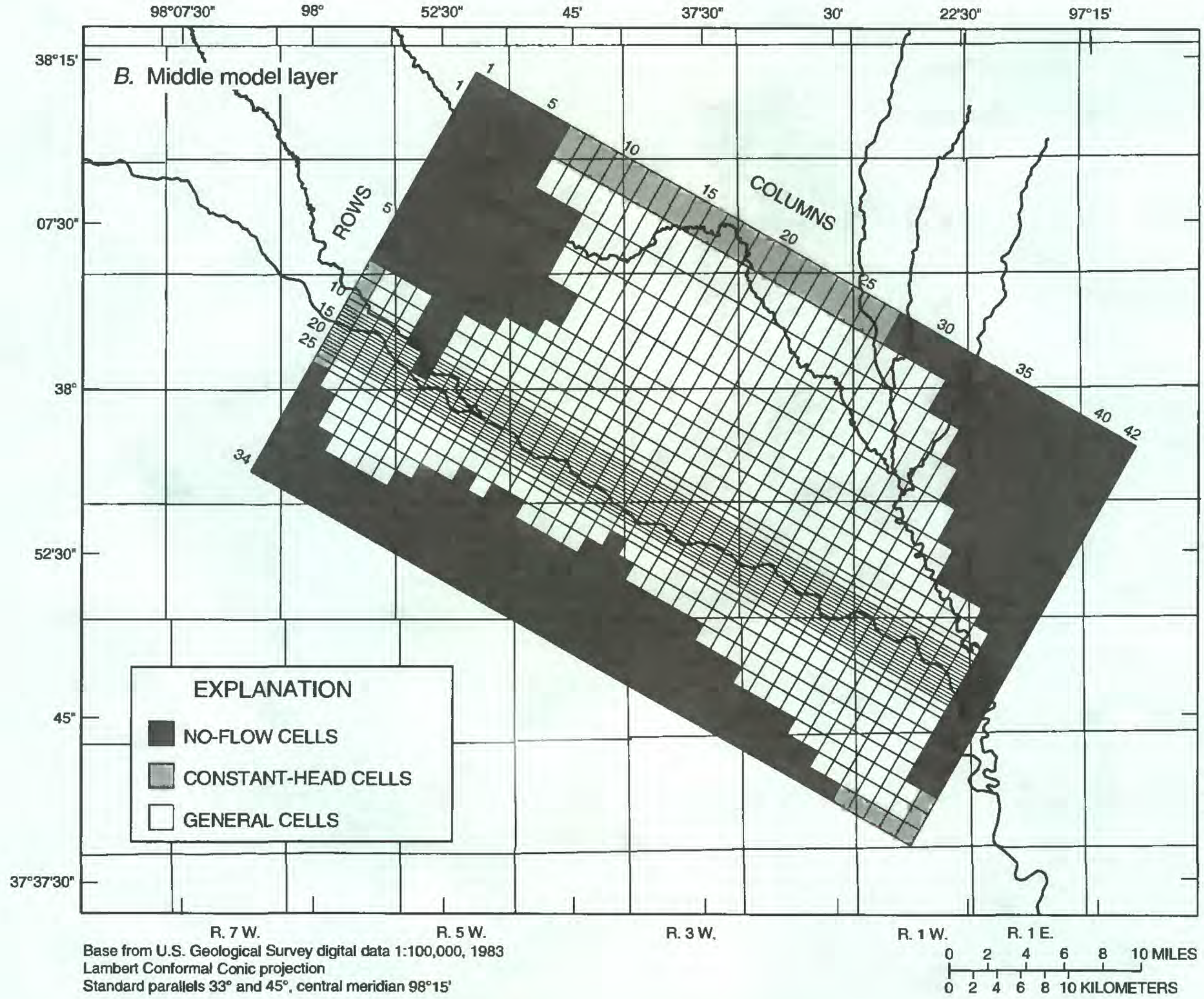
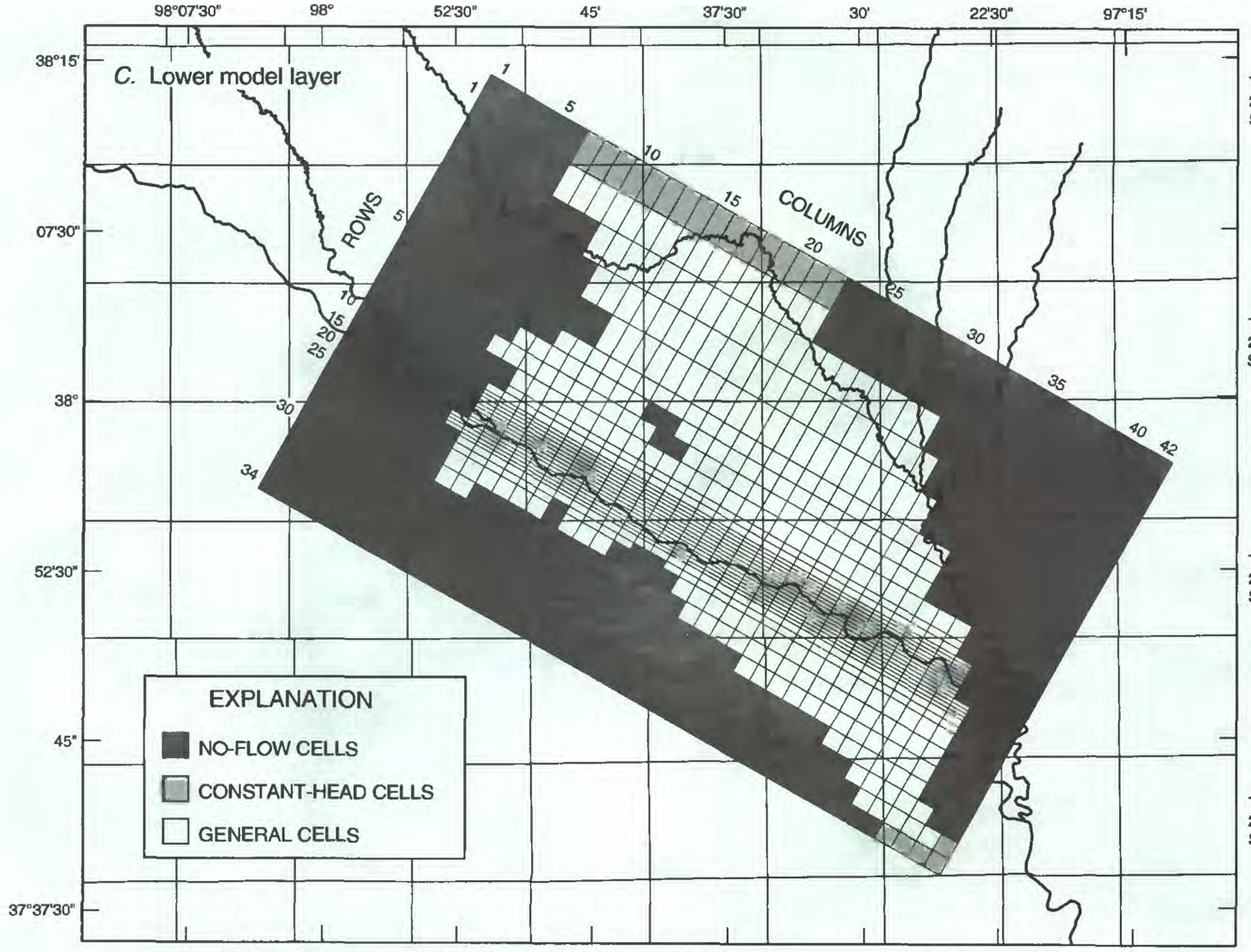


Figure 20. Model grid, row and column numbers, and boundary conditions for (*A*) upper, (*B*) middle, and (*C*) lower model layers—Continued.

wells. Spinazola and others (1985) calculated recharge to their model as a function of 1940 precipitation, the soil type, and thickness of clay in the unsaturated zone. It was assumed that the same recharge values and distribution would reflect 1935–39 conditions and would be appropriate for the steady-state model of this study. Recharge rates used in this model were in the range of 0.1 to 5.5 in/yr (fig. 22).

Evapotranspiration from the ground-water system was simulated in the model. Spinazola and others (1985) arrived at a maximum evapotranspiration rate from the ground-water system of 3.5 in/yr through a trial-and-error process. A maximum evapotranspiration rate of 3.5 in/yr was used in this model, with a linear decrease in evapotranspiration rate from 3.5 in/yr where the water table is at the land surface to 0 where the water table is 10 ft or more below the land surface.

Streamflow was simulated using a stream-routing module (Prudic, 1988) of the MODFLOW program. An estimated base flow was specified for the starting reach (one reach corresponds to one model cell) of each stream in the model (table 3). The stream-routing module calculated streamflow gain or loss in the remaining reaches on the basis of the difference in hydraulic head between the stream reach and the aquifer and on the basis of a streambed-conductance value specified for each stream reach. The streamflow then was calculated as the algebraic sum of streamflow in the upstream reach and gain or loss in each reach. The streamflow specified for the starting reach of the Arkansas River was based on streamflow records for



Base from U.S. Geological Survey digital data 1:100,000, 1983
Lambert Conformal Conic projection
Standard parallels 33° and 45°, central meridian 98°15'

Figure 20. Model grid, row and column numbers, and boundary conditions for (*A*) upper, (*B*) middle, and (*C*) lower model layers—Continued.

the Arkansas River near Hutchinson [period of record, October 1959–present (1992)], the Arkansas River at Wichita (period of record, October 1934–present), and the Little Arkansas River at Valley Center (period of record, June 1922–present).

Streamflow that was exceeded 70 percent of the time, assumed to represent base flow (Hedman and Engel, 1989), was used to simulate streamflow in the Arkansas River. Because of the lack of streamflow data prior to October 1959 for the Arkansas River near Hutchinson, the streamflow in the Arkansas River prior to this time was based on a mathematical relationship between October 1959–89 streamflow data from the Arkansas River near Hutchinson and contemporaneous streamflow data from the Arkansas River at Wichita and the Little Arkansas River at Valley Center. This mathematical relationship and October 1934–39 streamflow data from the Arkansas River at Wichita and the Little Arkansas River at Valley Center were used to estimate streamflow that was exceeded 70 percent of the time in the Arkansas River near Hutchinson for the steady-state model. Streamflow used for the Arkansas River in the steady-state model is smaller than streamflows used in any successive transient- or hypothetical-model simulations (table 3). However, streamflows occurring during the late 1930's reflect the appropriate conditions for the steady-state model of this study. Streamflow for the starting-model reach of the Arkansas River, which was upstream of the gage near Hutchinson, was determined through trial and error so that the simulated streamflow at the location of the Arkansas

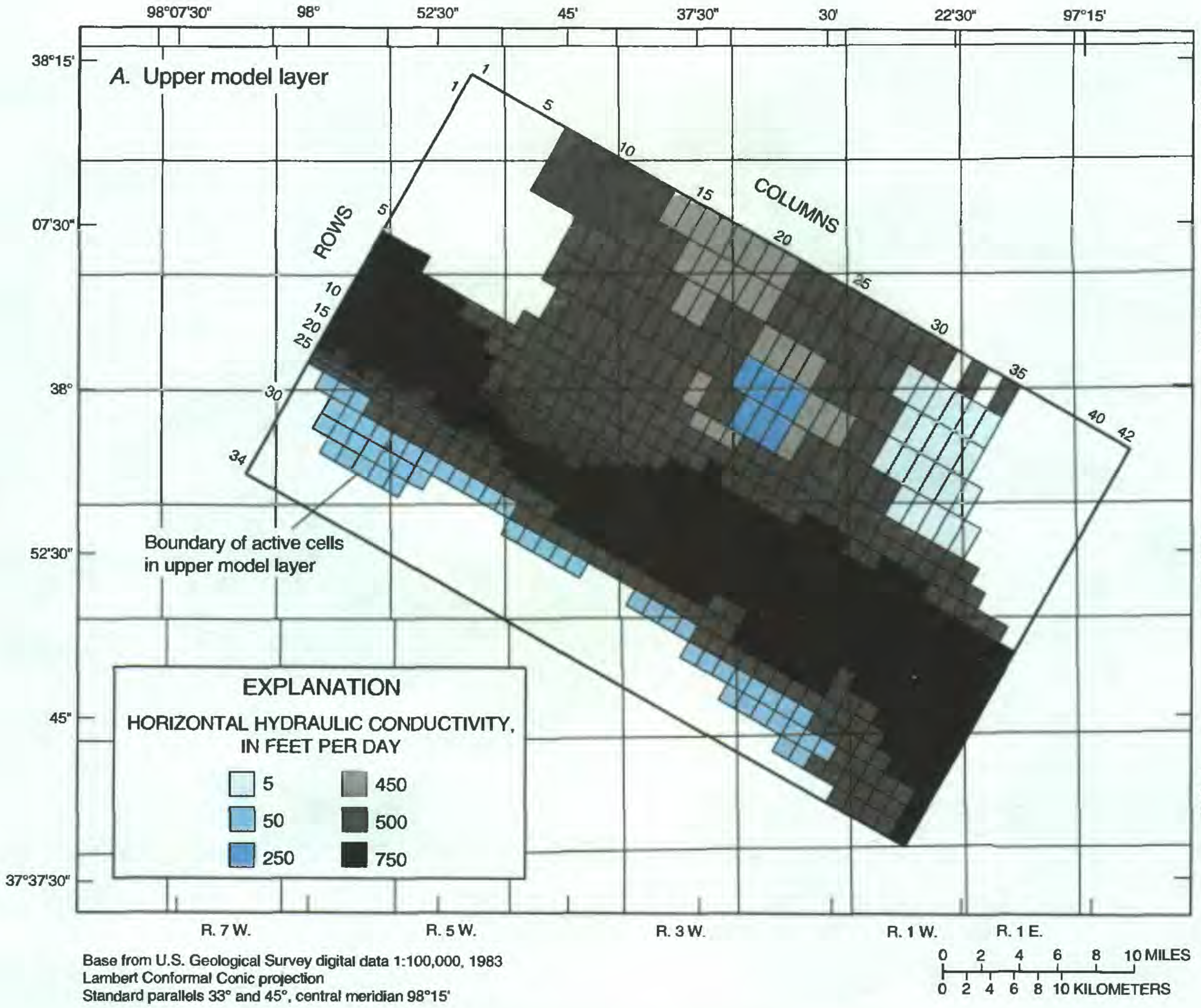


Figure 21. Distribution of horizontal hydraulic conductivity in (*A*) upper, (*B*) middle, and (*C*) lower model layers.

River gage near Hutchinson approximated the estimated streamflow exceeded 70 percent of the time.

Simulated streamflows for the Little Arkansas River were based on seepage-survey data (table 1) and streamflow data for the Little Arkansas River at Valley Center. Seepage-survey data were used to determine an approximate base flow for the starting reach of the river. Then streamflow for the starting-model reach of the Little Arkansas River was determined through trial and error so that the simulated streamflow at the location of the Little Arkansas River at Valley Center gage approximated the measured flow that was exceeded 70 percent of the time. Simulated flows specified for the starting reaches of East Emma, West Emma, and Sand Creeks were approximated on the basis of seepage-survey data. Streamflow in the starting reach of Emma Creek was calculated by the model as the outflow from East and West Emma Creeks.

Stream leakage was simulated by calculating a streambed-conductance term on the basis of the length and width of each stream reach (one stream reach for each model cell), the thickness of the streambed, and the vertical hydraulic conductivity of the streambed, and is expressed by the equation (McDonald and Harbaugh, 1988, p. 6–4):

$$criv = \frac{KLW}{M} \quad , \qquad (2)$$

where

$criv$ = streambed conductance, in feet squared per day;

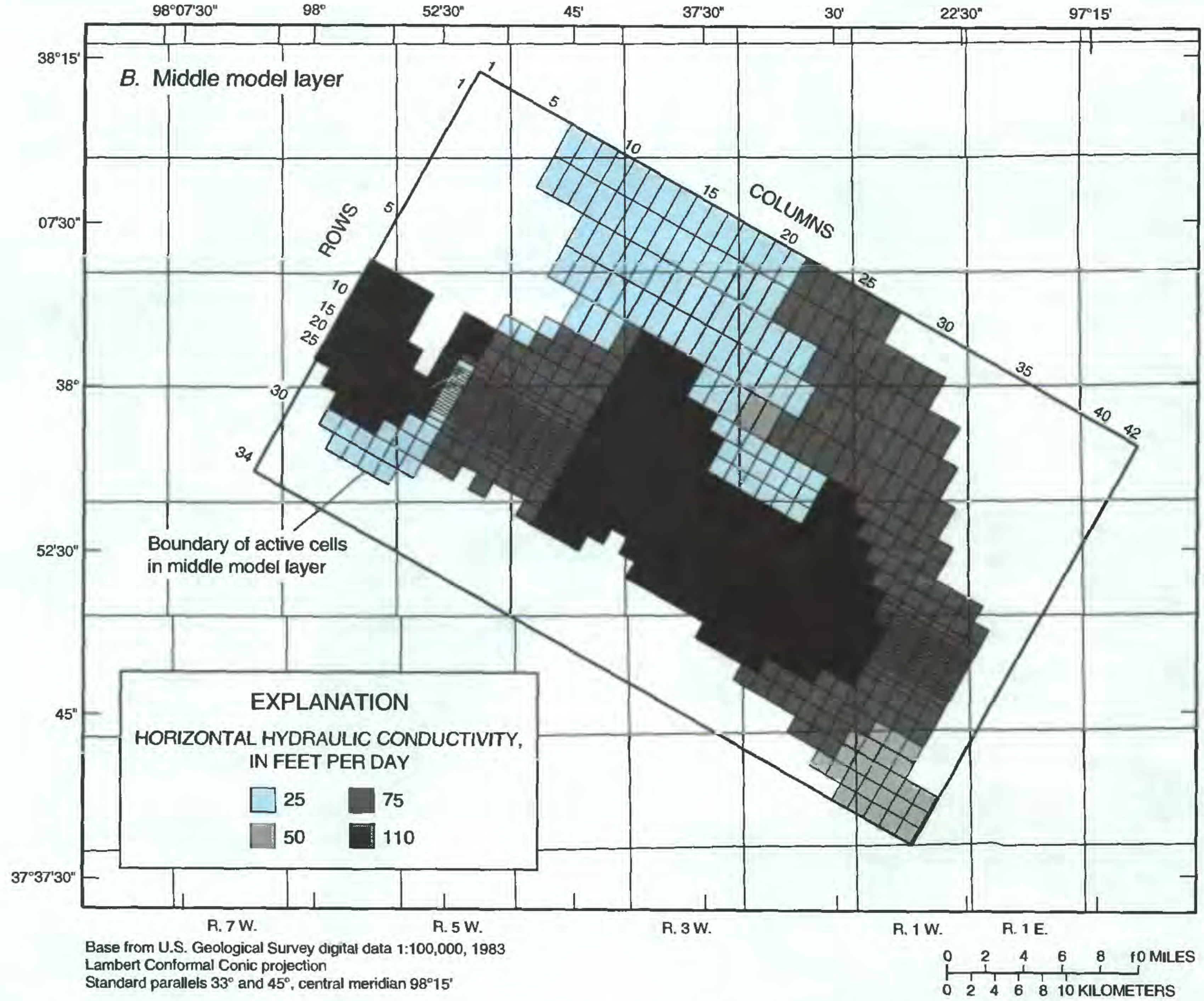


Figure 21. Distribution of horizontal hydraulic conductivity in (*A*) upper, (*B*) middle, and (*C*) lower model layers—Continued.

K = vertical hydraulic conductivity of the streambed, in feet per day;

L = length of stream reach, in feet;

W = width of the stream reach, in feet; and

M = thickness of the streambed, in feet.

The length of each stream reach was set equal to the length of the stream in each model cell. The width of the streams was estimated by onsite observation. Because no discrete streambed could be identified, the thickness of the streambeds was set to one-half of the saturated thickness of the upper model layer for each stream cell (McDonald and Harbaugh, 1988, p. 6–5, 6–6). The initial values of vertical hydraulic conductivity of streambeds were assigned assuming that the Arkansas River would have the largest vertical hydraulic conductivity. The final vertical hydraulic-conductivity values used in the model were 0.5 ft/d for Emma, East Emma, West Emma, and Sand Creeks; 5.0 ft/d for the Little Arkansas River; 1.0 ft/d for Cow Creek; and 50 ft/d for the Arkansas River. In addition to these properties, streambed slope, top-of-streambed altitude, bottom-of-streambed altitude, and a streambed-roughness coefficient were used by the flow-model program to calculate the flow and stream stage in each stream cell. Streambed slope and top-of-streambed altitude were determined from USGS 7 1/2-minute topographic maps. Assuming that there has not been any significant aggradation or degradation of streambed altitude since the topographic maps were made, the streambed altitude used in the model probably is accurate to ±2.5 ft (one-half the contour interval). A streambed-roughness coefficient was

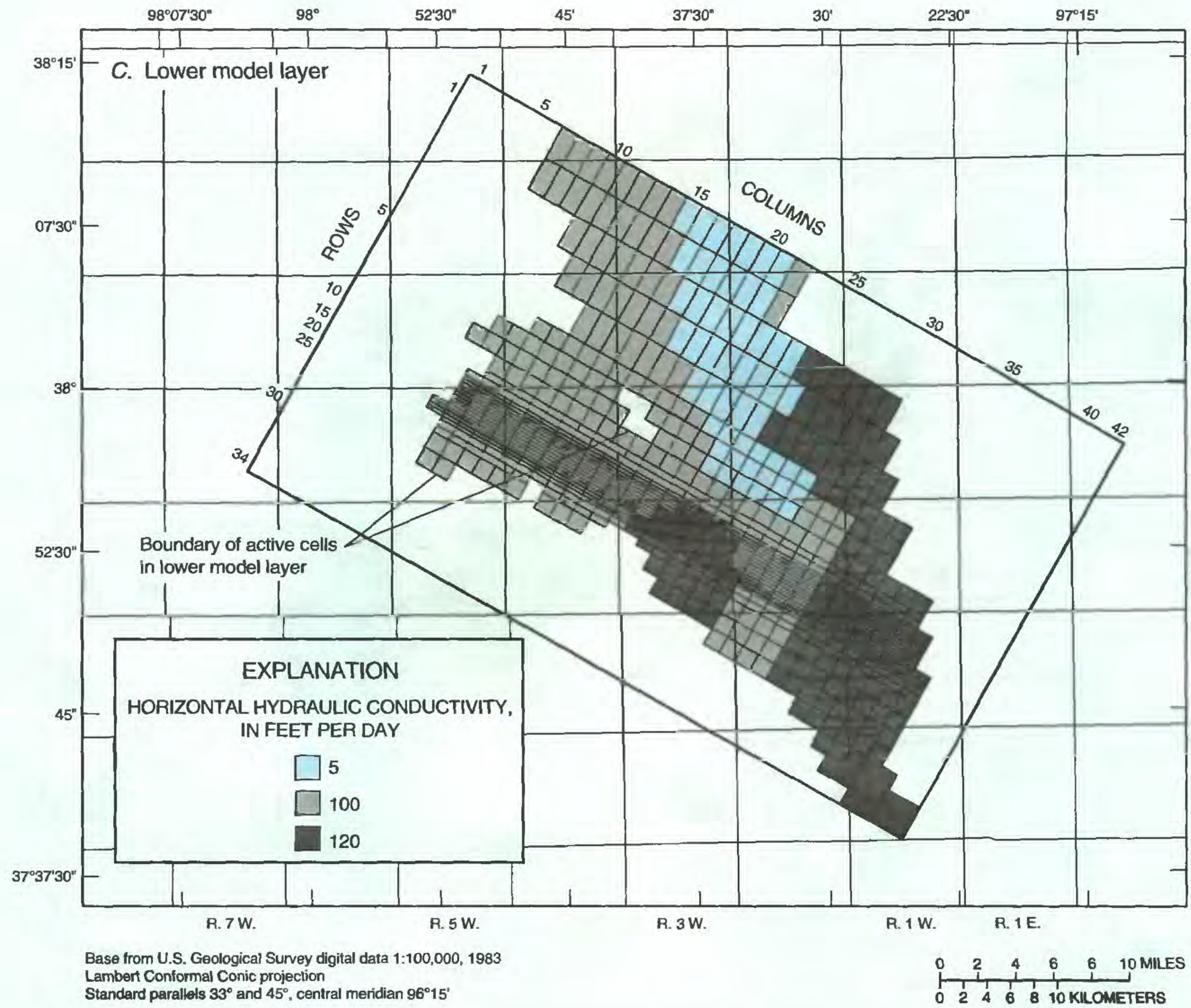


Figure 21. Distribution of horizontal hydraulic conductivity in (*A*) upper, (*B*) middle, and (*C*) lower model layers—Continued.

assigned to streams on the basis of onsite observation of stream channels and a table of Manning's roughness coefficients (Prudic, 1988, p. 10). The roughness coefficient assigned to Cow, Sand, and East and West Emma, and Emma Creeks was 0.03; to the Little Arkansas River, 0.04; and to the Arkansas River, 0.025.

Well pumpage simulated in the steady-state model was relatively small (about 2,066 acre-ft/yr). The location of that pumpage is shown later in the report along with pumpage simulated by the transient model.

Calibration of Steady-State Model

The purpose of calibration is to refine the model so that it is a reasonable representation of the stream-aquifer system. Calibration was done by adjusting the values of recharge, horizontal and vertical hydraulic conductivity, and streambed conductance, within reasonable ranges, to achieve the best fit between simulated and measured hydraulic heads and streamflows. Calibration adjustments later made to the transient model also were applied to the steady-state model. For the steady-state simulation, the simulated potentiometric surface for the middle model layer, assumed to be representative of the potentiometric surface of all three layers, was compared to the 1940 potentiometric surface (fig. 23).

The mean absolute difference between measured hydraulic heads for 235 individual wells and their corresponding layer-2, model-cell simulated hydraulic heads was computed for all and selected

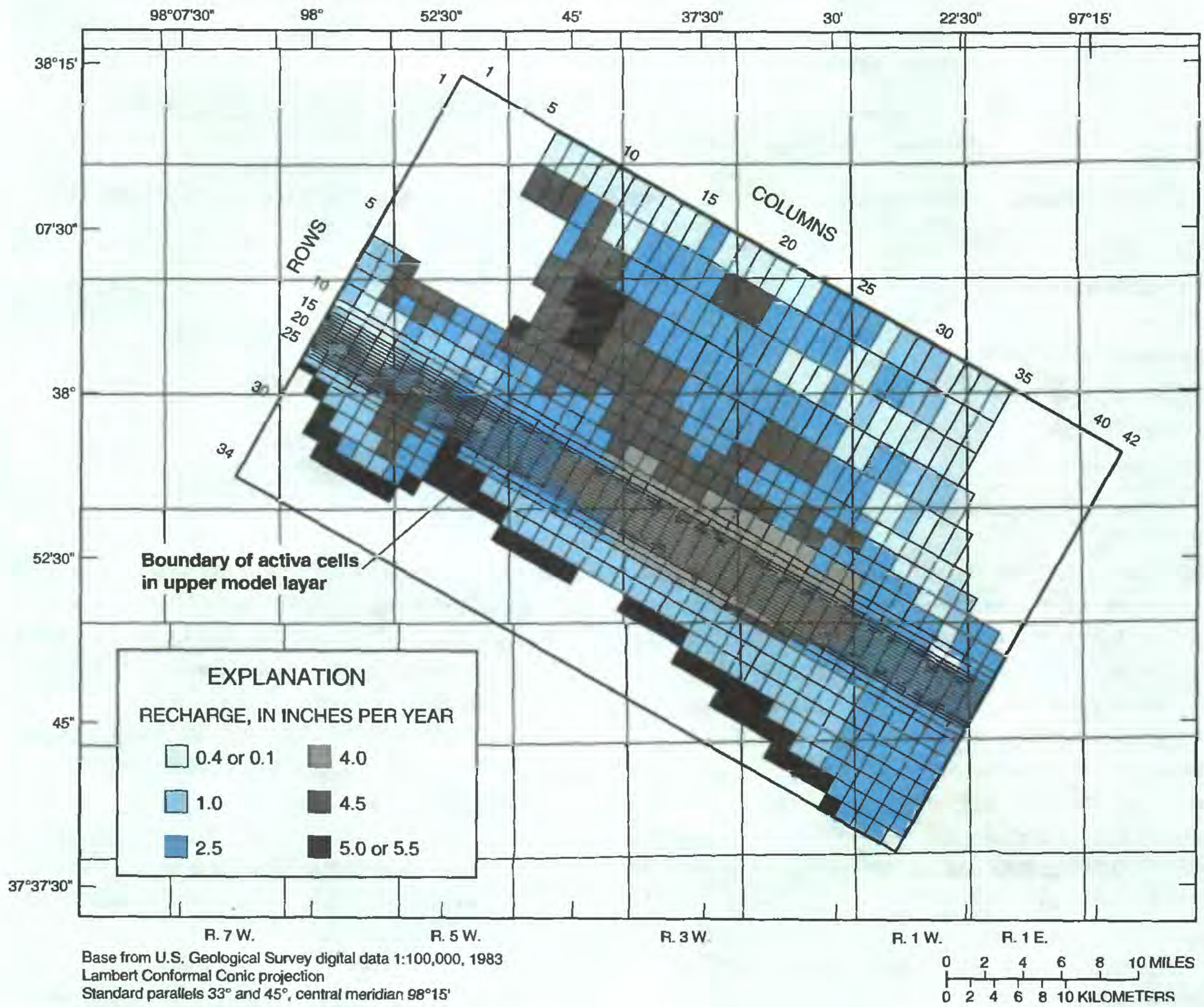


Figure 22. Ground-water recharge rates for steady-state model.

areas of the model (fig. 23). The mean absolute differences were: all of the model, 3.20 ft; area 1, 3.54 ft; area 2, 1.90 ft; area 3, 2.48 ft; area 4, 4.50 ft; and area 5, 2.85 ft.

Prior to 1959, there were no concurrent measurements of streamflow along the streams simulated in the model, so no values of gain or loss in the streams were available for calibration of the steady-state model. Simulated net gains or losses for these streams are shown in table 4.

Sensitivity Analysis

The purpose of sensitivity analysis is to measure how sensitive the model-computed results are to changes in aquifer properties and aquifer stresses. During sensitivity analysis, evapotranspiration, streambed conductance, streamflow, recharge, and hydraulic conductivity were varied from one-half to twice their calibration values. The resulting simulated hydraulic heads were used to calculate the mean absolute deviation from the accepted calibration heads (fig. 24). Changes in the rate of recharge and values of hydraulic conductivity had the most effect on the mean absolute deviation from the accepted calibration hydraulic heads, whereas changes in evapotranspiration, streambed conductance, and streamflow had little effect. Doubling the values of recharge and hydraulic conductivity changed the mean absolute deviation by about 2.9 and 1.4 ft, respectively. These relatively small changes are an indication that water-level changes in the aquifer are constrained by the presence

Table 3. Simulated streamflows, for the starting reach of each stream, used in steady-state and transient models

Name of stream	Layer-1 model cell where streamflow is introduced to model (row,column)	Flows for each stress period, in cubic feet per second						
		Steady-state model	Transient model					
		1935–39	1940–52	1953–58	1959–63	1964–70	1971–79	1980–89
Arkansas River	(17,1)	50	365	54	353	186	216	126
Little Arkansas River	(3,10)	2	2	5	1.5	6	4	4
Cow Creek	(11,3)	10	10	10	10	10	10	10
Sand Creek	(1,33)	1	1	1	1	1	1	1
East Emma Creek	(1,28)	1	1	1	1	1	1	1
West Emma Creek	(1,25)	1	1	1	1	1	1	1
Emma Creek[1]								

[1]Water from East Emma and West Emma Creeks join to form Emma Creek.

of the Arkansas River, by the generally shallow depth of the water table below land surface, and by the large hydraulic conductivity of the aquifer material. That is, water levels in the aquifer near the Arkansas River do not decline much below the level of water in the river, and water cannot rise above land surface without running off. Thus, water levels in the aquifer are constrained by natural conditions to a relatively small range. In such a constrained system, a larger range of aquifer properties and stresses will satisfy a given hydraulic-head distribution than in a less-constrained system. The set of data used to represent the stream-aquifer system is not unique but is one of many possible solutions.

Transient Ground-Water Flow Model

Aquifer Properties and Stresses

The transient model had the same aquifer properties as the steady-state model except that specific-yield and storage-coefficient values were included in the simulations. A specific yield of 0.15 was assigned uniformly to the upper model layer. For the middle and lower layers, a specific storage of 0.0001 ft^{-1} was assumed and multiplied by the layer thickness to get values of storage coefficient for each model cell. Thus, storage coefficients ranged from 0.0004 to 0.014 for the middle layer and 0.0003 to 0.018 for the lower layer.

The transient ground-water flow model also had the same geometry and maximum evapotranspiration rate as the steady-state model, but recharge, streamflow, and pumpage were varied for each stress period, and specific-yield and storage-coefficient values were included in the simulations. Six stress periods were defined for the transient model. The stress periods cover 1940–52, 1953–58, 1959–63, 1964–70, 1971–79, and 1980–89. The first five stress periods were defined by Spinazola and others (1985) on the basis of time periods when there was a relatively uniform trend in well pumpage (fig. 17). During the sixth stress period (1980–89), there were marked fluctuations in the volume of agricultural pumpage (fig. 17), but because the average of each increasing or decreasing trend was about the same, 1980–89 was simulated as one stress period. Stresses were held constant during each stress period but were varied from one stress period to the next.

Stresses in the transient model were defined by using available data. Recharge was based on the mean precipitation at climatic stations at Hutchinson, Mount Hope, and Wichita for each stress period (National Oceanic and Atmospheric Administration, 1935–89). The recharge for each stress period was estimated as follows: (1) The recharge specified for each steady-state model cell was divided by the mean annual precipitation for the pre-1940 period (represented by the steady-state model). (2) The resulting quotient for each model cell then was multiplied by the study-area mean annual precipitation (table 5) for each stress period in the transient model.

Streamflows in the first model reach of the Arkansas River were assigned as the streamflows that were exceeded 70 percent of the time for each stress

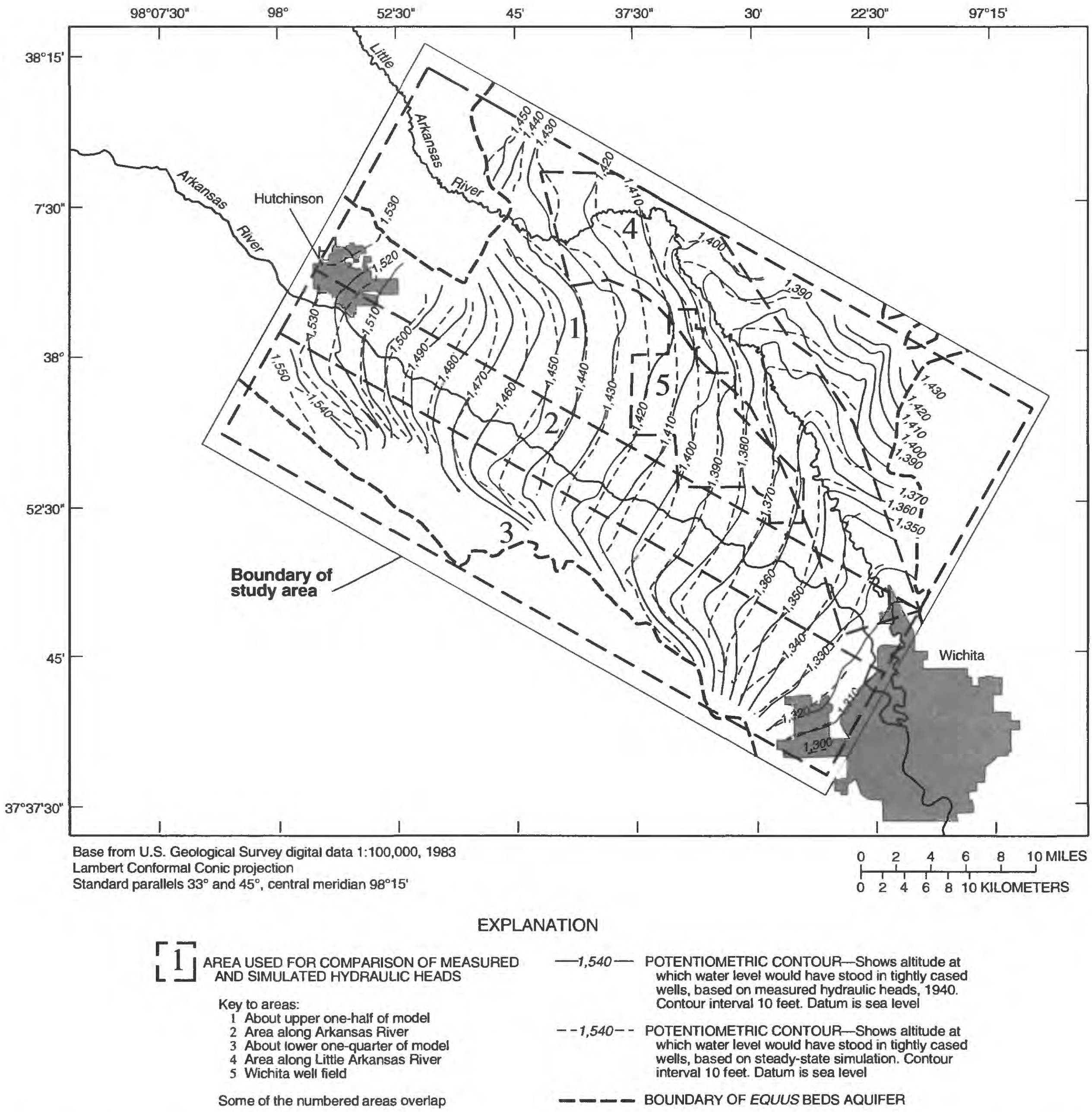


Figure 23. Measured and simulated potentiometric surfaces for middle model layer, 1940 (1940 potentiometric contours modified from Spinazola and others, 1985), and areas used for comparison of measured and simulated hydraulic heads.

period (table 3). For the first two stress periods, streamflow in the Arkansas River near Hutchinson was estimated from streamflow data from gages on the Arkansas River at Wichita and the Little Arkansas River at Valley Center by using the mathematical relation established between streamflow at the gages at Wichita, Valley Center, and the gage near Hutchison. Streamflow in the starting-model reach of the Little Arkansas River was estimated from streamflow data for the Little Arkansas River at Alta Mills and the Little Arkansas River at Valley Center. Streamflows for the starting-model reaches of Cow, Sand, and East and West Emma Creeks for every stress period were assigned the same as the streamflows used in the steady-state model.

Well pumpage for the first five stress periods was taken from model data sets developed by Spinazola and others (1985). Well-pumpage quantity

Table 4. Simulated streamflow at upstream and downstream ends of streams within steady-state model. Except for Emma Creek, upstream-end streamflow is specified in the model-input data sets. The upstream-end streamflow for Emma Creek is calculated by the model

[Flows are in cubic feet per second (ft^3/s)]

Stream	Streamflow at upstream end	Streamflow at downstream end	Net gain (+) or loss (-) of streamflow
Arkansas River	50.0	80.7	+[1]30.7
Little Arkansas River	2.0	73.7	+[2]71.7
Cow Creek	10.0	10.1	+.1
East Emma Creek	1.0	.16	-.84
West Emma Creek	1.0	2.97	+1.97
Emma Creek	3.13	3.95	+.82
Sand Creek	1.0	.67	-.33

[1]Includes tributary inflow from Cow Creek (10.1 ft^3/s).
[2]Includes tributary inflow from Emma and Sand Creeks (4.62 ft^3/s).

and location data for 1989, from the Kansas Department of Agriculture, Division of Water Resources computer files (Topeka), were used to represent pumpage during the sixth stress period. Total well pumpage for 1989 (about 116,265 acre-ft) (fig. 17) was very close to the average for the 1980–89 period (about 116,273 acre-ft). Pumpage was apportioned to the different model layers using the method suggested by McDonald and Harbaugh (1988, p. 8–2). Pumpage for municipal wells in the Wichita well field was apportioned to the three model layers on the basis of the length of well screen in each layer and the assigned hydraulic conductivity of the model layer at each location. Agricultural and industrial pumpage was apportioned to the three model layers on the basis of the assigned thickness and hydraulic conductivity at each pumping location because well-screen length and depth data were not available. Model cells where pumpage was simulated for each stress period are shown in figure 25. A plot of simulated pumpage from each model layer (fig. 26) shows that most of the simulated pumpage was from the upper model layer, and the least was from the middle model layer.

Calibration of Transient Model and Sensitivity Analysis

As a basis for calibration of the transient model, simulated hydraulic heads were compared to measured heads, and simulated streamflow was compared to

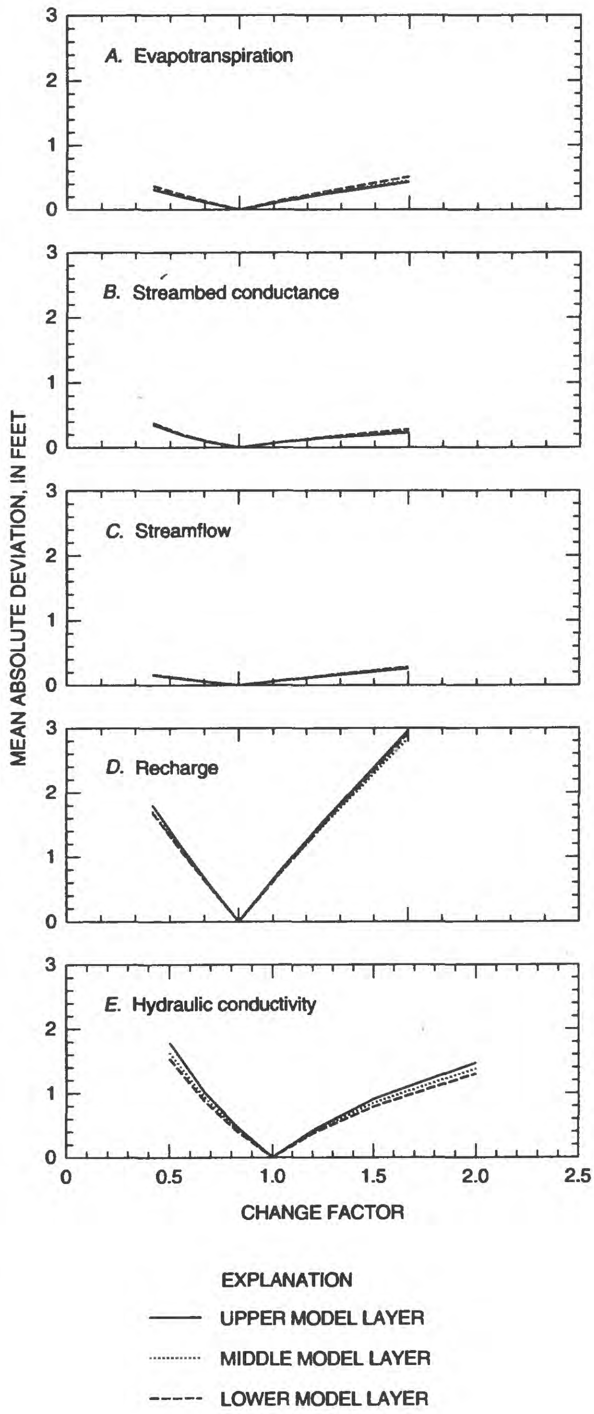


Figure 24. Mean absolute deviations of simulated hydraulic heads from accepted model-calibration heads for changes in (*A*) evapotranspiration, (*B*) streambed conductance, (*C*) streamflow, (*D*) recharge, and (*E*) hydraulic conductivity.

Table 5. Mean annual precipitation at Hutchinson, Mount Hope, and Wichita climatic stations and for the study area for steady-state and transient model stress periods

[Data from National Oceanic and Atmospheric Administration, 1935–89]

	Mean precipitation for stress periods, in inches per year						
	Steady-state model	Transient model					
Climatic station	**1935–39**	**1940–52**	**1953–58**	**1959–63**	**1964–70**	**1971–79**	**1980–89**
Hutchinson	27.83	[1]34.02	24.22	28.00	26.09	31.53	30.02
Mount Hope	27.87	[2]34.81	26.30	33.73	29.10	32.51	30.73
Wichita	33.42	34.19	23.16	34.06	28.81	29.26	30.52
Mean for the study area	**29.71**	**34.34**	**24.56**	**31.93**	**28.00**	**31.10**	**30.42**

[1]Mean annual precipitation for 1950 estimated on the basis of mean annual precipitation at Mount Hope and Wichita climatic stations.

[2]Mean annual precipitation for 1941–44 estimated on the basis of mean annual precipitation at Hutchinson and Wichita climatic stations.

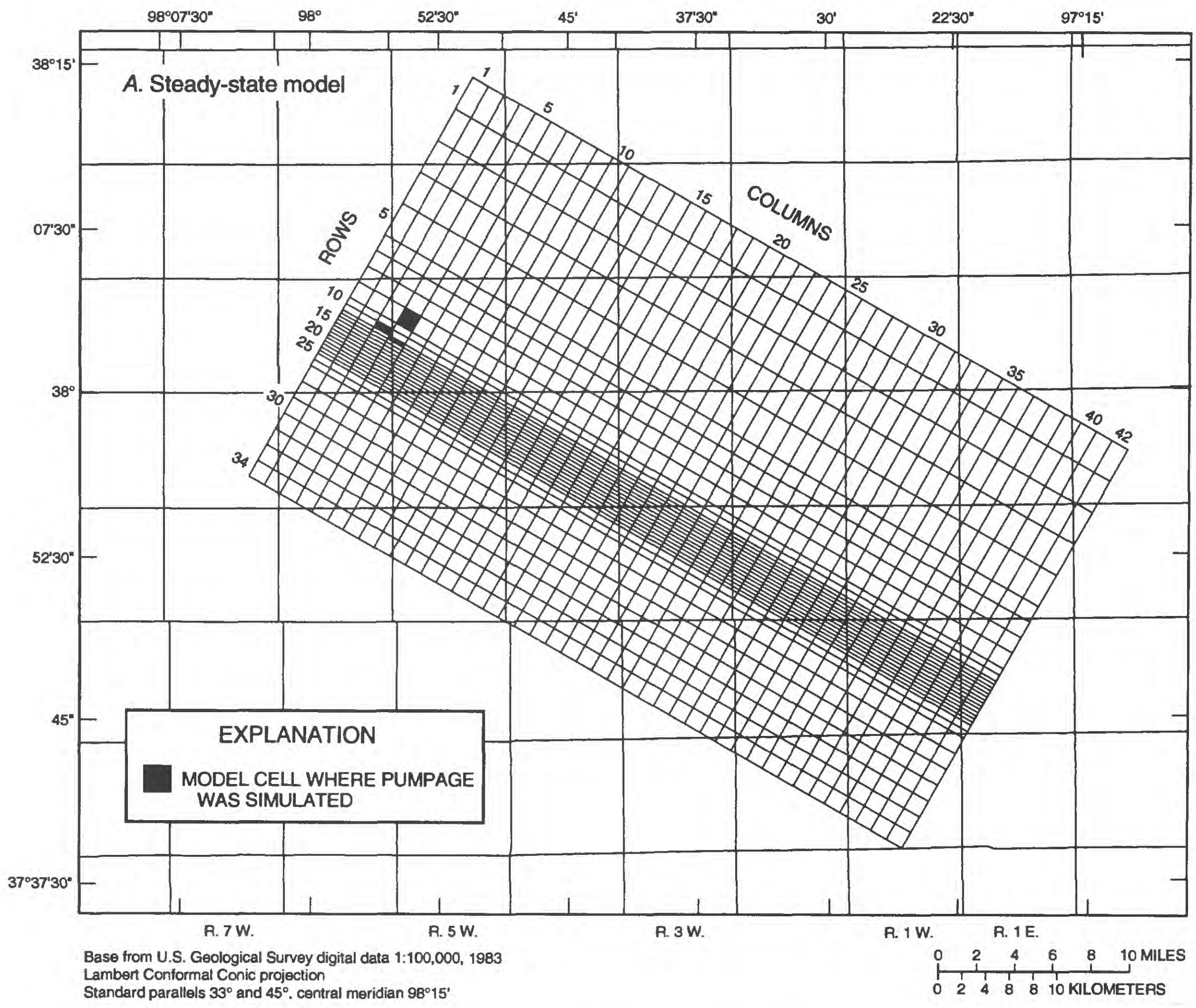


Figure 25. Model cells where pumpage from any of the three model layers was simulated in (*A*) steady-state model and in transient model for (*B*) 1940–52, (*C*) 1953–58, (*D*) 1959–63, (*E*) 1964–70, (*F*) 1971–79, and (*G*) 1980–89.

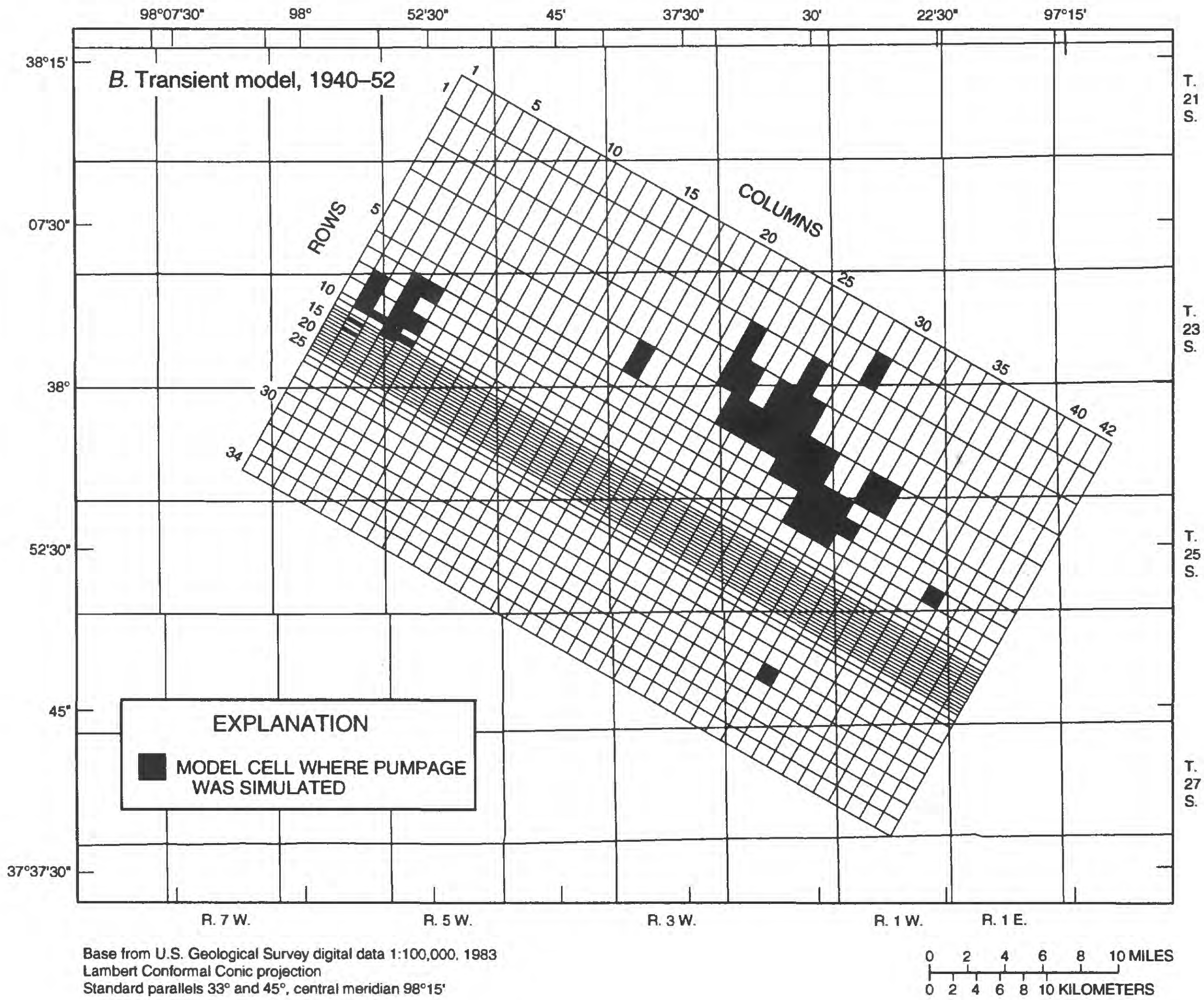


Figure 25. Model cells where pumpage from any of the three model layers was simulated in (*A*) steady-state model and in transient model for (*B*) 1940–52, (*C*) 1953–58, (*D*) 1959–63, (*E*) 1964–70, (*F*) 1971–79, and (*G*) 1980–89—Continued.

historic streamflow data. Simulated middle-layer hydraulic-head distributions were compared to measured head distributions for the end of 1989 (fig. 27). Minor adjustments to model-input hydraulic conductivity and recharge values were necessary before a satisfactory fit was achieved. These changes also were applied to the steady-state model. Simulated hydraulic heads also were compared to water-level hydrographs at 10 well locations (fig. 28). Simulated hydraulic heads follow the long-term trend of measured heads (fig. 28) but do not reflect seasonal or short-term variations in water levels because recharge, pumpage, and streamflows were held constant during each stress period.

The mean absolute difference between hydraulic heads for 232 individual wells and their corresponding middle-layer model cell for the end of 1989 were computed for all of and selected areas of the model (fig. 27). The mean absolute differences were: all of the model area, 4.67 ft; area 1, 5.76 ft; area 2, 2.47 ft; area 3, 2.15 ft; area 4, 4.56 ft; and area 5, 6.76 ft.

Streamflow that was exceeded 70 percent of the time at each gaging station, assumed to represent base flow, was compared to model-simulated flow in the model-stream reach where the gaging station was located (fig. 29). Because streamflows specified for the starting stream reach in the model were held constant for each stress period, the model did not simulate the

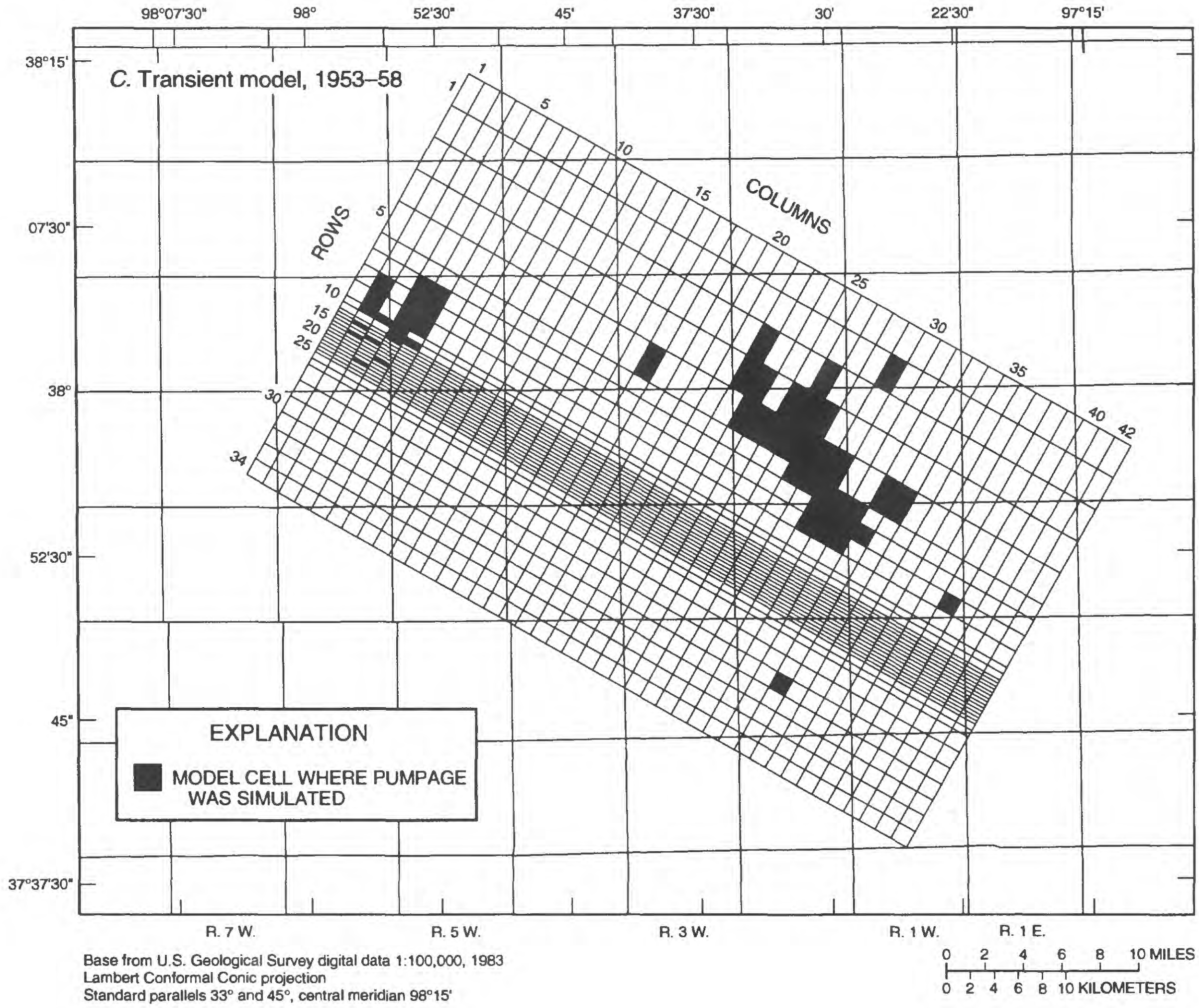


Figure 25. Model cells where pumpage from any of the three model layers was simulated in (*A*) steady-state model and in transient model for (*B*) 1940–52, (*C*) 1953–58, (*D*) 1959–63, (*E*) 1964–70, (*F*) 1971–79, and (*G*) 1980–89—Continued.

annual seasonal or short-term variation of measured streamflow. For most stress periods, the model approximately simulated the annual average base flow for that stress period (fig. 29). Increases or decreases in the rate of streamflow specified for each stress period result in large changes in simulated flow for the Arkansas River at the beginning of each stress period. The gradual changes in simulated streamflow within each stress period are caused by stream-aquifer interaction in the model (fig. 29).

Sensitivity analysis indicated that the transient model was most sensitive to changes in hydraulic conductivity and recharge and least sensitive to changes in streamflow, storage coefficient, and streambed conductance. Sensitivity analysis was done by comparing the mean absolute deviation of simulated hydraulic heads to the accepted transient-model calibration heads (fig. 30). A separate, complete, transient simulation (1940–89) was made for each property changed. A change factor of 0.83 or 1.2 times for hydraulic conductivity and recharge changed the mean absolute deviation from the calibration heads by about 0.45 and 0.18 ft, respectively (fig. 30).

Water Budgets

Water budgets for the ground-water flow model (table 6) show the inflow to and outflow from the model at the end of steady-state and transient stress

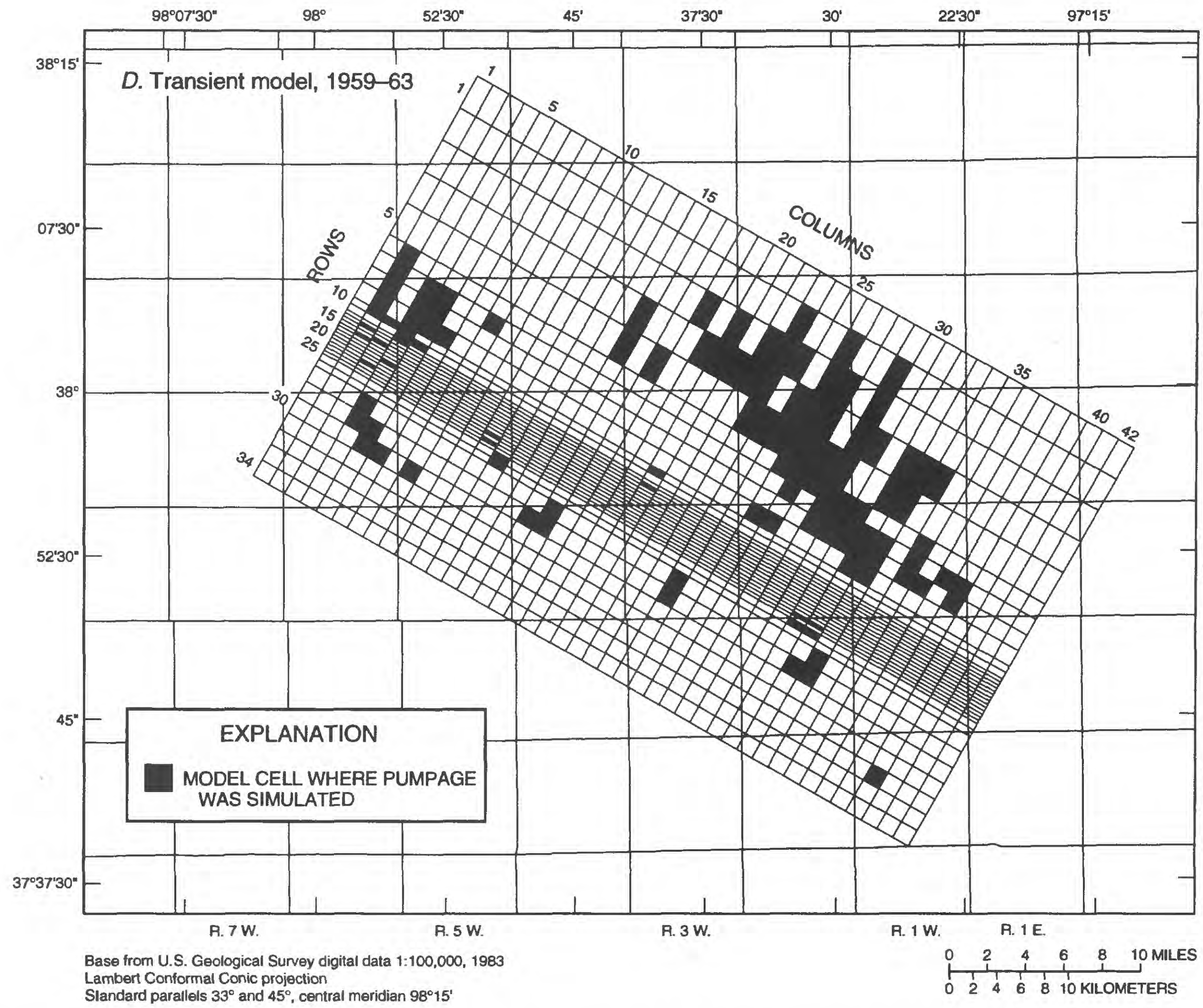


Figure 25. Model cells where pumpage from any of the three model layers was simulated in (*A*) steady-state model and in transient model for (*B*) 1940–52, (*C*) 1953–58, (*D*) 1959–63, (*E*) 1964–70, (*F*) 1971–79, and (*G*) 1980–89—Continued.

periods. In general, from 1940 to 1989 there were appreciable increases of boundary inflow in the upper layer, streamflow loss in the upper layer, and well pumpage in all layers; decreases of aquifer storage in the upper layer, boundary outflow in the upper layer, streamflow gain in the upper layer, and evapotranspiration in the upper layer; and increases of leakage from the upper layer to the middle layer, and from the middle layer to the lower layer. The increases of boundary inflow and streamflow loss, the decreases in boundary outflow, evapotranspiration, and streamflow gain, and the net change of storage resulted in a net increase of water available to the model of about 160 ft^3/s. Almost all of this net increase of water is accounted for by the 1940–89 increase in well withdrawals of about 158 ft^3/s. The increasing leakage to the middle and lower layers is due to increasing well pumpage from these layers.

Parameters for Simulations of Hypothetical Conditions

A series of transient simulations were used to estimate the possible effect of changing recharge, streamflow, and pumpage on ground-water levels, streamflow, the volume of water exchanged between the Arkansas River and the *Equus* beds aquifer, the quantity of chloride lost from the river to the aquifer, and the distribution in the aquifer of chloride originating from the river. All boundary conditions

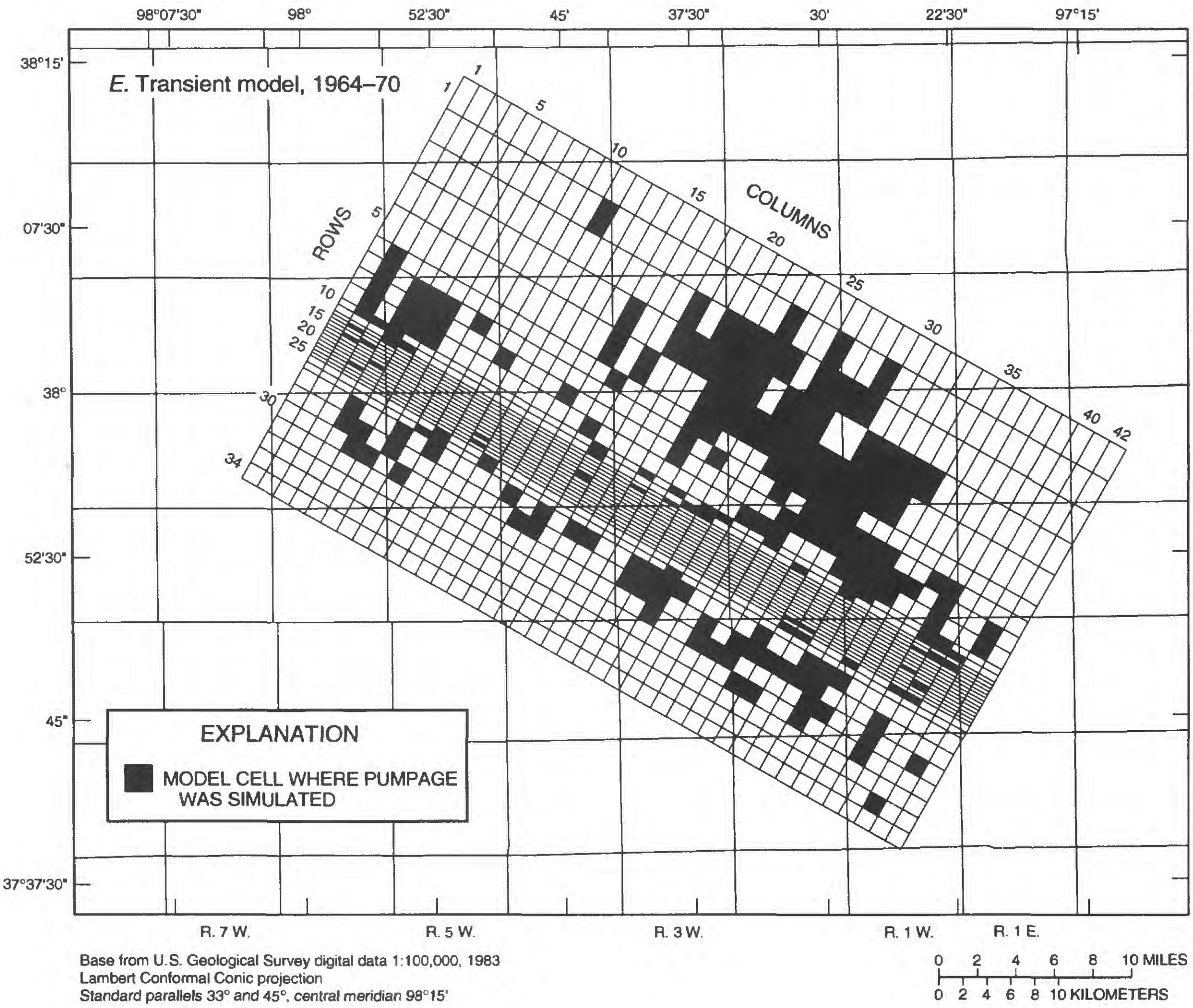


Figure 25. Model cells where pumpage from any of the three model layers was simulated in (*A*) steady-state model and in transient model for (*B*) 1940–52, (*C*) 1953–58, (*D*) 1959–63, (*E*) 1964–70, (*F*) 1971–79, and (*G*) 1980–89—Continued.

and aquifer properties were the same as those used in the transient model (1940–89). Recharge, streamflow, and pumpage were varied in these simulations of hypothetical conditions.

Recharge was varied to simulate dry, normal, and wet climatic conditions. Small and large values of recharge were based on the driest and wettest 10-year periods between 1940 and 1989 that were recorded at the Hutchinson, Mount Hope, and Wichita climatological stations. The average annual precipitation for the driest 10-year period, 1952–61, was 25.53 in. The average annual precipitation for the wettest 10-years, 1942–51, was 35.68 in. The average precipitation, based on the precipitation for the 1940–89 period, was 30.67 in. (National Oceanic and Atmospheric Administration, 1935–89). Thus, precipitation during the driest 10-year period was about 83 percent of the average precipitation. Precipitation during the wettest 10-year period was about 116 percent of the average precipitation. Recharge during dry and wet periods was assumed to differ from the average recharge by these same percentages.

Streamflow was varied to simulate periods of sustained low, average, and high streamflow. Small and large values of streamflow were based on the 10-year period with the smallest and largest flows exceeded 70 percent of the time in the Arkansas River near Hutchinson. For the period of no record at this site (prior to 1959), streamflows were extrapolated from records for the Arkansas River at Wichita and the

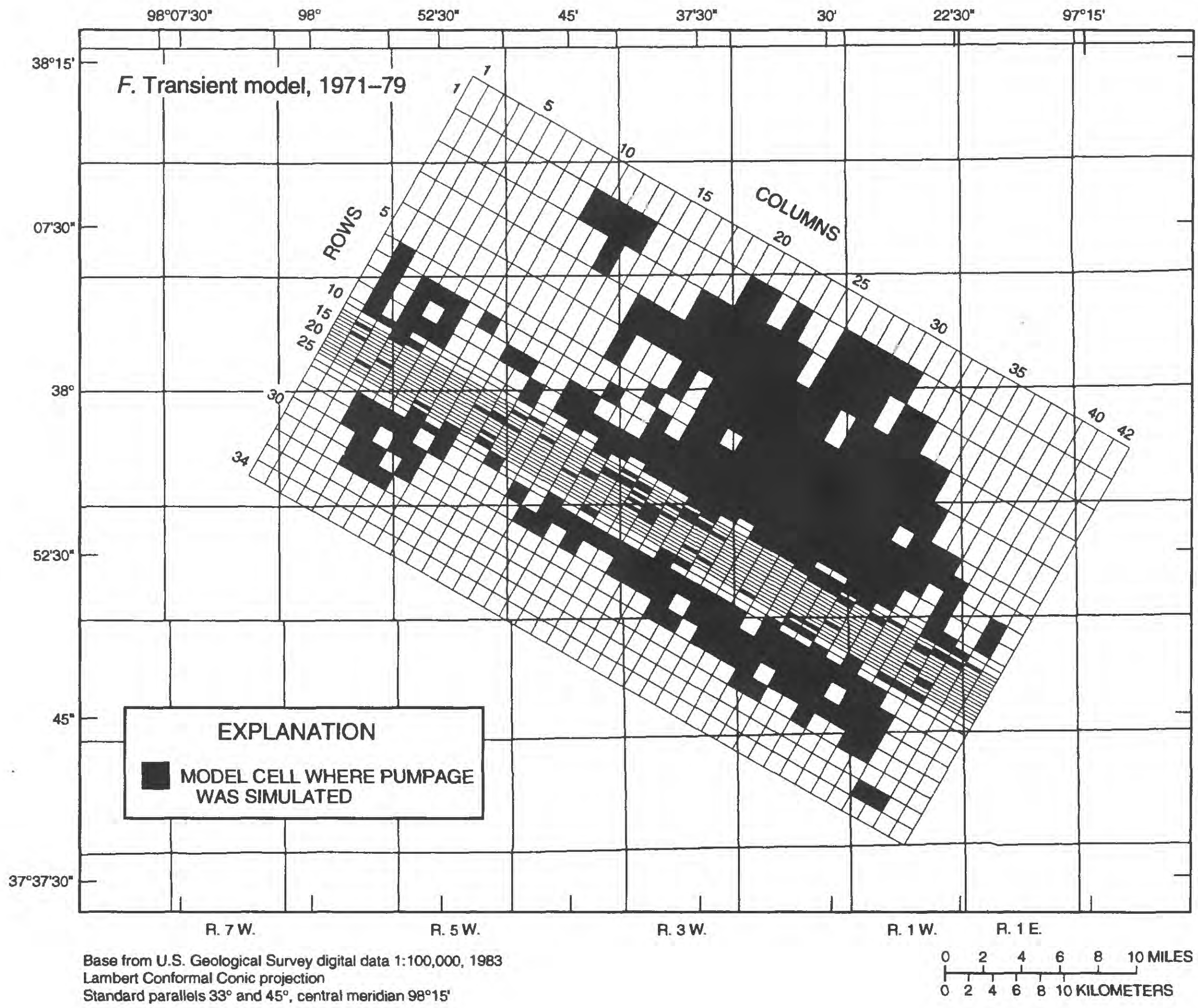


Figure 25. Model cells where pumpage from any of the three model layers was simulated in (*A*) steady-state model and in transient model for (*B*) 1940–52, (*C*) 1953–58, (*D*) 1959–63, (*E*) 1964–70, (*F*) 1971–79, and (*G*) 1980–89—Continued.

Little Arkansas River at Valley Center. The smallest 10-year-period streamflow that was exceeded 70 percent of the time was 75 ft^3/s, for 1934–43. The largest 10-year-period streamflow that was exceeded 70 percent of the time was 390 ft^3/s, for 1942–51. The average streamflow that was exceeded 70 percent of the time was taken as the average of the smallest 10-year period and largest 10-year-period streamflows, about 230 ft^3/s.

Pumpage in the simulations of hypothetical conditions was varied from no change, to a 1-percent per year increase of 1989 pumpage, a 2-percent per year increase of 1989 pumpage, and a 3-percent per year increase of 1989 pumpage. Hereinafter, the three percentage options will be referenced as the 1-percent per year, 2-percent per year, and 3-percent per year increases.

Least-squares regression analysis of pumpage data indicated that from 1960–89 pumpage volume increased by about 2,800 acre-ft or 2.4 percent per year of 1989 pumpage. Thus, the 1-, 2-, and 3-percent per year increases used in the hypothetical simulations represent relatively small, average, and large pumpage increases. The pumpage increases were assigned to model cells where ground-water withdrawals already were occurring in 1989. Therefore, the increases of pumpage may be unrealistic in some areas that already have reached the maximum pumpage allocation allowed by current (1992) law, such as parts of the Wichita well field.

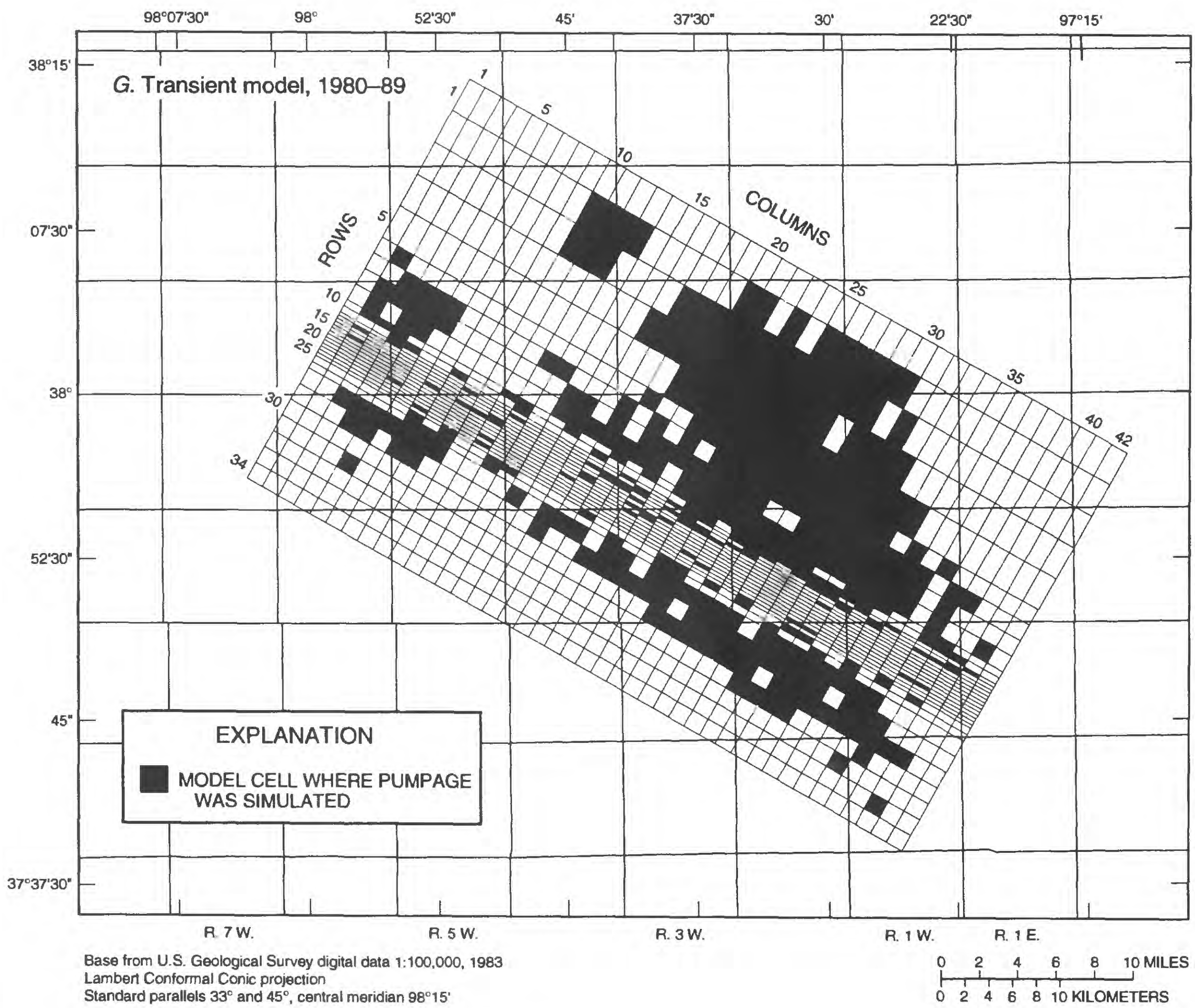


Figure 25. Model cells where pumpage from any of the three model layers was simulated in (*A*) steady-state model and in transient model for (*B*) 1940–52, (*C*) 1953–58, (*D*) 1959–63, (*E*) 1964–70, (*F*) 1971–79, and (*G*) 1980–89—Continued.

A total of 36 simulations were used for the combinations of three different recharge conditions, three different streamflow conditions, and four different pumpage conditions. The simulations were divided into three 10-year stress periods. Each stress period was divided into 10 time steps. Recharge and streamflow were held constant for each simulation, and except for the simulations of no change from 1989 conditions, pumpage was increased by 1, or 2, or 3 percent per year of 1989 pumpage. Thus, at the end of a 30-year simulation, a 1-percent per year increase in pumpage represented a 30-percent increase in pumpage over 1989 pumpage, a 2-percent per year increase in pumpage represents a 60-percent increase over 1989 pumpage; and a 3-percent per year increase in pumpage represents a 90-percent increase over 1989 pumpage.

The actual amount of pumpage simulated was less than 1-, 2-, or 3-percent per year for some of the simulations (fig. 31) when upper layer model cells were simulated as going dry. Model cells go dry when the simulated water level declines below the bottom of the cell. When this happens the stresses for that model cell, including pumpage, no longer are included in model calculations, so the total simulated pumpage is less than the amount in the input data sets. The decrease of pumpage in the model is similar to decline in the productivity of wells if water levels in the aquifer decline.

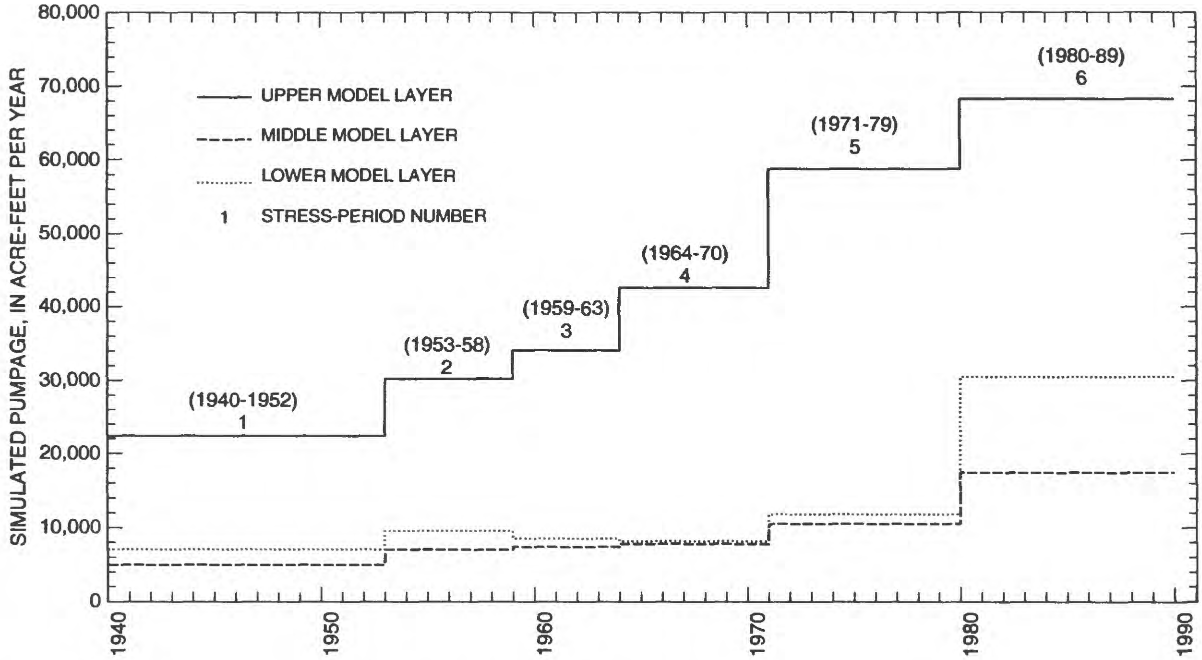


Figure 26. Simulated pumpage used in transient model for each model layer.

Discussion of Ground-Water Flow-Model Results

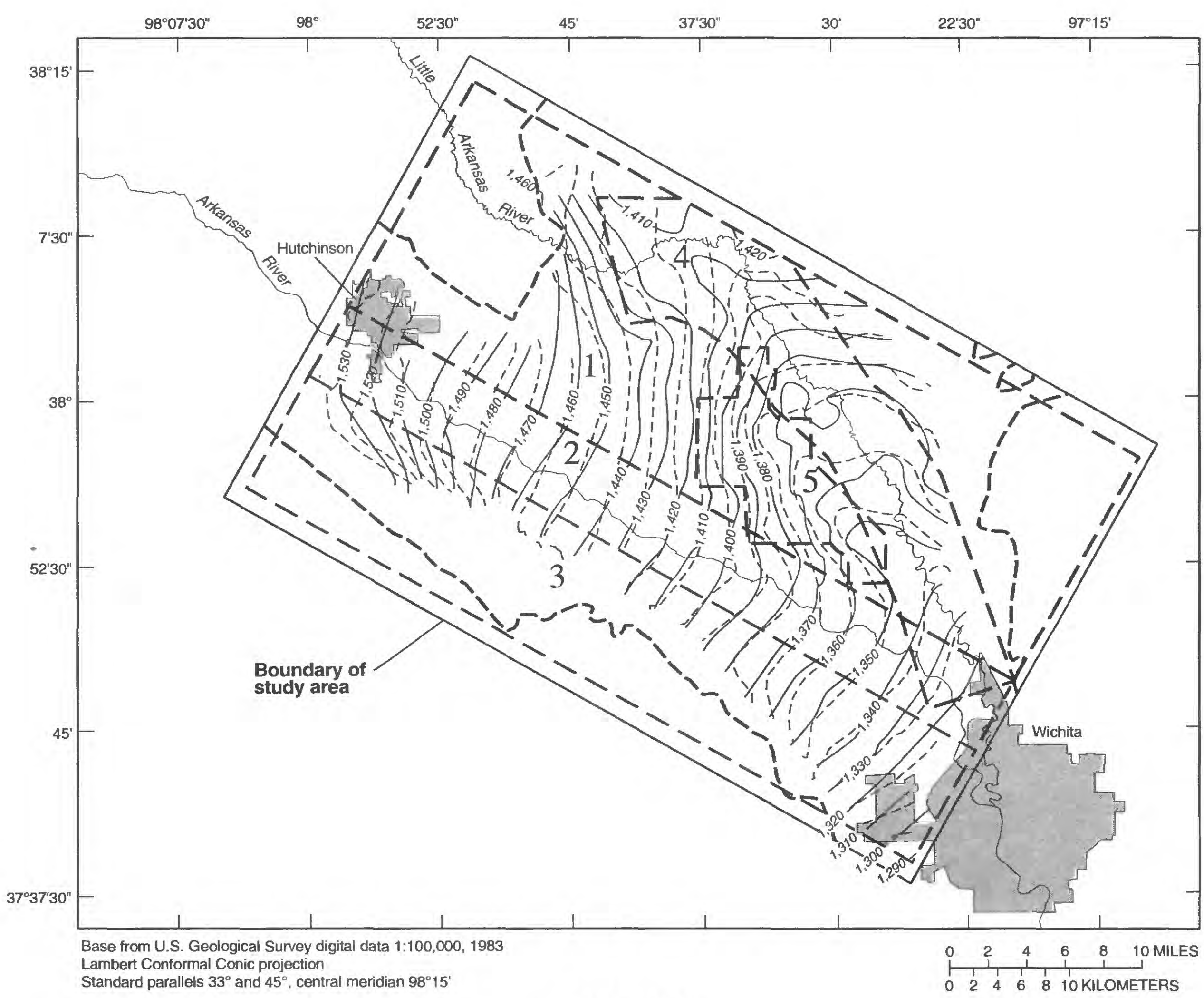
Discussion of flow-model results will focus on two transient-simulation periods—the simulation of historical conditions (1940–89) and the simulation of hypothetical conditions for 1990–2019.

Steady-State and Transient Simulations, 1940–89

During 1940–89, the Arkansas River, acting as a relatively constant-head source, has maintained aquifer water levels near the river at close to their 1940 levels. Measured water-level data and model results indicate that water levels in most of the *Equus* beds aquifer away from the river have experienced long-term declines since about 1940 (fig. 28) because of increasing ground-water pumpage from the aquifer. In part of the Wichita well field area, water levels have declined more than 30 ft (fig. 28, well 24S02W08DBB01). Near the Arkansas River, however, water levels have declined only about 1 ft (fig. 28, well 25S03W09CCC01) since the 1940's. Water-level declines in the aquifer near the Arkansas River were moderated by increasing streamflow losses from the river.

Declining water levels in the *Equus* beds aquifer during 1940–89 have resulted in decreased base flow in the Arkansas and Little Arkansas Rivers. In 1940, the Arkansas River had a simulated cumulative loss of about 12 ft^3/s and a simulated cumulative gain of about 33 ft^3/s for the stream reach within the model area, for a net cumulative gain of about 21 ft^3/s (fig. 32*A*). Since 1940, loss from the river has increased. At the end of 1989, the simulated cumulative loss was about 59 ft^3/s and the gain about 7 ft^3/s for a net cumulative loss of about 52 ft^3/s (fig. 32*A*, stress period 6). In 1940, the Little Arkansas River had a simulated net cumulative gain of about 67 ft^3/s for the river reach within the model area. By the end of 1989, simulated net cumulative gain in the Little Arkansas River had decreased to about 27 ft^3/s (fig. 32*B*, stress period 6).

During 1940–89, the quantity of chloride discharged from the Arkansas River to the *Equus* beds aquifer increased (fig. 33) in direct proportion to the volume of water loss from the river to the aquifer. Calculation of chloride discharge was based on simulated water loss from the river to the aquifer and on the median chloride concentration of 630 mg/L measured in Arkansas River water samples collected during this study. The median chloride concentration may have been larger or smaller in the past. The calculated cumulative load of chloride discharged from the river to the aquifer in 1940 was about 21 ton/d within the model area (fig. 33). At the end of 1989, the calculated load of chloride discharge had



EXPLANATION

1 — AREA USED FOR COMPARISON OF MEASURED AND SIMULATED HYDRAULIC HEADS

Key to areas:
1 About upper one-half of model
2 Area along Arkansas River
3 About lower one-quarter of model
4 Area along Little Arkansas River
5 Wichita well field

Some of the numbered areas overlap

—1,520— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells, based on measured hydraulic heads, 1989. Contour interval 10 feet. Datum is sea level

- -1,520- - POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells, based on end of transient simulation. Contour interval 10 feet. Datum is sea level

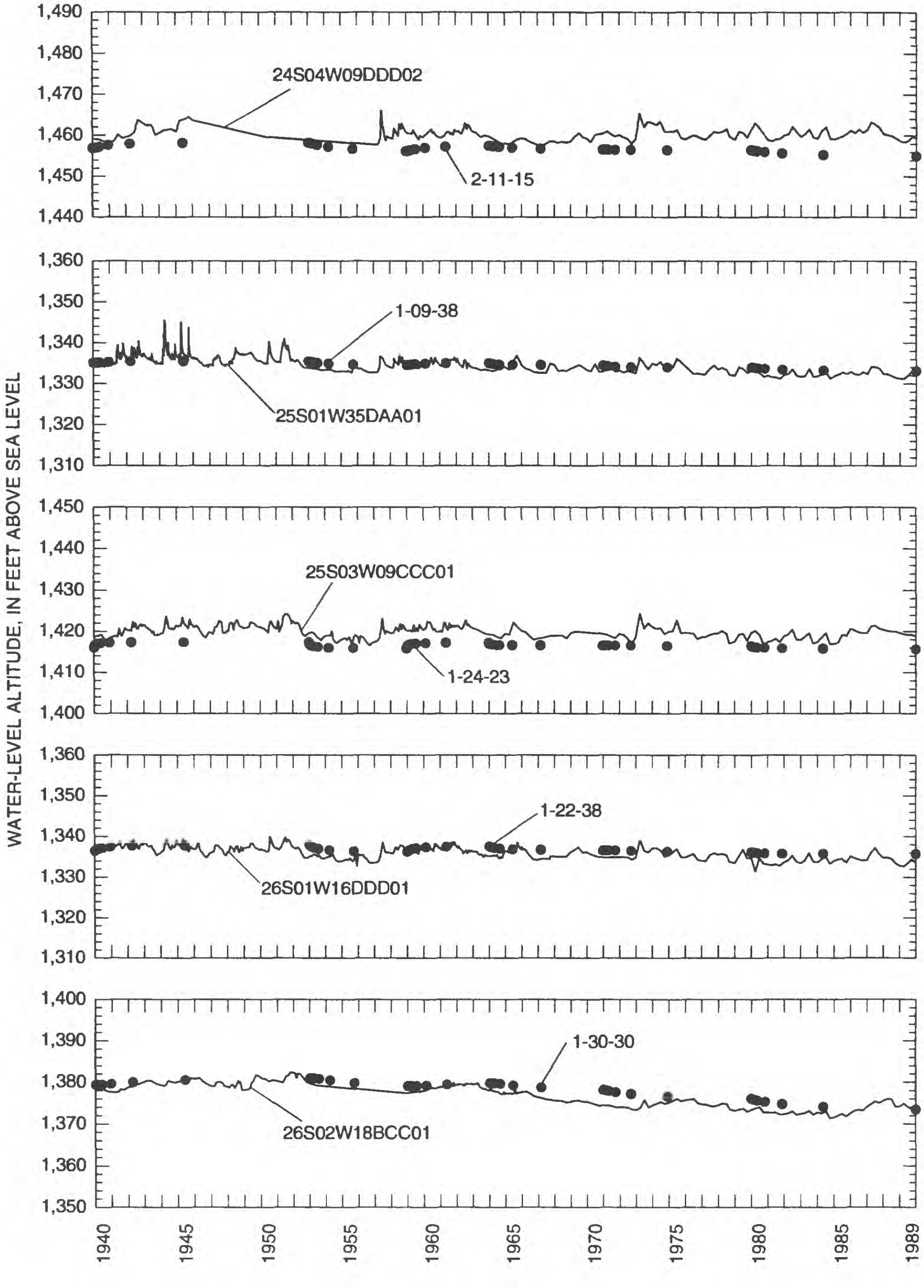
— — — — BOUNDARY OF *EQUUS* BEDS AQUIFER

Figure 27. Measured and simulated potentiometric surface for 1989 in the middle model layer (1989 potentiometric contours based on data available in U.S. Geological Survey WATSTORE data base) and areas used for comparison of measured and simulated hydraulic heads.

increased to about 100 ton/d within the model area (fig. 33). Some of the chloride discharged from the river probably was recaptured by the river throughout its gaining reaches. Because the Arkansas River has changed from a net gaining stream to a net losing stream, the proportion of chloride discharged to the aquifer to chloride recaptured from the aquifer increased during 1940–89.

Transient Simulations, 1990–2019

Transient simulations of hypothetical conditions were used to estimate the possible effect of changing recharge, streamflow, and pumpage on ground-water levels. Simulated water levels for a model cell (layer 1, row 5, column 24) located in the central part of the Wichita well field declined in all 36 simulations

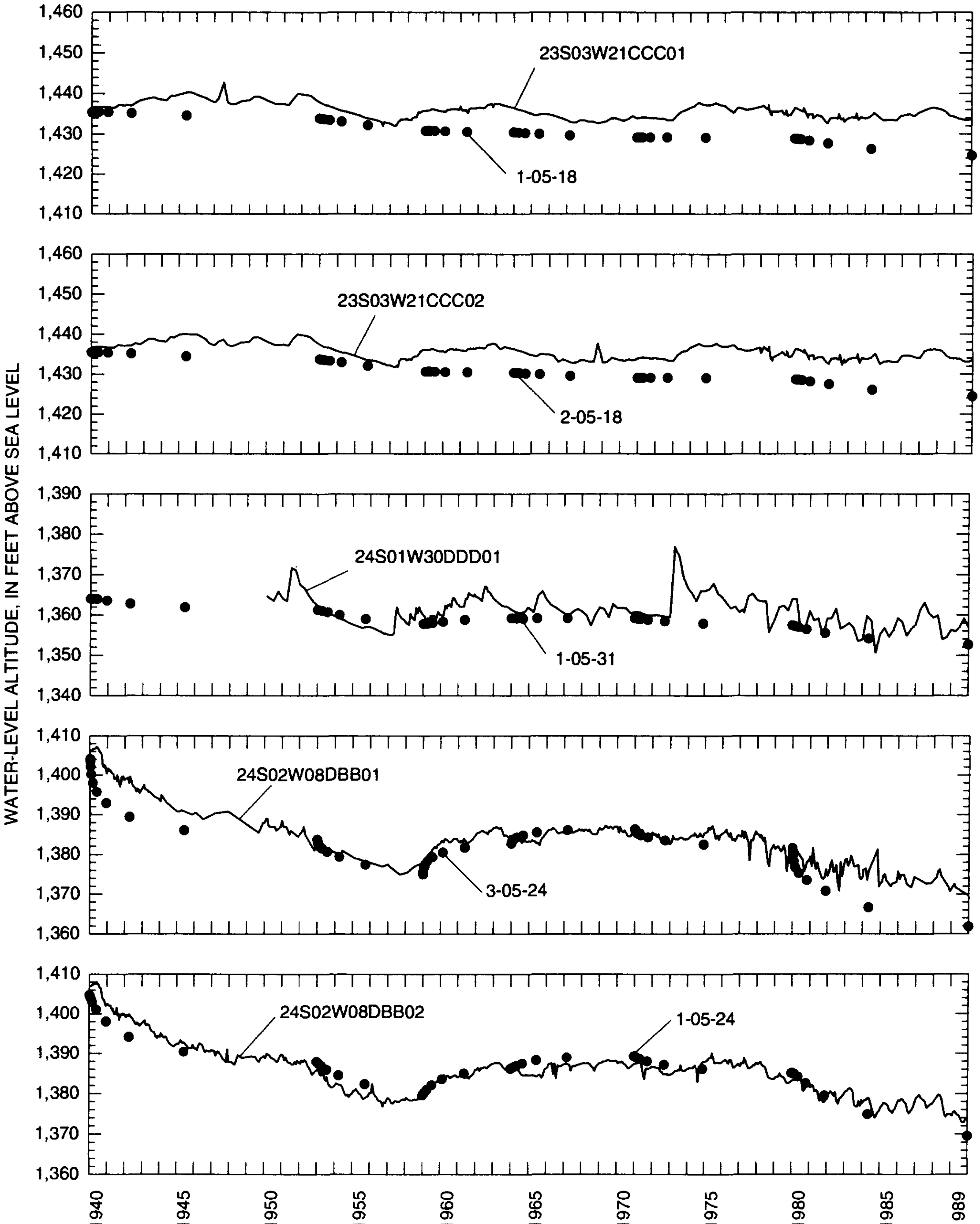


EXPLANATION

● 2-11-15—Simulated water-level altitude and model layer-row-column designation

24S04W09DDD02—Measured water-level altitude and well number

Figure 28. Measured and simulated water-level altitudes for transient simulation, 1940–89 (measured water levels on file with the U.S. Geological Survey, Lawrence, Kans.). Well locations shown in figure 6.



EXPLANATION

- ● 1-05-18—Simulated water-level altitude and model layer-row-column designation

23S03W21CCC02—Measured water-level altitude and well number

Figure 28. Measured and simulated water-level altitudes for transient simulation, 1940–89 (measured water levels on file with the U.S. Geological Survey, Lawrence, Kans.). Well locations shown in figure 6—Continued.

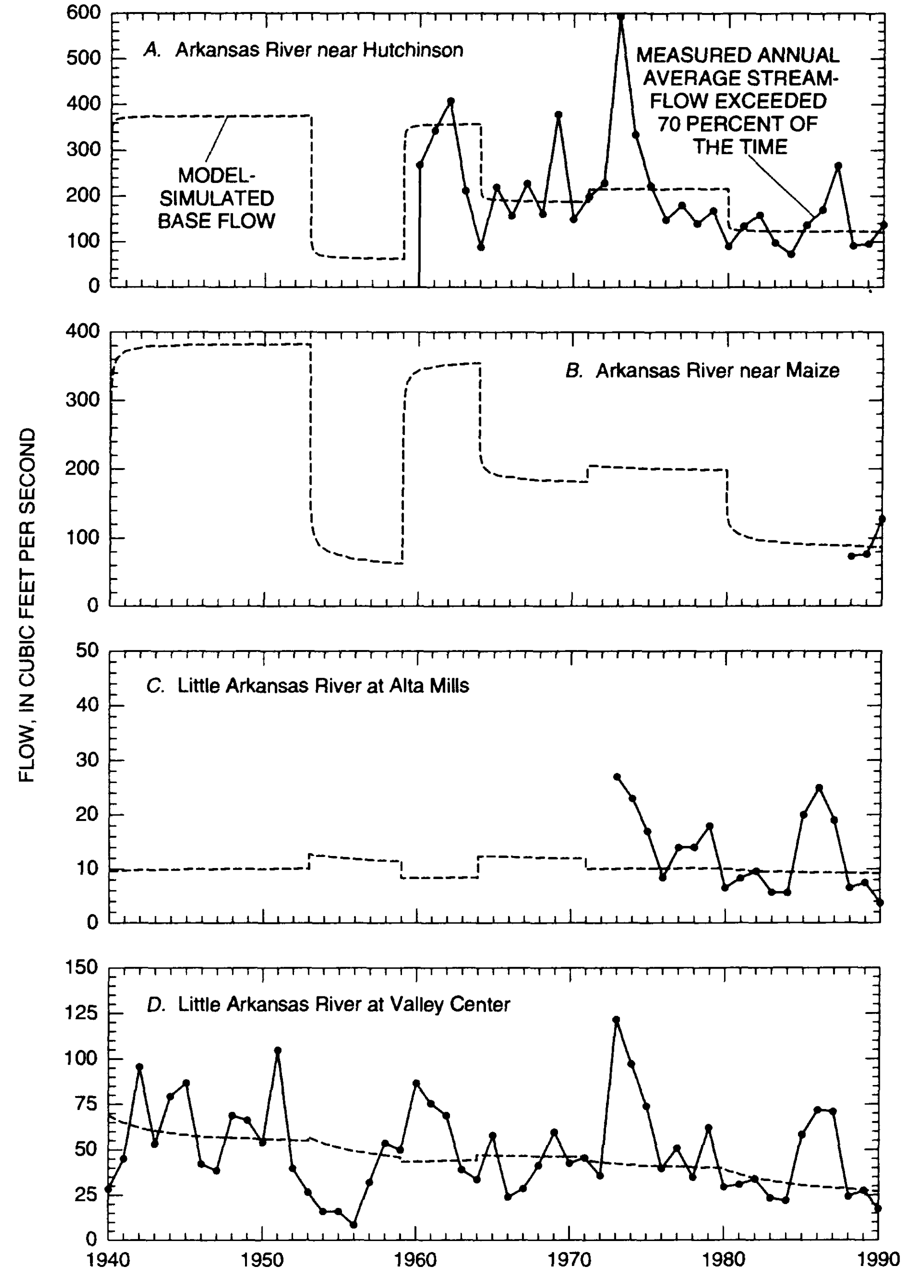


Figure 29. Measured annual average streamflow exceeded 70 percent of time and model-simulated base flow at gaging stations on the (*A*) Arkansas River near Hutchinson, (*B*) Arkansas River near Maize, (*C*) Little Arkansas River at Alta Mills, and (*D*) Little Arkansas River at Valley Center, 1940–90 (measured annual average flow data on file with the U.S. Geological Survey, Lawrence, Kans.).

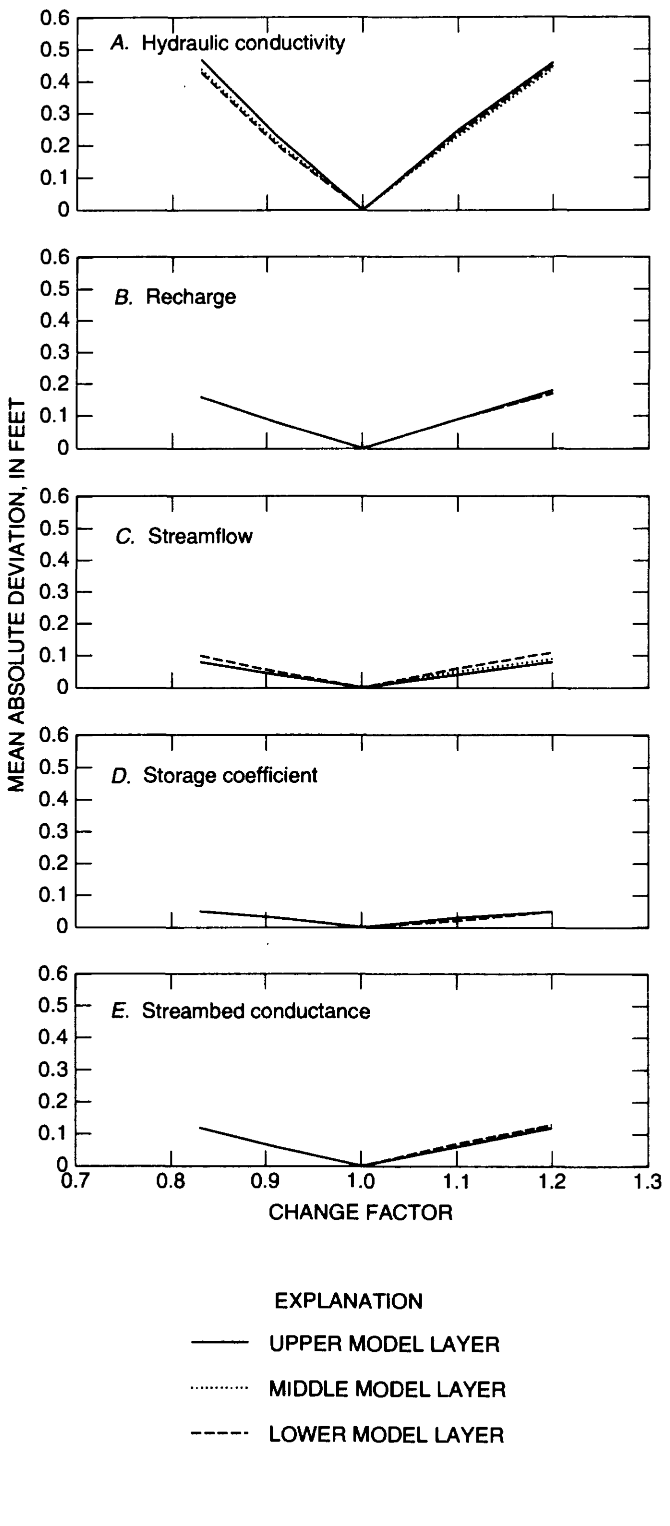


Figure 30. Mean absolute deviation of simulated hydraulic heads from accepted transient-model calibration heads for changes in (*A*) hydraulic conductivity, (*B*) recharge, (*C*) streamflow, (*D*) storage coefficient, and (*E*) streambed conductance.

(fig. 34). Changes in pumpage had the most effect on water levels. Changes in recharge had a moderate effect, and changes in streamflow had the least effect on water levels. Simulations with no increase in pumpage showed water-level declines from 1989 levels that ranged from 0.2 ft (large recharge, large streamflow) to about 10 ft (small recharge, small streamflow) by the end of 2019. These simulations show that, with no increase in pumpage in the Wichita well field area, water levels probably will remain within 10 ft of 1989 water levels, depending on long-term climatic conditions that affect recharge and streamflow. Simulations with a 1-percent per year increase in pumpage showed water-level declines from 1989 levels that ranged from about 27 to 42 ft by the end of 2019. Simulations with a 2-percent per year increase in pumpage showed water-level declines from 1989 levels that ranged from about 54 to 69 ft by the end of 2019. Simulations with a 3-percent per year increase in pumpage showed water-level declines from 1989 levels that ranged from about 75 to 78 ft by the end of 2019.

Simulated water levels for a model cell (layer 1, row 23, column 24) adjacent to the Arkansas River remained relatively stable compared to water levels in the Wichita well field because of the nearby presence of the Arkansas River (fig. 35). Changes in streamflow had the most effect on water levels, whereas pumpage and recharge showed the least effect. Simulations with no increase in pumpage since 1989 showed water-level changes from 1989 levels that ranged from about +1.3 ft (large recharge, large streamflow) to about -0.5 ft (small recharge, small streamflow). Simulations with a 1-percent per year increase in pumpage showed water-level changes from 1989 levels that ranged from about +1.0 to -0.7 ft. Simulations with a 2-percent per year increase in pumpage showed water-level changes from 1989 levels that ranged from about +0.9 to -1.0 ft. Simulations with a 3-percent per year increase in pumpage showed water-level changes from 1989 levels that ranged from about +0.7 to -1.2 ft.

Simulations using average recharge and streamflow were used to estimate the possible effect of changes in pumpage on the volume of water lost from the Arkansas River to the *Equus* beds aquifer and on base flow in the Arkansas River (fig. 36). Within the model area, the estimated cumulative loss from the Arkansas River to the aquifer by the end of 2019, assuming no increase in pumpage since 1989, was

Table 6. Simulated steady-state and transient ground-water budgets

[Values are given in cubic feet per second; E, exponential]

	Budget term	Steady state pre-1940	Transient stress periods					
			1 1940–52	2 1953–58	3 1959–63	4 1964–70	5 1971–79	6 1980–89
			Upper model layer					
Inflow	Change in storage	0	2.35	16.42	1.26	5.39	2.92	9.07
	Boundary flow	26.57	27.85	32.16	29.48	31.94	32.01	34.68
	Recharge	131.76	142.55	104.11	135.17	118.45	131.81	128.87
	Streamflow loss	13.32	26.15	27.66	34.38	37.23	46.13	63.00
	Leakage from middle layer	39.63	29.66	26.99	25.75	24.96	22.30	17.75
	Total inflow	**211.28**	**228.56**	**207.34**	**226.04**	**217.97**	**235.17**	**253.37**
Outflow	Change in storage	0	1.26	0	6.01	.26	.30	.06
	Boundary flow	32.62	35.55	31.52	33.85	31.63	30.60	29.23
	Well pumpage	2.79	30.88	41.70	47.06	58.92	81.22	94.36
	Evapotranspiration	31.62	28.49	18.79	22.91	19.51	17.48	12.01
	Streamflow gain	102.68	84.46	65.80	66.86	60.30	52.07	34.41
	Leakage to middle layer	41.48	47.94	49.69	49.24	47.41	53.50	83.32
	Total outflow	**211.19**	**228.58**	**207.50**	**225.93**	**218.03**	**235.17**	**253.39**
			Middle model layer					
Inflow	Change in storage	0	.09	.56	.06	.16	.11	.35
	Boundary flow	2.34	2.41	2.72	2.56	2.72	2.73	2.94
	Leakage from upper layer	41.48	47.94	49.69	49.24	47.41	53.50	83.32
	Leakage from lower layer	21.30	14.45	13.06	12.90	12.52	11.18	9.87
	Total inflow	**65.12**	**64.89**	**66.03**	**64.76**	**62.81**	**67.52**	**96.48**
Outflow	Change in storage	0	.03	0	.18	8.94E-3	5.17E-3	6.39E-4
	Boundary flow	1.60	1.66	1.49	1.49	1.38	1.32	1.28
	Well pumpage	.06	6.85	9.68	10.20	10.76	14.56	24.12
	Leakage to upper layer	39.63	29.66	26.99	25.75	24.96	22.30	17.75
	Leakage from lower layer	23.80	26.70	27.89	27.08	25.71	29.35	53.34
	Total outflow	**65.09**	**64.90**	**66.05**	**64.70**	**62.83**	**67.53**	**96.49**

Table 6. Simulated steady-state and transient ground-water budgets—Continued

	Budget term	Steady state pre-1940	Transient stress periods 1 1940–52	2 1953–58	3 1959–63	4 1964–70	5 1971–79	6 1980–89
			Lower model layer					
Inflow	Change in storage	0	0.11	0.59	0.07	0.15	0.11	0.40
	Boundary flow	.47	.43	.49	.50	.53	.52	.54
	Leakage from middle layer	23.80	26.70	27.89	27.08	25.71	29.35	53.34
	Total inflow	**24.27**	**27.24**	**28.97**	**27.65**	**26.39**	**29.98**	**54.28**
Outflow	Change in storage	0	.02	0	.19	.01	2.55E-3	9.03E-5
	Boundary flow	2.95	3.07	2.74	2.75	2.55	2.47	2.31
	Well pumpage	0	9.71	13.18	11.77	11.31	16.34	42.11
	Leakage to middle layer	21.30	14.45	13.06	12.90	12.52	11.18	9.87
	Total outflow	**24.25**	**27.25**	**28.98**	**27.61**	**26.39**	**29.99**	**54.29**
			All model layers					
Inflow	Change in storage	0	2.55	17.57	1.39	5.70	3.14	9.82
	Boundary flow	29.38	30.69	35.37	32.54	35.19	35.26	38.16
	Recharge	131.76	142.55	104.11	135.17	118.45	131.81	128.87
	Streamflow loss	13.32	26.15	27.66	34.38	37.23	46.13	63.00
	Total inflow	**174.46**	**201.94**	**184.71**	**203.48**	**196.57**	**216.34**	**239.85**
Outflow	Change in storage	0	1.31	0	6.38	.28	.31	.06
	Boundary flow	37.17	40.28	35.75	38.09	35.56	34.39	32.82
	Well pumpage	2.85	47.44	64.56	69.03	80.99	112.12	160.59
	Evapotranspiration	31.62	28.49	18.79	22.91	19.51	17.48	12.01
	Streamflow gain	102.68	84.46	65.80	66.86	60.30	52.07	34.41
	Total outflow	**174.32**	**201.98**	**184.90**	**203.27**	**196.64**	**216.37**	**239.89**

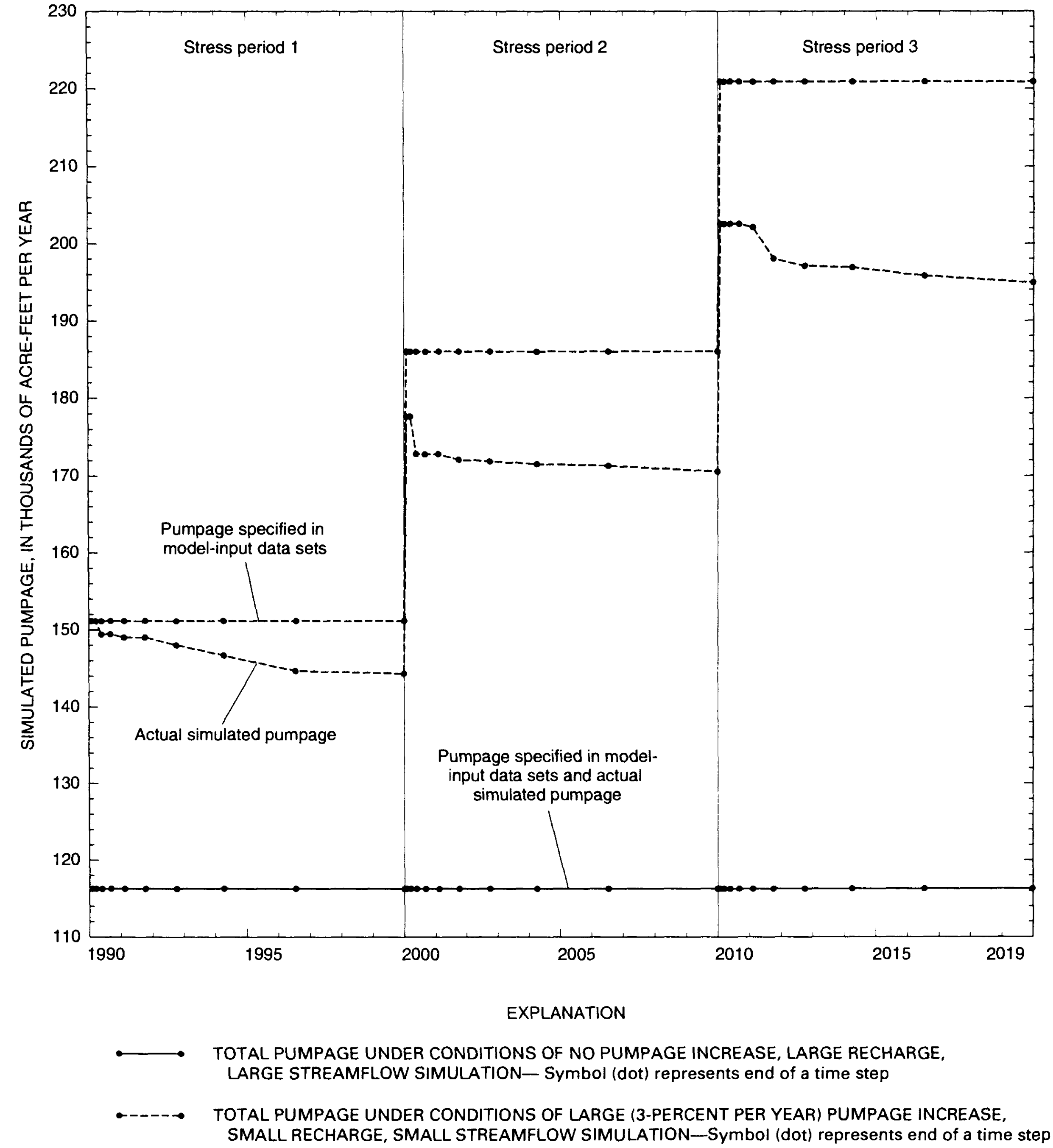


Figure 31. Pumpage specified in model-input data sets and actual simulated pumpage for two simulations of hypothetical conditions: (1) no pumpage increase, large recharge, large streamflow, and (2) large pumpage increase, small recharge, small streamflow. These two simulations represent the extremes (smallest and largest, respectively) of stress on the aquifer.

about 65 ft^3/s, and the cumulative gain was about 6 ft^3/s, giving a net base-flow loss from the river of 59 ft^3/s (fig. 36*A*). Assuming a 1-percent per year increase in pumpage, the estimated cumulative loss from the river by the end of 2019 was about 84 ft^3/s, and the cumulative gain was about 4 ft^3/s, giving a net base-flow loss from the river of 80 ft^3/s (fig. 36*B*). Assuming a 2-percent per year increase in pumpage, the estimated cumulative loss from the river by the end of 2019 was about 99 ft^3/s, and the cumulative gain

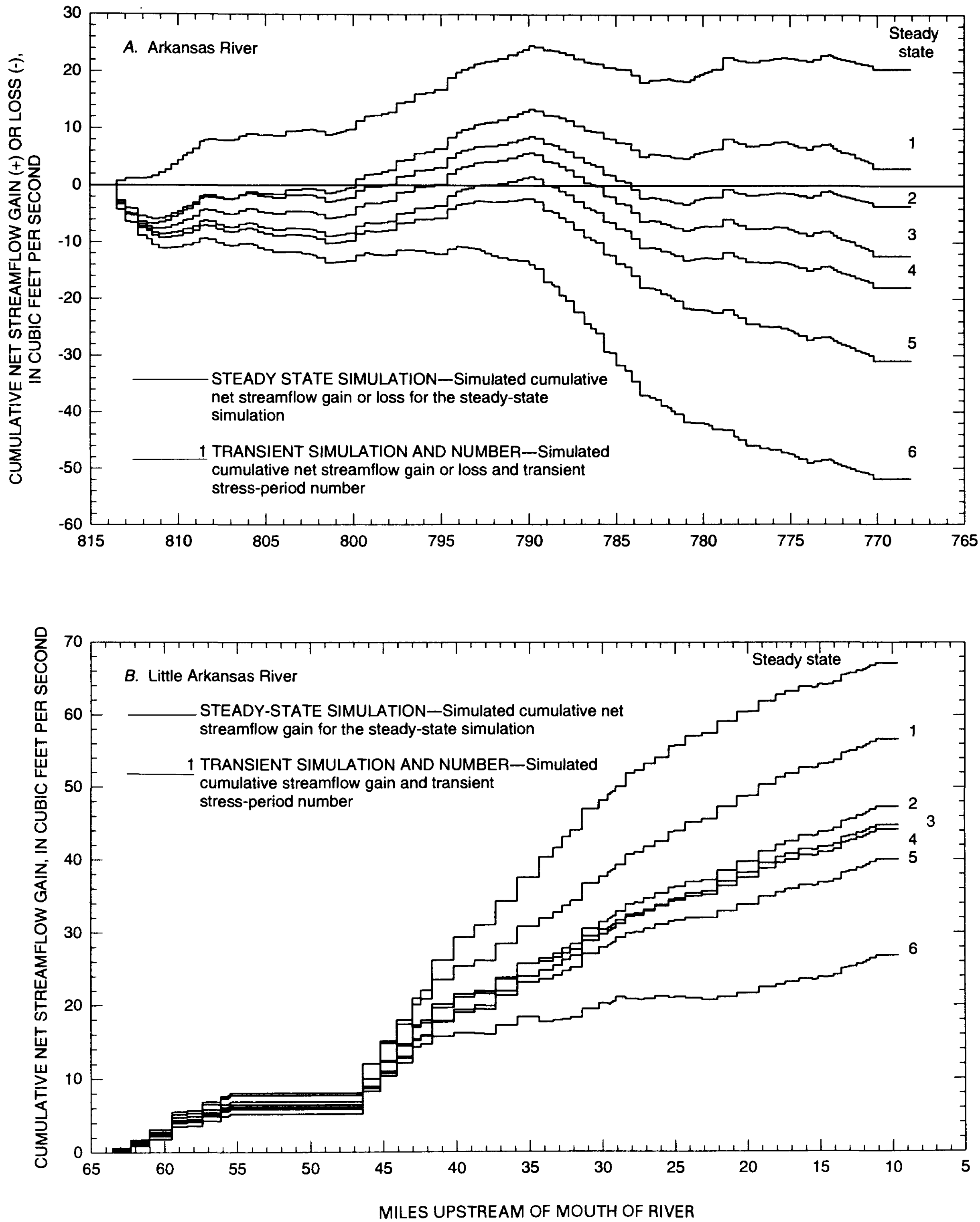


Figure 32. Simulated cumulative net streamflow gain from or loss to the *Equus* beds aquifer at end of each stress period for the (*A*) Arkansas River and (*B*) Little Arkansas River.

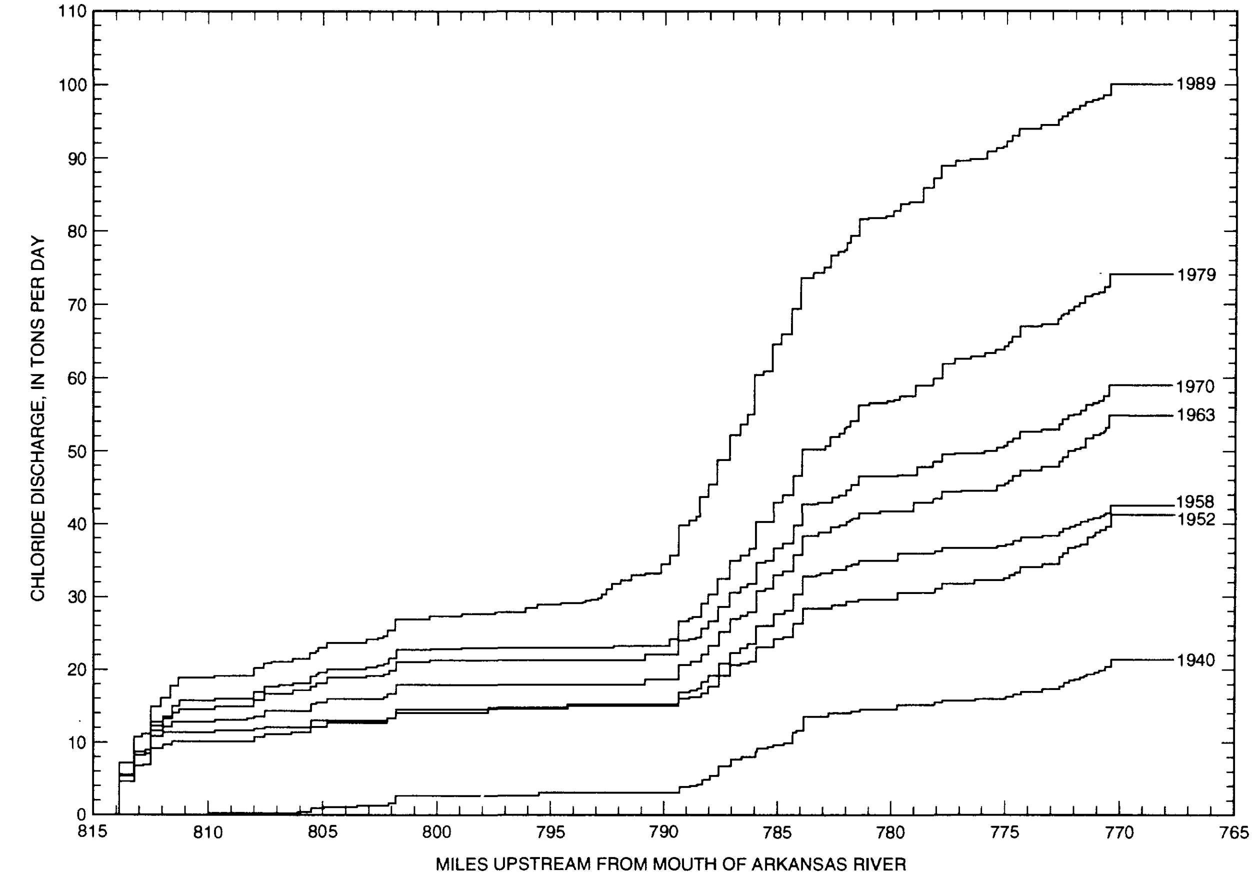


Figure 33. Estimated cumulative chloride discharge from Arkansas River to *Equus* beds aquifer at end of each stress period based on simulated streamflow loss from the Arkansas River and assuming a chloride concentration of 630 milligrams per liter.

was about 2 ft^3/s, giving a net base-flow loss from the river of 97 ft^3/s (fig. 36*C*). Assuming a 3-percent increase in pumpage, the estimated cumulative loss from the river by the end of 2019 was about 118 ft^3/s, and the cumulative gain was about 1 ft^3/s, giving a net base-flow loss from the river of 117 ft^3/s (fig. 36*D*).

During the simulated 1990–2019 period, estimated chloride discharge from the Arkansas River to the aquifer increased over 1989 estimated quantities (fig. 37) in proportion to increases in loss of river water. Assuming no increase in pumpage since 1989 and a 630-mg/L chloride concentration in Arkansas River water, the estimated cumulative chloride-load discharge within the model area was about 110 ton/d by the end of 2019 (fig. 37*A*). Assuming a 1-percent per year increase in pumpage since 1989, the estimated cumulative chloride-load discharge within the model area was about 142 ton/d by the end of 2019 (fig. 37*B*). Assuming a 2-percent per year increase in pumpage since 1989, the estimated cumulative chloride-load discharge within the model area was about 169 ton/d by the end of 2019 (fig. 37*C*). Assuming a 3-percent per year increase in pumpage since 1989, the estimated cumulative chloride-load discharge within the model area was about 200 ton/d by the end of 2019 (fig. 37*D*).

Particle Tracking

MODPATH is a program developed by Pollock (1989) that computes and displays the location through time of water particles using results from the MODFLOW flow-model program. MODPATH was used to display the zones of interaction between the Arkansas River and the *Equus* beds aquifer and to simulate the paths that particles of water from the Arkansas River follow as they move through the aquifer. Assuming that dissolved constituents, such as

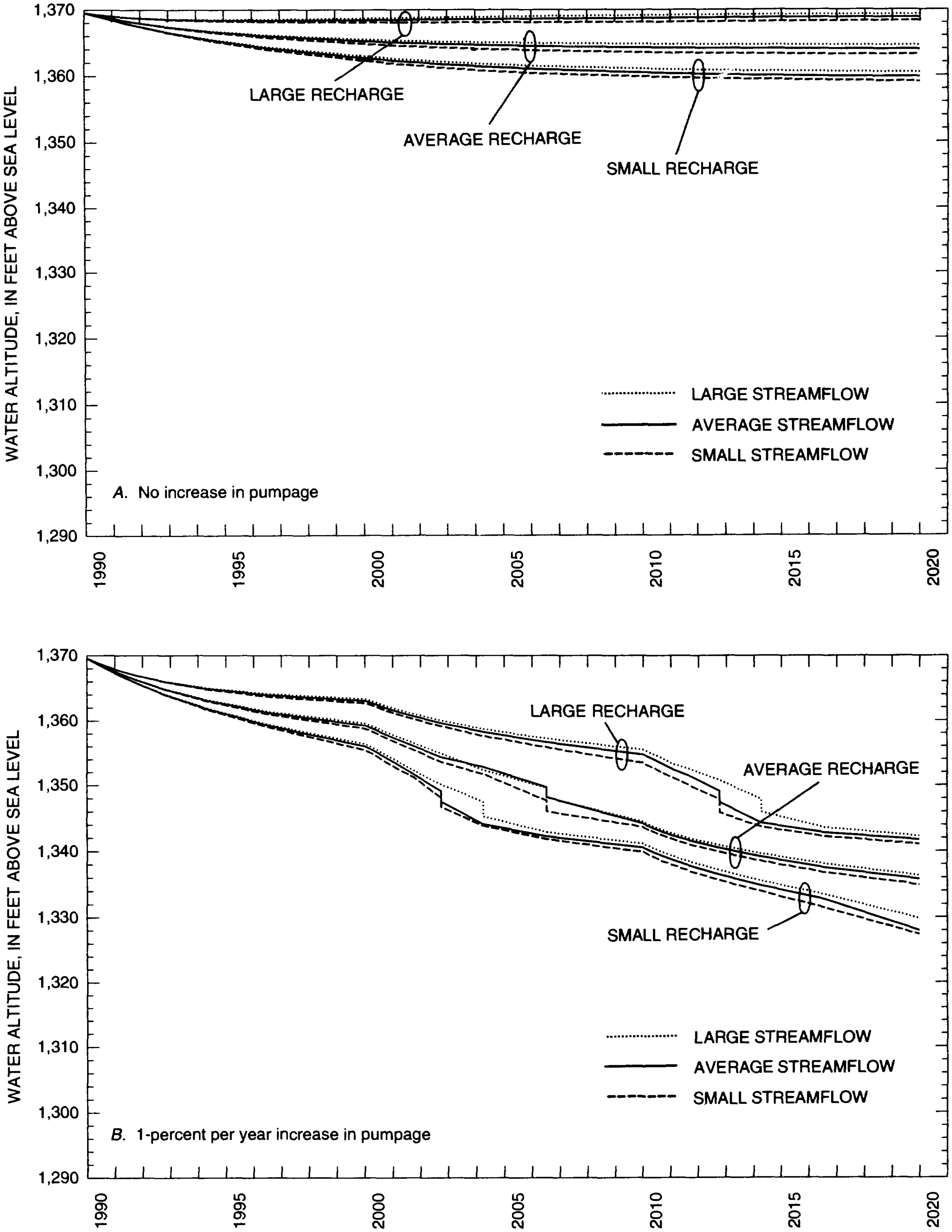
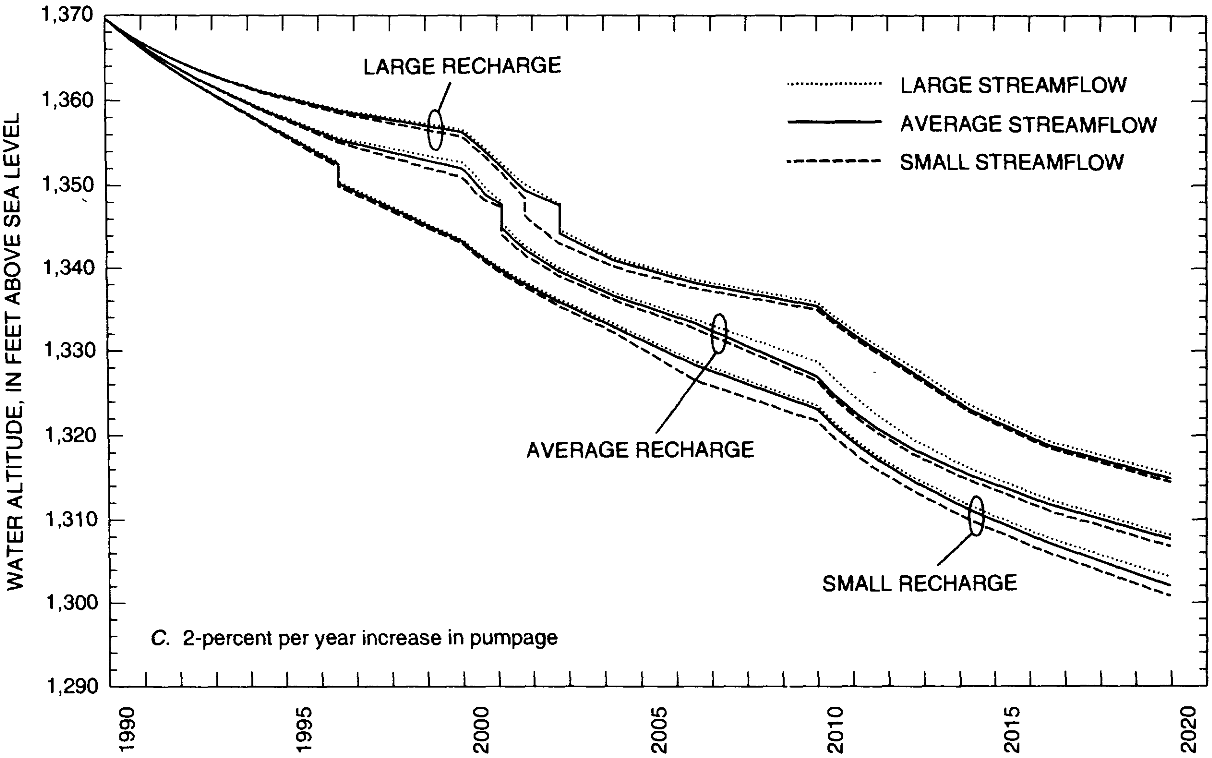


Figure 34. Estimated water levels at model row-5, column-24 in Wichita well field for simulations assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989. The abrupt declines of water-level altitude in (*B*), (*C*), and (*D*) result from switching from upper layer to middle layer water-level altitudes when the water-level altitude declined below the bottom of the upper layer model cell.



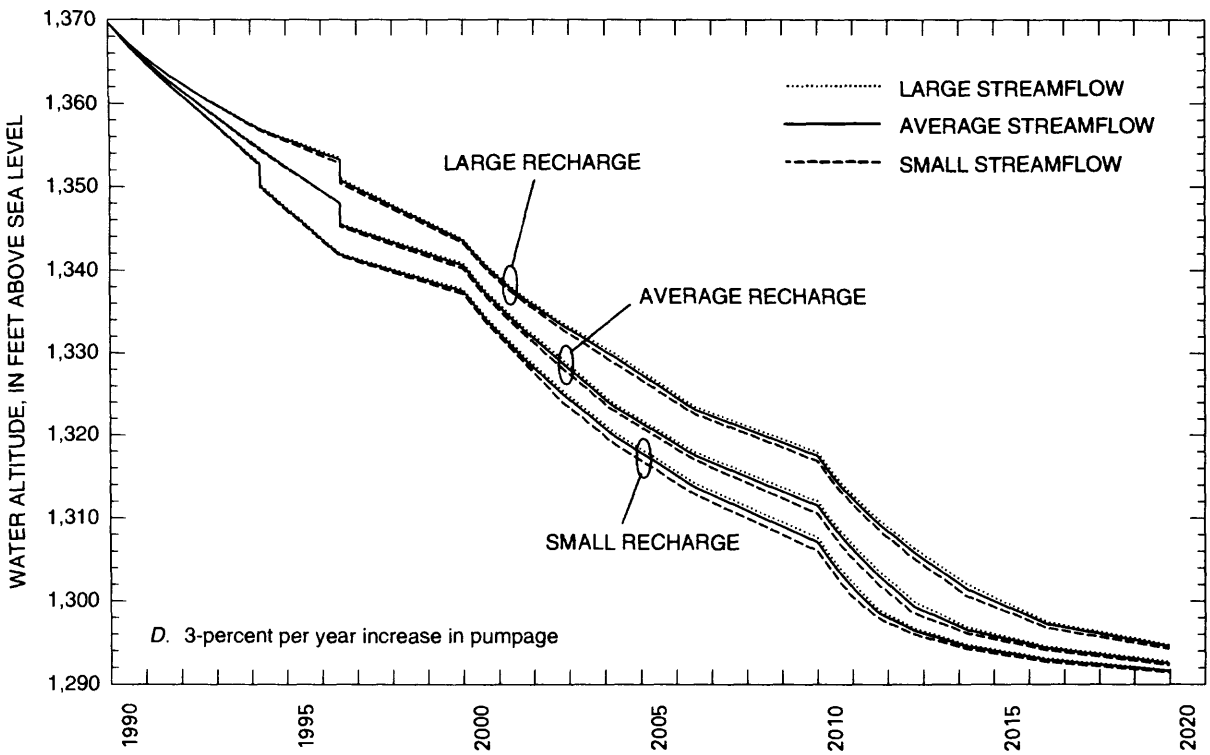


Figure 34. Estimated water levels at model row-5, column-24 in Wichita well field for simulations assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989. The abrupt declines of water-level altitude in (*B*), (*C*), and (*D*) result from switching from upper layer to middle layer water-level altitudes when the water-level altitude declined below the bottom of the upper layer model cell—Continued.

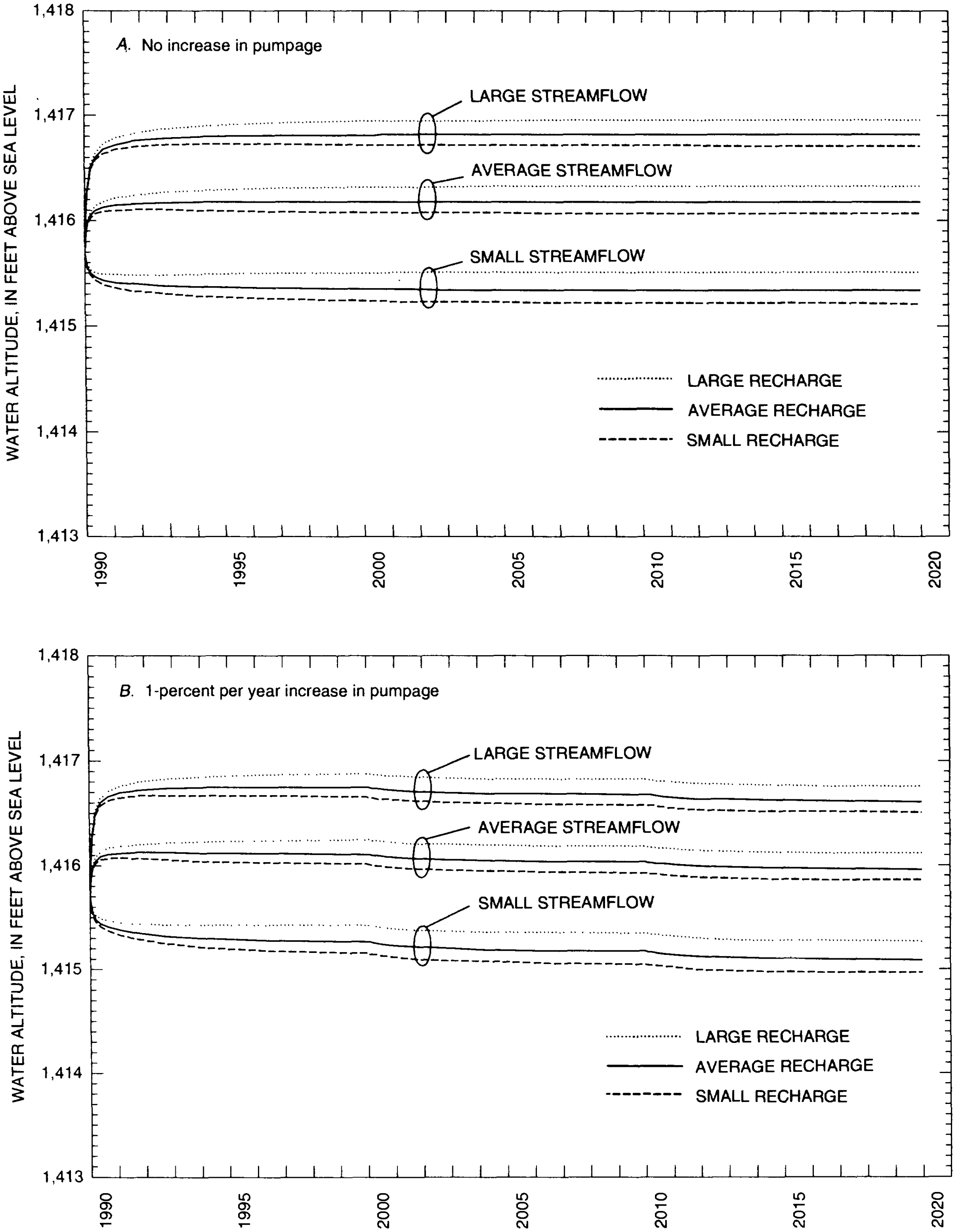
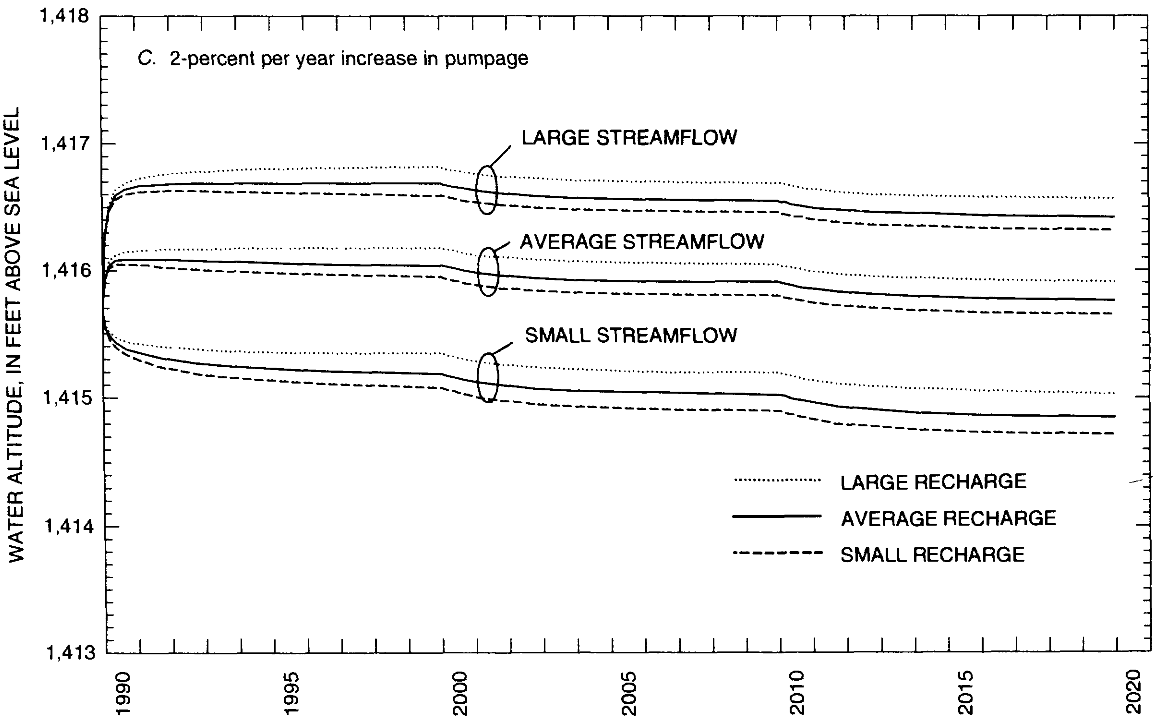


Figure 35. Estimated water levels at model row-24, column-23 near Arkansas River for simulations assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989.



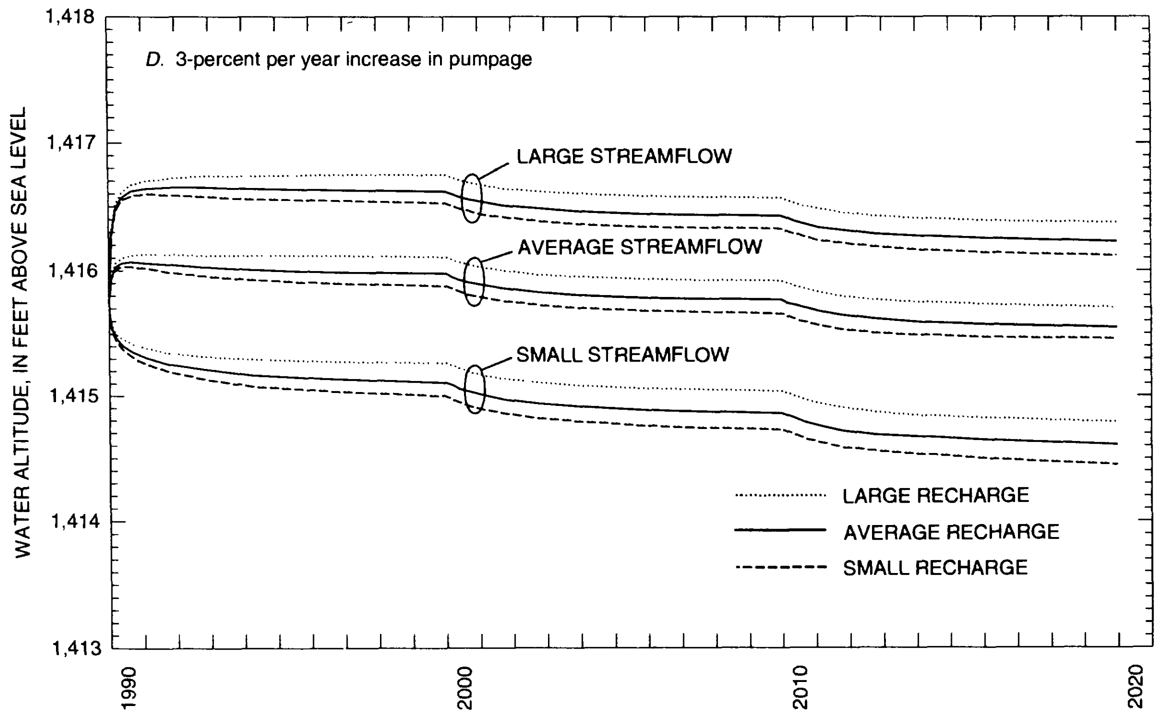


Figure 35. Estimated water levels at model row-24, column-23 near Arkansas River for simulations assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

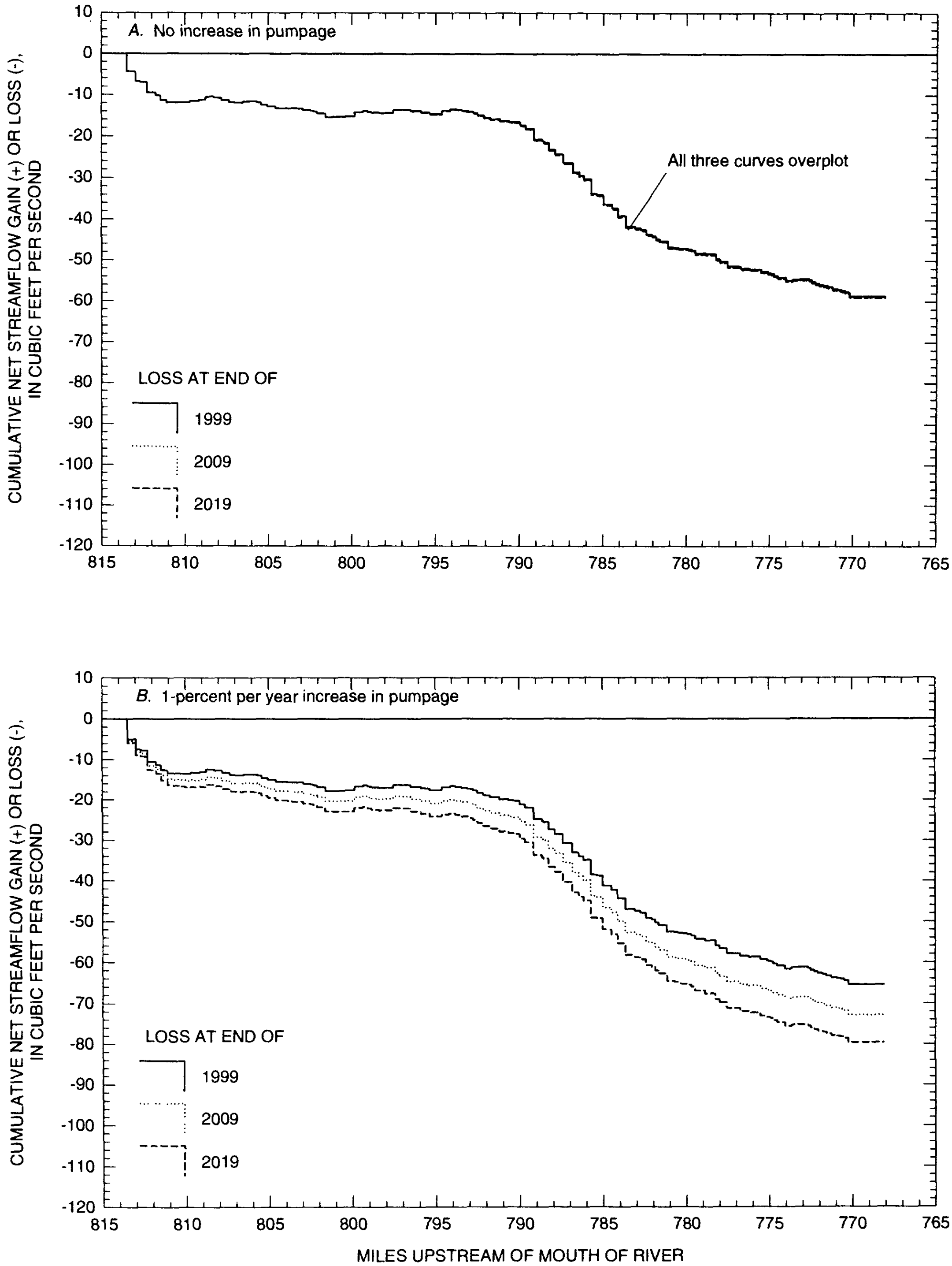
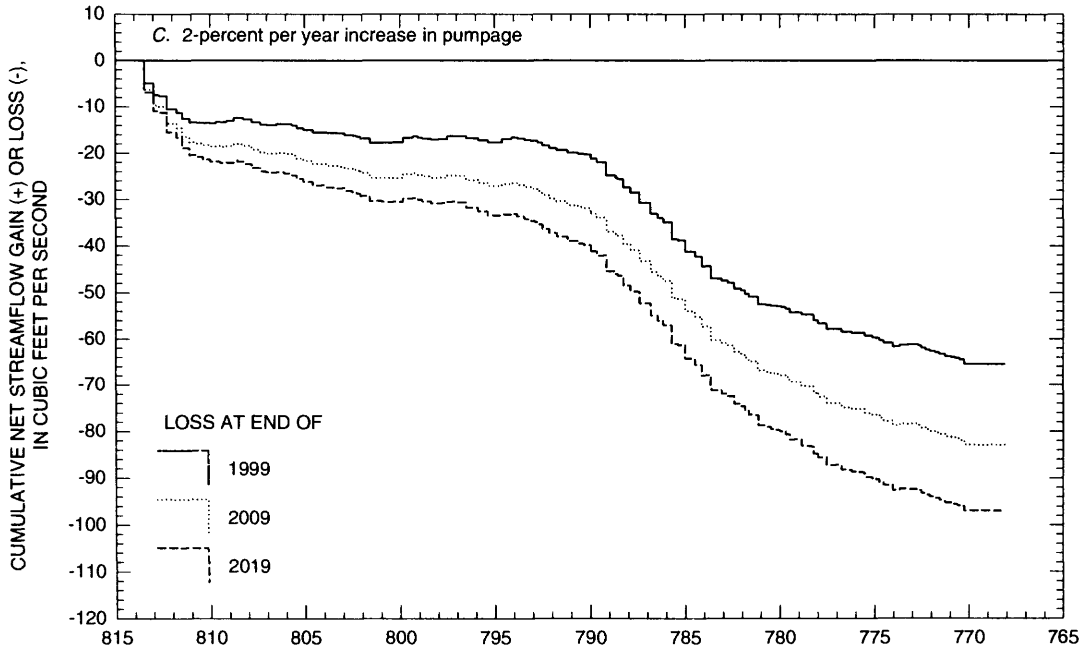


Figure 36. Estimated cumulative net streamflow loss of water from Arkansas River to *Equus* beds aquifer at end of each stress period assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989.



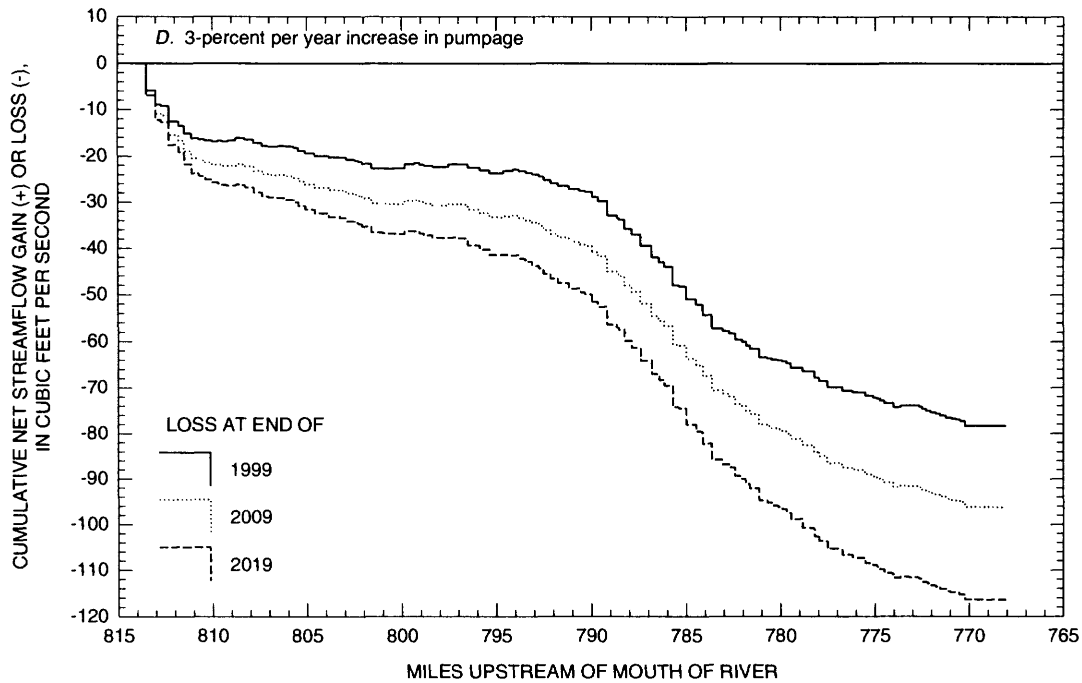


Figure 36. Estimated cumulative net streamflow loss of water from Arkansas River to *Equus* beds aquifer at end of each stress period assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

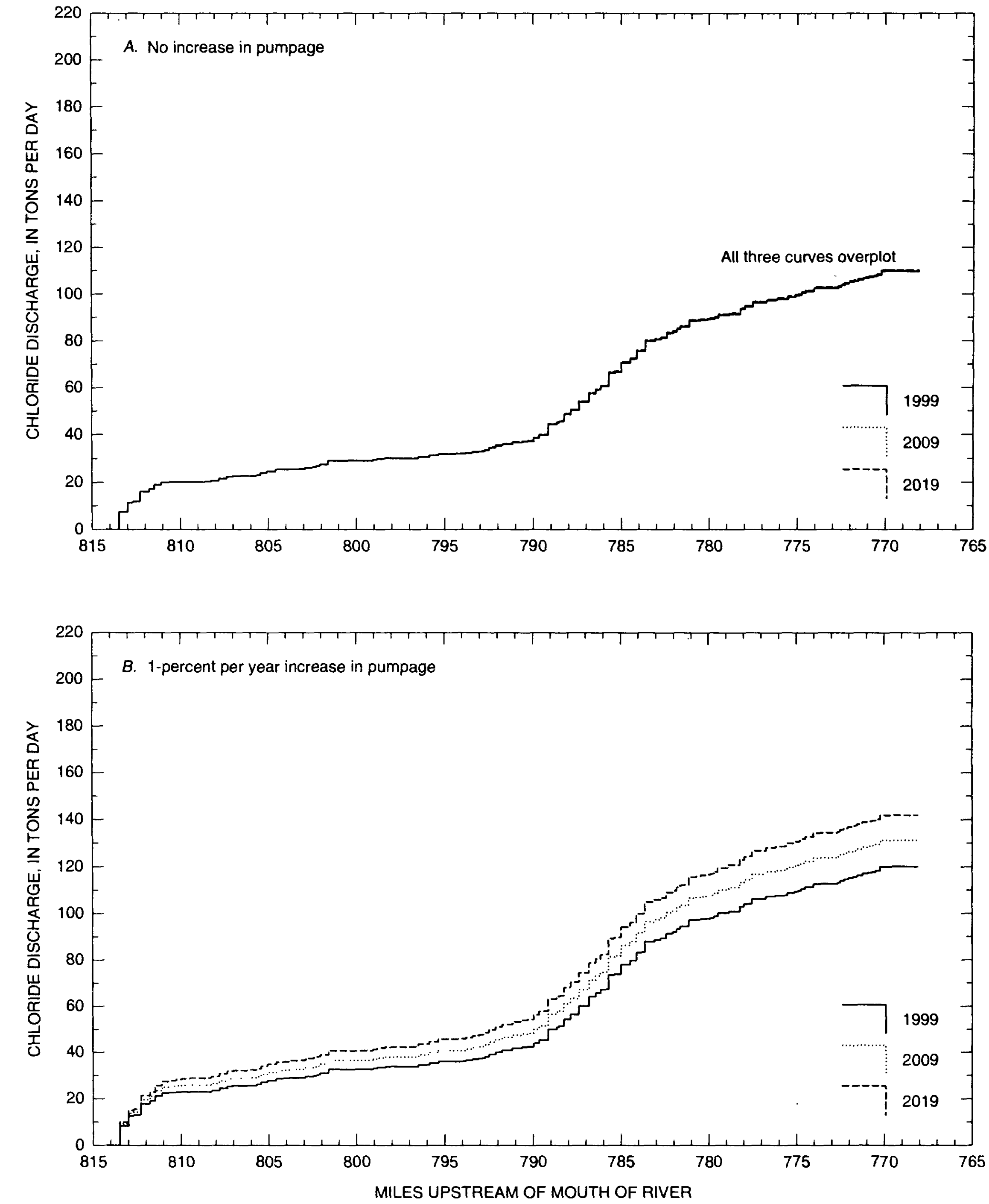
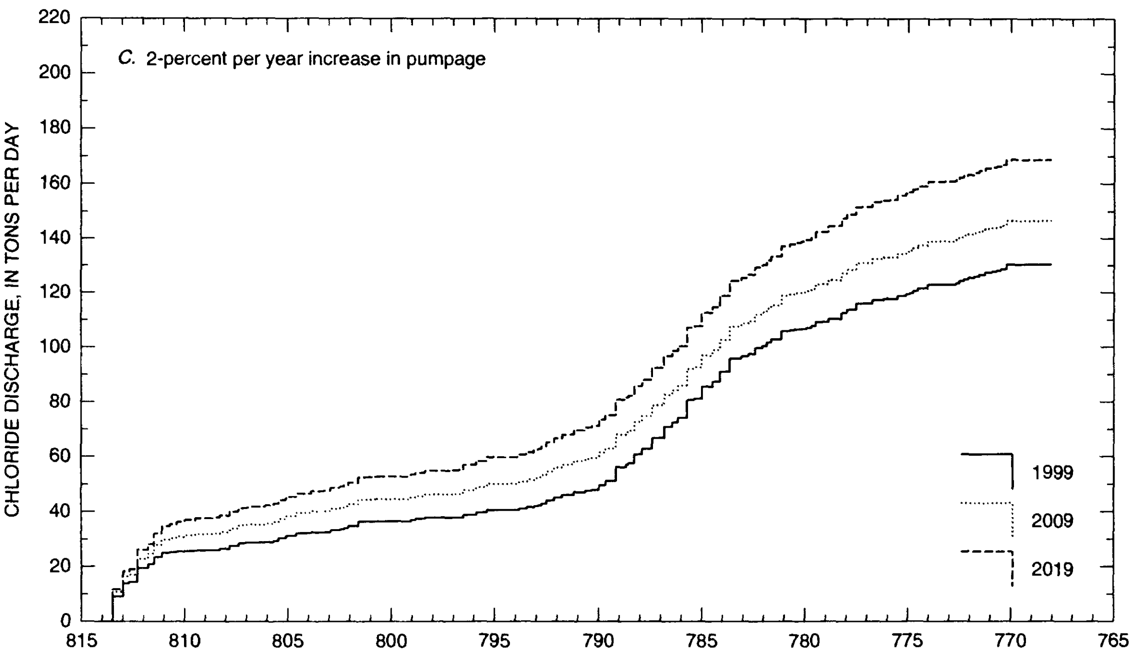


Figure 37. Estimated cumulative chloride discharge from Arkansas River to *Equus* beds aquifer at end of each stress period assuming a chloride concentration of 630 milligrams per liter and (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989.



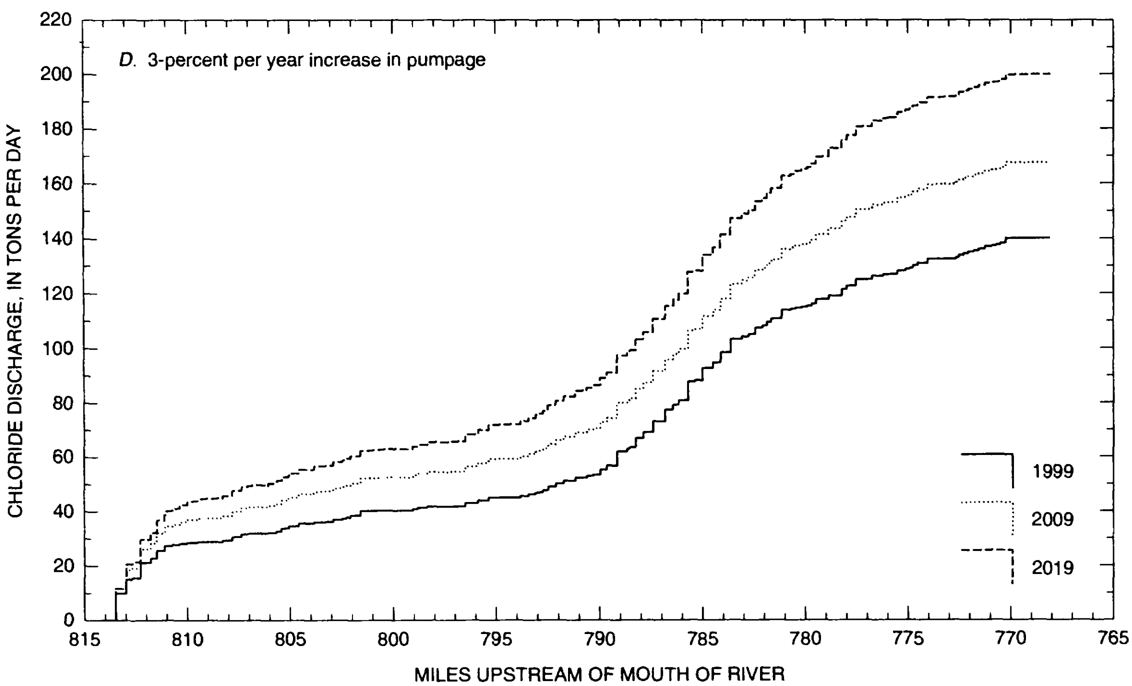


Figure 37. Estimated cumulative chloride discharge from Arkansas River to *Equus* beds aquifer at end of each stress period assuming a chloride concentration of 630 milligrams per liter and (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

chloride, move with ground water, the particle tracker also was used to simulate the location through time of chloride particles in the aquifer.

Although MODPATH simulates the advective transport of constituents such as chloride, it does not simulate the concentration of chloride in the aquifer. MODPATH does not account for dispersion, mixing, or retardation that may occur during the transport of the chemical constituent and does not correctly simulate the flow paths of particles in a solution that is much denser than the surrounding solution, such as concentrated oil-field brine in freshwater.

In addition to the aquifer properties, stresses, and boundary conditions required by MODFLOW, one additional property, aquifer porosity, was required for the particle-tracking program. A porosity of 0.20 was uniformly assigned for all three layers of the model and was chosen as an average of the 0.15 specific yield used in the flow model and the 0.25 porosity used by Spinazola and others (1985) in their solute-transport model.

The assumptions and limitations of the MODPATH program are:

(1) MODFLOW output represents steady-state conditions (the version of MODPATH used did not simulate transient conditions).
(2) Particles moving horizontally from one model cell to another cell in the same model layer move to the same location coordinates within the new cell as in the previous cell.
(3) For cells in which the volume of discharge to a well or river or other hydraulic sink is less than the volume of ground-water flow into the cell (weak sinks), it cannot be determined whether any particular particle discharges to the hydraulic sink or flows through the cell.
(4) Particle paths through weak-sink cells may not be accurate if discharge from the cell cannot be represented as being uniformly distributed across a cell.

In addition to these assumptions and limitations, all of the assumptions and limitations inherent in the MODFLOW program applied. Path-line accuracies due to weak-sink cells and large cell sizes (discretization error) may be improved by finer discretization in space and time.

Particle-tracking simulations were done using ground-water flow-model results from the steady-state simulation, from the end of each stress period in the transient simulation, and from the end of each stress period in the transient hypothetical simulations. Ending conditions from each transient stress period were used in the steady-state particle-tracking simulations to represent each transient stress period. This approach is generally valid if it is assumed that most of the change in storage occurs early in the transient stress periods and that the later part of each transient stress period approaches steady-state conditions. These assumptions are generally satisfied for stress periods 1–6 (1940–89, fig. 38) and for stress periods for all variations of the hypothetical simulations except for the large pumpage, small recharge, small streamflow simulation (fig. 38). The error in simulated particle location will be larger for those stress periods where most of the storage change does not occur early in the stress period. This error cannot be quantified without a transient particle-tracking simulation. Generally, however, the error probably would be to overestimate the distance of particle movement.

To track the flow of water from the Arkansas River into the aquifer, one particle was placed near the upper surface of each Arkansas River model cell. This distribution of particles in river model cells will be called the "source distribution." The particle tracker then was used to simulate particle flow paths through the aquifer, for specified periods of time, under the steady-state conditions used to represent ground-water flow-model stress periods.For the steady-state ground-water flow-model simulation, particles representing chloride from the river were tracked to represent the steady-state distribution of particles in the aquifer in the late 1930s. This steady-state distribution of particles and the source distribution of particles were combined and used as the starting particle distribution for particle-tracking simulations during the first transient stress period. The resulting particle distribution from each stress period and the source distribution of particles were combined and used as the starting particle distribution for each following stress period. For the 1940–89 and 1990–2019 stress periods, the particle-tracking simulations were made for a period of time corresponding to the length of each transient stress period. Thus, the MODPATH program was used to simulate the distribution of Arkansas River chloride in the aquifer at the end of each stress period.

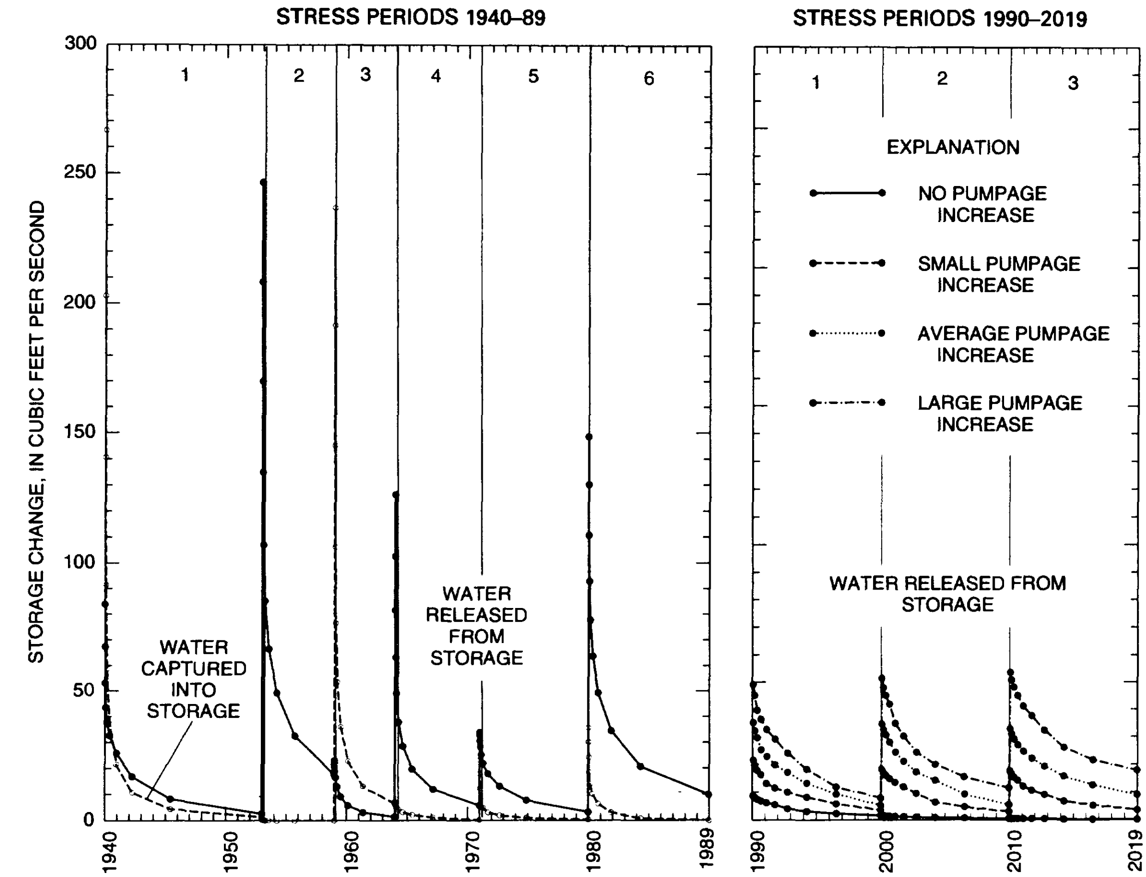


Figure 38. Simulated rate of storage change for stress periods 1–6 (1940–89) and hypothetical stress periods 1–3 (1990–2019). Hypothetical stress-period rates of storage change are for no, small, average, and large pumpage increases and small recharge and small streamflow simulations.

Discussion of Particle-Tracking Results, 1940–89

The MODPATH program was used to simulate the distribution in the aquifer of particles representing chloride from the Arkansas River (fig. 39). The lines in figure 39 show the maximum extent of chloride from the river at the end of each stress period; the lines do not indicate chloride concentration. In the upper model layer, the steady-state (pre-1940) distribution of chloride particles was limited to a small area near Hutchinson, a narrow band along part of the upstream reach of the river, and a wider band along the downstream reach of the river (fig. 39*A*). In the middle and lower model layers, particles are distributed in narrow bands near part of the downstream reach of the river (figs. 39*B* and 39*C*). The distribution of particles in the upper layer indicates areas where the Arkansas River was naturally losing water to the aquifer prior to 1940. For 1940–89, the particle-distribution areas in all three layers are larger with each successive stress period (fig. 39), and new distributions of particles emerge as longer reaches of the river begin to lose water to the aquifer. The particle-tracking simulations indicate that most of the chloride from the river stayed in the upper model layer, but some moved into the lower two layers. The shape of the 1989 distribution of particles in the upper layer generally is similar to the shape of the 100-mg/L line of equal chloride concentration in the upper unit (fig. 19*A*). Particle distributions indicate that chloride in the upper and middle aquifer units may

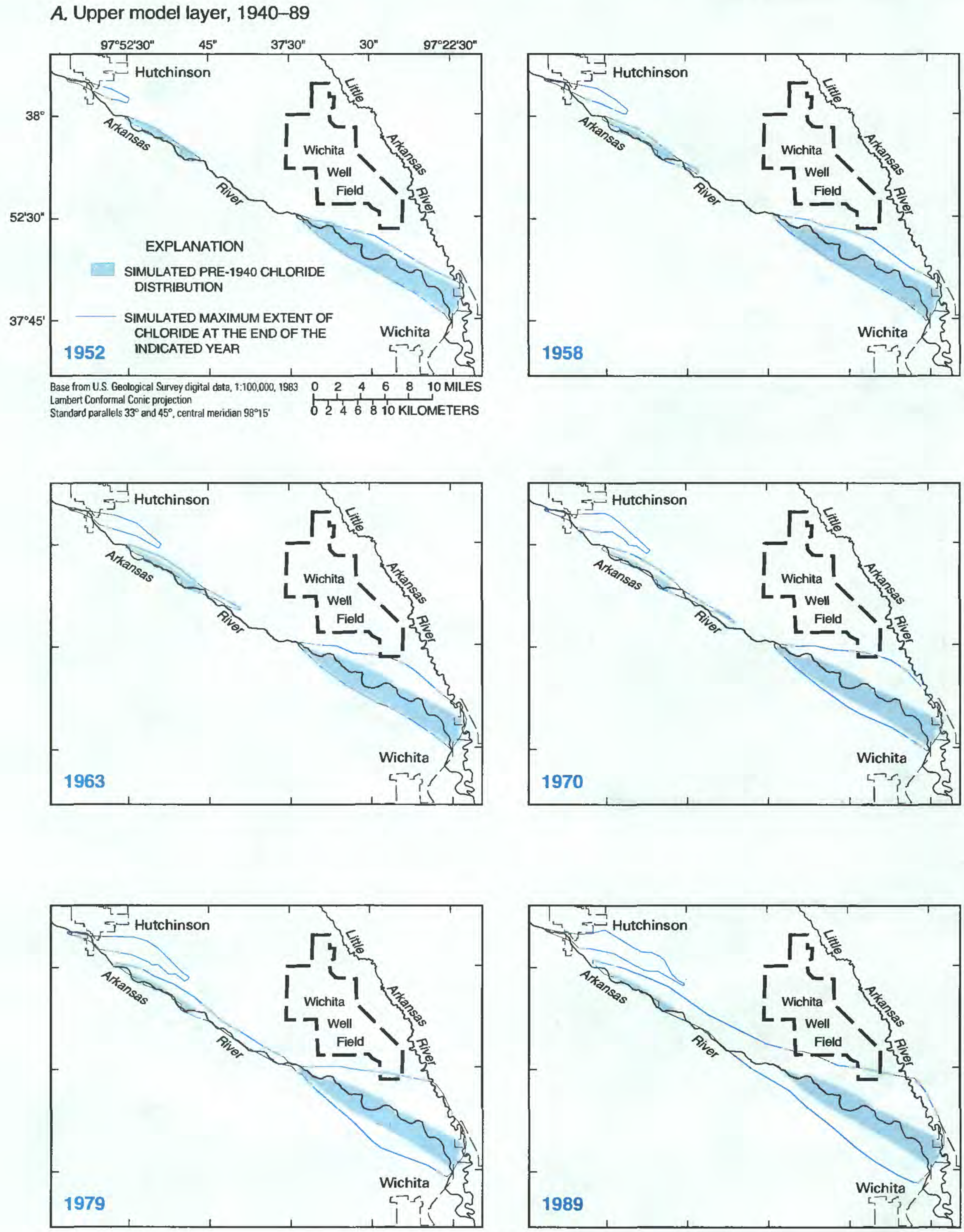


Figure 39. Simulated distribution of chloride from Arkansas River at end of each stress period in (*A*) upper, (*B*) middle, and (*C*) lower model layers.

B. Middle model layer, 1940–89

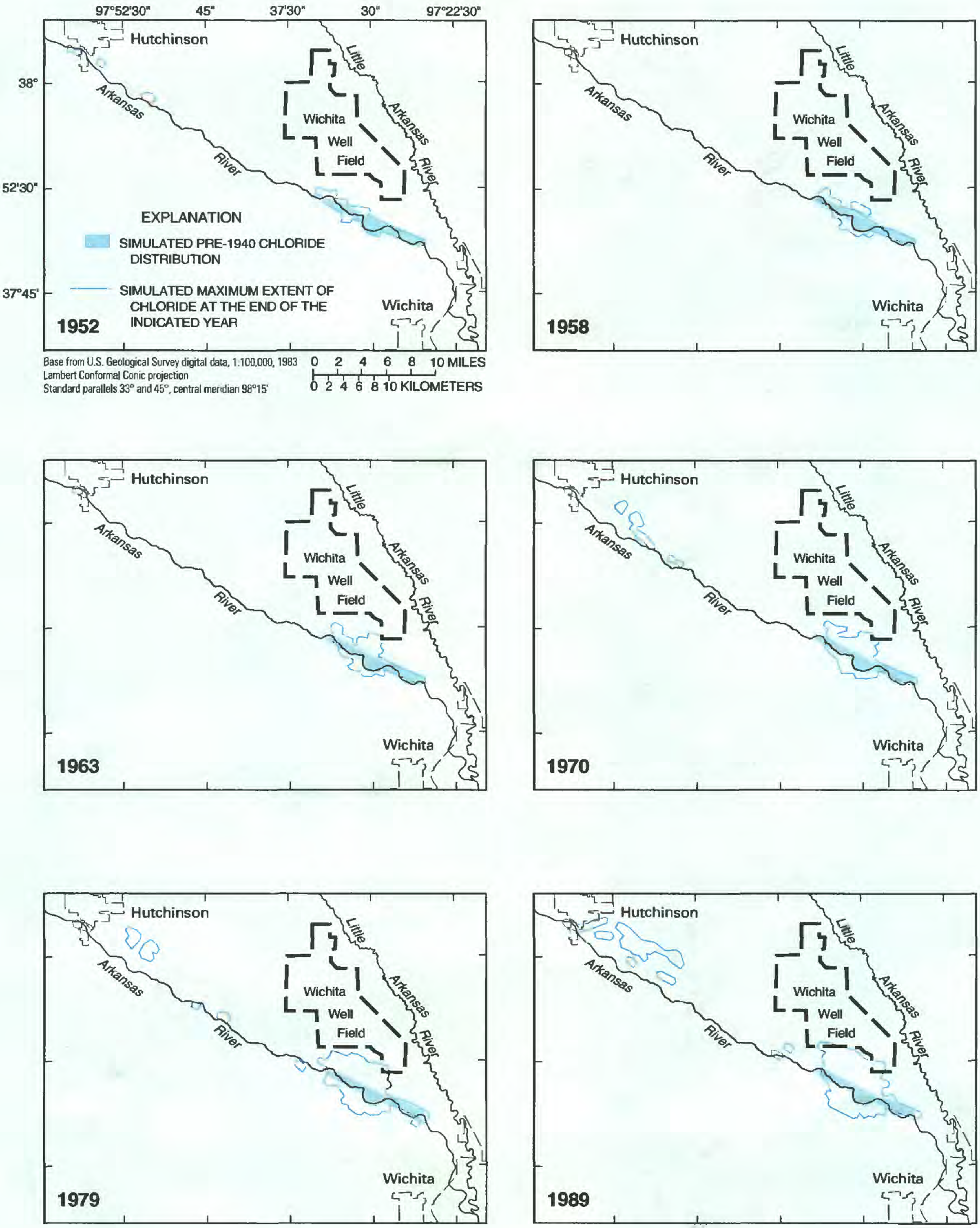


Figure 39. Simulated distribution of chloride from Arkansas River at end of each stress period in (*A*) upper, (*B*) middle, and (*C*) lower model layers—Continued.

C. Lower model layer, 1940–89

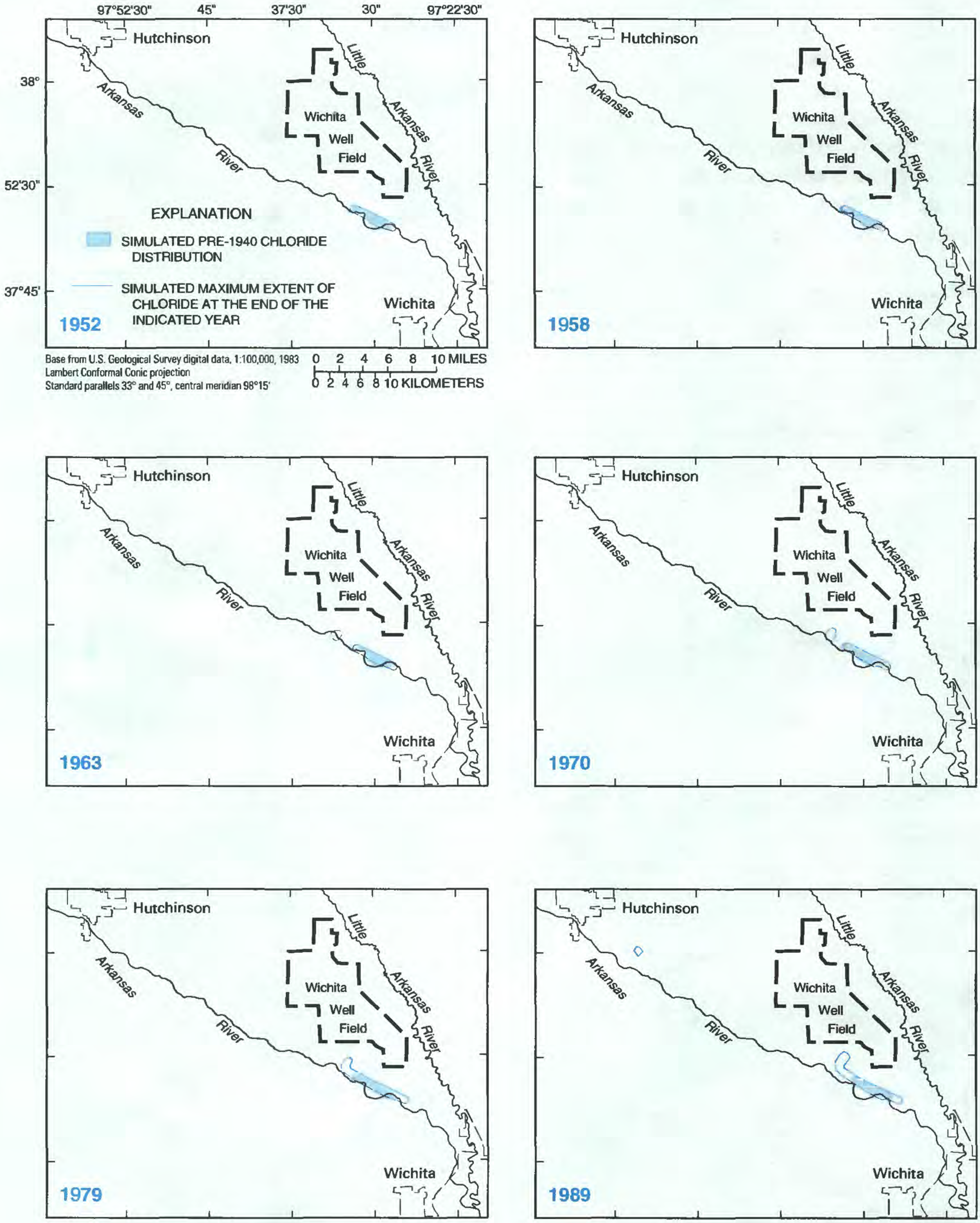


Figure 39. Simulated distribution of chloride from Arkansas River at end of each stress period in (*A*) upper, (*B*) middle, and (*C*) lower model layers—Continued.

have reached the edge of the Wichita well field as early as 1963 (fig. 39). Measured concentrations near the edge of the Wichita well field (fig. 19*A*), however, only are about 50 mg/L in the upper unit, probably because of dilution and dispersion of the chloride from the river as it moved through the aquifer. Measured natural chloride concentrations generally are the same or larger in the middle and lower units than in the upper unit (fig. 19). Because the particle-tracking simulations indicate that most of the chloride from the river stays in the upper unit, the measured chloride in the lower two units apparently is derived primarily from another source, such as the Hutchinson Salt Member of the Wellington Formation.

Discussion of Particle-Tracking Results, 1990–2019

Particle-tracking simulations for 1990–2019 show the distribution of chloride in the upper model layer north of the river expanding towards the Wichita well field and, south of the downstream reach of the river, expanding to the southwest (fig. 40). Particle distributions in the middle and lower layers also show expanded or modified distributions (fig. 40). The simulations with larger pumpage rates showed more extensive particle movement than simulations with smaller pumpage rates. In the middle and lower model layers, particles are simulated as reaching the edge of or entering the Wichita well field by the end of 1999.

A. No increase in pumpage, upper model layer

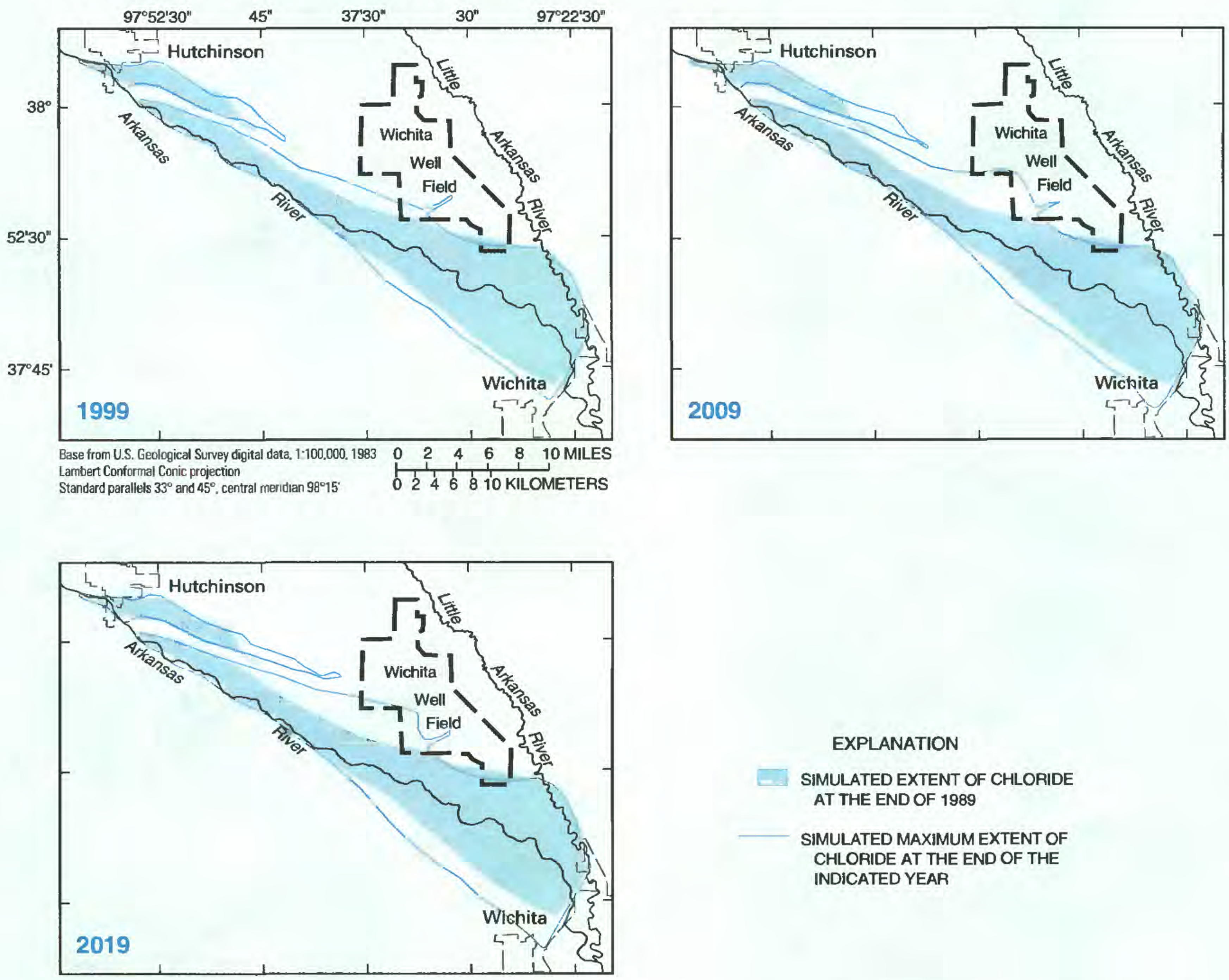


Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989.

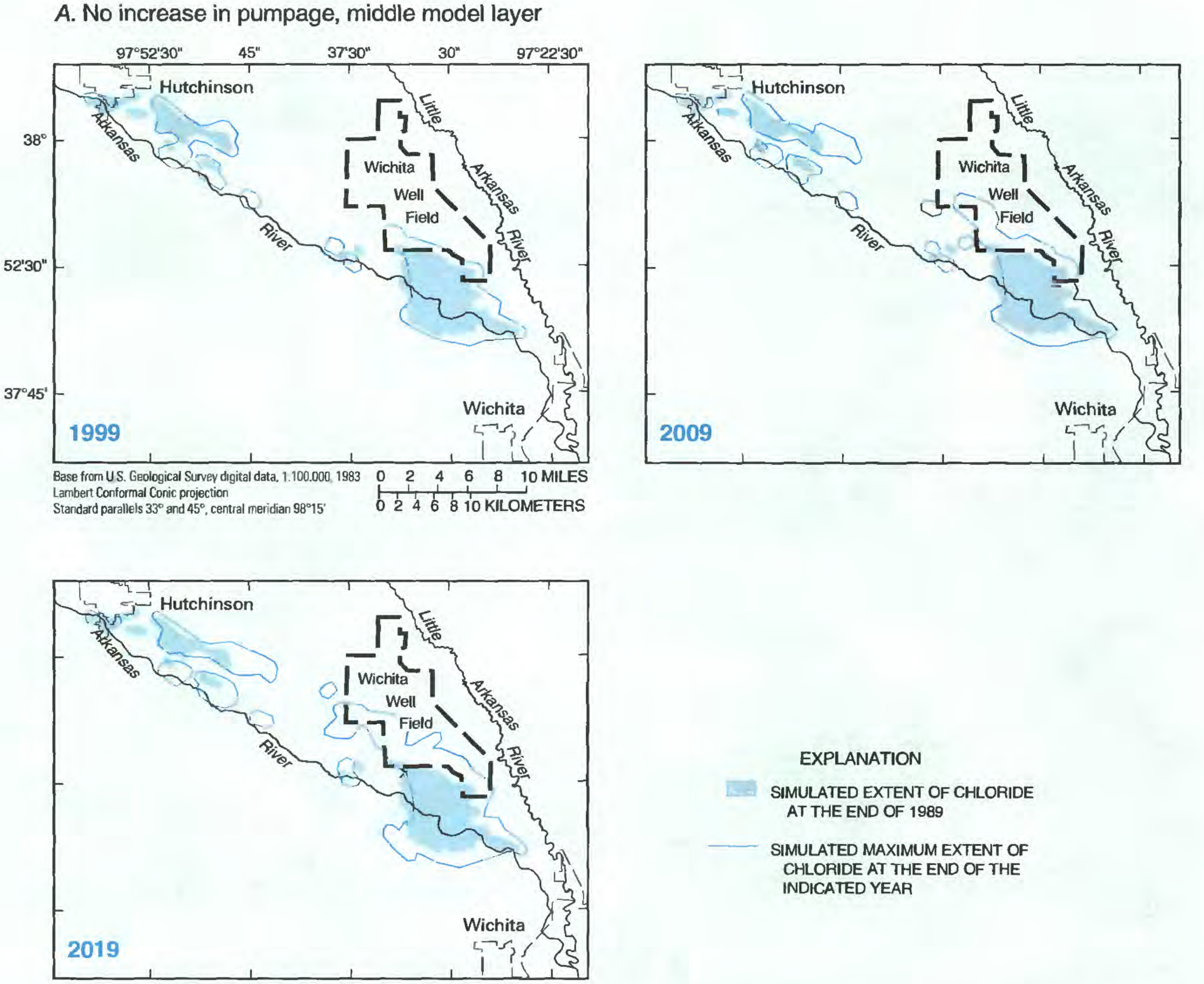


Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

Because most of the municipal wells in the Wichita well field are screened in the middle and lower units of the aquifer, the chloride in the middle and lower layers would move toward the Wichita well field and eventually be found in well water.

SUMMARY

In 1988, a 4-year study was undertaken to improve understanding of the hydrologic and chemical interaction between the Arkansas River and the *Equus* beds aquifer in south-central Kansas so that water-management agencies can develop strategies to minimize the effects of poor river-water quality on the aquifer and of increasing ground-water withdrawals on consequent streamflow decreases. A network of 155 clustered observation wells at 55 sites was established along lines perpendicular and parallel to the Arkansas River between Hutchinson and Wichita. Water levels in these wells were measured monthly during most of the study period, and water samples for chemical analysis were obtained annually. On the basis of gamma logs and lithologic descriptions, the *Equus* beds sediment was divided into lower, middle, and upper units.

Analysis of water-level data from circa 1940 and 1989 shows that ground water near the Arkansas River flows parallel to the general direction of river flow, whereas ground water near the Little Arkansas River flows at an angle towards the river. Very little

A. No increase in pumpage, lower model layer

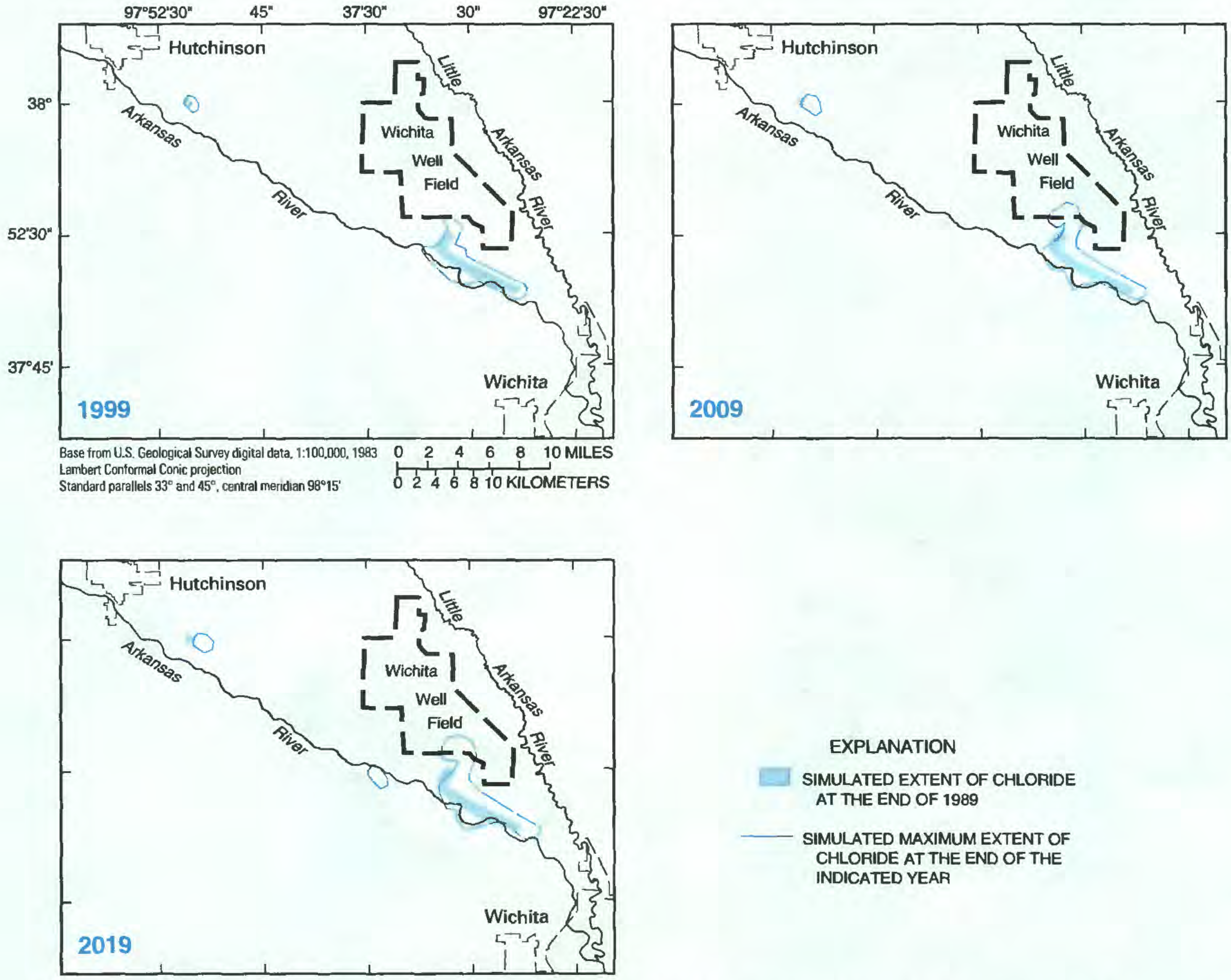


Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

vertical flow was indicated by the data except near well sites EB-203 and EB-204.

Withdrawal of ground water by wells from the *Equus* beds aquifer has been increasing since 1940 when the Wichita well field was first developed. In the late 1950's and early 1960's, agricultural and industrial water use began increasing. Since the late 1970's, agricultural water use has been the single largest use of water. Continuous pumping of municipal wells and irrigation wells in the Wichita well field has caused ground-water levels to decline as much as 30 ft or more.

Two natural and three human-induced sources of chloride affect water quality in the study area. The natural sources are Arkansas River water and water from the Permian-age Wellington Formation. The human-induced sources are brine from oil-field, salt-mining, and salt-refining activities. Chloride concentrations measured in Arkansas River water at two sites during the winter of 1934–35 ranged from 392 to 1,895 mg/L. The median chloride concentration in Arkansas River water samples collected from five sites during 1988–91 ranged from 620 to 640 mg/L. The natural chloride concentration in the upper unit of the *Equus* beds aquifer is progressively smaller farther from the river. During this study the largest concentrations of natural chloride were found in the lower unit of the aquifer. Most of the natural chloride in the upper

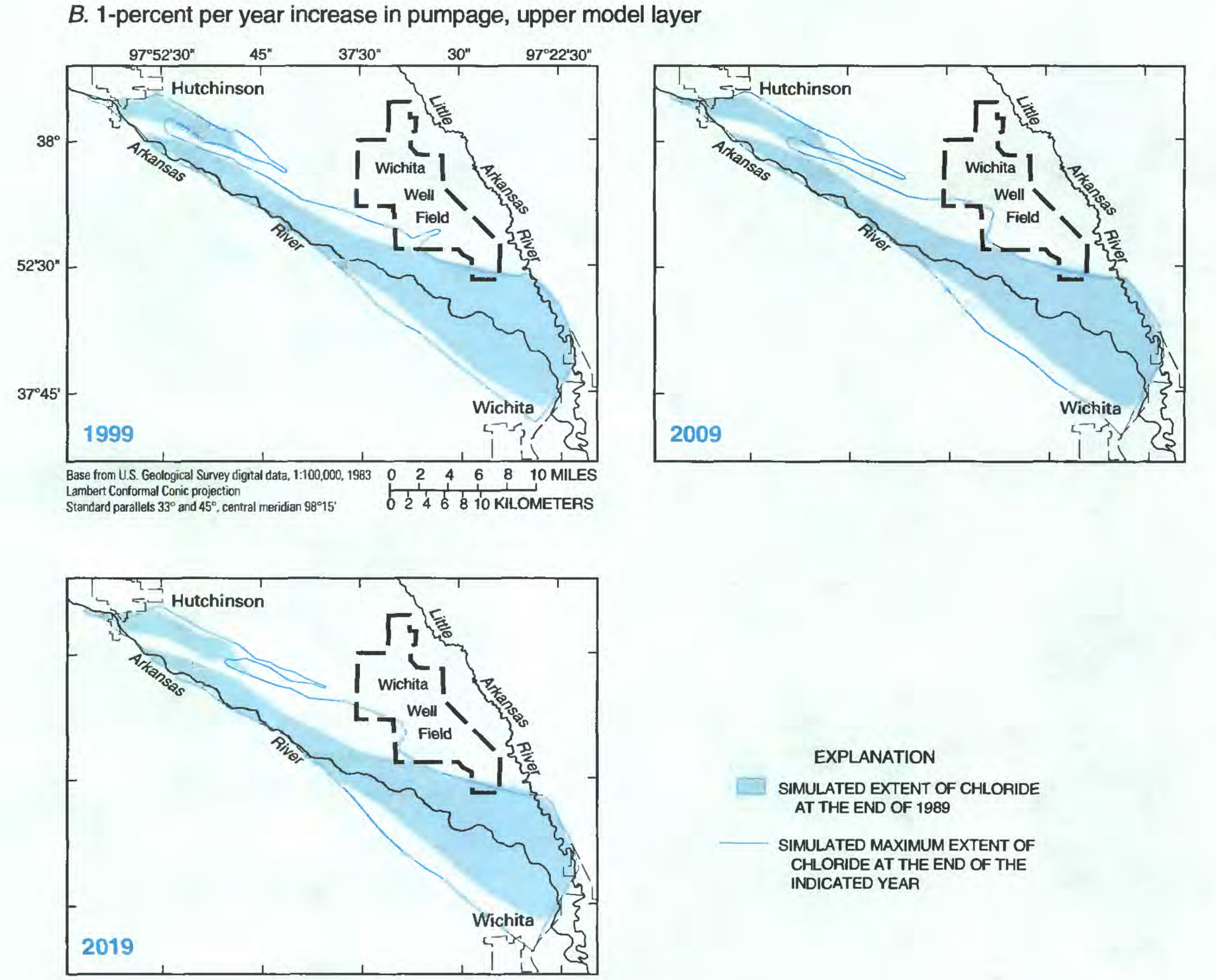


Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

unit of the aquifer is probably from the Arkansas River, and most of the natural chloride in the lower unit of the aquifer is probably from saline water in the Wellington Formation.

The hydraulic interaction of the stream-aquifer system was simulated using the three-dimensional, finite-difference, flow-model program, MODFLOW. A steady-state model was developed and calibrated to simulate pre-1940 aquifer and stream conditions, and a transient model was developed and calibrated to simulate 1940–89 aquifer and stream conditions. The transient model then was used to estimate possible aquifer and stream conditions during 1990–2019.

Ground-water levels declined in the study area during 1940–89. Data and the results of model simulations indicate that water levels in the Wichita well field area declined as much as 30 ft or more because of increasing ground-water withdrawals from the aquifer. Near the Arkansas River, however, ground-water-level declines have been moderated by streamflow losses from the river.

In response to the declining ground-water levels, streamflow gains decreased in the Arkansas and Little Arkansas Rivers during 1940–89. In 1940, the Arkansas River had a simulated base-flow gain of about 21 ft^3/s within the model area, but by the end of 1989 had a simulated base-flow loss of about 52 ft^3/s.

B. 1-percent per year increase in pumpage, middle model layer

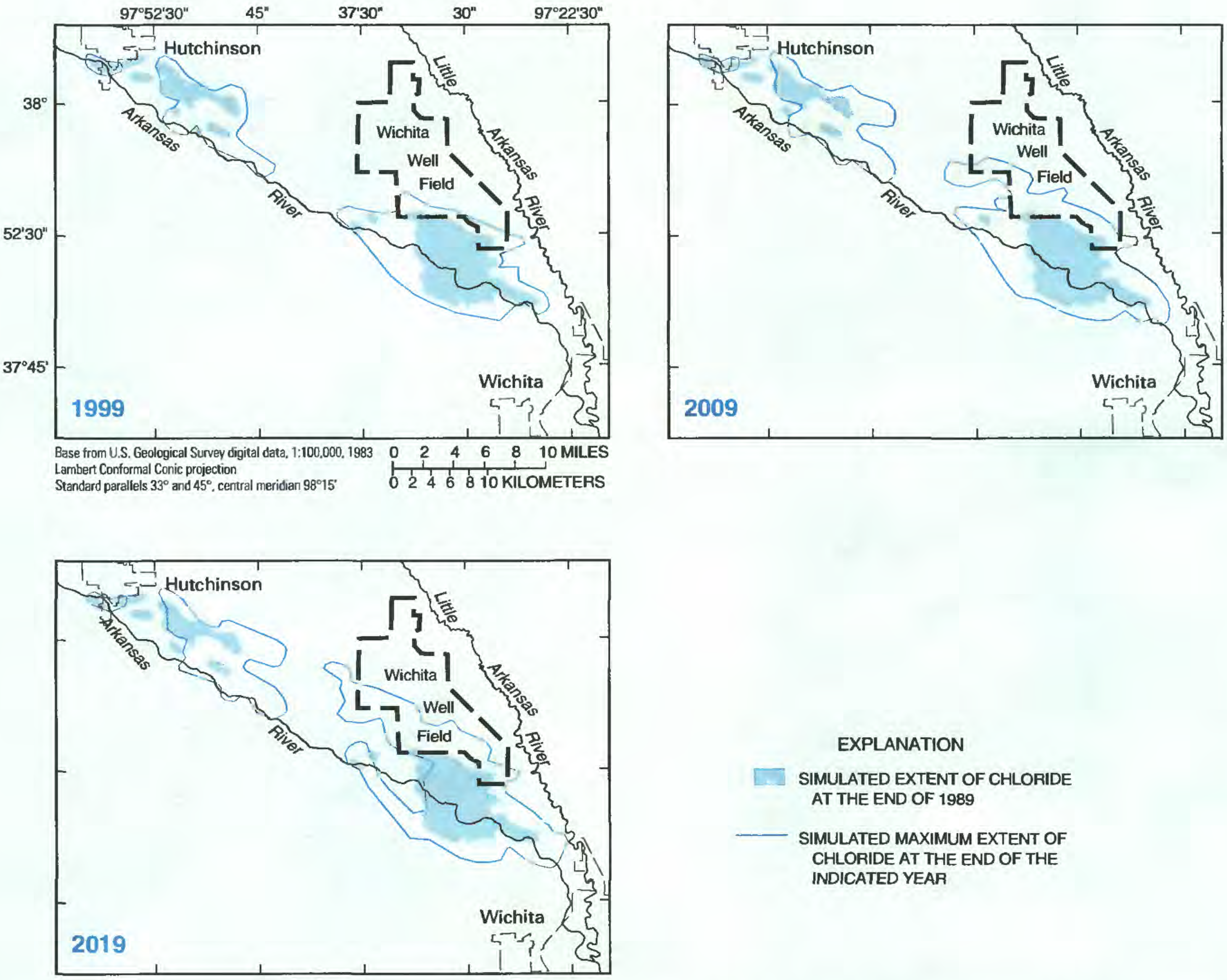


Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

In 1940, the Little Arkansas River had a simulated base-flow gain of about 67 ft^3/s within the model area, but by the end of 1989 had a simulated base-flow gain of about 27 ft^3/s.

During 1940–89, the quantity of chloride discharged from the Arkansas River to the *Equus* beds aquifer increased in direct proportion to the volume of water loss from the river. On the basis of simulated streamflow and assuming that the chloride concentration in river water that moves into the aquifer is 630 mg/L, the chloride-load discharge from the river to the aquifer was estimated to be about 21 ton/d in 1940 and about 100 ton/d by 1989.

Results of simulations of hypothetical conditions during 1990–2019, using projected ranges of recharge, streamflow, and pumpage, indicate that water levels could decline from 1989 water levels by 0.2 to 78 ft in the central part of the Wichita well field and increase as much as 1.3 ft or decline as much as 1.2 ft near the Arkansas River by 2019 depending on the values of recharge, streamflow, and pumpage. With *no increase in pumpage over 1989 quantities*, simulations show that water levels in the Wichita well field probably will remain within 10 ft of 1989 water levels, depending on long-term climatic conditions that affect recharge and streamflow. The largest simulated water level decline from 1989 water levels in the Wichita

B. 1-percent per year increase in pumpage, lower model layer

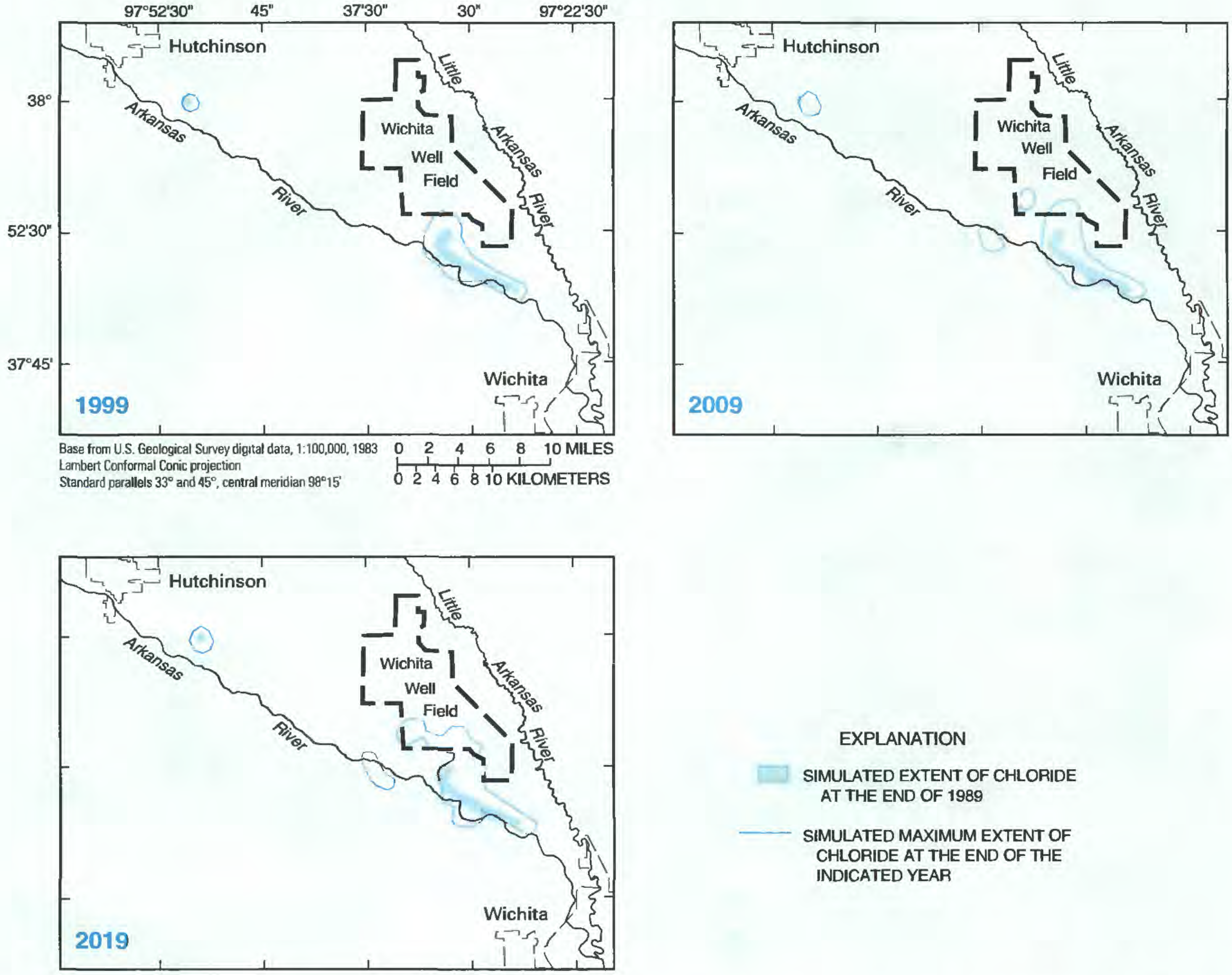


Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

well field (78 ft) could occur under conditions of small recharge and streamflow and a 3-percent per year increase in pumpage. The largest simulated water-level decline from 1989 water levels near the Arkansas River (1.2 ft) could occur under conditions of small recharge and streamflow and a 3-percent per year increase in pumpage.

Results of simulations of hypothetical conditions during 1990–2019 indicate that streamflow losses from the Arkansas River could increase as pumpage increases because more river water would be lost to the aquifer. For hypothetical conditions of average recharge and streamflow, base-flow loss within the model area ranged from 59 to 117 ft^3/s, for no increase and a 3-percent per year increase in pumpage since 1989, respectively.

During 1990–2019, estimated chloride discharge from the Arkansas River to the *Equus* beds aquifer increased over 1989 estimated quantities in proportion to increases in loss of river water. Assuming hypothetical conditions of average recharge and streamflow and a 630-mg/L concentration of chloride in river water, the chloride-load discharge from the river in the model area could range from 110 to 200 ton/d by 2019.

The distribution in the aquifer of chloride from the river was simulated using the particle-tracking program MODPATH. Although MODPATH cannot

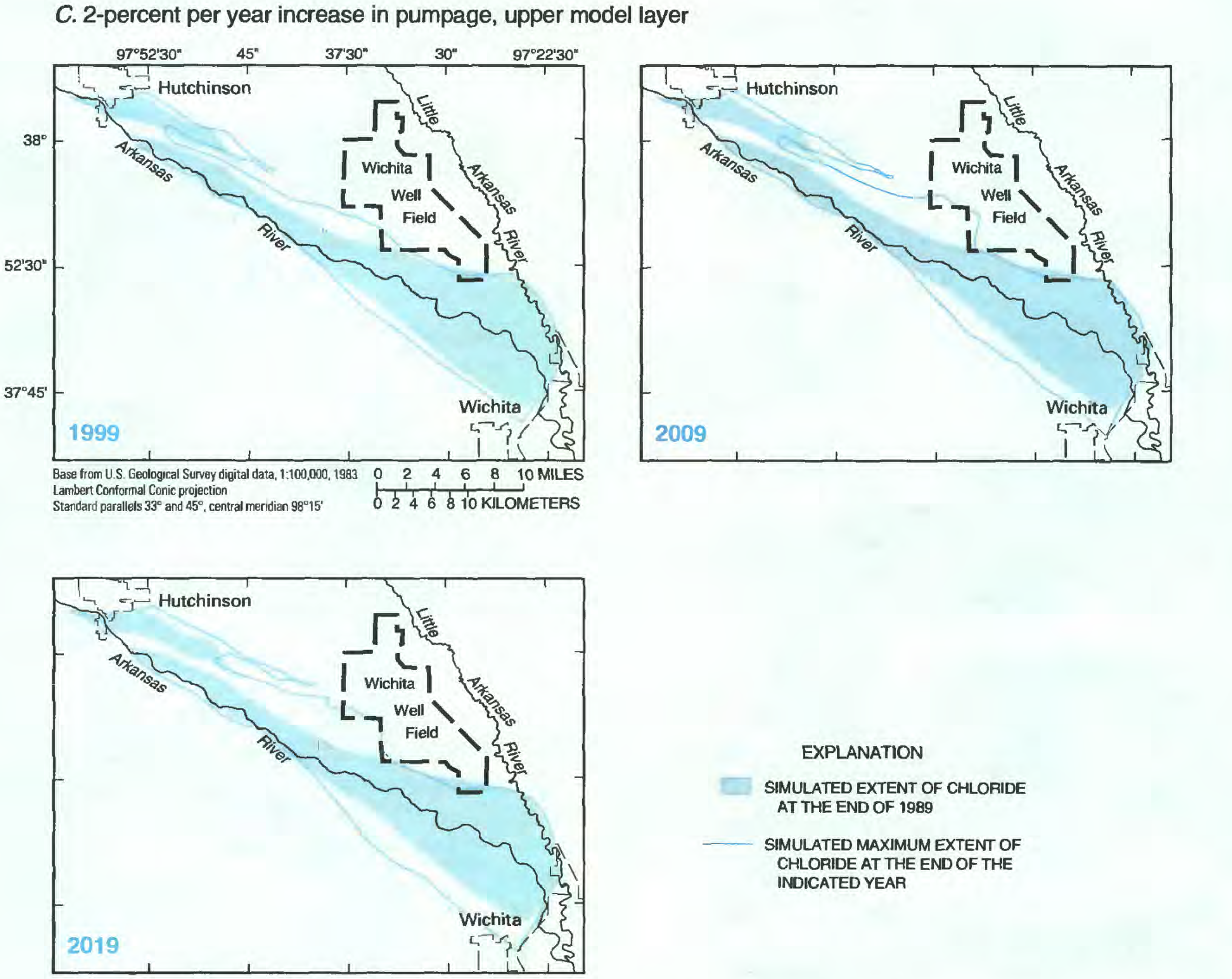


Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

calculate chloride concentration, it can show the path that dissolved constituents would follow assuming that there is no dispersion, mixing, or retardation of those constituents. Results from the steady-state and transient flow-model simulations were used to simulate the flow paths of particles representing chloride from the river to the aquifer and the distribution of those particles at the end of each stress period. During 1940–89, the simulated distribution of particles representing Arkansas River chloride in the aquifer expanded from relatively narrow bands near the river to a wider distribution within the aquifer and may have reached the edge of the Wichita well field as early as 1963. Most of the chloride stayed in the upper aquifer unit, but some moved into the lower two units.

Particle-tracking simulations of 1990–2019 hypothetical conditions show the distribution of chloride expanding north towards the Wichita well field and southwest from the downstream reach of the Arkansas River. Simulations with larger pumpage rates show farther movement of chloride than simulations with smaller pumpage rates.

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C. 2-percent per year increase in pumpage, middle model layer

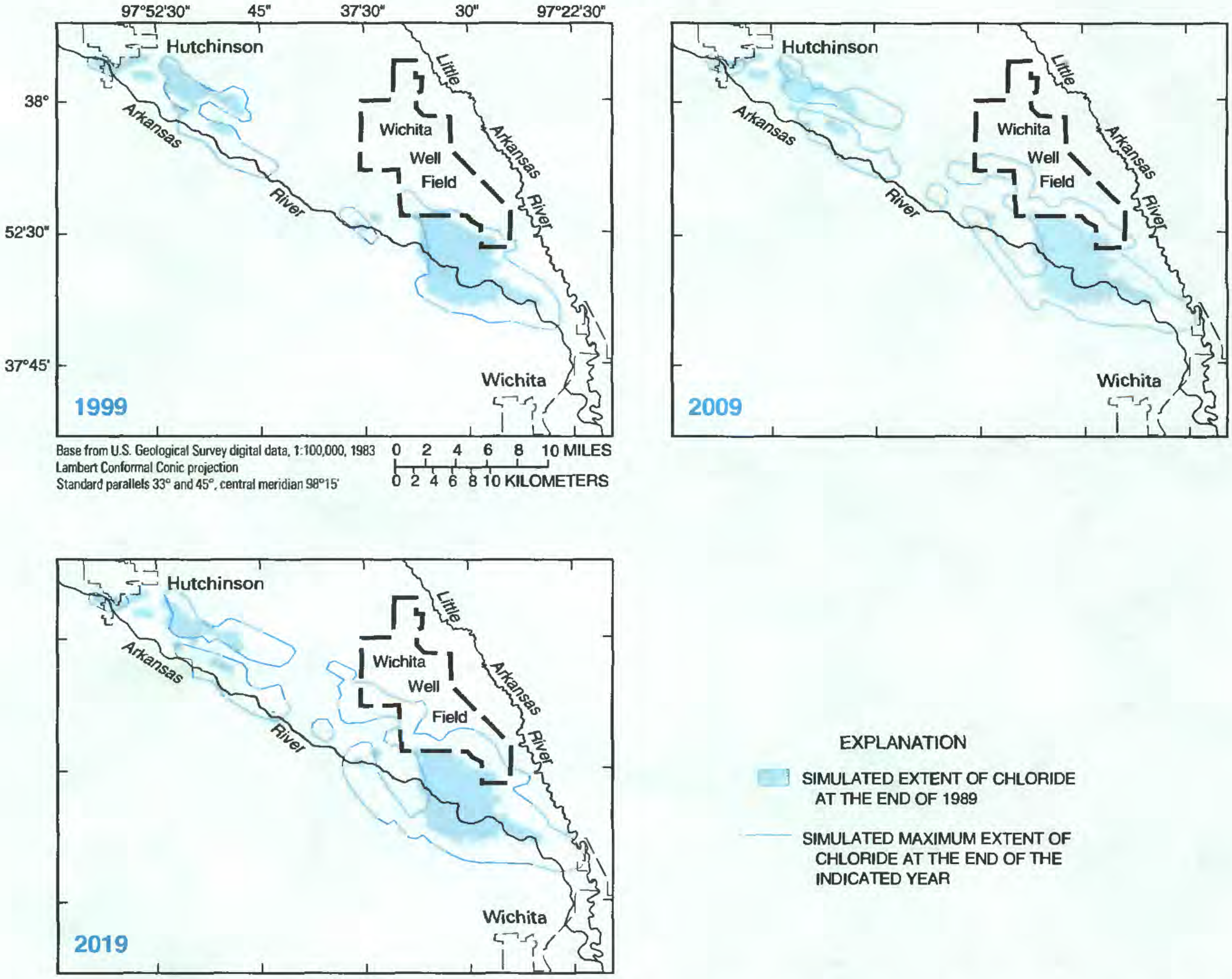

Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

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C. 2-percent per year increase in pumpage, lower model layer

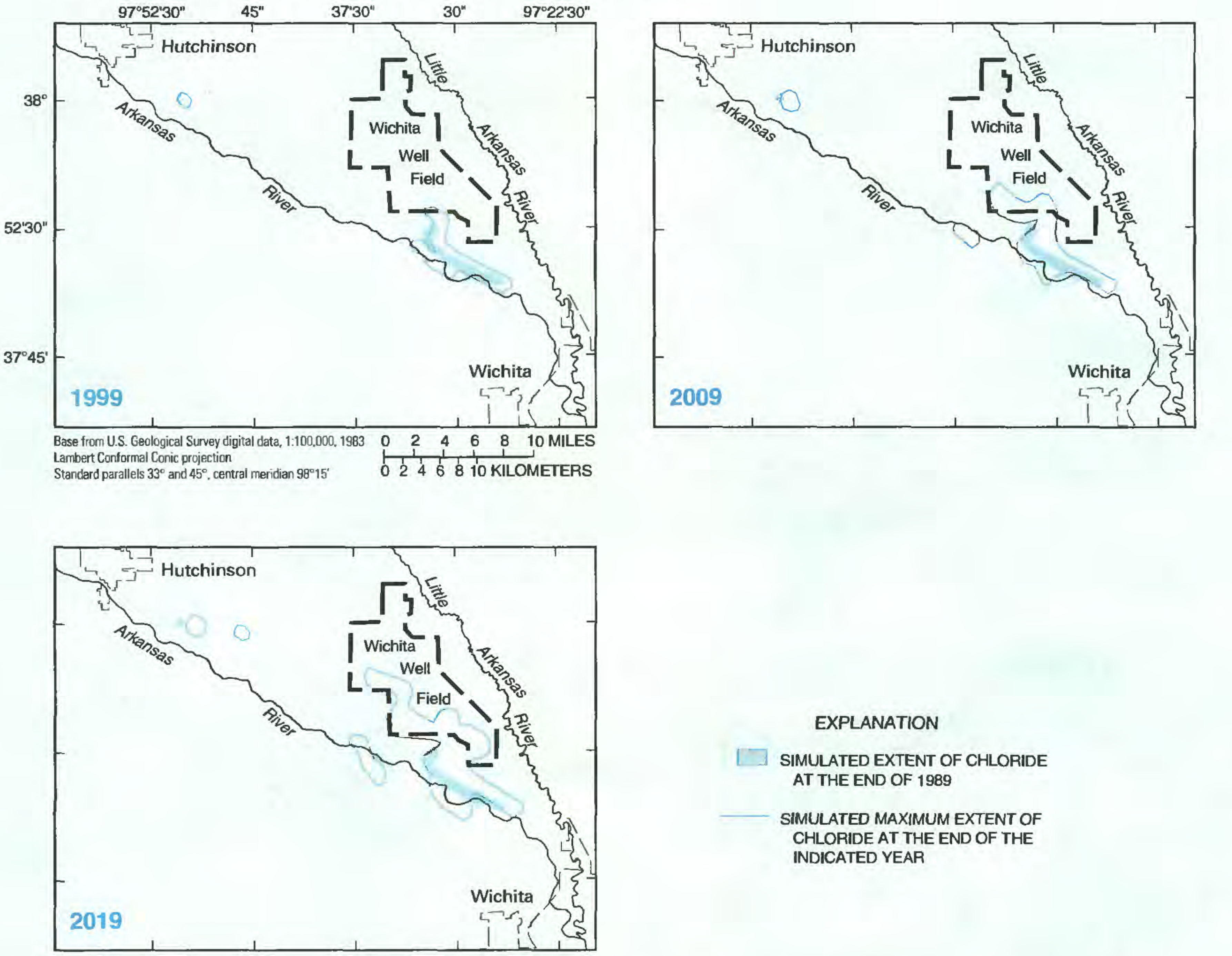

Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

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D. 3-percent per year increase in pumpage, upper model layer

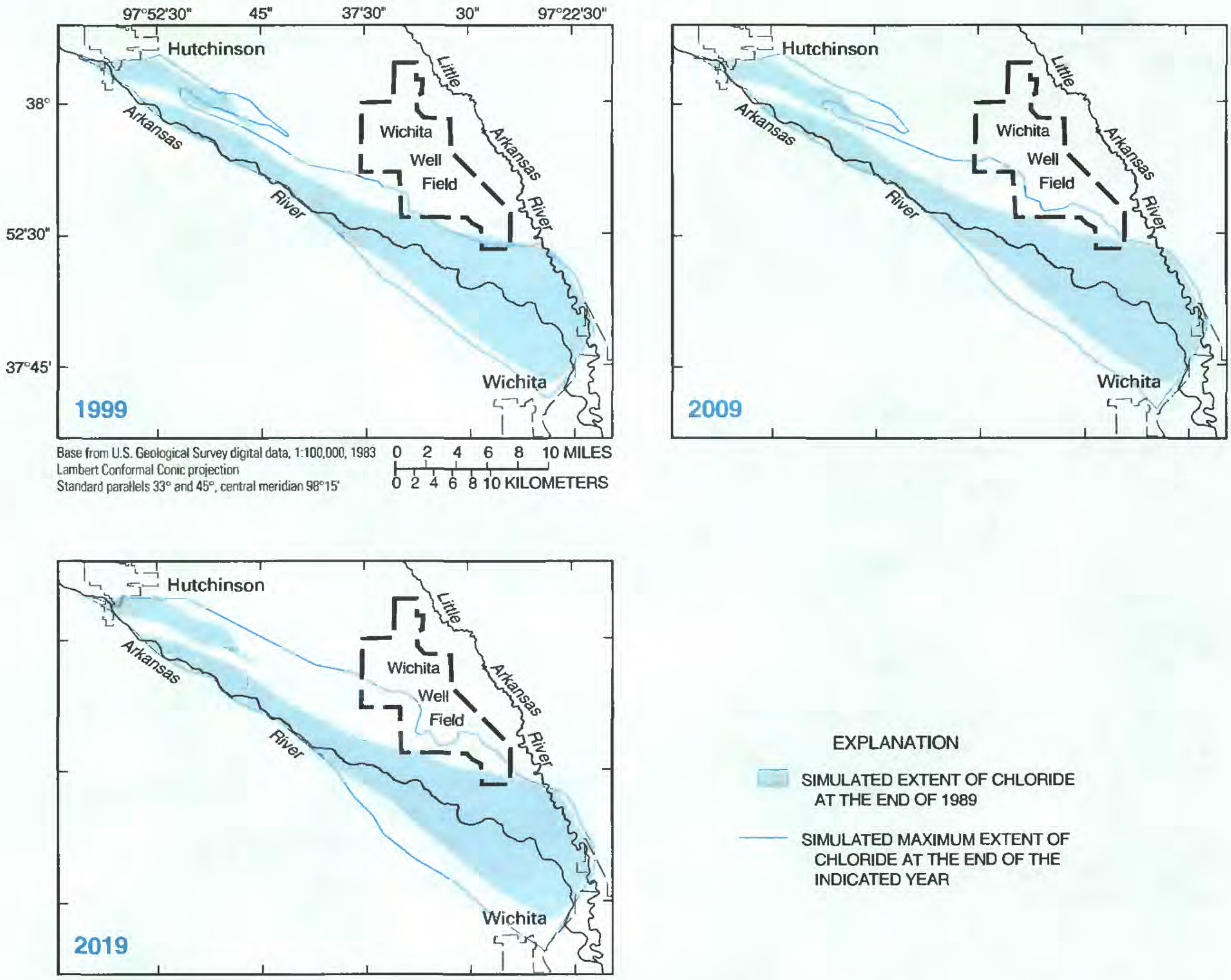

Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

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D. 3-percent per year increase in pumpage, middle model layer

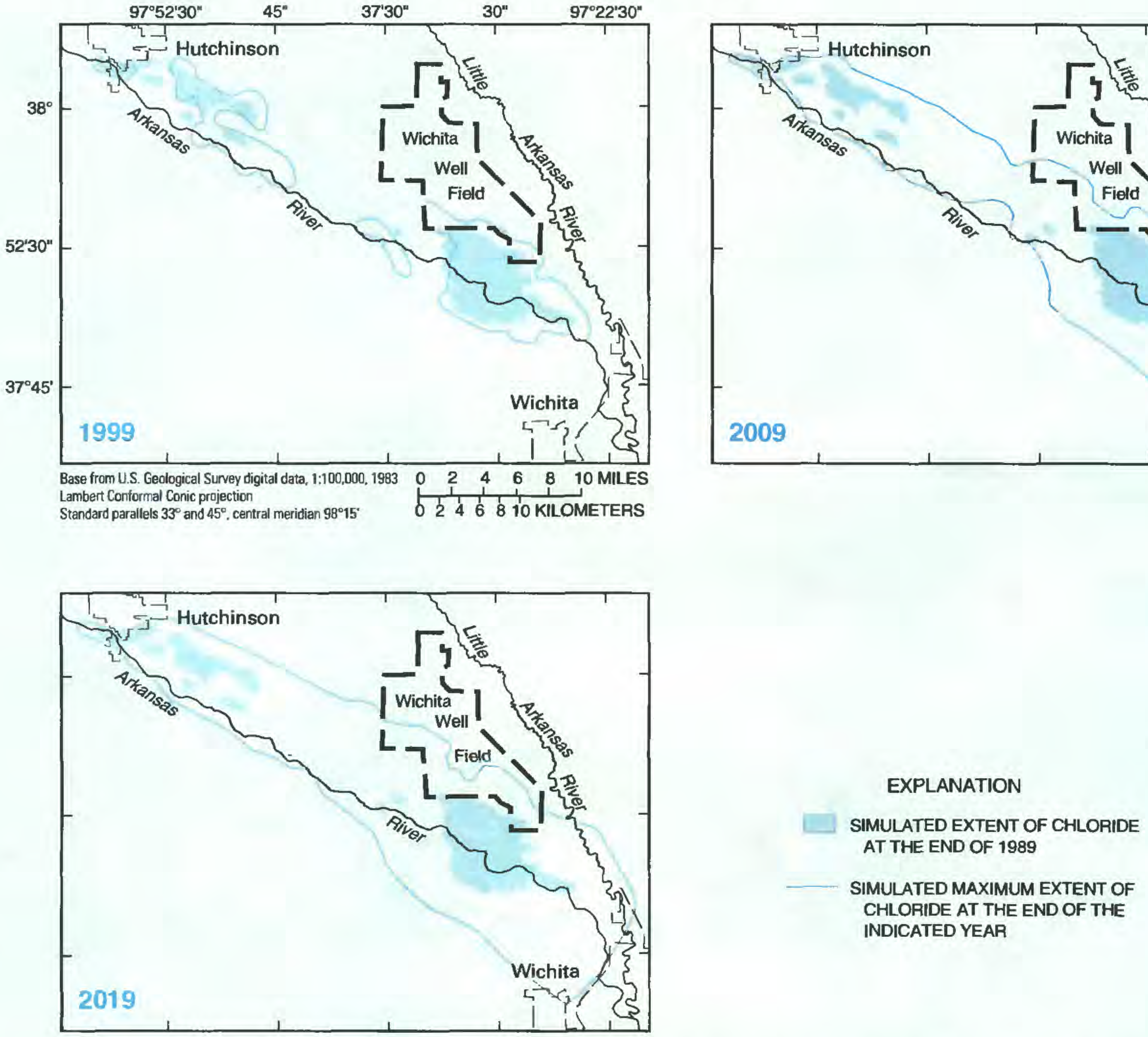

Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

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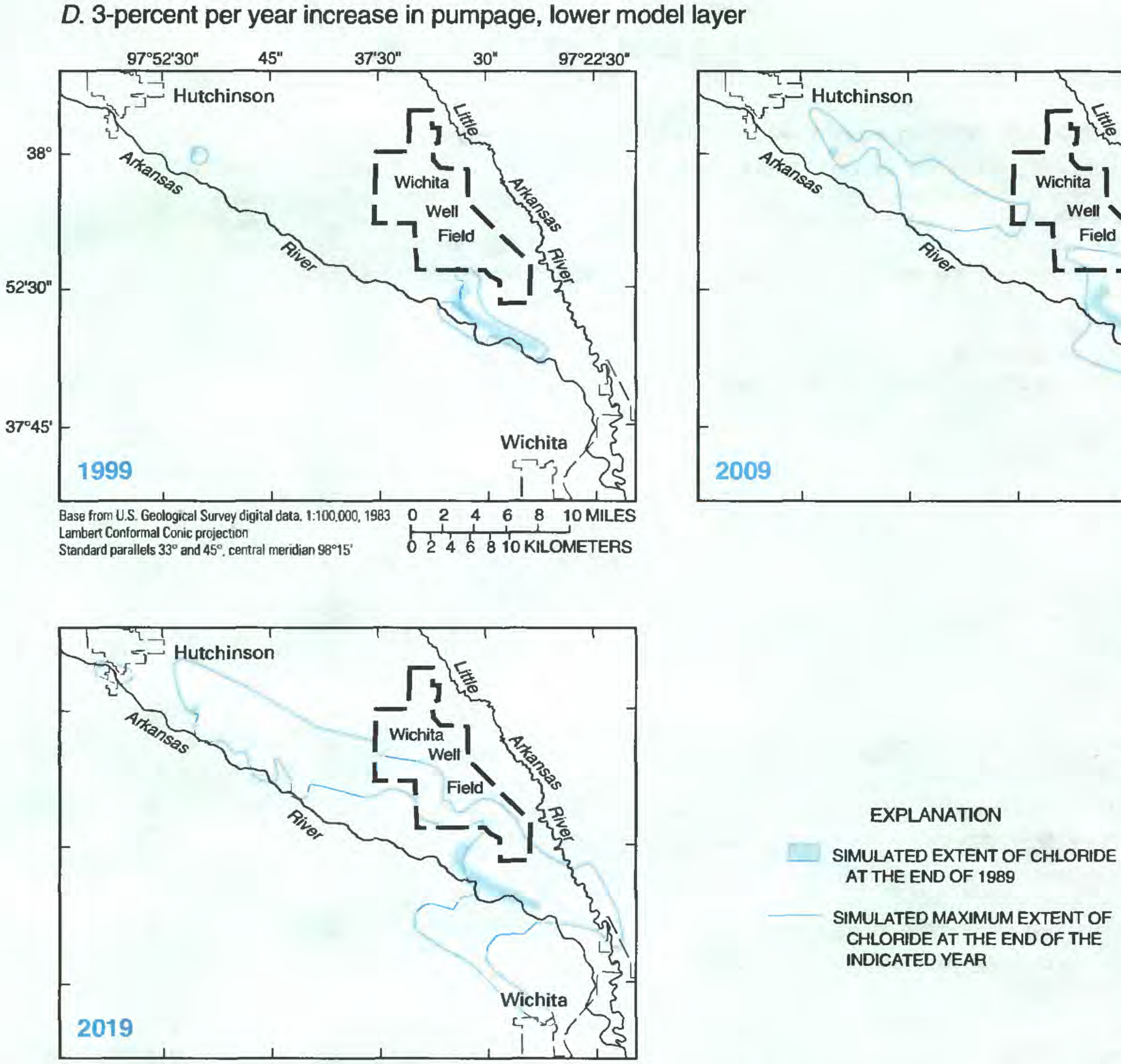

Figure 40. Simulated extent of chloride from Arkansas River at end of each stress period in upper, middle, and lower model layers assuming (*A*) no increase in pumpage since 1989, (*B*) a 1-percent per year increase in pumpage since 1989, (*C*) a 2-percent per year increase in pumpage since 1989, and (*D*) a 3-percent per year increase in pumpage since 1989—Continued.

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SUPPLEMENTAL INFORMATION

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249

[There are no lithologic logs for wells at well sites EB-211 and EB-212. Lithologic descriptions for abandoned wells near well sites USGS-H-1, USGS-H-2, USGS-H-3, USGS-H-4, NAS-1 and NAS-2 are similar to previously published lithologic logs (Williams, 1946). Wells 69, 59, 72, and 76 (Williams, 1946) correspond to well sites USGS-H-1, USGS-H-2, USGS-H-3, and USGS-H-4, respectively. Well 67 (Williams, 1946) corresponds to well sites NAS-1 and NAS-2. All altitudes are referenced to sea level and are reported to the nearest 0.1 foot. Depth of well is reported in feet below land surface]

EB-201-C.—Drilled December 10, 1986.
Altitude of land surface, 1,380.7 feet.

	Thickness, in feet	Depth, in feet
Clay, silty	5	5
Clay	10	15
Sand, coarse-grained, and gravel	10	25
Sand, coarse- to medium-grained	10	35
Clay, light-gray	8	43
Sand, medium- to fine-grained	12	55
Clay, silty, tan	8	63
Sand, coarse-grained, and gravel	7	70
Sand, medium- to fine-grained	6	76
Clay, silty, tan	3	79
Sand, medium- to fine-grained	14	93
Clay, silty	4	97
Sand, medium- to fine-grained	1	98
Clay and sand, medium- to coarse-grained	20	118
Sand, medium- to coarse-grained	8	126
Clay, silty, tan	4	130
Sand, medium- to coarse-grained	35	165
Sand and shale pieces	5	170
Shale, gray	8	178

EB-202-C.—Drilled December 6, 1986.
Altitude of land surface, 1,379.5 feet.

	Thickness, in feet	Depth, in feet
Soil, silty	2	2
Sand, fine-grained	6	8
Sand, medium- to coarse-grained	2	10
Sand, coarse-grained, and gravel	25	35
Clay, sandy, silty, tan	25	60
Clay, silty, tan to orange	18	78
Clay, silty, tan to gray	67	145
Clay, gray	3	148
Sand, fine- to medium-grained	30	178
Sand, medium- to coarse-grained	12	190
Shale, with traces of gypsum	5	195
Shale	3	198

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-203-C.—Drilled December 2, 1986.
Altitude of land surface, 1,380.8 feet.

	Thickness, in feet	Depth, in feet
Clay, silty, brown	4	4
Sand, fine- to medium-grained, and gravel	39	43
Silt, clayey, tan	34	77
Sand and gravel; clayey, arkosic	35	112
Silt, clayey, sandy, tan	48	160
Sand, medium- to coarse-grained, and gravel; arkosic	56	216
Shale, gray, with thin limestone and gypsum layers	12	228

EB-204-C.—Drilled November 18, 1986.
Altitude of land surface, 1,378.2 feet.

	Thickness, in feet	Depth, in feet
Silt, sandy	10	10
Sand, coarse-grained, and gravel	38	48
Clay, silty	10	58
Sand, medium-grained, and gravel	40	98
Sand, fine-grained, and clay	104	202
Gravel	1	203
Clay	2	205
Sand, fine- to medium-grained	28	233
Shale	4	237

EB-205-C.—Drilled November 24, 1986.
Altitude of land surface, 1,380.5 feet.

	Thickness, in feet	Depth, in feet
Silt, clayey, dark-brown	10	10
Sand, medium- to coarse-grained, and gravel	8	18
Clay, silty, gray to tan	10	28
Clay, silty; sand, coarse-grained; and gravel	10	38
Sand, coarse-grained, and gravel	10	48
Sand, medium- to coarse-grained	10	58
Sand, medium-grained, clayey	10	68
Clay, tan	7	75
Sand, fine-grained	5	80
Sand, medium- to coarse-grained	18	98
Sand, medium- to coarse-grained	75	173
Clay, hard, dark-gray	35	208
Shale	3	211

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-206-C.—Drilled November 9, 1986.
Altitude of land surface, 1,396.9 feet.

	Thickness, in feet	Depth, in feet
Silt, clayey	10	10
Sand, fine-grained, silty	25	35
Sand, coarse-grained	30	65
Sand, coarse-grained, and gravel	5	70
Clay, sandy	25	95
Sand, medium- to fine-grained	70	165
Sand, medium- to coarse-grained, and gravel	95	260
Shale	8	268

EB-207-C.—Drilled December 14, 1986.
Altitude of land surface, 1,392.8 feet.

	Thickness, in feet	Depth, in feet
Clay, brown	42	42
Sand, medium- to coarse-grained, and gravel	60	102
Silt, clayey, and clay, silty	18	120
Sand, fine- to medium-grained	30	150
Silt, clayey	10	160
Sand, medium- to coarse-grained, and gravel	30	190
Sand, medium- to coarse-grained, clayey	10	200
Sand, medium-grained	40	240
Sand, medium- to coarse-grained	6	246
Shale	4	250

EB-208-C.—Drilled October 28, 1980.
Altitude of land surface, 1,418.7 feet.

	Thickness, in feet	Depth, in feet
Soil, black	5	5
Clay, tan, and sand, fine-grained	5	10
Sand, coarse-grained, with a few thin clay layers	75	85
Clay, green	15	100
Clay, blue-gray	23	123

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-209-C.—Drilled May 26, 1987.
Altitude of land surface, 1,423.7 feet.

	Thickness, in feet	Depth, in feet
Soil	4	4
Sand, coarse-grained, arkosic	51	55
Clay, silty, sandy	5	60
Sand, fine-grained	30	90
Clay, tan, white, brown	10	100
Sand, fine- to medium-grained, with a few thin clay layers	73	173
Shale, tan, yellow, grading to dark-gray	9	182

EB-210-C.—Drilled June 1, 1987.
Altitude of land surface, 1,424.7 feet.

	Thickness, in feet	Depth, in feet
Clay, silty, sandy, red-brown	25	25
Clay, silty, sandy, gray	5	30
Sand, fine-grained	8	38
Clay, silty, sandy, gray	17	55
Sand, fine-grained	25	80
Sand, medium- to coarse-grained, arkosic	15	95
Clay, silty, tan, brown	21	116
Sand, fine- to coarse-grained, arkosic	70	186
Clay, silty, tan, brown	1	187
Sand, fine- to coarse-grained, arkosic, gypsiferous	55	242

EB-213-C.—Drilled April 6, 1988.
Altitude of land surface, 1,475.8 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, sandy	12	12
Sand and gravel; arkosic	37	49
Clay, tan, yellow	1	50
Sand and gravel; arkosic	32	82
Silt, clayey, sandy, tan, gray	21	103
Sand, fine- to medium-grained	9	112
Sand and gravel; arkosic	4	116
Clay, silty, sandy, tan, gray	6	122
Sand, fine- to medium-grained, arkosic, with a few thin clay layers	73	195
Clay, gray, and pieces of green shale	5	200
Sand and gravel; arkosic	16	216
Clay, white, grading to sand, clayey, red-brown	4	220
Sand, fine- to medium-grained	18	238
Clay, gray	2	240
Sand and gravel	2	242
Clay, silty, and silt, clayey	40	282
Shale, maroon, gray, green, weathered	23	305
Shale, dark-gray	8	313

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-214-C.—Drilled April 12, 1988.
Altitude of land surface, 1,473.1 feet.

	Thickness, in feet	Depth, in feet
Soil	4	4
Sand, fine-grained, and gravel; arkosic	54	58
Clay, silty, gray	16	74
Sand and gravel; arkosic	23	97
Clay, tan, yellow	12	109
Silt, gray	84	193
Sand, fine-grained, and gravel; arkosic	23	216
Clay, sandy, tan	19	235
Clay, silty, sandy, gray	36	271
Sand and gravel; arkosic	9	280
Silt, sandy, red to brown	8	288
Sand and gravel, some dark red-brown ironstone	3	291
Shale, gray, weathered	19	310
Shale, dark-gray	20	330

EB-215-C.—Drilled March 31, 1988.
Altitude of land surface, 1,464.9 feet.

	Thickness, in feet	Depth, in feet
Soil, brown	5	5
Silt, sandy, tan, brown	5	10
Sand and gravel; arkosic	23	33
Clay, tan, gray, yellow	3	36
Sand and gravel; arkosic, pink	12	48
Sand, fine- to medium-grained, tan	70	118
Clay, silty, gray	15	133
Sand, fine- to medium-grained, arkosic, pink	25	158
Clay, sandy, tan, yellow	9	167
Sand	5	172
Clay, tan, gray	3	175
Sand, fine- to coarse-grained, arkosic, pink	37	212
Clay, tan to gray	3	215
Sand, fine, to medium-grained, arkosic, pink	13	228
Clay, tan	2	230
Sand, fine- to medium-grained, arkosic, pink	55	285
Shale, gray	13	298

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-216-C.—Drilled November 19, 1987.
Altitude of land surface, 1,464.3 feet.

	Thickness, in feet	Depth, in feet
Clay, sandy, brown	7	7
Sand and gravel; arkosic	81	88
Clay	2	90
Sand and gravel	5	95
Clay	9	104
Sand and gravel	6	110
Clay	6	116
Sand and gravel	28	144
Clay	5	149
Sand and gravel	61	210
Clay	4	214
Sand and gravel	30	244
Clay	1	245
Sand and gravel	46	291
Clay	1	292
Sand and gravel	8	300
Sandstone	5	305
Sand, fine-grained	9	314
Shale, gray, some anhydrite	7	321

EB-217-C.—Drilled November 11, 1987.
Altitude of land surface, 1,460.0 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, sandy, brown	1	1
Sand and gravel	129	130
Clay	3	133
Sand and gravel	18	151
Clay	4	155
Sand	15	170
Clay	2	172
Sand	9	181
Clay	1	182
Sand	16	198
Clay	8	206
Sand	44	250
Shale	2	252

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-218-C.—Drilled November 5, 1987.
Altitude of land surface, 1,472.7 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, silty, tan to brown	15	15
Sand, fine- to medium-grained, and gravel; with clay, red to brown	88	103
Shale	5	108

EB-219-C.—Drilled October 23, 1987.
Altitude of land surface, 1,465.6 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, silty, tan to brown	15	15
Sand, fine- to medium-grained, tan to brown	73	88
Clay, silty, brown	25	113
Sand and gravel	17	130
Shale, gray	3	133

EB-220-C.—Drilled November 15, 1988.
Altitude of land surface, 1,337.3 feet

	Thickness, in feet	Depth, in feet
Soil, silty, brown	7	7
Sand and gravel; arkosic, pink	40	47
Shale, gray	13	60

EB-221-C.—Drilled November 7, 1988.
Altitude of land surface, 1,340.2 feet.

	Thickness, in feet	Depth, in feet
Soil, sandy, brown	2	2
Sand, fine-grained, tan	5	7
Sand and gravel, arkosic, tan to orange	44	51
Dolomite, sandy, tan to yellow	1	52
Shale, tan	6	58
Shale, gray	6	64
Sandstone, fine-grained, gray	1	65
Shale, gray	6	71

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-222-C.--Drilled November 11, 1988.
Altitude of land surface, 1,337.7 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, silty, sandy, brown	5	5
Sand and gravel; arkosic, tan	12	17
Sand and gravel; arkosic, tan to orange	62	79
Dolomite or limestone	2	81
Shale, gray	10	91

EB-223-C.—Drilled November 14, 1988.
Altitude of land surface, 1,337.6 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, brown	6	6
Sand, fine-grained, tan	5	11
Sand and gravel; arkosic, pink	32	43
Sand, clayey, yellow tan	2	45
Sand, fine- to medium-grained, tan	10	55
Clay, sandy, tan to brown	3	58
Sand, fine-grained, tan	13	71
Clay, sandy, tan to yellow	3	74
Sand, fine-grained, tan	6	80
Sand, fine-grained, tan, with a few thin clay layers	8	88
Sandstone, white	3	91
Sand, fine-grained, tan	2	93
Sandstone, white	3	96
Shale, gray	5	101

EB-224-C.—Drilled November 17, 1988.
Altitude of land surface, 1,342.2 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, sandy	11	11
Sand, medium- to coarse-grained, and gravel; arkosic, pink	57	68
Clay, sandy, tan to yellow	2	70
Clay, silty, sandy, tan	12	82
Sand, fine-grained, and silt, clayey, tan	60	142
Sand, fine-grained	12	154
Sandstone, white	6	160
Shale, gray	1	161

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-225-C.—Drilled November 22, 1988.
Altitude of land surface, 1,350.3 feet.

	Thickness, in feet	Depth, in feet
Soil, brown	8	8
Silt, clayey, brown	2	10
Sand, fine- to medium-grained, and clay, yellow; clay layers near bottom of interval	28	38
Sand, fine- to coarse-grained, and gravel	2	40
Sand, fine- to coarse-grained, tan	18	58
Clay, tan	2	60
Sand, fine- to coarse-grained, tan	12	72
Sand, coarse-grained, and gravel	9	81
Silt, sandy, tan	9	90
Clay, silty, gray	2	92
Sand, fine- to coarse-grained, tan	18	110
Sand, fine- to medium-grained, tan	7	117
Clay, sandy, yellow	4	121
Sand, fine- to coarse-grained, tan	4	125
Clay, sandy, tan	4	129
Sand, fine- to coarse-grained, tan	6	135
Clay, tan	10	145
Sand, fine-grained, tan	17	162
Clay, tan	5	167
Sand, fine- to coarse-grained, tan, and gravel	9	176
Shale, silty, gray	6	182

EB-226-C.—Drilled November 26, 1988.
Altitude of land surface. 1,354.1 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, brown	10	10
Clay, sandy, red	9	19
Sand, fine- to coarse-grained, tan	18	37
Sand, fine- to medium-grained, silty, tan	9	46
Clay, silty, tan to yellow	9	55
Sand, fine- to coarse-grained, tan	6	61
Sand, fine- to medium-grained, silty, tan	20	81
Sand, fine- to coarse-grained, and gravel, tan	30	111
Clay, sandy, yellow	1	112
Sand, fine- to medium-grained, and gravel; tan	14	126
Clay, tan	2	128
Sand, fine- to medium-grained, tan	8	136
Clay, gray	1	137
Sand, fine- to coarse-grained, tan	43	180
Shale, gray	4	184

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-227-C.—Drilled December 1, 1988.
Altitude of land surface, 1,355.1 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, brown	7	7
Clay, sandy, red to brown	10	17
Sand, fine-grained, clayey, gray	11	28
Sand and gravel; arkosic, orange	30	58
Clay, silty, sandy, yellow	2	60
Sand and gravel; arkosic, with ironstone	35	95
Clay, silty, sandy, tan to yellow to red	17	112
Sand, fine-grained, silty, tan	14	126
Shale, gypsiferous, tan to gray	19	145

EB-228-C.—Drilled December 7, 1988.
Altitude of land surface, 1,493.8 feet.

	Thickness, in feet	Depth, in feet
Clay, sandy, brown	4	4
Sand, fine- to medium-grained, tan	6	10
Sand, fine- to coarse-grained, tan	14	24
Clay, sandy, gray	6	30
Sand, fine- to coarse-grained, and gravel; tan	20	50
Sand, fine-grained, and gravel; gray	7	57
Clay, silty, green to gray	3	60
Sand, fine- to coarse-grained, and gravel; tan, with a few thin clay layers	25	85
Shale, brown to red, with some gypsum	15	100

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-229-C.—Drilled December 9, 1988.
Altitude of land surface, 1,493.8 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, silty, brown	4	4
Gravel and sand, medium- to coarse-grained; tan; with a few thin clay layers	13	17
Sand, medium- to coarse-grained, and gravel	6	23
Clay, yellow	1	24
Sand, fine- to coarse-grained, tan	15	39
Clay, sandy, gray, and gravel	6	45
Sand, fine- to coarse-grained, tan, and gravel	25	70
Clay, gray	1	71
Sand, fine- to coarse-grained, tan	4	75
Clay, gray	1	76
Sand, clayey, tan, and gravel	7	83
Clay, sandy, tan, and gravel	3	86
Sand, fine- to coarse-grained, tan	4	90
Clay, gray	1	91
Sand, fine- to coarse-grained, tan	4	95
Clay, red	1	96
Clay, yellow	1	97
Sand, fine-grained, tan	4	101
Sand, fine-grained, silty	6	107
Shale, red	14	121

EB-230-C.—Drilled December 13, 1988.
Altitude of land surface, 1,497.3 feet.

	Thickness, in feet	Depth, in feet
Soil, brown	6	6
Sand, fine-grained, tan	3	9
Sand and gravel; arkosic, orange, with a few thin clay layers	74	83
Sand, silty, red to brown	7	90
Clay, silty, sandy, gray	16	106
Sand, clayey, red to gray	9	115
Sand, fine- to medium-grained, tan	4	119
Sand, fine-grained	16	135
Sand, fine- to coarse-grained, arkosic	38	173
Clay, sandy, red to brown	4	177
Sand and gravel; arkosic, pink	9	186
Shale, silty, sandy, maroon to green	5	191

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-231-C.—Drilled December 31, 1988.
Altitude of land surface, 1,498.8 feet.

	Thickness, in feet	Depth, in feet
Clay, silty, sandy, brown, yellowish-tan	8	8
Sand, fine-grained, yellow, and gravel	9	17
Clay, yellow, tan	12	29
Clay, silty, green	4	33
Sand, fine- to coarse-grained, clayey	27	60
Clay, silty, green	1	61
Sand, fine- to coarse-grained, tan	2	63
Clay, silty, green	1	64
Sand, fine- to medium-grained, clayey, tan	9	73
Clay, sandy, yellow	3	76
Sand, fine- to medium-grained, clayey, yellow	12	88
Clay, silty, pink, green	10	98
Caliche, white	1	99
Shale, red, green	22	121

EB-232-C.—Drilled January 9, 1989.
Altitude of land surface, 1,496.6 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, sandy, brown	3	3
Sand, fine-grained, tan, and gravel	5	8
Clay, sandy, gray	10	18
Sand, fine-grained, and gravel; tan to gray	32	50
Clay, tan	4	54
Sand and gravel; arkosic	26	80
Sand, fine-grained, tan	12	92
Clay, sandy, tan	1	93
Sand, fine-grained, and gravel	17	110
Sand and gravel; tan to orange	10	120
Sand, fine-grained, tan	10	130
Clay, tan	1	131
Sand, coarse-grained, and gravel; tan to orange	12	143
Shale, green, gray, with some gypsum	11	154

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-233-C.—Drilled January 13, 1989.
Altitude of land surface, 1,553.1 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, brown	4	4
Clay, silty, tan	50	54
Sand, fine- to coarse-grained, arkosic, orange	33	87
Clay, silty, sandy, tan, gray	13	100
Sand and gravel; tan	8	108
Sand, clayey, tan	6	114
Sand, fine-grained, tan	16	130
Sand, coarse-grained, and gravel; arkosic, orange with pieces of ironstone	15	145
Shale, silty, red to green	7	152

EB-234-C.—Drilled January 17, 1989.
Altitude of land surface, 1,548.5 feet.

	Thickness, in feet	Depth, in feet
Clay, tan to gray	34	34
Sand, fine- to coarse-grained, and gravel; tan	34	68
Clay, sandy, tan, brown	22	90
Clay, sandy, with interbedded sand layers	21	111
Shale, silty	10	121

EB-235-C.—Drilled January 19, 1989.
Altitude of land surface, 1,551.4 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, silty	2	2
Clay, silty, sandy, brown, yellowish to tan	26	28
Sand, fine- to coarse-grained, tan	17	45
Clay, tan, and sand layers	17	62
Clay, tan	3	65
Shale, red, green	11	76

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-236-C.—Drilled December 9, 1989.
Altitude of land surface, 1,476.6 feet.

	Thickness, in feet	Depth, in feet
Clay, tan, gray	17	17
Sand, fine-grained	1	18
Clay, gray	5	23
Sand, fine- to medium-grained	7	30
Sand, fine- to coarse-grained, tan, and gravel; arkosic	32	62
Clay, silty, sandy, tan	6	68
Clay, gray	4	72
Sand and gravel; tan	21	93
Sand, fine- to coarse-grained, clayey, and gravel; tan	7	100
Sand	120	220
Shale, gray	25	245

EB-237-D.—Drilled December 17, 1989.
Altitude of land surface, 1,516.8 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, silty, brown	3	3
Clay, tan, red to brown	31	34
Clay, silty, tan, red-brown	9	43
Shale, red; weathered	2	45
Shale, silty, red to maroon, green	31	76
Dolomite (?)	1	77
Shale, silty, red to maroon	8	85

EB-238-C.—Drilled February 12, 1990.
Altitude of land surface, 1,394.0 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, brown	2	2
Clay, silty, red to brown	26	28
Sand and gravel; arkosic, orange	33	61
Clay, tan to white	7	68
Sand and gravel; clayey, orange	21	89
Shale, gray-green	11	100

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-239-C.—Drilled November 11, 1989.
Altitude of land surface, 1,512.2 feet.

	Thickness, in feet	Depth, in feet
Soil, sandy, gray	2	2
Silt, clayey, gray	9	11
Sand, arkosic, tan to orange	39	50
Clay, tan	2	52
Sand and gravel; tan to orange	19	71
Shale, silty, red to maroon	4	75

EB-240-C.—Drilled November 14, 1989.
Altitude of land surface, 1,485.7 feet.

	Thickness, in feet	Depth, in feet
Soil, sandy, brown	5	5
Sand, fine-grained, tan to orange	4	9
Sand and gravel; arkosic, tan to orange	51	60
Clay, sandy, silty, tan	10	70
Sand, fine- to medium-grained, tan	11	81
Clay, gray	3	84
Sand, fine-grained, tan	11	95
Clay, gray	35	130
Sand and gravel; tan	30	160
Sand, fine-grained, clayey, lignitic, tan	9	169
Clay, lignitic, tan to gray	3	172
Sand, fine-grained, clayey	8	180
Sand, fine- to medium-grained, tan; with calcium carbonate cemented layers at 192 to 193 and 260 to 261 feet.	112	292
Sand, fine-grained, tan; with some ironstone gravel	21	313
Shale, gray, maroon	27	340

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-241-C.—Drilled January 13, 1990.
Altitude of land surface, 1,444.4 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, sandy, brown	5	5
Sand and gravel; arkosic, orange	35	40
Clay, sandy, tan to brown	14	54
Sand and gravel; clayey, tan to orange	17	71
Clay, sandy, silty, tan to gray	14	85
Sand and gravel; arkosic, tan to orange	30	115
Clay, tan to gray	8	123
Sand, arkosic, orange	34	157
Silt, clayey, black	13	170
Sand, fine-grained, tan to gray	60	230
Clay, sandy, tan	10	240
Sand, tan	36	276
Sandstone, white	3	279
Sand and gravel; orange	11	290
Sand, clayey, tan	5	295
Sand and gravel; arkosic, orange	26	321
Shale, gray	4	325

EB-242-C.—Drilled January 4, 1990.
Altitude of land surface, 1,462.6 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, brown	5	5
Sand, coarse-grained, and gravel; arkosic, tan	47	52
Clay, silty, tan to yellow	11	63
Silt, clayey, tan to yellow	19	82
Sand and gravel; arkosic, tan to orange	26	108
Sand, coarse-grained, and gravel; arkosic	12	120
Silt and sand, fine-grained, micaceous, tan to gray	10	130
Clay, gray, lignitic	29	159
Sand, fine- to medium-grained, tan	13	172
Silt, clayey, gray	6	178
Sand and gravel, arkosic, tan to orange	39	217
Sandstone, white, calcareous cement	2	219
Clay, silty, tan	10	229
Sand and gravel; arkosic, tan to orange	41	270
Clay, silty, sandy, tan	10	280
Sandstone, calcareous cement	1	281
Silt and sand, fine, tan	19	300
Sand and gravel, some ironstone	6	306
Shale, gray	19	325

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-243-C.—Drilled January 24, 1990.
Altitude of land surface, 1,434.2 feet.

	Thickness, in feet	Depth, in feet
Sand, silty, brown	7	7
Sand and gravel; arkosic, orange	14	21
Clay, sandy, yellow to gray	5	26
Sand, fine- to medium-grained, tan	6	32
Clay, silty, sandy, tan to yellow	6	38
Sand and gravel	13	51
Clay, silty, tan	10	61
Sand and gravel; arkosic, tan to orange	57	118
Clay, silty, tan to gray	7	125
Sand, fine-grained, tan	68	193
Clay, tan to brown	9	202
Sand and gravel; arkosic, tan to orange	25	227
Shale, gray to maroon	13	240

EB-244-C.—Drilled February 1, 1990.
Altitude of land surface, 1,393.8 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, sandy, brown	4	4
Sand, fine- to medium-grained, arkosic, tan to orange	37	41
Clay, tan to yellow	22	63
Sand and gravel; arkosic, tan to orange	57	120
Shale, gray	5	125

EB-245-C.—Drilled February 6, 1990.
Altitude of land surface, 1,378.5 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, clayey, brown	3	3
Clay, tan to gray	4	7
Clay, silty, sandy, tan to gray	13	20
Sand, fine- to medium-grained, tan to orange	15	35
Sand and gravel; arkosic, orange, with clay layers at 50 to 52, 60–61, 80–81, and 102–103 feet.	119	154
Clay, sandy, gray to tan	7	161
Sand and gravel; arkosic, tan to orange	34	195
Sand, arkosic, tan to white	31	226
Dolomite or limestone, gray	1	227
Shale, gray	13	240

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-246-C.—Drilled February 9, 1990.
Altitude of land surface, 1,347.5 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, sandy, brown	6	6
Sand and gravel; arkosic, tan to orange	21	27
Clay, tan to yellow	8	35
Sand, fine-grained, tan	10	45
Clay, sandy, brown to tan	25	70
Sand, fine-grained, and silt; tan	16	86
Sand, fine-grained, tan	12	98
Clay, tan to gray	28	126
Sand, fine-grained, and silt; tan	27	153
Sand, white	1	154
Shale, gray	11	165

EB-247-C.—Drilled January 29, 1990.
Altitude of land surface, 1,431.9 feet.

	Thickness, in feet	Depth, in feet
Soil, silty, brown	3	3
Clay, gray	5	8
Sand, arkosic, tan to orange	78	86
Clay, sandy, tan	5	91
Sand, clayey, tan	10	101
Clay, sandy, tan	9	110
Sand, with caliche	17	127
Shale	13	140

EB-248-C.—Drilled November 6, 1989.
Altitude of land surface, 1,522.3 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, gray	1	1
Clay, sandy, gray to tan	10	11
Clay, sandy, brown to tan	6	17
Sand, fine- to coarse-grained, and gravel	38	55
Clay, sandy, gray	4	59
Sand, fine- to medium-grained, tan	3	62
Clay, tan	13	75
Sand, silty, tan	30	105
Sand, fine- to coarse-grained, tan, with red chert pieces	15	120
Clay, sandy, tan	9	129
Sand, fine- to coarse-grained, and gravel	6	135
Shale, green to gray to red	10	145

Table 7. Lithologic logs of deep wells at well sites EB-201 through EB-249—Continued

EB-249-C.—Drilled December 2, 1989.
Altitude of land surface, 1,476.3 feet.

	Thickness, in feet	Depth, in feet
Sand, fine- to coarse-grained, gray to brown	5	5
Sand and gravel, silty, tan to brown	5	10
Clay, sandy, gray, tan	8	18
Sand and gravel; tan	9	27
Clay, tan	15	42
Sand, fine-grained, white	4	46
Clay, sandy, tan to gray	30	76
Sand, fine- to coarse-grained, tan	26	102
Clay, sandy, gray	23	125
Sand, fine- to medium-grained, orange	54	179
Clay, black	10	189
Sand, clayey, tan	12	201
Sand, fine- to medium-grained, tan	11	212
Clay, sandy, tan	7	219
Sand, fine- to coarse-grained, tan	21	240
Clay, sandy, white	6	246
Sand, fine- to coarse-grained, white to tan	69	315
Sandstone, white	1	316
Shale, gray	9	325