Effects of Pumping Municipal Wells at Manhattan, Kansas, on Streamflow in the Big Blue and Kansas Rivers, Northeast Kansas, 1992–94

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per second (acre-ft/s)	1,233	cubic meter per second
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day[1] (ft/d)	0.3048	meter per day
foot per day[1] (ft/d)	0.0003528	centimeter per second
foot squared per day[2] (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

[1]The standard unit for hydraulic conductivity (K) is cubic foot per day per square foot [$(ft^3/d)/ft^2$]. This mathematical expression reduces to foot per day (ft/d), which is used in this report.

[2]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. This mathematical expression reduces to foot squared per day (ft^2/d), which is used in this report.

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.

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 Water withdrawn from a land area by evaporation from water surfaces and moist soil and by plant transpiration.

Gaging station. A particular site on a stream, canal, lake, or reservoir where systematic observations of gage height or streamflow are obtained.

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. The standard unit for **hydraulic conductivity** is cubic foot per day per square foot [$(ft^3/d)/ft^2$)]. This mathematical expression reduces to foot per day (ft/d).

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.

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**.

Saturated zone. The subsurface zone in which all openings are full of water.

Specific capacity. The volume of water yielded from a well per unit of drawdown in the well.

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, and water inflow and outflow from the **aquifer** are constant.

Transient. Condition under which the magnitude and direction of ground-water flow velocities vary with time, and water inflow and outflow from the **aquifer** are not constant.

Transmissivity. The volume of water at the existing kinematic viscosity that will move in unit time under a unit **hydraulic gradient** through a unit width of the **aquifer**. The standard unit for **transmissivity** is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)ft^2$)/ft]. This mathematical expression reduces to foot squared per day (ft^2/d).

Effects of Pumping Municipal Wells at Manhattan, Kansas, on Streamflow in the Big Blue and Kansas Rivers, Northeast Kansas, 1992–94

By Xiaodong Jian, Nathan C. Myers, *and* Gerald D. Hargadine

Abstract

A ground-water flow model was developed to simulate the effects of municipal well pumping on streamflow in the Big Blue and Kansas Rivers near Manhattan, Kansas, from 1992 through 1994. Model simulations of the effects of municipal well pumping on streamflow in the Big Blue and Kansas Rivers indicate that well pumping decreases streamflow. Simulations of May 1993 conditions indicate that well pumping decreased simulated streamflow in the Big Blue and Kansas Rivers by 5.28 ft^3/s (cubic feet per second) for the month, of which 3.22 ft^3/s were contributed from the streams (induced infiltration) and 2.06 ft^3/s were contributed from ground water that would have seeped to the streams if the wells had not been pumping (intercepted base flow). Of the total 414 acre-feet pumped by municipal wells during May 1993, about 48 percent was from induced infiltration, and about 31 percent was from intercepted base flow. Simulations of October 16 through November 14, 1994, conditions indicate that well pumping decreased simulated streamflow in the Big Blue and Kansas Rivers by 6.67 ft^3/s for the period, of which 6.51 ft^3/s was from induced infiltration and 0.16 ft^3/s was from intercepted base flow. Of the total 506 acre-feet pumped by municipal wells during October 16 through November 14, 1994, about 76 percent was induced from infiltration, and about 2 percent was from intercepted base flow. Steady-state simulations of hypothetical conditions were conducted to develop relations among average and minimum ground-water altitudes in the Manhattan municipal well field and precipitation, pumping, and streamflow rates.

INTRODUCTION

Background

Alluvial aquifers of the Big Blue and Kansas Rivers provide an important source of water to industry and agriculture in northeast Kansas and are a sole source of water to some public suppliers. During periods of low streamflow, water releases from Tuttle Creek Lake and other lakes on Kansas River tributaries have been used to maintain streamflow at desirable rates. Water-release rates from the lakes have been determined on the basis of the needs of river-water users and State of Kansas minimum desirable streamflow requirements [Kansas Statutes Annotated (K.S.A.) 82a.7c]. However, ground-water withdrawals from the alluvial aquifer, which may induce significant recharge of river water into the aquifer, generally are not considered when making lake releases. Consideration of ground-water withdrawals is especially important during periods of low streamflow when ground-water withdrawals may substantially decrease streamflow and the amount of water available to river-water users.

Beginning in 1992, a 3-year study to determine the effects of pumping municipal wells completed in the alluvial aquifers at Junction City and Manhattan, Kansas, on streamflows in the Republican, Big Blue, and Kansas Rivers was conducted by the U.S. Geological Survey (USGS) in cooperation with the Kansas Water Office (KWO) and supported in part by the Kansas State Water Plan Fund. The amount of river water that infiltrates into the aquifer to satisfy pumping demands needed to be quantified so that the effect of pumping during low streamflow conditions could be assessed. The results of the study of the aquifer at Junction City, Kansas, are presented by Myers and others (1996).

Purpose and Scope

This report presents the results of the study of the effects of known and hypothetical municipal well pumping at Manhattan, Kansas, on streamflow in the Big Blue and Kansas Rivers. This report presents data for the Manhattan study area (fig. 1), including geology, hydrology, stream-aquifer hydraulic interaction, water use (1960–94), and the results of ground-water flow model simulations of the effects of Manhattan municipal well pumping on streamflow in the Big Blue and Kansas Rivers.

Description of Study Area

The study area is located in the Flint Hills Upland physiographic division (Schoewe, 1949) (fig. 1), which is a prominent upland area characterized by rolling topography and deep stream valleys with steep valley walls. The study area lies within the low-relief flood plains of the Big Blue and Kansas River Valleys. The study area includes reaches of the Big Blue and Kansas Rivers as follows: The Big Blue River from Tuttle Creek Dam to its junction with the Kansas River; the Kansas River from a point about 5 mi upstream to about 3 mi downstream from the junction of the Big Blue and Kansas Rivers (fig. 2).

Tuttle Creek Dam, completed in July 1962, was built on the Big Blue River for flood-control, water-supply, streamflow regulation, recreation, and fish and wildlife management purposes. The dam is located about 3 mi north of Manhattan and about 10 river mi upstream from the confluence of the Big Blue and Kansas Rivers.

The Manhattan municipal well field can be divided into two areas comprising the old and new parts of the well field (fig. 2). The old part of the well field extends from near the western edge of the Big Blue River Valley to the east about 3,100 ft. This area is approximately 2,700 ft west of the nearest segment of the Big Blue River and 3,600 ft north of the nearest segment of the Kansas River. The new part of the well field is located near the north and west banks of the Big Blue River. All wells in the new part of the well field are located within about 1,100 ft of the Big Blue River, and municipal wells MM–16 through MM–22 are located within about 300 ft of the Big Blue River. Currently (1996), there are seven municipal supply wells in operation in the old part and nine municipal wells in the new part of the well field.

Approach

Information pertaining to well locations, well construction, geology, and hydrology was obtained from the city of Manhattan, the KWO, the Kansas Department of Health and Environment, the U.S. Army Corps of Engineers (USACE), the USGS, well owners, and published reports. Water-use information was obtained from the city of Manhattan and the Kansas Department of Agriculture, Division of Water Resources (DWR).

Eleven observation wells located in and near the Manhattan municipal well field (fig. 2) were installed by the USGS and the KWO during September and October 1992 and April 1993. Boreholes for observation wells USGS–1 through USGS–11 and for observation wells installed for an aquifer test (wells USGS–500W, USGS–250W, USGS–50W, USGS–50E, USGS–250E, and USGS–500E) were drilled using 4 1/4-in. inside-diameter, hollow-stem augers. All equipment and materials were cleaned with a high-pressure jet of potable water prior to installation of each well. A steel plate, placed in the auger bit, prevented sediment from clogging the inside of the auger flights while drilling. At the desired depth, the auger flights were filled with potable water to compensate for hydrostatic pressure outside the auger flights, then the pipe for the observation well was lowered inside the auger flights, which was used to knock out the steel plate in the auger bit. Except for well USGS–7, observation wells were 2-in. inside-diameter, polyvinyl-chloride (PVC) pipe that had flush-threaded joints, a 5-ft PVC screen with 0.01-in. slots, and a capped bottom. Observation well USGS–7 was 4-in. inside-diameter, PVC pipe with flush-threaded joints, a 5-ft PVC screen with 0.01-in. slots, and a capped bottom. Except for well USGS–7, no glue or solvent was used in the construction of these wells. Centralizers, located about 2 ft above the well screens, were used to keep the well casing centered in the hole. Natural sand packing resulted from the caving of sand as the auger flights were removed. About 2 ft of bentonite chips were

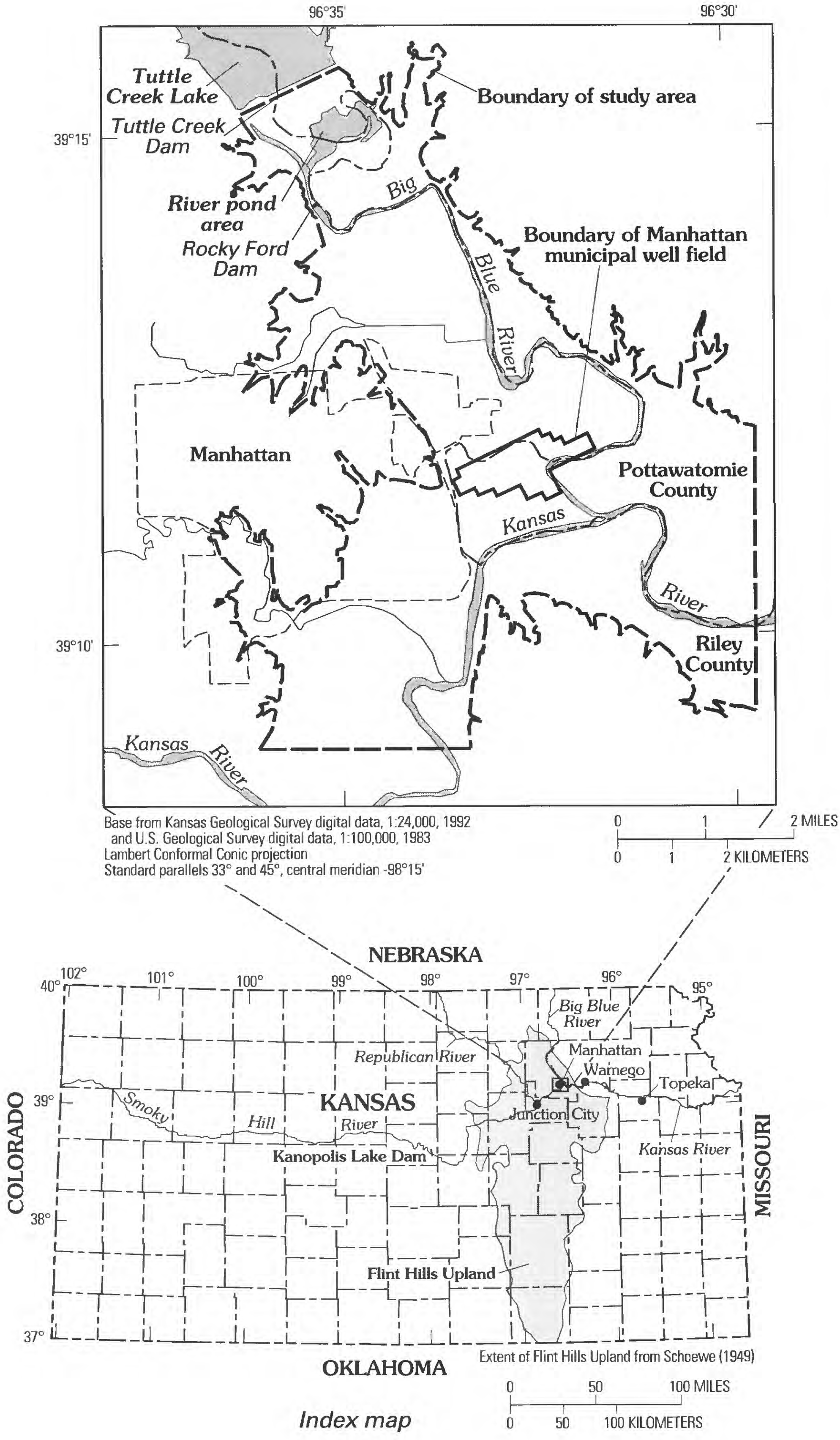


Figure 1. Location of study area.

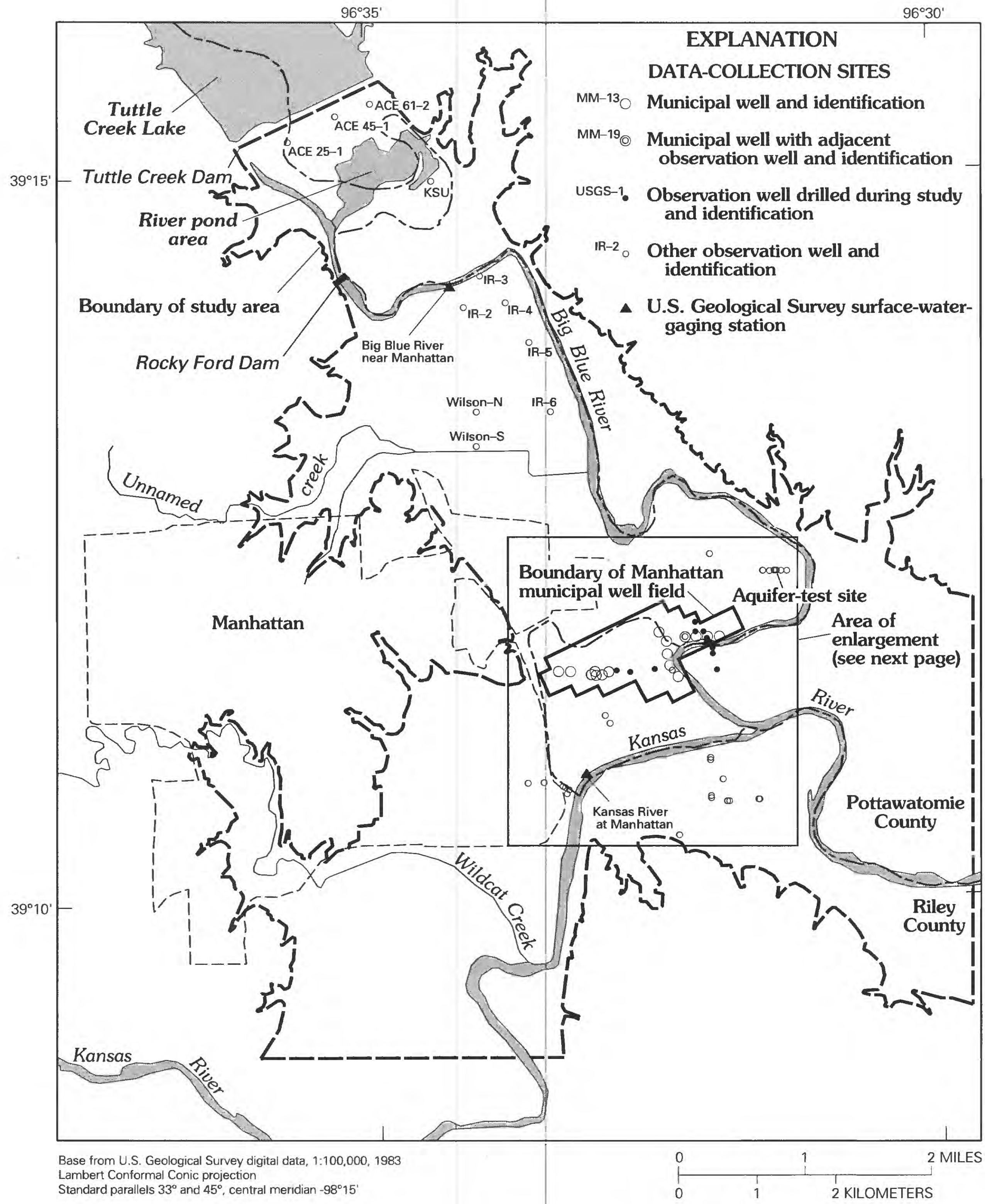


Figure 2. Boundary of study area, streams, data-collection sites, and boundary of Manhattan municipal well field.

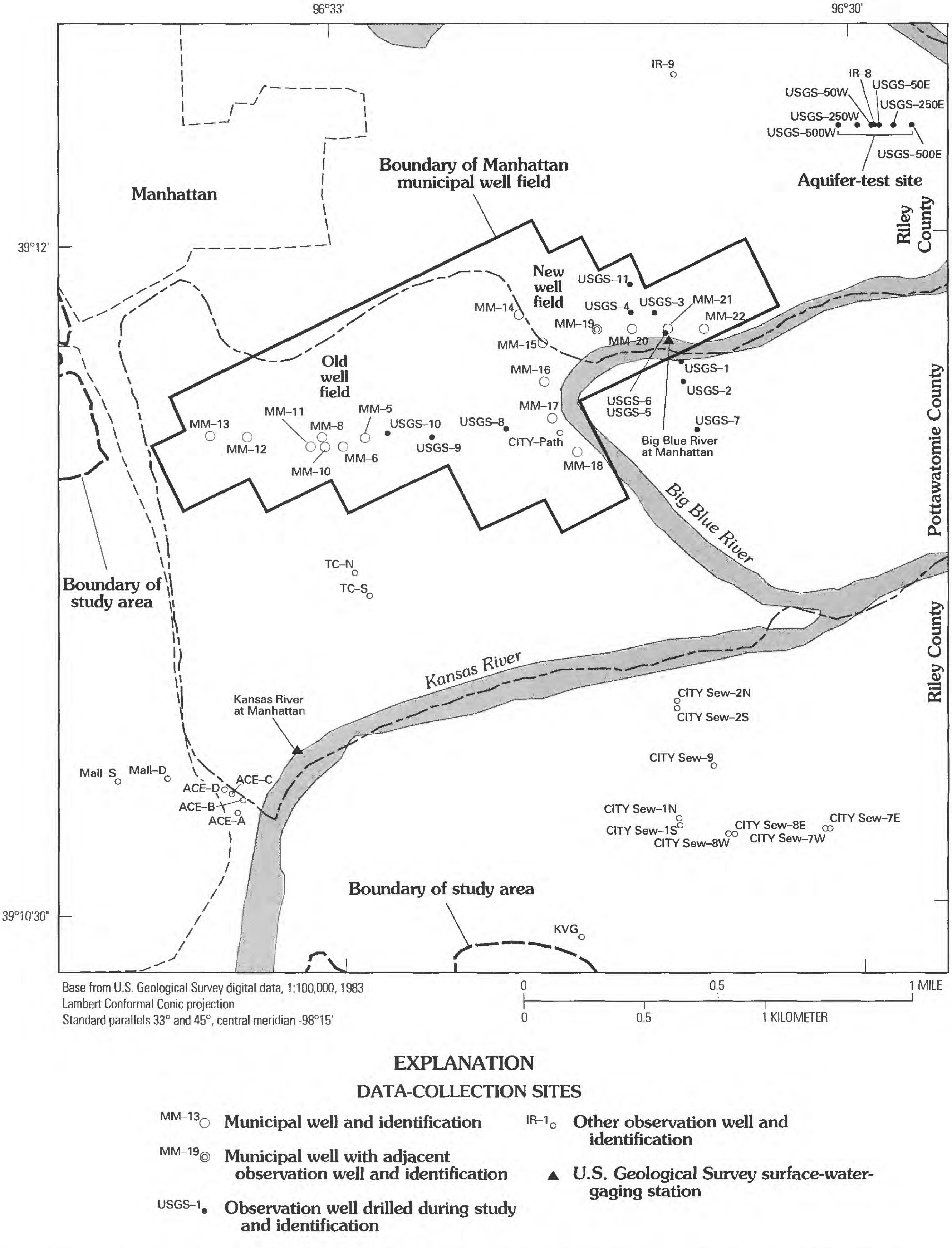


Figure 2. Boundary of study area, streams, data-collection sites, and boundary of Manhattan municipal well field—Continued.

placed on the top of the silica sand and allowed to hydrate for 1 to 2 hours, then a high-solids bentonite grout was added using a tremie pipe to the annular space to within 18 in. of land surface. Finally, bentonite chips were added from 18 in. to land surface. The wells were developed using filtered, pressured air. The air provided a surging action, which was continued until the turbidity cleared. A locking steel casing was set around the well casings.

Observation wells USGS–1 through USGS–4 and USGS–7 through USGS–11 were equipped with digital punch-tape water-level recorders. Water levels in these wells were recorded at hourly intervals. Observation wells USGS–5 and USGS–6 initially were equipped with electronic shaft encoders and later with submersible pressure transducers. These instruments were connected to a data logger-transmitter, which collected water-level data at 15-minute intervals.

A network of 50 observation wells (fig. 2) was established in and near the Manhattan municipal well field for the purpose of collecting water-level data in and around the well-field area. These wells consisted of existing supply and observation wells, in addition to wells drilled during this study. Water levels were measured about monthly.

An aquifer test was conducted during August 1994 using irrigation well IR–8 (fig. 2). Six observation wells, spaced at about 50, 250, and 500 ft on two sides of the irrigation well, and an access well located in the concrete pad of the irrigation well and screened in the irrigation well's gravel pack, were equipped with submersible pressure transducers and data loggers. Hourly water levels were collected from these wells for about 1 month prior to the aquifer test. The irrigation well was not pumped for 3 weeks before the test. During the test, water levels were collected from the access well and from the other observation wells at 30-second or shorter intervals. Water levels were collected manually during the aquifer test to verify instrument results. Aquifer-test data were analyzed using a method for unconfined aquifers developed by Neuman (1975).

A stage-only surface-water-gaging station (Big Blue River near Manhattan) was established at the well field adjacent to observation wells USGS–5 and USGS–6. Stream stage was measured initially with a submersible pressure transducer fixed in place inside the end of an orifice pipe anchored in the streambed. After sustaining flood damage during July 1993, the submersible transducer was replaced with a gas-purge system and a nonsubmersible transducer. Steel fence posts, driven at intervals down the streambank, served as external reference points for measuring stream stage. The pressure transducer was connected to a data logger-transmitter, which collected stream-stage data at 15-minute intervals.

Geologic information was recorded while drilling all observation wells. Gamma-ray logs were obtained from USGS boreholes drilled to bedrock. Water-level measuring-point altitudes were determined by level survey (table 1). Water levels were measured to the nearest 0.01 ft using a steel tape. Water-level altitudes were used to construct potentiometric-surface maps for selected times to show directions of ground-water flow and the interaction of ground and surface water. Discharge measurements were conducted using standard USGS methods (Rantz and others, 1982).

Previous Studies

General studies of geology and (or) hydrology near the study area include "The Geology of Riley and Geary Counties, Kansas" by Jewett (1941) and "Ground Water in the Kansas River Valley, Junction City to Kansas City, Kansas" by Fader (1974). No previous reports of ground- and surface-water interaction studies or ground-water flow model development for the study area have been published. A ground- and surface-water interaction study using a finite-element, ground-water flow model (Wolf and Helgesen, 1993) was done for a reach of the Kansas River Valley between Wamego and Topeka, Kansas, about 20 river mi downstream from the study area.

Acknowledgments

The authors appreciate the cooperation of Manhattan city officials and private landowners, who provided access to drilling sites and data for the study, and the cooperation of private landowners and the USACE, who gave permission for water-level data to be collected from their wells. Mr. Rodney Moyer kindly permitted the use of his irrigation well for the aquifer test.

Table 1. Observation wells and measuring-point altitudes

Well name (fig. 2)	Measuring-point (top of casing) altitude (feet above sea level)	Well name (fig. 2)	Measuring-point (top of casing) altitude (feet above sea level)
USGS–1	1,010.18	Wilson–S	1,020.91
USGS–2	1,009.08	TC–N	1,007.06
USGS–3	1,010.57	TC–S	1,008.68
USGS–4	1,011.61	KVG	1,009.26
USGS–5	1,012.00	City Sew–1N	1,005.71
USGS–6	1,011.90	City Sew–1S	1,005.51
USGS–7	1,010.65	City Sew–2N	1,006.50
USGS–8	1,010.11	City Sew–2S	1,008.02
USGS–9	1,010.46	City Sew–7E	1,008.34
USGS–10	1,010.17	City Sew–7W	1,008.37
USGS–11	1,009.90	City Sew–8E	1,008.50
City-Path	1,009.68	City Sew–8W	1,007.72
MM–19	1,006.86	City Sew–9	1,007.00
IR–2	1,026.25	IR–8	1,016.03
IR–3	1,021.33	IR–9	1,016.37
IR–4	1,021.67	USGS–500E	1,013.85
IR–5	1,020.69	USGS–250E	1,016.67
IR–6	1,020.54	USGS–50E	1,017.14
Mall–S	1,013.86	USGS–50W	1,014.57
Mall–D	1,011.87	USGS–250W	1,014.66
ACE–A	1,013.33	USGS–500W	1,014.83
ACE–B	1,012.52	ACE 25–1	1,027.90
ACE–C	1,007.80	ACE 45–1	1,030.40
ACE–D	1,011.87	ACE 61–2	1,031.70
Wilson–N	1,020.90	KSU	1,025.88

GEOLOGY AND HYDROLOGY

Geology

The study area is located in alluvial and terrace deposits of the Big Blue and Kansas Rivers (fig. 3). Alluvial deposits are defined by Fader (1974, p. 4) as occurring "...from the river to the first distinguishable escarpment toward the valley wall on either or both sides of the river... ." On the basis of geologic information from wells drilled during this study and drill logs for Manhattan municipal wells, the alluvial deposits generally consist of as much as a 90-ft-thick sequence of sand and gravel, coarse-to-fine sand, and silt, with some interbedded clay layers (table 13 at the end of this report). The coarser sediments generally are found near the bottom of the alluvial deposits. The alluvial deposits occupy stream channels eroded into the bedrock surface (fig. 4) during Pleistocene and Holocene time (Frye and Leonard, 1952). Most of the alluvium probably was deposited in the bedrock

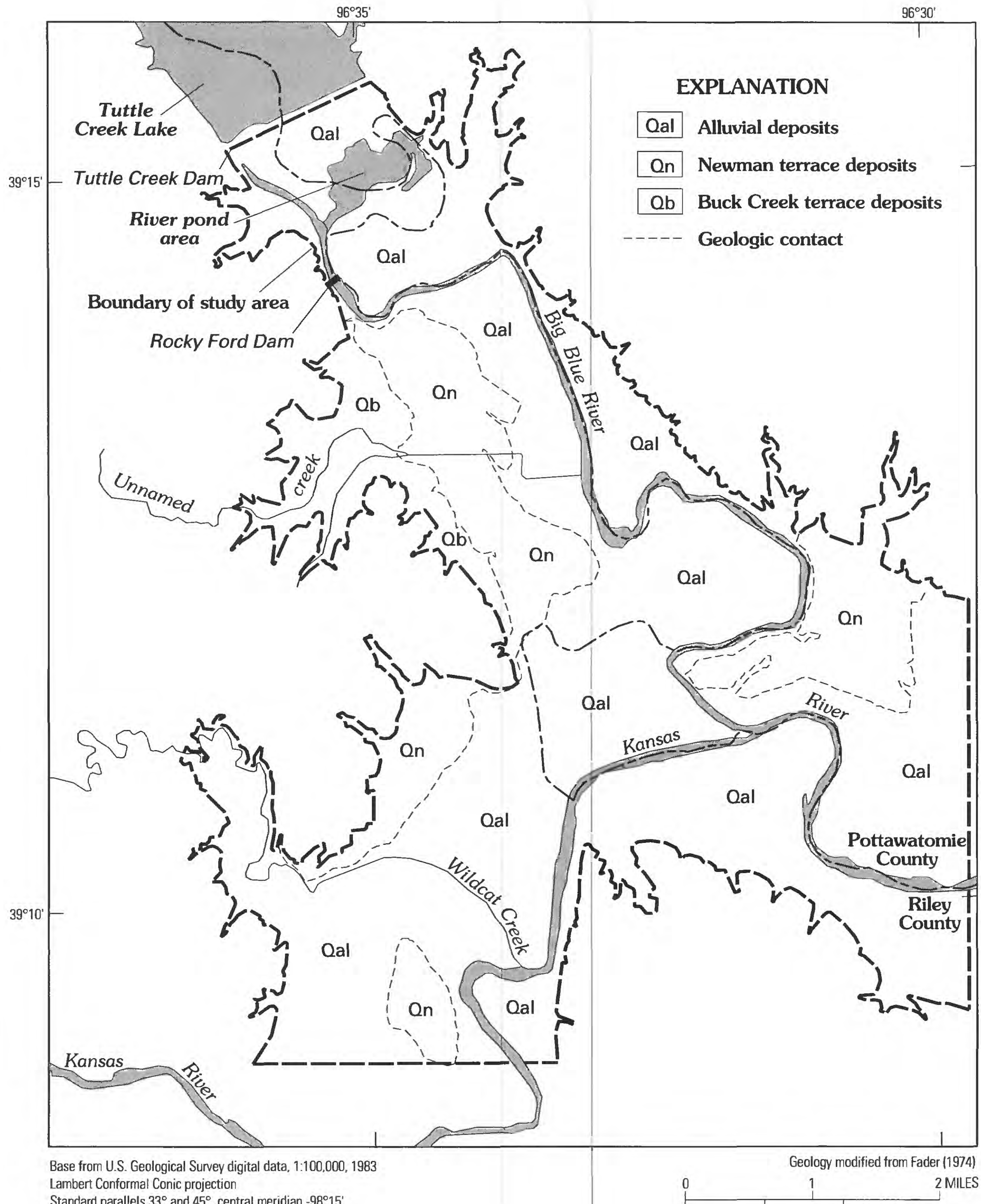
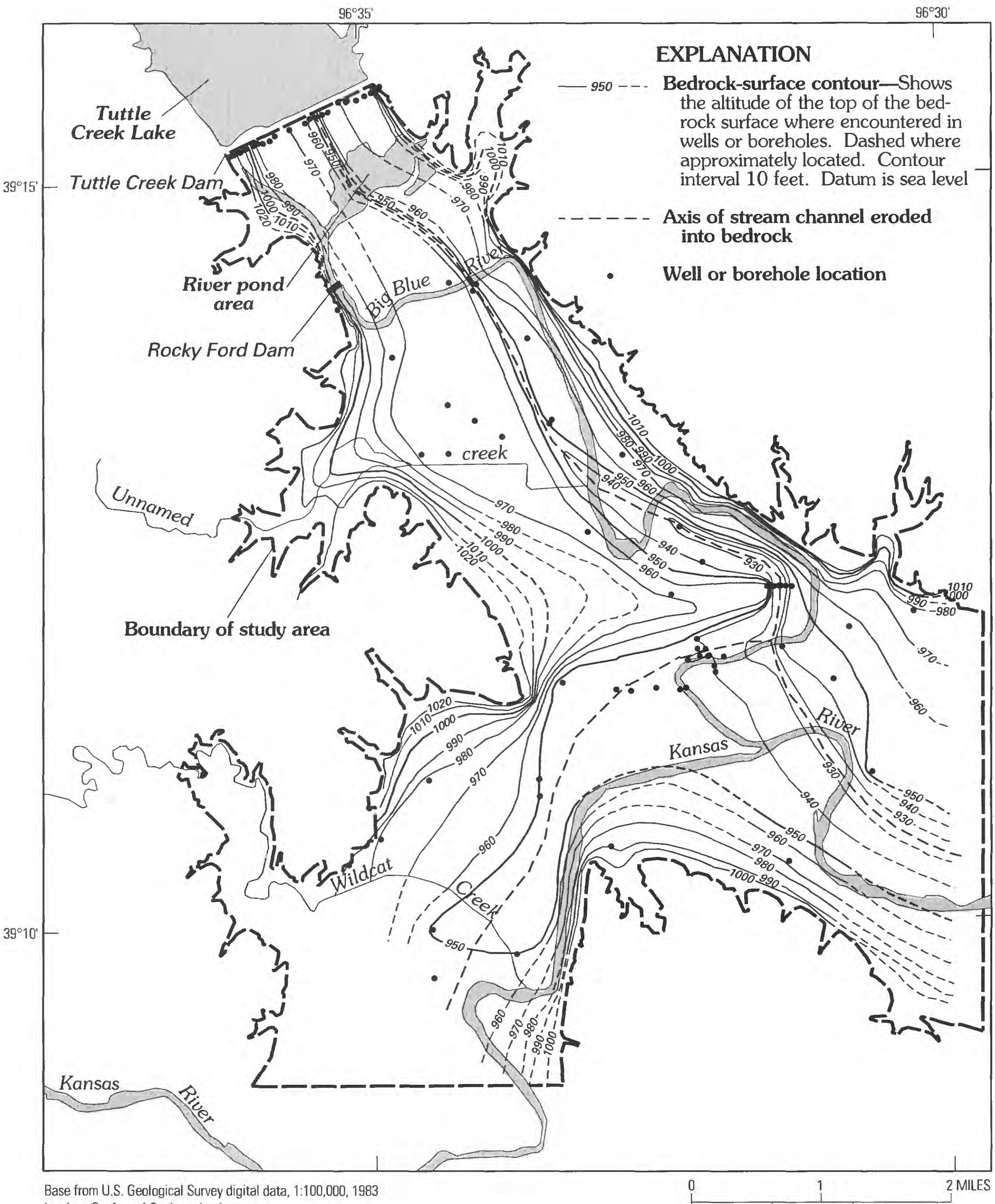


Figure 3. Surficial geology in the study area.



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 4. Bedrock-surface topography in the study area (contours are based on well or borehole data on file with the U.S. Geological Survey in Lawrence, Kansas).

channels during periods of glacial retreat (Frye and Leonard, 1952).

Newman and Buck Creek terrace deposits (fig. 3) consist of fining-upward sequences of gravel, sand, silt, and clay (Fader, 1974). Newman terrace deposits generally occur from the first escarpment above alluvial deposits to the next higher escarpment, and Buck Creek terrace deposits generally occur adjacent to the valley wall (Fader, 1974).

Alluvial and terrace deposits are underlain by shale and limestone of Permian age. The oldest bedrock encountered in boreholes drilled by the USACE near the axis of Tuttle Creek Dam (fig. 4) was the West Branch Member of the Janesville Shale. Because bedrock dips northwest in the study area (Jewett, 1941) and because bedrock-surface altitude decreases in a downstream (southeast) direction (fig. 4), bedrock at the axis of the bedrock channel probably is progressively older downstream in the study area.

Surface Water

The Big Blue River, which drains areas of Kansas and Nebraska, and the Kansas River, which drains areas of Kansas, Nebraska, and Colorado, join near Manhattan. Flow in these streams was largely unregulated until a series of dams and lakes were constructed during the 1960's to help prevent disastrous flooding, such as that which occurred during 1951 (U.S. Geological Survey, 1952). Except during July 1993, streamflow in the Big Blue River downstream from Tuttle Creek Dam has been completely regulated since July 1962. Streamflow in the Big Blue River (fig. 5) downstream from Tuttle Creek Lake generally is related to rainfall to the extent that lake outflow is matched to lake inflows. However, during periods of significant precipitation or drought, water releases are controlled by lake- and river-management needs and may not be related directly to precipitation. During July 1993, extremely large amounts of rainfall and runoff filled Tuttle Creek Lake and necessitated a maximum release of about 60,000 ft^3/s (about 1.4 acre-ft/s) through the lake's spillway. During the following months, large outflow rates were maintained to reduce the volume of water in the lake even though precipitation amounts were at or below normal.

Ground Water

Ground water in the alluvial deposits (alluvial aquifer) is unconfined throughout the study area. Thickness of the saturated zone in the alluvial aquifer ranges from zero at the valley edges to about 70 ft or more in the deepest part of the valley. Saturated thickness is dependent on the altitude of the water table, which changes with time, and on the thickness of the alluvial deposits. The average saturated thickness in the Manhattan municipal well-field area was about 44 ft during May 1993. The average saturated thickness was about 36.5 ft during late October and early November 1994. These values were estimated on the basis of measured ground-water altitudes in USGS observation wells and an average bedrock-surface altitude of about 950 ft in the well-field area.

Potentiometric-surface maps for May 25–26, 1993, and December 7–8, 1994 (fig. 6) show that ground water in the alluvial aquifer flows generally down the valley and either towards or away from the rivers. In the vicinity of the Manhattan municipal well field, a depression in the water table has formed (fig. 6) as a result of pumping of the municipal wells. The drawdown caused by pumping also occurs south of the Big Blue River near the new part of the well field (fig. 6). Ground water in the vicinity of the well field flows towards the pumping wells. Near Tuttle Creek Dam and the river pond area, potentiometric contours are closely spaced (fig. 6), indicating that the hydraulic gradient was steeper in this area than farther downstream. The river pond area and the Big Blue River, where it cuts across the river valley from west to east at the Rocky Ford Dam, intersect these areas of steep hydraulic gradient and are probably ground-water discharge locations along their north sides.

Stream-Aquifer Hydraulic Interaction

Ground-water flow near streams may be towards or away from the streams depending on the relative difference between stream stage and ground-water levels in the alluvial aquifer adjacent to the stream. When stream stage is higher than the ground-water level, the stream will lose some water to the aquifer (figs. 6*A* and 6*B*). When stream stage is lower than ground-water level, the stream will gain some water from the aquifer (fig. 6*A*, south of Kansas River). If pumping wells near a stream lower the ground-water level below the adjacent stream water level, the stream will lose water to

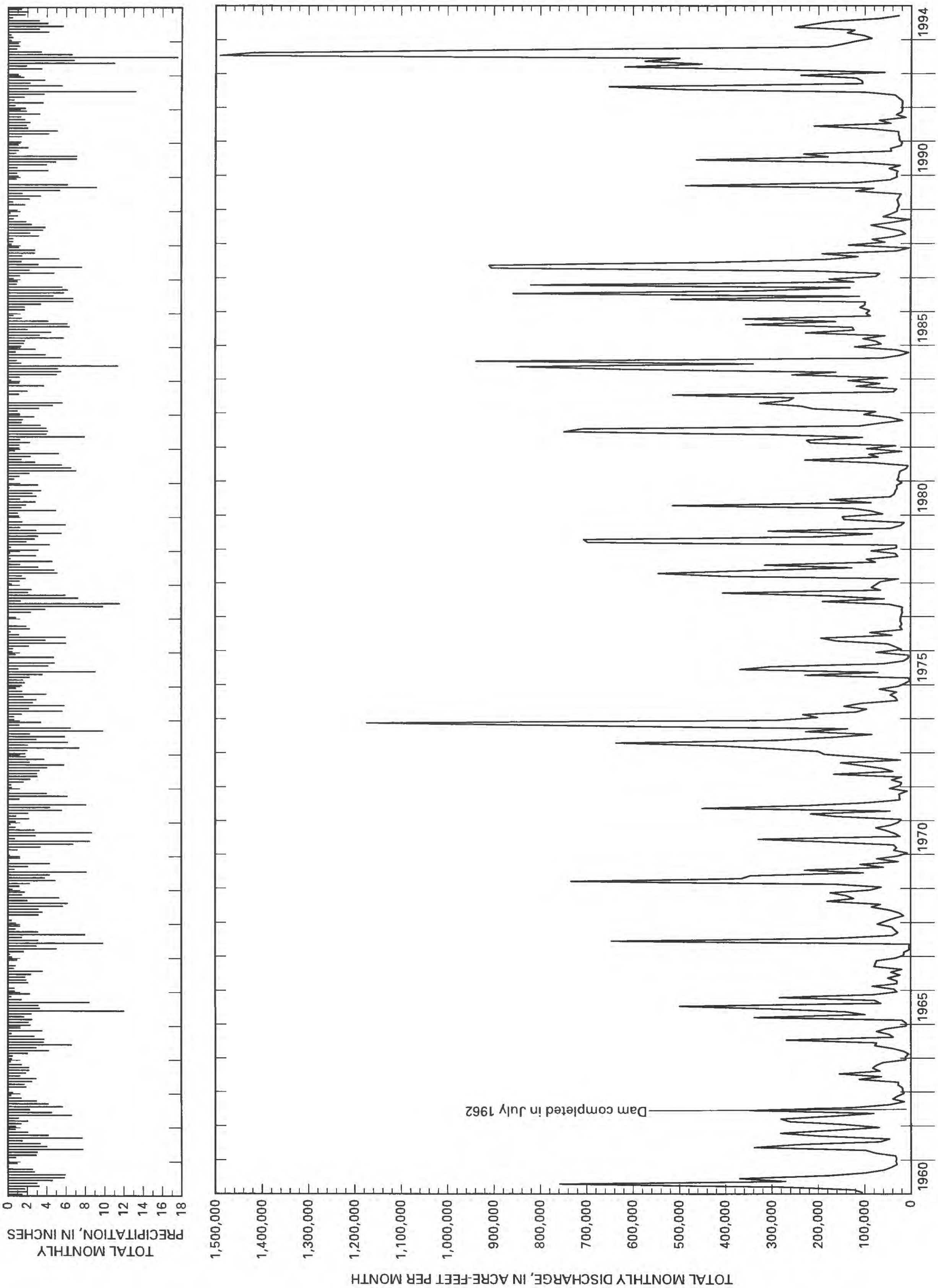


Figure 5. Total monthly precipitation at Manhattan and monthly discharge computed from daily mean discharge at Big Blue River near Manhattan surface-water-gaging station, January 1960 through September 1994 (data on file with the U.S. Geological Survey, Lawrence, Kansas).

A. May 25–26, 1993

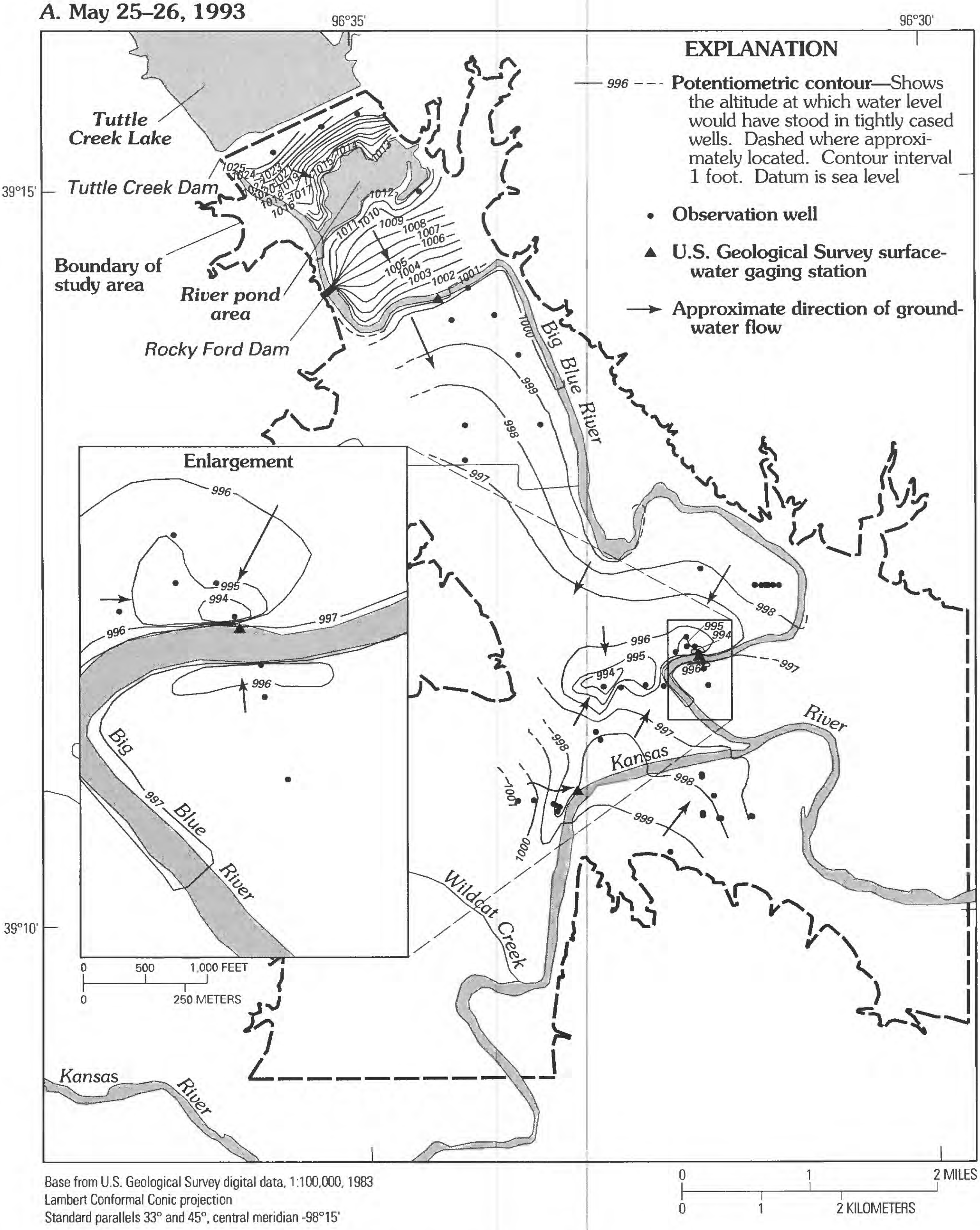


Figure 6. Potentiometric surface in alluvial aquifer for (*A*) May 25–26, 1993, and (*B*) December 7–8, 1994.

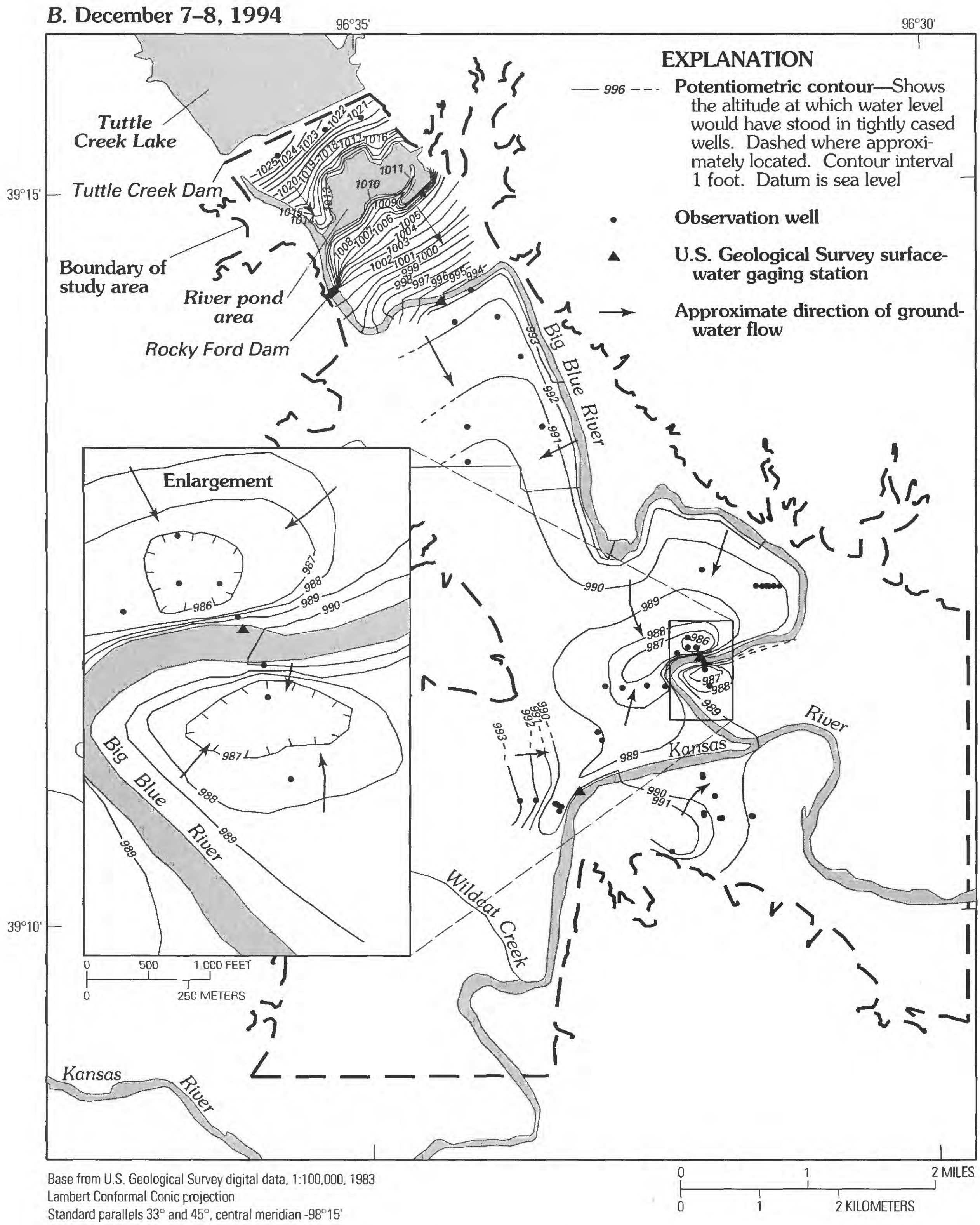


Figure 6. Potentiometric surface in alluvial aquifer for (*A*) May 25–26, 1993, and (*B*) December 7–8, 1994—Continued.

the aquifer in the area affected by pumping (fig. 6*A* and 6*B*, Manhattan municipal well field).

Ground-water levels and stream stages measured during this study indicate that the Big Blue and Kansas Rivers and alluvial aquifer near Manhattan are an integrated system. Water levels in wells near the rivers respond very quickly to and match closely changes in stream stage (fig. 7, observation well USGS–5). Water levels in wells located in the well field show more variability than wells farther from the well field because of the effects of well pumping on ground-water levels, but those more distant wells are still affected by stream stage (fig. 7, well USGS–7). Plots show that there is a strong correlation between river water-surface and ground-water-level altitudes, although more variability in ground-water-level altitude is evident for well USGS–5 (fig. 7), which is located in the well field. The correlation coefficients between river water-surface and ground-water-level altitudes are 0.86 and 0.94 for wells USGS–5 and USGS–7, respectively. Figure 7 indicates that river stage is the primary factor affecting ground-water levels in the alluvial aquifer adjacent to the river. River water may penetrate a great distance into the aquifer during rising river stage because water levels rise in response to a combination of decreases of ground-water outflow and river-water inflow. Other factors, such as pumping from the Manhattan municipal well field and elsewhere, affect ground-water levels in local areas.

Aquifer Properties

Two sources of data were used to determine hydraulic-conductivity values for the alluvial aquifer near Manhattan—

1. On the basis of 18 aquifer tests in the Kansas River Valley alluvium between Manhattan and Kansas City (Fader, 1974), hydraulic conductivity ranged from 200 to 960 ft/d. The average value was about 675 ft/d. Hydraulic conductivity for three aquifer tests conducted near Manhattan ranged from 750 to 910 ft/d (Fader, 1974).
2. During July and August 1994, the USGS conducted an aquifer test using an irrigation well (IR–8, fig. 2) near the Big Blue River. Results of this aquifer test indicate that the hydraulic conductivity was about 450 ft/d in the vicinity of the irrigation well.

Transmissivity, the product of hydraulic conductivity and saturated thickness, would vary with changes in saturated thickness. For a saturated thickness range of 36.5 to 44 ft, transmisssivity at the aquifer-test site would range from about 16,400 to 19,800 ft^2/d. Maximum transmissivity in the Manhattan area would range from about 33,200 to 40,000 ft^2/d, assuming the same range of saturated thickness.

On the basis of Fader's (1974) study, specific yield for the Kansas River alluvial aquifer between Manhattan and Kansas City ranges from 0.10 to 0.25. Fader (1974) estimated that mean specific yield is 0.15. Specific yield calculated for the aquifer test conducted during this study was 0.25.

The vertical hydraulic conductivity of the streambed and the hydraulic gradient between the stream and the aquifer are factors in stream-aquifer interchange. The vertical hydraulic-conductivity values of the streambeds of the Big Blue and Kansas Rivers were assumed to be 1 ft/d. The streambed hydraulic gradient, in feet per foot, between the stream and aquifer near the well field was determined by subtracting hydraulic head in observation well USGS–5 (adjacent to the Big Blue River) from hydraulic head in the Big Blue River and dividing by the vertical distance between the streambed and the well screen. The daily mean streambed hydraulic gradient for January through December 1994 ranged from +0.03 to +0.39 and averaged about +0.21, where positive values indicate downward flow of water from the river into the alluvial aquifer. During November 1994, the daily mean streambed hydraulic gradient ranged from +0.21 to +0.39 and averaged +0.29. Data were not available to calculate a gradient for May 1993. (May 1993 and November 1994 were times used in the model simulations). The streambed hydraulic gradients calculated at the well field are probably larger than for the rest of the Big Blue River in the study area because of the drawdown in the well field caused by pumping wells.

Water Use

Water is used primarily for municipal, agricultural, and industrial purposes within the study area (fig. 8). Ground water is the principal source of the water for all uses. Municipal supply was the primary water use and increased from about 1,700 to about 7,400 acre-ft/yr during 1960–94. Municipal water use during 1993 was about 6,233 acre-ft for all municipal wells in the study area and about 5,640 acre-ft for Manhattan municipal wells. Water used for agricultural purposes is pumped

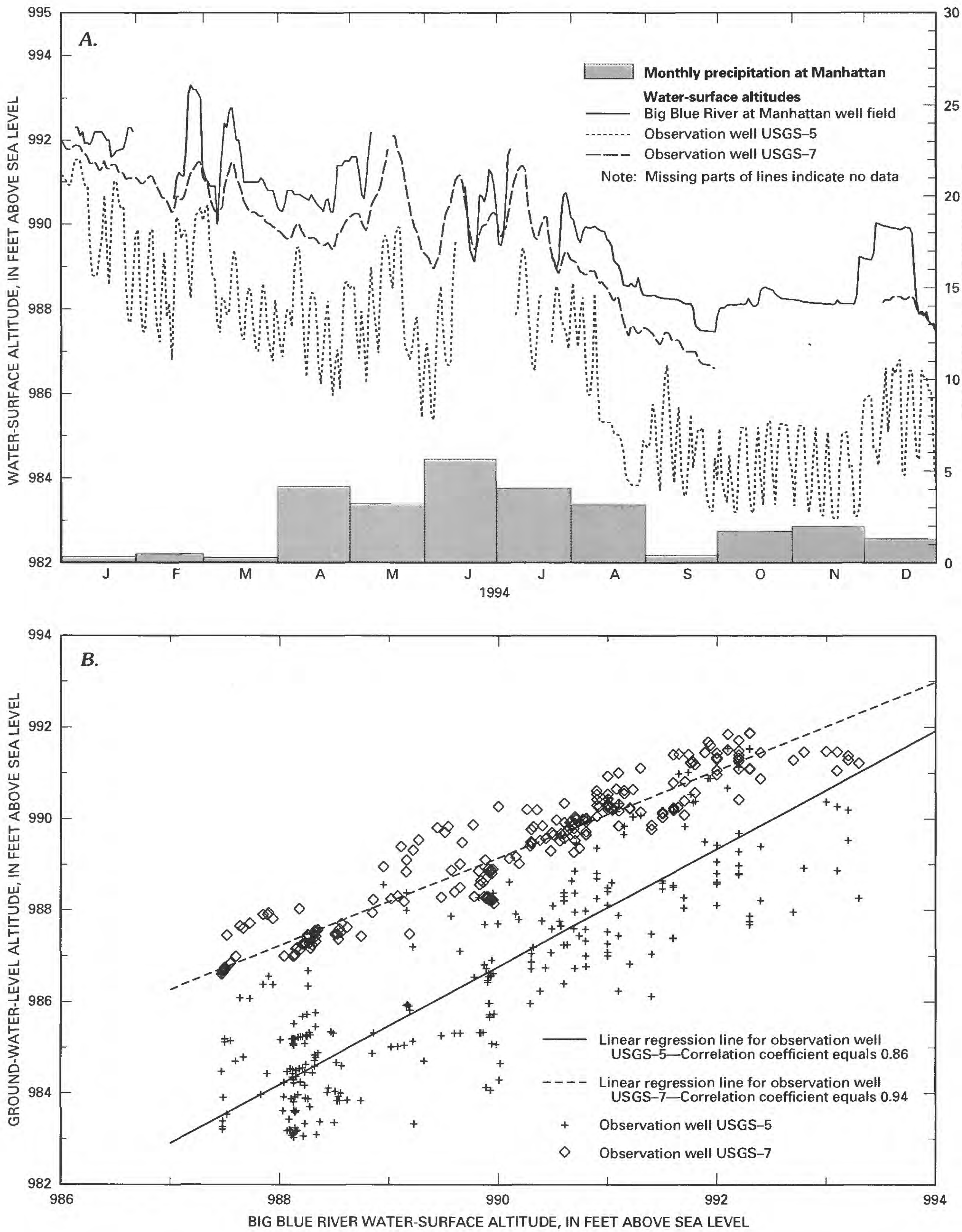


Figure 7. (*A*) Monthly precipitation, January through December 1994, and daily water-surface altitudes, and (*B*) comparison of water-surface altitudes in the Big Blue River at the Manhattan municipal well field and ground-water altitudes in observation wells USGS–5 and USGS–7. Precipitation data are from the National Oceanic and Atmospheric Administration (1993–94).

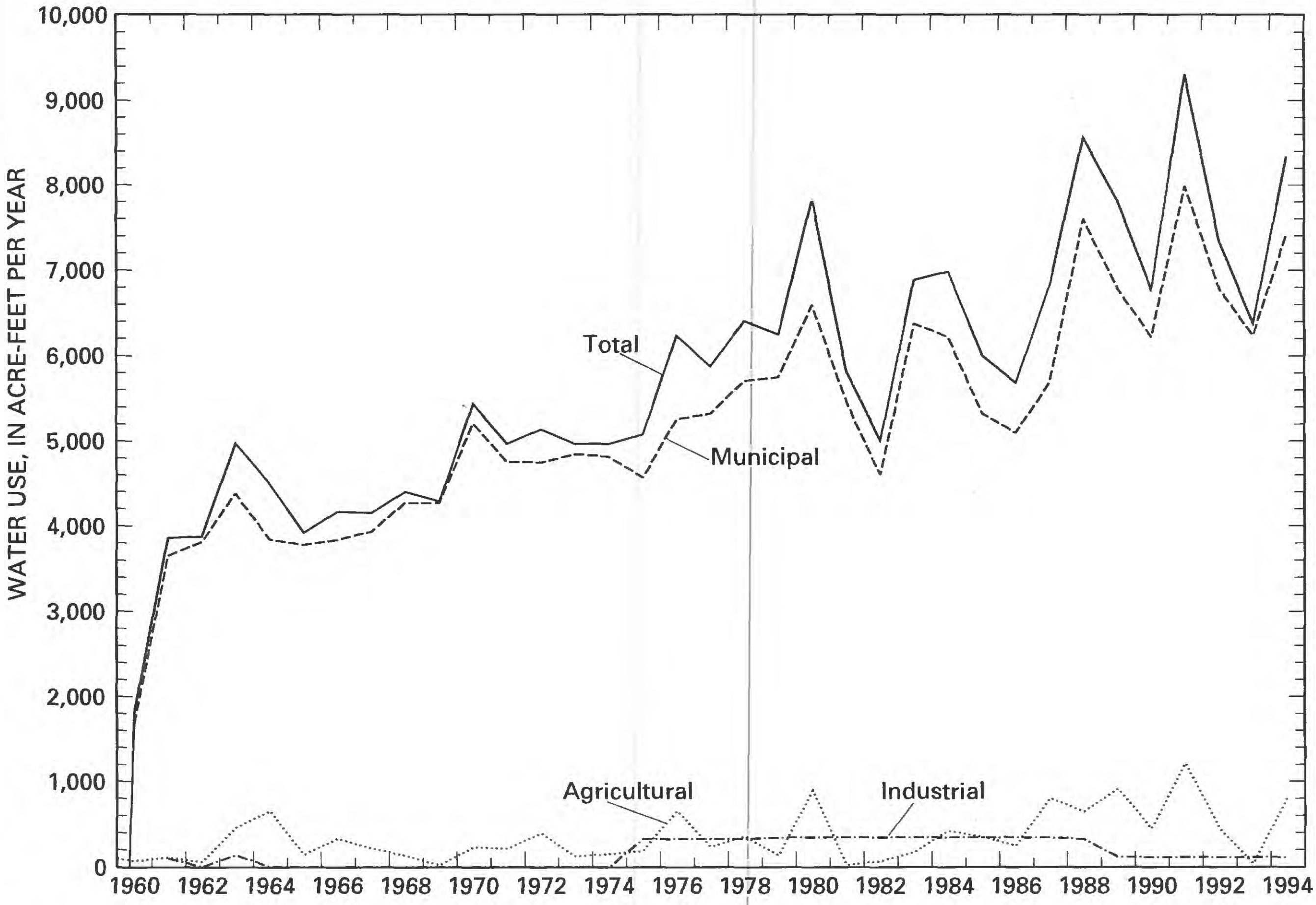


Figure 8. Reported water use in study area, 1960–94 (data from the Kansas Department of Agriculture, Division of Water Resources, Topeka, Kansas, written commun., 1995).

from the aquifer during the irrigation season, which lasts from about June through mid-September. Agricultural water use generally was less than about 600 acre-ft/yr during 1960–94, except for drier years when more water was used (fig. 8). Very little agricultural water use was reported for 1993 (about 35 acre-ft) because of the extremely wet conditions experienced that year, whereas about 800 acre-ft were reported for 1994 because of the dryer conditions that year. Industrial water use during 1960–94 was less than 400 acre-ft/yr and declined to about 110 acre-ft/yr after 1988.

Non-domestic supply wells in the study area have been allocated water according to Kansas law K.S.A. 82a–701 through 82a–733 and have been issued water-use permits by the DWR. Each permit sets the maximum allowable amount of water that may be pumped from a well or group of wells during a year. Domestic wells that are used to supply water for household or farmstead use are not required to have permits. Within the study area, the maximum allowable pumpages for municipal, agricultural, and industrial uses are 11,871, 2,793, and 1,167 acre-ft per year, respectively.

EFFECTS OF PUMPING ON STREAMFLOW

The effects of well pumping on streamflow depend on several factors, including the hydraulic conductivity of the streambed and aquifer, the saturated thickness and specific yield of the aquifer, the distance between the wells and the river, and the well-pumping rate. A decrease in streamflow due to well pumping can be computed using equations from Jenkins (1968) for wells at different distances from a stream (fig. 9). Wells close to a stream generally affect streamflow sooner and to a greater extent than wells farther from a stream (fig. 9), assuming the wells all have the same pumping rate and the pumps were turned on at the same time.

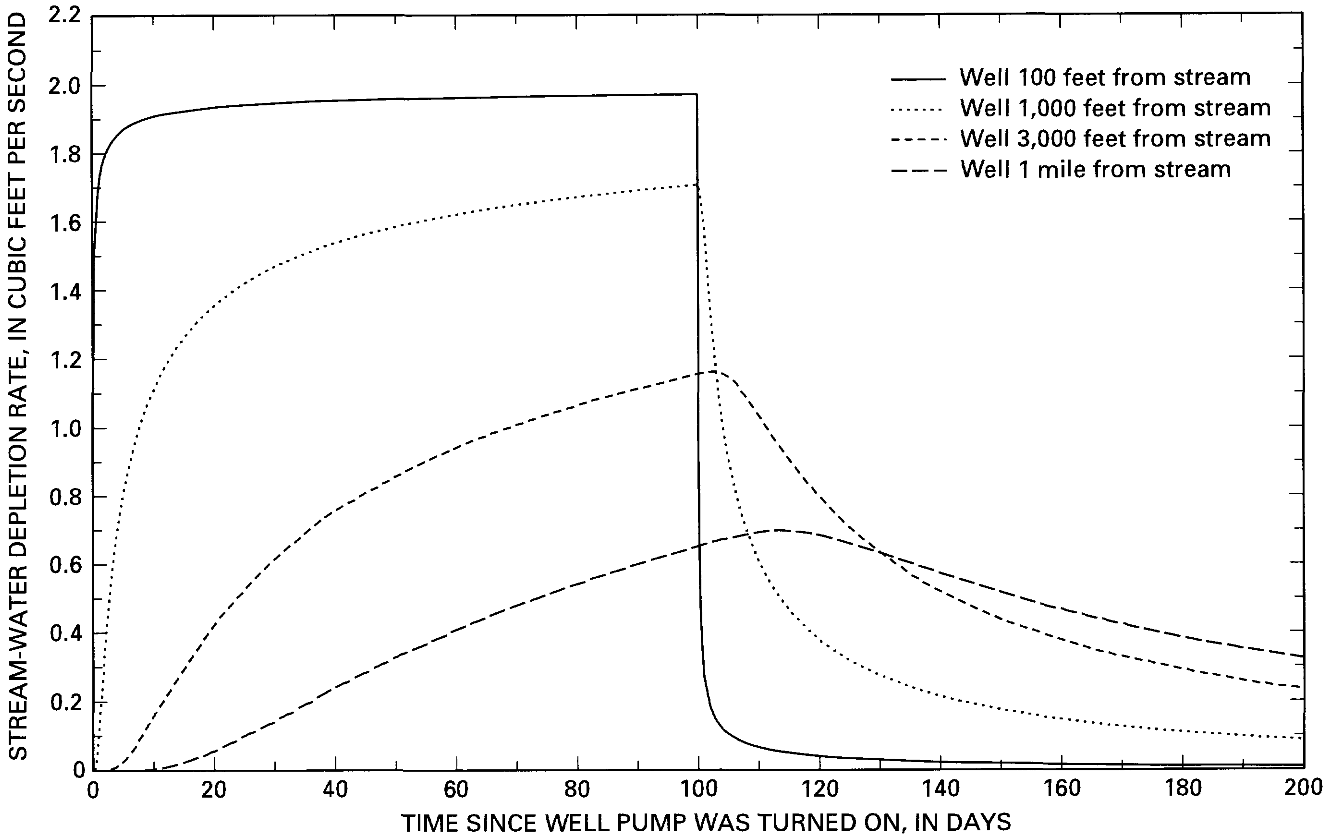


Figure 9. Hypothetical stream-water depletion rate by pumping wells that are 100, 1,000, and 3,000 feet and 1 mile from a stream, assuming hydraulic conductivity = 600 feet per day, saturated thickness = 60 feet, specific yield = 0.25, and well-pumping rate = 2 cubic feet per second (897.6 gallons per minute). The well pumps were assumed to have been turned off at 100 days.

The maximum decrease in streamflow occurs at some time after the well pumps have been turned off. The delay occurs because the drawdown effects of pumping propogate through the aquifer for a period of time after the well pump has been turned off and is longer for wells farther from the stream (fig. 9). The curves in figure 9 are examples and do not specifically apply to the Manhattan area.

A streamflow decrease may not consist entirely of water from the stream (induced infiltration) (fig. 10) but also may consist of ground water that would have become base flow in the stream under a nonpumping hydraulic gradient (intercepted base flow), or may consist entirely of intercepted base flow. Jenkins (1968, p. 3) writes:

> Both during and after pumping, some part, and at times all of stream depletion can consist of ground water intercepted before reaching the stream. Thus, a stream can be depleted over a certain reach, yet still be a gaining stream over that reach. The flow at the lower end of the reach is less than it would have been had depletion not occurred, and less by the amount of depletion.

The stream-water depletion equations (Jenkins, 1968) and curves shown in figure 9 incorporate the following assumptions:

1. Transmissivity of the aquifer does not change with time.
2. The temperature of the stream and aquifer are the same and are constant.
3. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent.
4. The stream is straight and fully penetrates the aquifer.
5. Water is released instantaneously from storage.
6. The well is open to the full saturated thickness of the aquifer.
7. The pumping rate is steady.

Departure from these assumptions and other factors, such as ground-water recharge from precipitation and

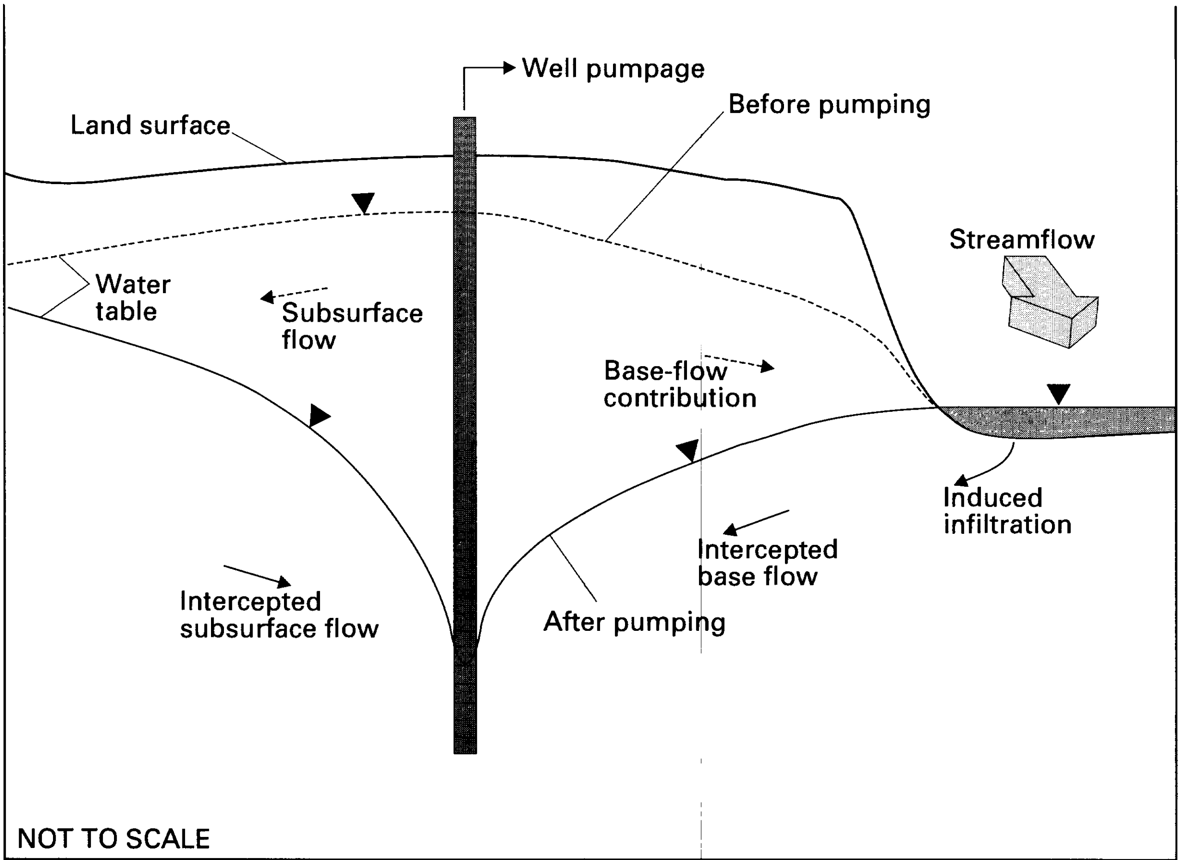


Figure 10. Ground- and surface-water components that make up well pumpage and streamflow decrease caused by pumping.

lateral ground-water flow or ground-water discharge from evapotranspiration, will cause variations from the calculated stream-water depletion. A more comprehensive analysis of stream-water depletion and the effects of aquifer recharge and discharge may be made by use of conceptual and digital ground-water flow models.

Conceptual Ground-Water Flow Model

A conceptualization of the ground-water flow system of the area to be studied (conceptual ground-water flow model) is developed prior to construction of a digital ground-water flow model to ensure that available hydrologic information is integrated to develop an understanding of the system. The area of the model for this study is a 11.38-mi^2 part of the study area. The model area extends downstream from where the Big Blue River cuts from west to east across its valley in the northern part of the study area and, on the Kansas River, from about 4 mi upstream from the junction with the Big Blue River to about 2 mi downstream from the junction. Within this area, the alluvial aquifer was conceptualized as an unconfined aquifer with boundaries, recharge, and discharge as discussed in the following sections.

Boundaries of Aquifer

Except for the upstream and downstream edges of the area, the alluvial aquifer near Manhattan is underlain and laterally bounded by relatively impermeable bedrock, generally comprised of shale and limestone. Flow of ground water across the bedrock boundary is assumed to be relatively small.

Recharge to or Discharge From Aquifer

The major sources of recharge (in this report, recharge equals precipitation that infiltrates the land surface minus evapotranspiration) to the aquifer in the conceptual model are precipitation, subsurface inflow, seepage from streams, and agricultural and urban water applications. The major sources of discharge from the aquifer in the conceptual model are subsurface outflow, pumping, and base flow to streams. Evapotranspiration directly from below the water table was considered to be insignificant. A conceptual model area water budget is summarized in table 2. Parts of the following discussion focus on May 1993 and October 16 through November 14, 1994, conditions because these periods were selected for digital-model simulations (discussed later in report).

Recharge from precipitation is water that reaches the water table through the unsaturated zone and adds water to the alluvial aquifer. The amount of recharge depends on the rate and duration of precipitation, the rate of potential evapotranspiration, and the moisture capacity of the soil zone. On the basis of a study by Dugan and Peckenpaugh (1985), the mean annual ground-water recharge is 2 to 5 in/yr (6 to 15 percent of the mean annual precipitation at Manhattan) in central Kansas. There exists a close relation between precipitation and recharge, and this relation becomes approximately linear for mean annual precipitation exceeding 30 in. (Dugan and Peckenpaugh, 1985). Mean annual precipitation at Manhattan is 32.88 in. (National Oceanic and Atmospheric Administration, 1993–94). Within the conceptual model area, therefore, mean annual recharge from precipitation is estimated to range from about 1.7 to 4.2 ft^3/s (2 to 5 in/yr). Recharge may vary depending on seasonal climatic conditions and the activity of plant transpiration. Thus, recharge may be larger during cool or rainy months when there is less evaporation and plant transpiration or more available water, and smaller during hot months when there is more evaporation and plant transpiration. During May 1993 (rainy month) and October 16 through November 14, 1994 (cool month), precipitation totaled 10.99 and 0.48 in., respectively. Assuming that recharge from precipitation during these months was at the high end of the 6- to 15-percent range, recharge from precipitation within the conceptual model area would have been about 16.3 ft^3/s for May 1993 and about 0.7 ft^3/s for October 16 through November 14, 1994 (table 2).

Subsurface inflow to the aquifer in the conceptual model area occurs in the Big Blue and Kansas River Valleys at the upstream (parts of northwest and southwest) edges of the area. Subsurface outflow from the aquifer in the conceptual model area occurs in the Kansas River Valley at the downstream (southeast) edge of the area. Subsurface ground-water inflow and outflow

Table 2. Water budget for area of conceptual ground-water flow model

[Values, in cubic feet per second, are rounded to the nearest 0.1]

Budget item	May 1993			October 16 through November 14, 1994		
	Aquifer recharge	Aquifer discharge	Net (recharge minus discharge)	Aquifer recharge	Aquifer discharge	Net (recharge minus discharge)
Recharge from precipitation	16.3	0	16.3	0.7	0	0.7
Subsurface inflow (recharge) and outflow (discharge)	17.3	2.2	15.1	2.3	1.0	1.3
Seepage from Big Blue River	20.5	0	20.5	7.7	0	7.7
Seepage from Kansas River	19.3	0	19.3	6.4	0	6.4
Manhattan municipal wells	0	7.0	-7.0	0	8.5	-8.5
Agricultural wells	0	0	0	0	0	0
Industrial wells	0	.2	-.2	0	.2	-.2
Change in aquifer storage		**Added to storage**			**Added to storage**	
		64.0			7.4	

rates were estimated using Darcy's law expressed by equation 1 below:

$$Q_{sub} = \frac{K}{86{,}400} A \frac{dh}{dl}, \quad (1)$$

where

Q_{sub} is the subsurface flow into or out of the aquifer, in cubic feet per second;

K is the hydraulic conductivity of the aquifer, in feet per day;

86,400 is used to convert from days to seconds;

A is the cross-sectional area of the aquifer that is saturated, which changes with ground-water level, in square feet; and

$\frac{dh}{dl}$ is the ground-water hydraulic gradient (dimensionless), which was estimated from the potentiometric-surface maps for May 25–26, 1993, and December 7–8, 1994 (figs. 6*A* and 6*B*).

The net subsurface flow is the difference between subsurface inflow and subsurface outflow. On the basis of parameter values listed in table 3, the subsurface inflow was 17.3 ft^3/s and subsurface outflow was 2.2 ft^3/s for May 1993, and the subsurface inflow was 2.3 ft^3/s and subsurface outflow was 1.0 ft^3/s for October 16 through November 14, 1994 (table 2). Therefore, the net subsurface flow for May 1993 was 15.1 ft^3/s (into the system) and for October 16 through November 14, 1994, was 1.3 ft^3/s (into the system).

Stream seepage between the alluvial aquifer and the Big Blue and Kansas Rivers depends on river stages, ground-water levels, streambed vertical hydraulic conductivity, thickness of the streambed, and other factors, such as pumping and agricultural water applications. An estimate of seepage was based on Darcy's law (equation 1), in which A is average water-surface area (channel width x length), K is streambed vertical hydraulic conductivity, and $\frac{dh}{dl}$ is hydraulic gradient across the streambed.

On the basis of parameter values listed in table 4, the calculated seepage from the Big Blue River was about 20.5 ft^3/s for May 1993 and about 7.7 ft^3/s for October 16 through November 14, 1994 (table 2). The calculated seepage from the Kansas River was 19.3 ft^3/s for May 1993 and 6.4 ft^3/s for October 16 through November 14, 1994 (table 2). The streambed hydraulic gradient values used in these calculations are in the range of those observed for well USGS–5.

Municipal pumpage data obtained from the city of Manhattan include pumping rate, hours of operation for each well, and daily discharges for each well. There were 16 municipal wells in operation during 1993. The mean pumping rate (all wells) for 1993 was 7.8 ft^3/s; for May 1993, 7.0 ft^3/s; and for October 16 through November 14, 1994, 8.5 ft^3/s. Well-permit data obtained from DWR indicate that the maximum

Table 3. Parameter values for subsurface inflow and outflow calculations for the conceptual model area

[NA, not applicable]

Parameter	Big Blue River Valley: May 1993	Big Blue River Valley: October 16 through November 14, 1994	Kansas River Valley: May 1993	Kansas River Valley: October 16 through November 14, 1994
Hydraulic conductivity, in feet per day	650	650	650	650
Inflow cross-sectional area, in square feet	182,585	127,016	387,412	299,000
Outflow cross-sectional area, in square feet	NA	NA	294,329	238,049
Inflow hydraulic gradient (dimensionless)	.002	.0001	.005	.001
Outflow hydraulic gradient (dimensionless)	NA	NA	.001	.0005

Table 4. Parameter values for stream-seepage calculations for the conceptual model area

Parameter	Big Blue River: May 1993	Big Blue River: October 16 through November 14, 1994	Kansas River: May 1993	Kansas River: October 16 through November 14, 1994
Streambed vertical hydraulic conductivity, in feet per day	1	1	1	1
Channel length, in feet	44,200	44,200	27,800	27,800
Channel width, in feet	200	150	300	200
Streambed hydraulic gradient (dimensionless)	.2	.1	.2	.1

allowable amount of water that may be pumped from all 16 of the Manhattan municipal wells is about 14.8 ft^3/s (10,740 acre-ft/yr, table 5).

Well-permit data show that the maximum allowable pumpage rate for non-Manhattan municipal, agricultural, and industrial wells in the conceptual model area is 3.3 ft^3/s (2,395 acre-ft/yr, table 5). On the basis of data obtained from DWR about 35 acre-ft of agricultural and 111 acre-ft of industrial water use within the conceptual model area were reported for 1993, and about 805 and 111 acre-ft, respectively, were reported for 1994. Only water for industrial use, 0.2 ft^3/s, would have been pumped during May 1993 or October–November 1994.

Agricultural and urban water applications probably do not contribute much to ground-water recharge. Dugan and Peckenpaugh's (1985) data show that agricultural applications generally do not exceed crop consumptive (evapotranspiration) requirements. For urban water applications, it also was assumed that application amounts to lawns did not exceed grass consumptive requirements.

On the basis of the preceding discussion, total recharge to the conceptual model area during May 1993 was estimated to be 73.4 ft^3/s, and total discharge was estimated to be 9.4 ft^3/s. For October 16 through November 14, 1994, total recharge was estimated to be 17.1 ft^3/s, and discharge was estimated to be 9.7 ft^3/s. Therefore, 64.0 ft^3/s was added to aquifer storage during May 1993, and 7.4 ft^3/s was added aquifer storage during October–November 1994 (table 2).

Digital Ground-Water Flow Model

A modular, three-dimensional, finite-difference, ground-water flow model (MODFLOW) (McDonald and Harbaugh, 1988) was used to simulate the aquifer and the response of the stream-aquifer system. The alluvial aquifer near Manhattan was represented in this study by steady-state and transient, one-layer, ground-water flow simulations. For steady-state simulations, the magnitude and direction of ground-water flow, the hydraulic head, and aquifer storage are constant with time. For transient simulations, the magnitude and direction of ground-water flow, hydraulic head, and aquifer storage may change with time.

Geometry and Boundary Conditions

In the finite-difference flow model, the aquifer was represented by an array of nodes and associated finite-difference blocks (cells). The finite-difference grid was 42 columns by 60 rows of cells, each with a cell size of 500 by 500 ft (fig. 11). The valley boundary, which corresponds in part to the boundary of the study area (fig. 11), represents the physical edge of the alluvial aquifer.

Several different kinds of cells were used in the model to represent different boundary or flow conditions (fig. 12). No-flow cells are inactive cells that represent boundaries, such as relatively impermeable bedrock or a ground-water flow divide, where the flux across the boundary is zero. In the model, no-flow cells were used to represent the physical edge of the alluvial aquifer. General flow cells are active model cells with no specialized boundary conditions. General-head cells are active cells that were used to represent the

Table 5. Maximum allowable pumpage for non-domestic supply wells in model area

[More than one well may be associated with a DWR permit number, and more than one permit number may be associated with one well. Data from Kansas Department of Agriculture, Division of Water Resources (DWR), Topeka, Kansas]

Map no. (fig. 11)	DWR permit number	Maximum allowable pumpage, in acre-feet per year	Use of water
MM–5, MM–6, M–8, MM–10 through MM–22	A01635300, VPT002100, A03782600, A04098200-8800	10,740	municipal (Manhattan)
M–8	A01893400	7	municipal
M–5	A03925000	90	municipal
M–6, M–7	A03960500	91	municipal
M–3, M–4	A04015400	4	municipal
M–1, M–2	A04023500	3	municipal
IR–2, IR–4, IR–5	A00300000	596	agricultural
IR–7	A00995800	47	agricultural
IR–8	A01122000	100	agricultural
IR–11	A01168300	66	agricultural
IR–13	A01268600	77	agricultural
IR–14	A01299000	13	agricultural
IR–1	A03090800	3	agricultural
IR–15	A03075400	79	agricultural
IR–12	A03854100	145	agricultural
IR–13	A03854200	97	agricultural
IR–9, IR–10	A03884400	148	agricultural
IR–3	A03940000	199	agricultural
IR–6	A04002400	163	agricultural
IN–3	A03832300	20	industrial
IN–1, IN–2	VRL001300	429	industrial
IN–4	VRL001500	18	industrial

hydraulic connection between the model and the laterally adjacent alluvial aquifer. The hydraulic head in general-head cells changes during model stress periods. The simulated ground-water system may induce flow into or out of the model across a general-head boundary through the external source. Flow into or out of these cells is unlimited. Stream cells are active cells that are used to simulate water flow through the streambed between the streams and the alluvial aquifer. In stream cells, the simulated streamflow is tracked and is used to calculate stream stage and streamflow gain or loss for each cell (Prudic, 1989). Stream cells were used to represent both the Big Blue and Kansas Rivers. Pumping cells are active cells that allow pumpage out of the simulated aquifer at these cell locations. In this model, pumping cells are used to simulate pumpage from municipal wells. Model simulations of pumpage yield results for these cells as if all pumping wells within the cell were combined into one well located at the center of the cell.

Aquifer Properties

To use a grid-based model, aquifer properties are assigned to each model cell. For a one-layer, unconfined, steady-state model of the flow system, the values of hydraulic conductivity and the top of the bedrock-surface altitudes underlying the aquifer are needed for each cell. For a one-layer transient model, specific yield also is needed. For stream cells, the streambed vertical hydraulic conductivity and thickness of the streambed are needed. The ranges of values of these properties are discussed in the earlier "Aquifer Properties" section of this report. To simplify the steady-state and transient models, hydraulic properties were assumed to be relatively uniformly distributed. In the model, the hydraulic conductivity was 650 ft/d, the specific yield was 0.20, and the streambed hydraulic conductivity was 1 ft/d, and the streambed thickness was 1 ft for both the Big Blue and the Kansas Rivers. These values were arrived at through the calibration process (see "Calibration of Model to May 1993 Conditions").

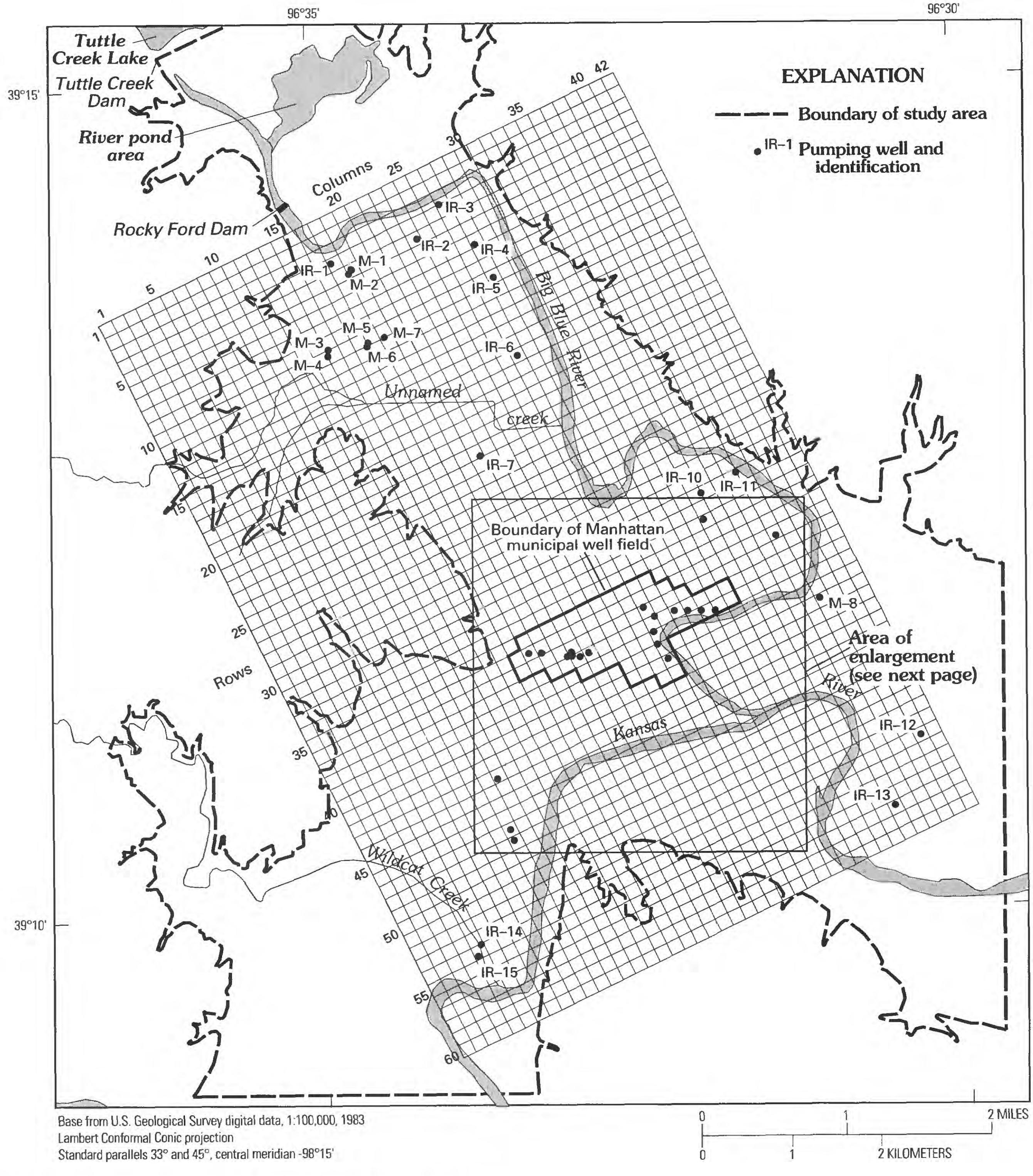


Figure 11. Areal extent and dimensions of digital model.

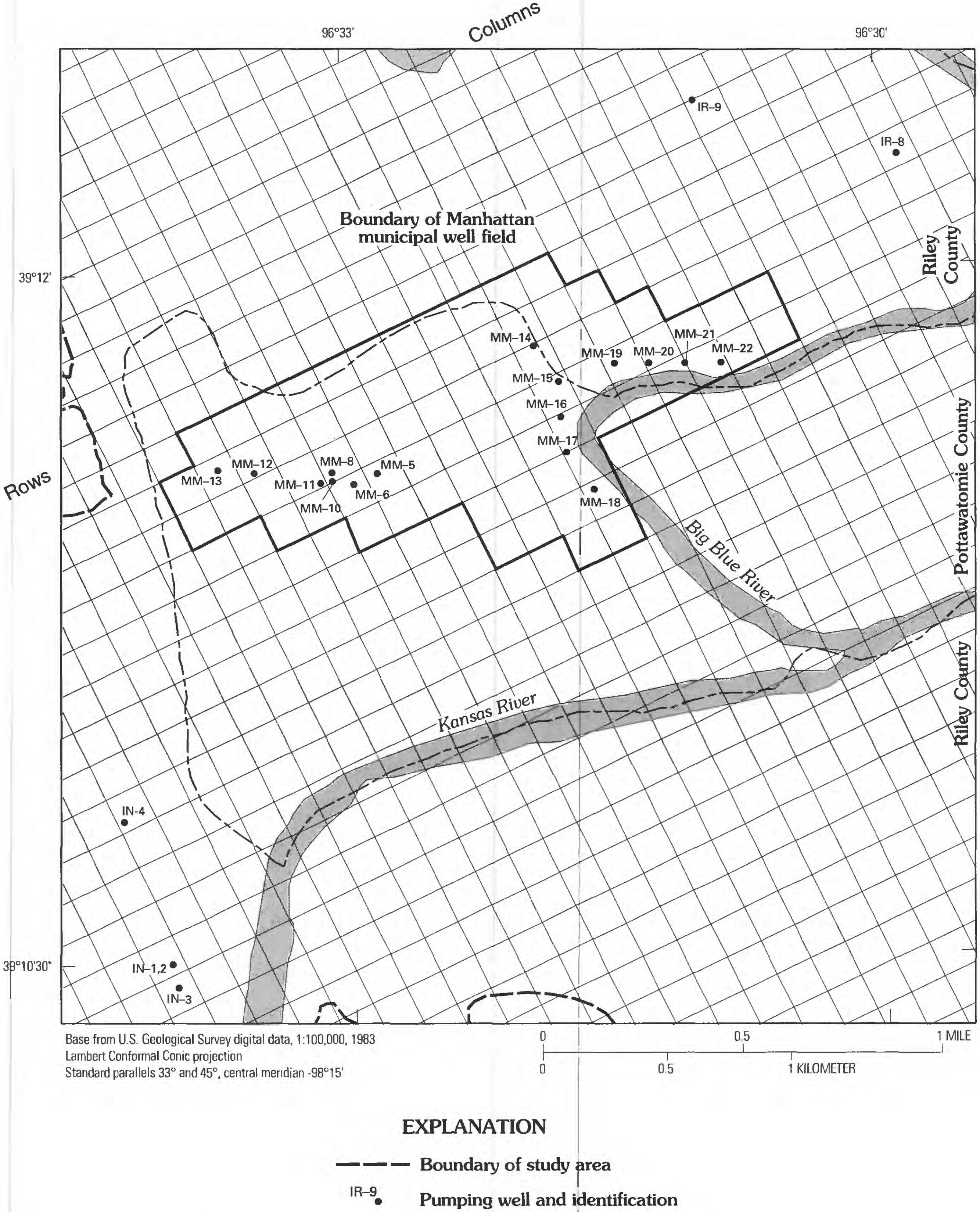


Figure 11. Areal extent and dimensions of digital model—Continued.

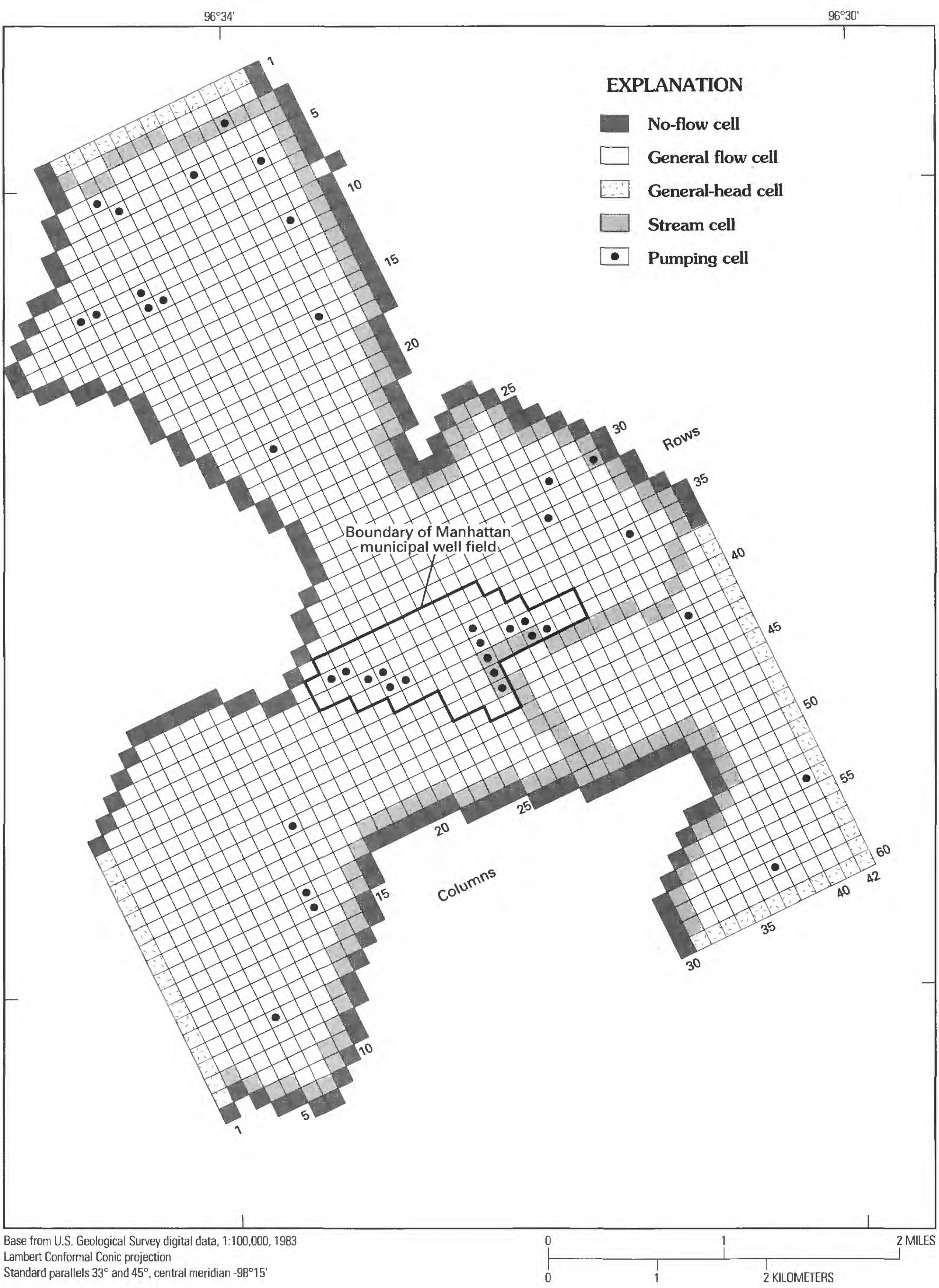


Figure 12. Model cells and boundary conditions.

Types and Locations of Stresses

Several kinds of stresses were simulated by MODFLOW for the model. Stresses, as used in this report, are forces external to the ground-water system that affect ground-water levels and movement. These stresses included recharge from precipitation, pumpage for municipal, agricultural, and industrial uses, and streamflows in the Big Blue and Kansas Rivers.

Precipitation was assumed to be uniformly distributed for each cell over the entire model area. The recharge rate for May 1993 and for October 16 through November 14, 1994, was assumed to be 15 percent of precipitation, 10.99 and 0.48 in., respectively. Daily precipitation values observed at Manhattan were used for model calibration and verification (figs. 13*A* and 14*A*). For hypothetical simulations, recharge (4.93 in.) was based on 15 percent of the long-term mean precipitation observed at Manhattan (32.88 in/yr).

The model cells where pumping wells were simulated in the model are shown in figure 12. In this study, the Manhattan municipal well-field mean daily pumpage reported for May 1993 (fig. 13*B*) and October 16 through November 14, 1994 (fig. 14*B*), were used for calibration of and verification of the model, respectively (see the following section). The mean Manhattan municipal well-field pumpage of 7.8 ft^3/s for 1993 and maximum allowable pumpage of 14.8 ft^3/s were used for hypothetical simulations.

The mean daily streamflows measured at the Big Blue River near Manhattan surface-water-gaging station (figs. 13*C* and 14*C*) and stream stages measured at the Big Blue River at Manhattan municipal well field and at the Kansas River at Manhattan surface-water-gaging stations were used for model calibration and verification. The slopes of the stream-surface profile for the Big Blue and Kansas Rivers were estimated on the basis of stream stages from these gaging stations. The slopes were used to assign river stages to model stream cells. For hypothetical model simulations, stream discharges for the Big Blue River ranged from 100 to 10,000 ft^3/s, and the stream slope for the Big Blue River was estimated by computing the median of daily slopes between observed river stages at the Big Blue River gaging stations for 1993 and 1994. The mean slope was 0.000092 for the Big Blue River. The only slope available for the Kansas River, 0.004, was calculated on the basis of a level survey of the altitude of the Kansas River surface on January 6, 1994, between the Kansas River at Manhattan gaging station and the junction of the Big Blue and Kansas Rivers.

Calibration of Model to May 1993 Conditions

To use the model as a simulative tool for the stream-aquifer system near Manhattan, it was necessary to demonstrate that the model was capable of reproducing measured ground-water altitudes. Model calibration was accomplished by identifying a set of aquifer properties, boundary conditions, and stresses such that simulated hydraulic heads matched measured values within a reasonable range of error. Several comparisons were made during the calibration process among measured and simulated potentiometric surfaces, river-surface altitudes, and ground-water altitudes for selected observation wells. Comparisons of measured and simulated fluxes, such as stream-seepage rates, are also desirable for model calibration; however, no stream-seepage measurements were attempted because of the large streamflows and high water conditions that existed during most of the study.

In this study, the model calibration process involved numerous trial simulations in which values of hydraulic conductivity, specific yield, and streambed vertical hydraulic conductivity, and recharge were adjusted within reasonable hydrologic limits. The initial hydraulic-conductivity value used in the model was 600 ft/d. The final value, arrived at through trial and error, was 650 ft/d. The initial specific yield used was 0.20. Other values were tried, but 0.20 gave the most satisfactory results. The initial value of streambed vertical hydraulic conductivity was 1 ft/d, which produced satisfactory results. Recharge was varied during calibration from 10 to 20 percent of precipitation, but 15 percent of precipitation gave the most satisfactory results.

Determination of Initial Hydraulic Heads

For the transient model simulation of May 1993 conditions, initial hydraulic heads were specified for each model cell in a two-step process. First, a steady-state model simulation using transient model aquifer parameters and the mean precipitation and streamflow conditions and mean pumping rates for April 1993 was used to specify a set of starting hydraulic heads. Second, these heads were adjusted up or down in local areas to more closely match measured hydraulic heads in observation wells and to minimize aquifer-storage changes resulting from differences in

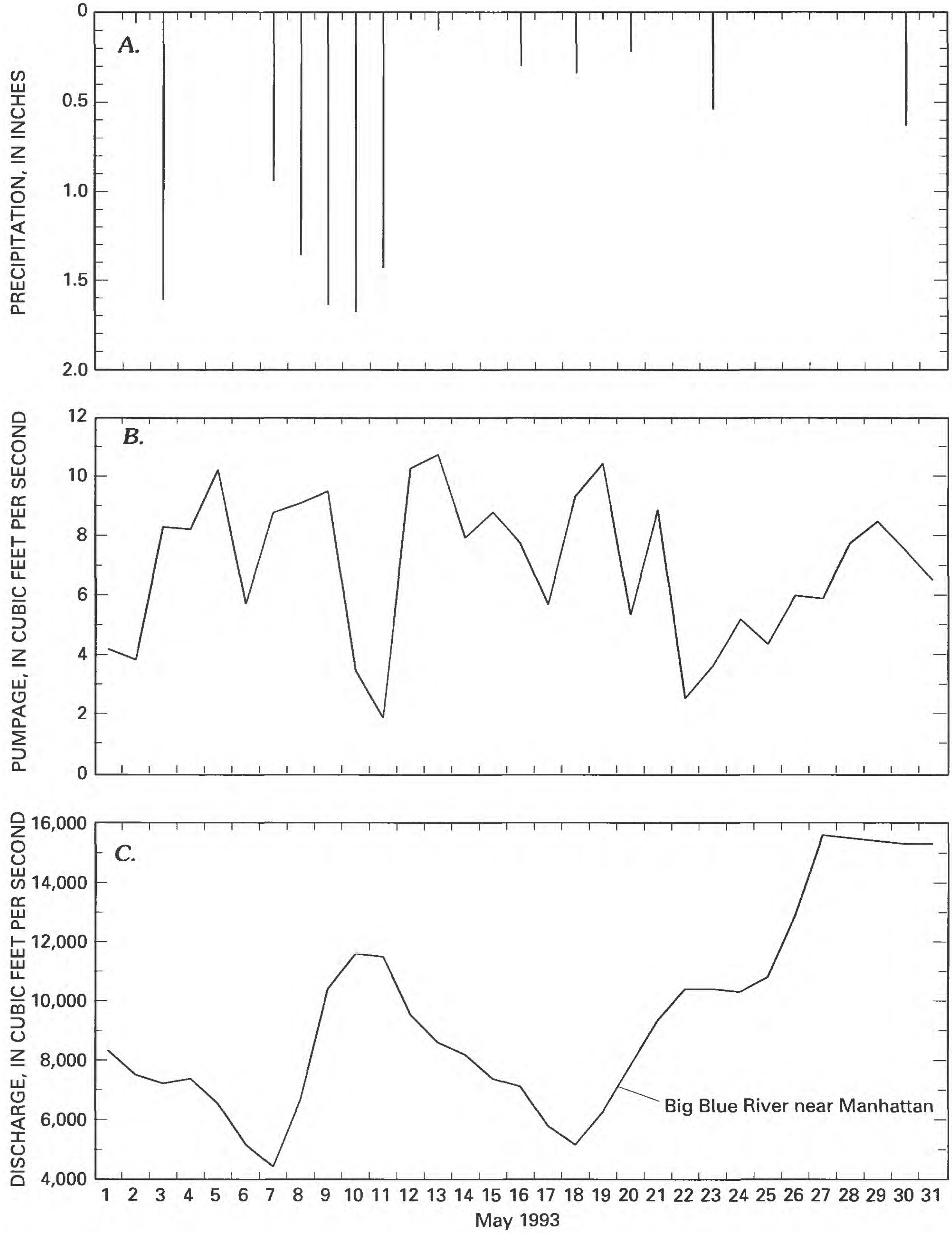


Figure 13. Measured (*A*) precipitation at Manhattan (National Oceanic and Atmospheric Administration, 1993–94), (*B*) pumpage from the Manhattan municipal well field (data from city of Manhattan), and (*C*) discharge for the Big Blue River near Manhattan surface-water-gaging station, May 1993.

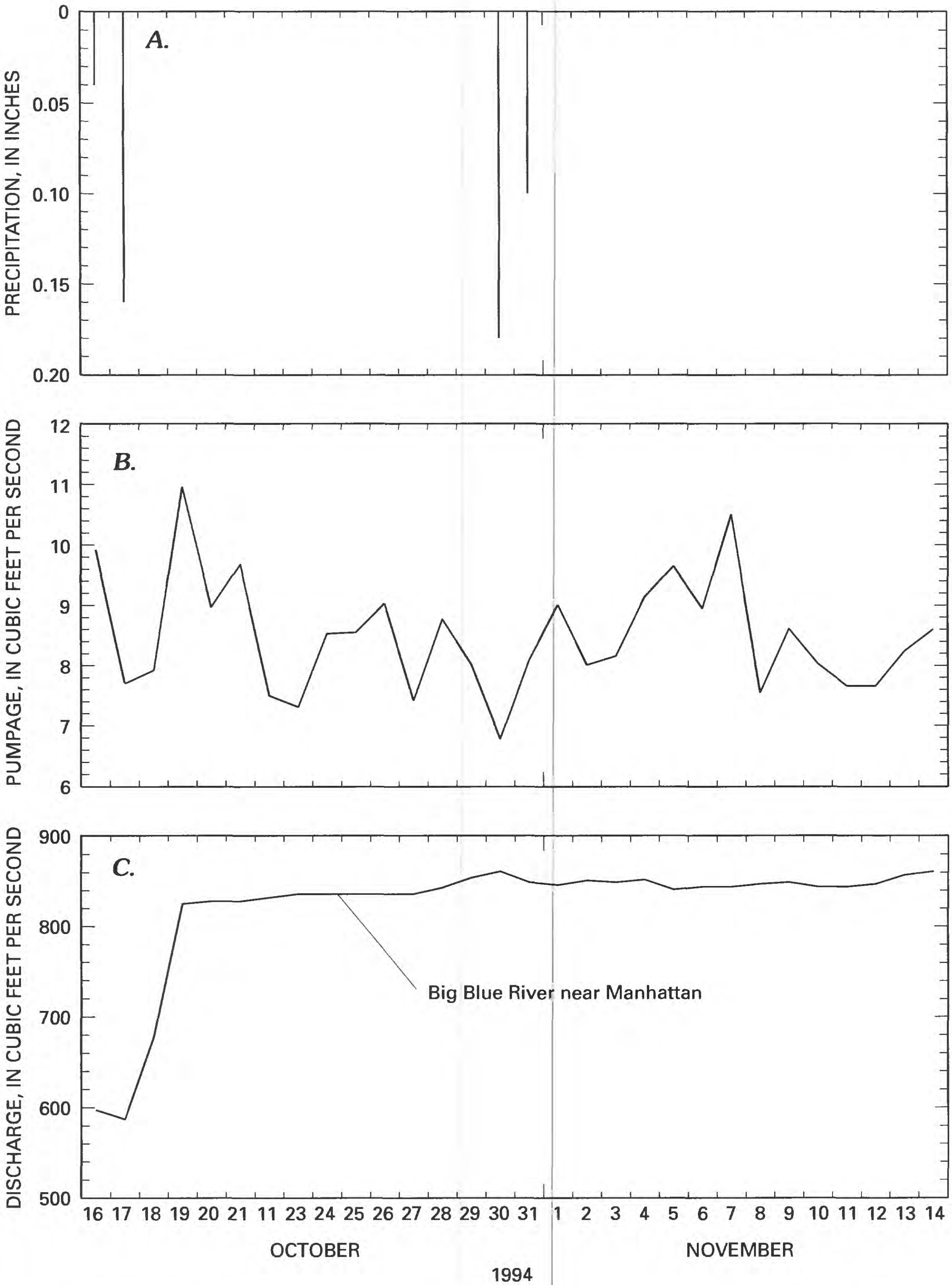


Figure 14. Measured *(A)* precipitation at Manhattan (National Oceanic and Atmospheric Administration, 1993–94), *(B)* pumpage from the Manhattan municipal well field (data from city of Manhattan), and *(C)* discharge for the Big Blue River near Manhattan surface-water-gaging station, October 16 through November 14, 1994.

hydraulic heads generated by the steady-state and transient simulations. (The head adjustment was 1 ft or less.)

Comparison of Measured to Simulated Potentiometric Surfaces and Hydraulic Heads

Several comparisons were made during the calibration process between measured and simulated potentiometric surfaces for May 25–26, 1993 (fig. 15), and the measured and simulated ground-water altitudes for selected observation wells (fig. 16). Final parameter values for the calibrated transient model characterizing the stream-aquifer system are summarized in table 6. Simulated ground-water altitudes generally match measured ground-water altitudes in terms of shapes and altitudes. The differences between measured and simulated values in an observation well can be expressed as the root mean square error (RMSE), which is given by:

$$RMSE = \left(\frac{\sum_{i=1}^{31} (Z_i - \hat{Z}_i)^2}{31} \right)^{\frac{1}{2}}, \qquad (2)$$

where

Z_i is the measured ground-water altitude, in feet above sea level;

$\hat{Z}_i$ is the simulated ground-water altitude, in feet above sea level; and

i is the day index.

The RMSE for four selected observation wells (wells USGS–2, USGS–4, USGS–7, and USGS–10) along with other statistics are summarized in table 7.

Comparison of Simulated and Conceptual Model Water Budgets

A simulated water budget for the entire model area for the May 1993 transient model simulation is given in table 8. Both Big Blue River and Kansas River provided seepage into the aquifer to offset well pumpage and increases in ground-water storage (shown as negative number in table 8 because addition to storage is considered to be outflow from the digital and conceptual models). Table 8 also shows a comparison of the simulated and conceptual difference between recharge and discharge.

Simulated Streamflow Decrease Induced by Municipal Well-Field Pumping

Transient model simulations without and with pumping, and climatic conditions of May 1993, were used to simulate streamflow decreases in the Big Blue and Kansas Rivers and ground-water-altitude changes induced by the pumping of Manhattan municipal wells. The daily streamflow decrease for the Big Blue River for without-pumping and with-pumping simulations (fig. 17*A*) shows that pumping increased the amount of streamflow loss. The monthly mean streamflow decrease was 24.68 ft^3/s without pumping and 29.48 ft^3/s with pumping. Figure 17*B* shows the net daily streamflow decrease, the induced infiltration, and the intercepted base flow resulting from pumping. The net streamflow decrease in figure 17*B* equals the streamflow decrease with pumping minus the streamflow decrease without pumping in figure 17*A*. The monthly mean net streamflow decrease was about 4.80 ft^3/s, and the monthly mean induced infiltration and intercepted base flow were about 2.93 and 1.87 ft^3/s, respectively. At the end of the simulation period, the cumulative net streamflow decrease for May 1993 caused by pumping was about 295 acre-ft, of which induced infiltration was about 180 acre-ft, or about 61 percent of the net streamflow decrease, and intercepted base flow was about 115 acre-ft, or about 39 percent of the net streamflow decrease (fig. 17*C*).

The daily streamflow decrease for the Kansas River for without-pumping and with-pumping simulations (fig. 18*A*) shows that pumping had much less effect on the amount of streamflow loss from the Kansas River than from the Big Blue River. The monthly mean streamflow decrease was 13.59 ft^3/s with pumping and 13.11 ft^3/s without pumping. Figure 18*B* shows the net daily and monthly mean streamflow decrease and the induced infiltration and intercepted base flow resulting from pumping. The net monthly mean streamflow decrease was 0.48 ft^3/s, and the monthly mean induced infiltration and intercepted base flow were 0.29 and 0.19 ft^3/s, respectively. At the end of the simulation period, the cumulative net streamflow decrease for May 1993 caused by pumping was about 30 acre-ft, of which induced infiltration was about 18 acre-ft, or about 60 percent of the cumulative net streamflow decrease, and intercepted base flow was about 12 acre-ft, or about 40 percent of the cumulative net streamflow decrease (fig. 18*C*).

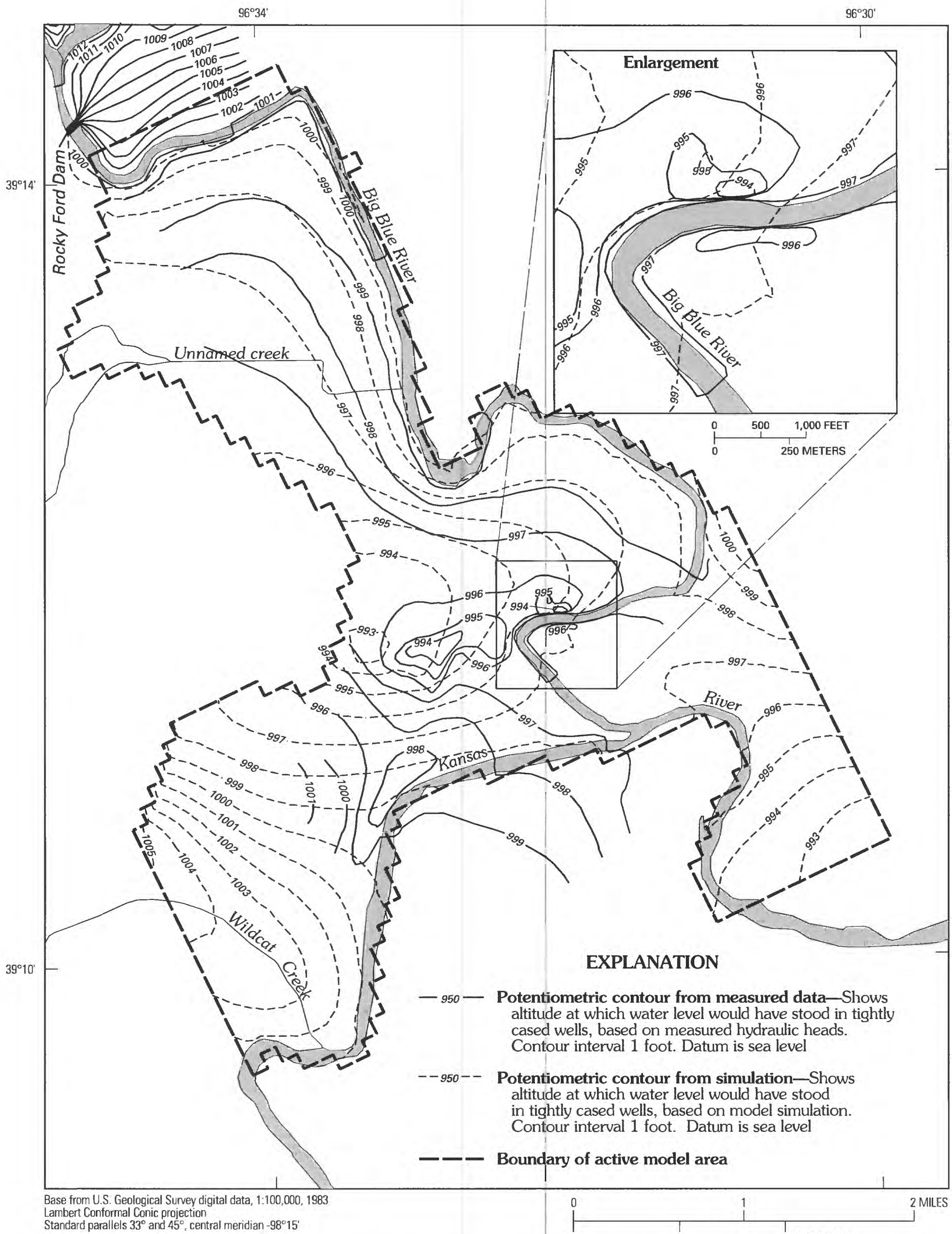


Figure 15. Measured and simulated potentiometric surfaces for May 25–26, 1993.

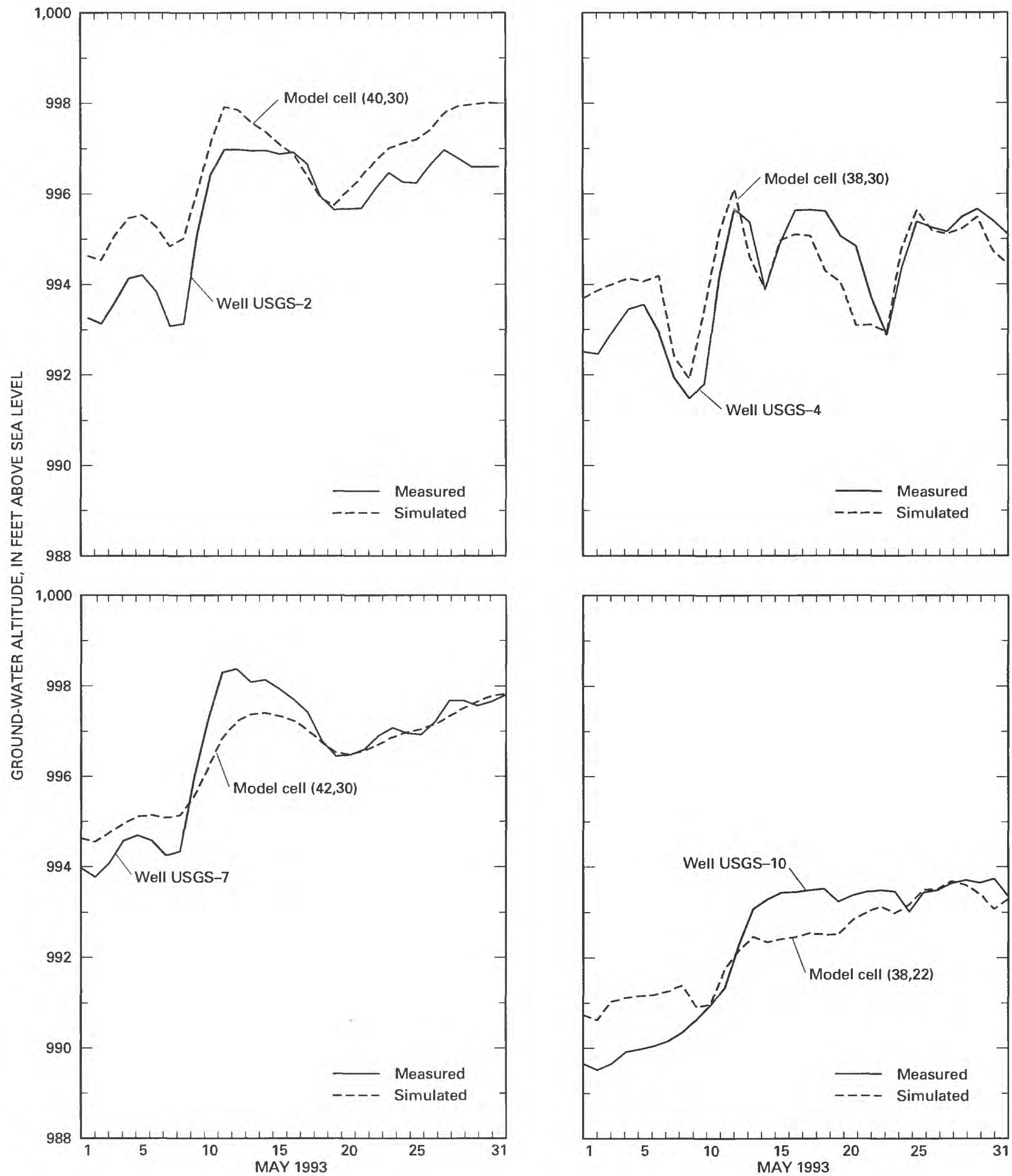


Figure 16. Measured and simulated ground-water altitudes for selected observation wells in model area, May 1993.

The combined net monthly mean streamflow decrease for the Big Blue and Kansas Rivers was 5.28 ft^3/s, and the mean monthly induced infiltration and intercepted base flow were about 3.22 and 2.06 ft^3/s, respectively. At the end of the simulation period, the combined cumulative net streamflow decrease for the Big Blue and Kansas Rivers for May 1993 caused by pumping was about 325 acre-ft, of which induced infiltration was about 198 acre-ft, or about 61 percent of the combined cumulative net streamflow decrease, and intercepted base flow was

Table 6. Calibrated model parameters for May 1993 conditions

Parameter	Value
Aquifer hydraulic conductivity	650 feet per day
Specific yield	0.20
Recharge rate	15 percent of precipitation
Streambed vertical hydraulic conductivity for Big Blue and Kansas Rivers	1 foot per day
Streambed thickness for Big Blue and Kansas Rivers	1 foot

Table 7. Difference between selected measured and simulated ground-water altitudes, May 1993
[RMSE, root mean square error]

Well (fig. 2)	Model cell (row, column shown in fig. 11)	Mean difference (feet)	Standard deviation of difference (feet)	RMSE of difference (feet)
USGS–2	40, 30	-0.89	0.55	1.00
USGS–4	38, 30	-.08	.83	.82
USGS–7	42, 30	.08	.58	.57
USGS–10	38, 22	-.03	.77	.76

about 127 acre-ft, or about 39 percent of the combined cumulative net streamflow decrease. Total well-field pumpage for May 1993 was about 414 acre-ft, so about 48 percent of the total well-field pumpage was from induced infiltration and about 31 percent was from intercepted base flow, and the remainder of the pumpage (21 percent) came from decreased aquifer storage, decreased subsurface outflow from the aquifer, and increased recharge and inflow to the aquifer.

Figure 19 shows simulated daily ground-water altitudes in the Manhattan municipal well field and daily drawdowns caused by pumping. The simulated monthly mean ground-water altitude was 995.06 ft without pumping and 993.88 ft with pumping (fig. 19*A*). The monthly mean drawdown caused by pumping was 1.18 ft (fig. 19*B*).

Verification of Model to October 16 through November 14, 1994, Conditions

Because the set of parameter values used in the calibrated model were developed for May 1993 hydrologic stresses, the model was verified under a different set of stresses to help establish greater confidence in the model. A typical verification process is to use the values of model parameters determined during calibration to simulate the hydrologic conditions for a different time period. October 16 through November 14, 1994, was selected as the verification time period because climatic conditions were much drier and because streamflow was small, compared to the wet, relatively large streamflow conditions of May 1993.

For the verification, values of hydraulic conductivity, specific yield, streambed vertical hydraulic conductivity and thickness, and recharge rate were not adjusted. Satisfactory results in matching simulated with measured hydrologic data for the October 16 through November 14, 1994, verification were achieved using the same model parameters as used in the May 1993 calibration.

Determination of Initial Hydraulic Heads

For the transient model simulation of October 16 through November 14, 1994, initial hydraulic heads were specified for each model cell in a two-step process. First, a steady-state model simulation using the mean precipitation and streamflow conditions and mean pumping rates for October 1–15, 1994, were used to specify a set of starting heads. Second, these hydraulic heads were adjusted up or down in local areas to more closely match measured heads in observation wells and to minimize aquifer-storage changes resulting from differences in hydraulic heads generated by steady-state and transient simulations. (The head adjustment was 1 ft or less.)

Comparison of Measured to Simulated Potentiometric Surfaces, River Water-Surface Altitudes, and Hydraulic Heads

Several comparisons were made during the verification process among measured and simulated potentiometric surfaces (fig. 20), measured and simulated river water-surface altitudes (fig. 21), and measured and simulated ground-water altitudes for selected observation wells (fig. 22). The measured and simulated potentiometric-surface contours (fig. 20) are for December 7–8 and November 9, 1994, respectively, and so do not match well in some areas of the model. However, the patterns of drawdown in the well-field area are generally the same for both measured and simulated potentiometric surfaces. The reasons for using the potentiometric-surface map constructed from data

Table 8. Simulated water budget for the alluvial aquifer for the May 1993 transient model simulation and comparison of simulated and conceptual differences between recharge and discharge

[Values are in cubic feet per second. +, recharge is greater than discharge; -, recharge is less than discharge]

Budget term	Simulated recharge to aquifer	Simulated discharge from aquifer	Simulated difference between recharge and discharge	Conceptual difference between recharge and discharge (table 2)
Recharge from precipitation	16.27	0	+16.27	+16.3
Subsurface inflow (recharge) and outflow (discharge)	17.36	4.84	+12.52	+15.1
Seepage from Big Blue and Kansas Rivers	50.98	15.75	+35.23	+39.8
Well pumpage	0	6.96	-6.96	-7.2
Aquifer storage	29.84	86.86	[1]-57.02	[1]-64.0
Total	**114.45**	**114.41**	**+.04**	**0**

[1]Shown as a negative number because addition of water to storage is considered to be a discharge from the digital and conceptual models.

collected on December 7–8 for comparison to simulated data are:

1. Discharges in Big Blue River from late October through early December were relatively small. Conditions during the low-flow period were used for model verification. Due to missing ground-water-level data for late November, the verification period of October 16 through November 14 was selected. Water levels in the study-wide well network were not measured during the verification period. The water-level data were not available to construct a potentiometric-surface map for the entire model area for the verification period.
2. Similar flow conditions occurred in the Big Blue and Kansas Rivers near the Manhattan municipal well field from late October through early December 1994. Also, pumpages were similar. Therefore, it is assumed that the ground-water flow pattern did not change much from late October through early December.

Simulated river water-surface and ground-water altitudes compare well with the measured ones. An RMSE of about 0.03 ft was calculated for the comparison of simulated and measured river water-surface altitude (fig. 21). Simulated ground-water levels match measured levels in terms of shapes and altitudes. A maximum RMSE of 0.62 ft was calculated for the model cell that contains the location of well USGS–4 (table 9). Simulated ground-water altitudes match well with measured ground-water altitudes (fig. 22). A mean RMSE value of 0.46 ft was calculated for the comparison of simulated and measured ground-water altitudes at five observation wells.

Comparison of Simulated and Conceptual Model Water Budgets

A simulated water budget for the October 16 through November 14, 1994, model verification is listed in table 10. The simulated recharge and discharge values were calculated by the model. Both the Big Blue and Kansas Rivers generally lost water to the aquifer, and water entered aquifer storage as a result of excess recharge to the system. Table 10 also shows a comparison of the simulated and conceptual model differences between recharge and discharge.

Simulated Streamflow Decrease Induced by Municipal Well-Field Pumping

Transient model simulations without and with pumping, and climatic conditions of October 16 through November 14, 1994, were used to simulate streamflow decreases in the Big Blue and Kansas Rivers and ground-water-altitude changes induced by the pumping of Manhattan municipal wells.

The simulated streamflow decreases in the Big Blue River for without-pumping and with-pumping simulations (fig. 23*A*) show that pumping increased the amount of streamflow loss. The monthly mean streamflow decrease was 6.79 ft^3/s without pumping and 13.27 ft^3/s with pumping. The monthly mean net

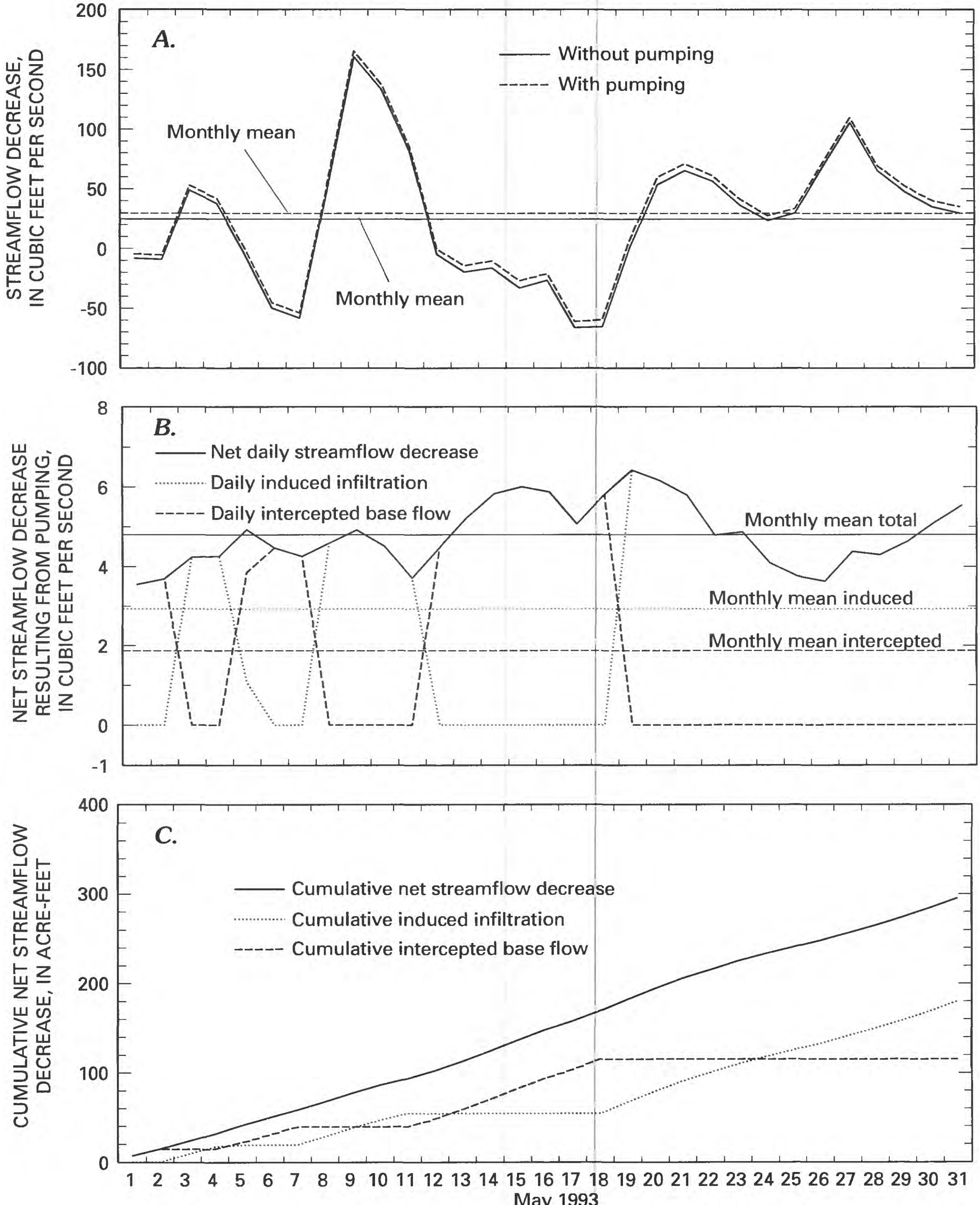


Figure 17. Simulated May 1993 (*A*) daily and monthly mean streamflow decrease from Big Blue River without and with pumping, (*B*) net streamflow decrease and stream- and ground-water contributions to net streamflow decrease caused by pumping, and (*C*) cumulative net streamflow decrease and stream- and ground-water contributions to net streamflow decrease caused by pumping.

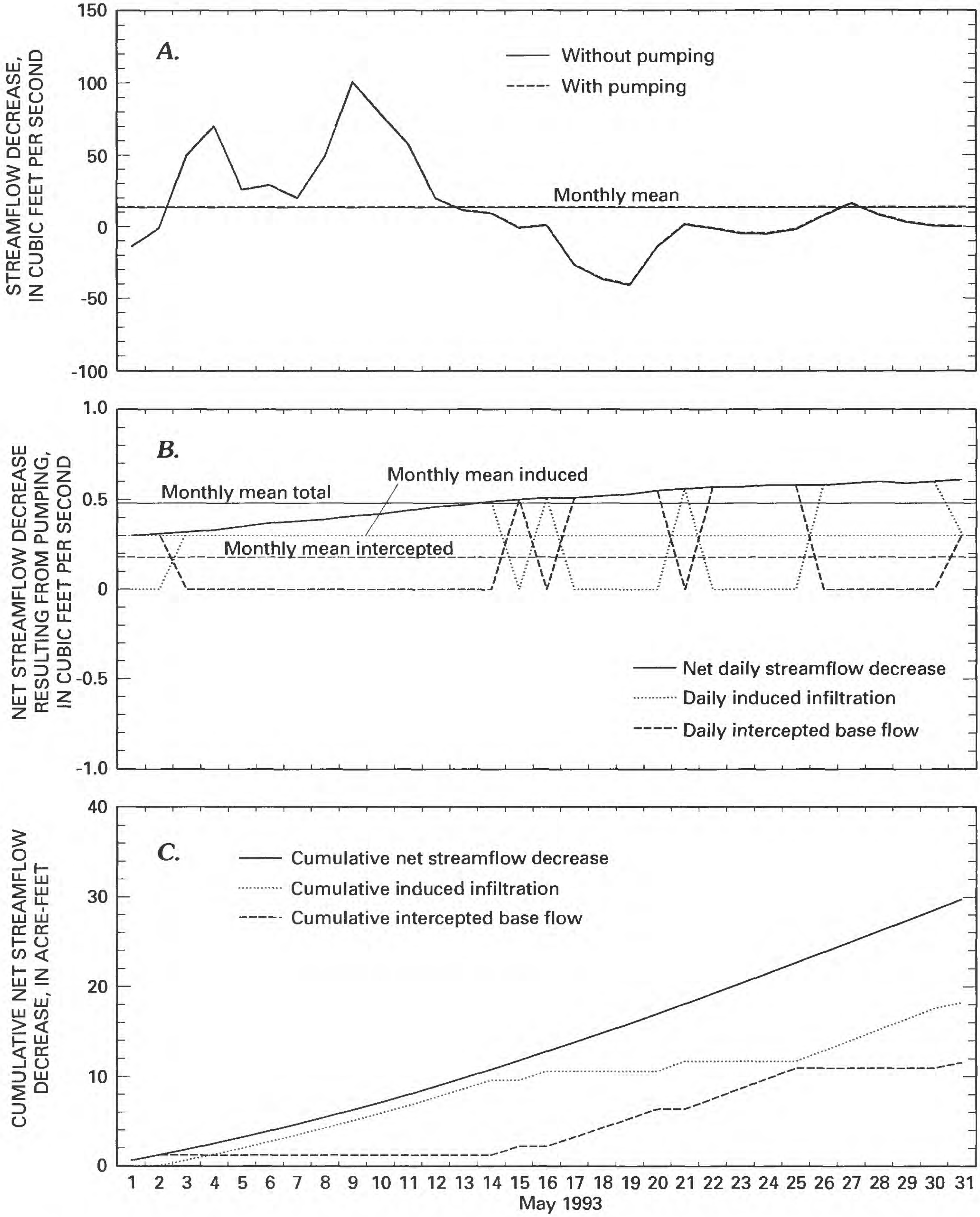


Figure 18. Simulated May 1993 (*A*) daily and monthly streamflow decrease from Kansas River without and with pumping, (*B*) net streamflow decrease and stream- and ground-water contributions to net streamflow decrease caused by pumping, and (*C*) cumulative net streamflow decrease and stream- and ground-water contributions to net streamflow decrease caused by pumping.

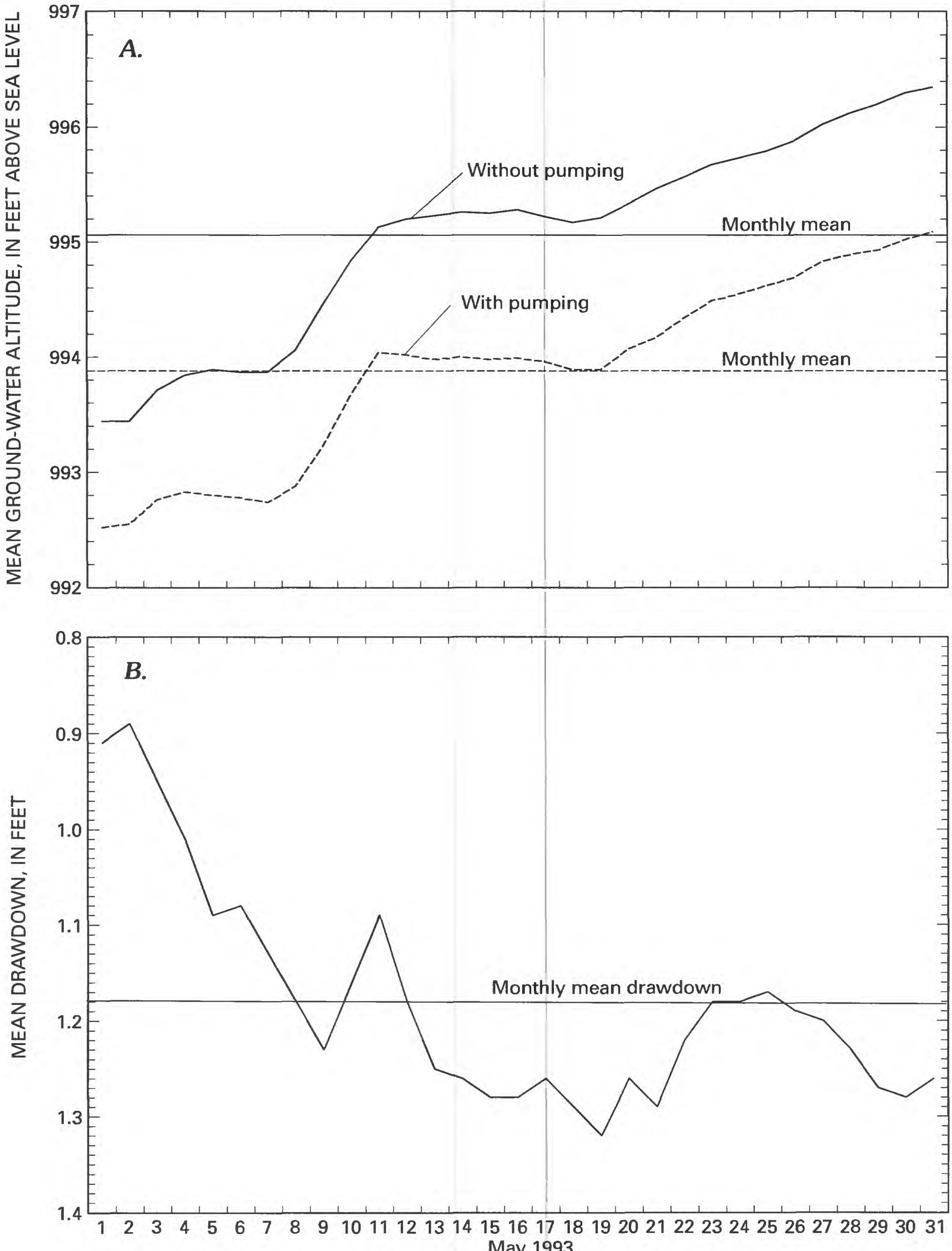


Figure 19. Simulated *(A)* daily and monthly mean ground-water altitudes and *(B)* daily and monthly mean drawdown caused by pumping in the Manhattan municipal well field, May 1993.

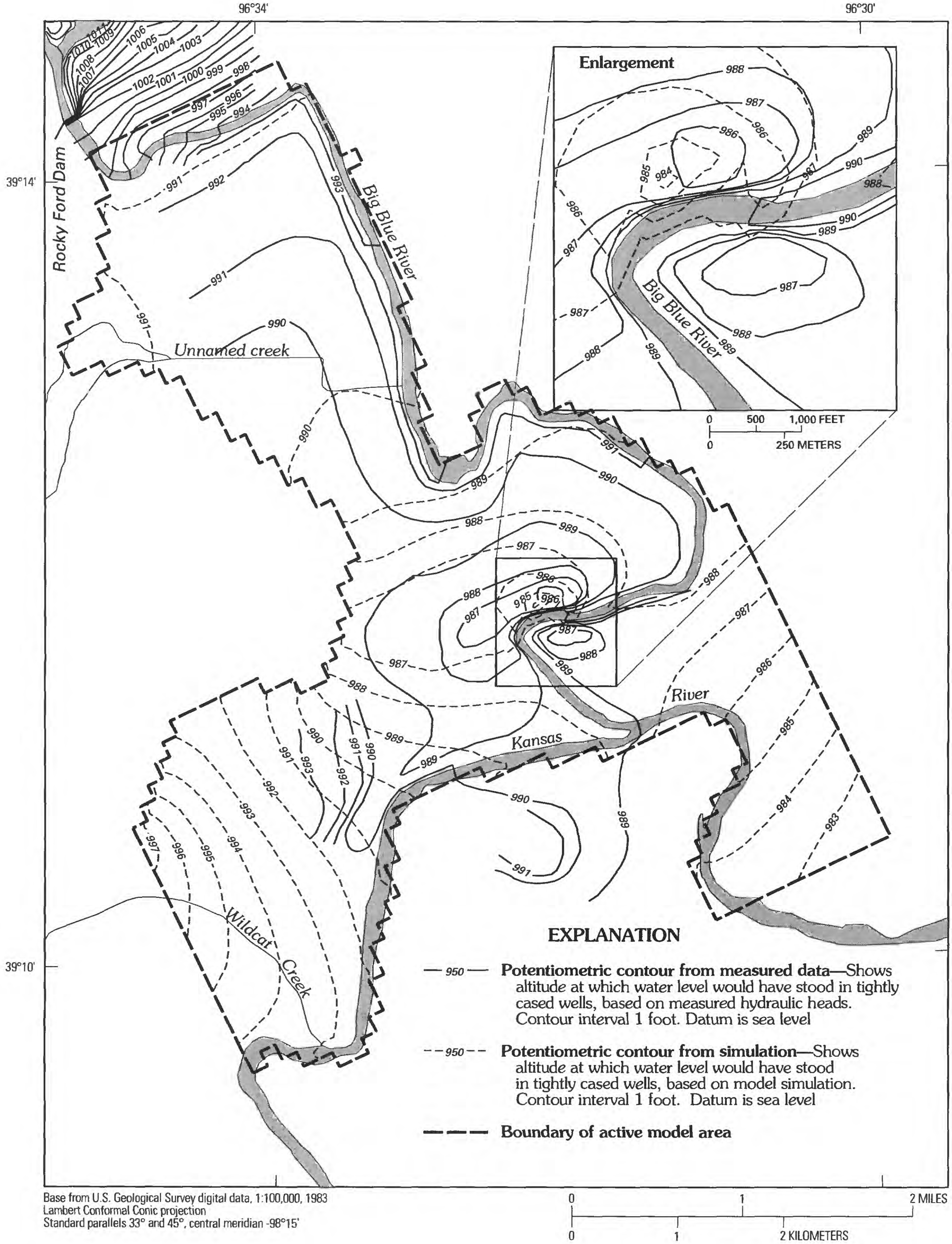


Figure 20. Measured and simulated potentiometric surfaces for December 7–8 and November 9, 1994, respectively.

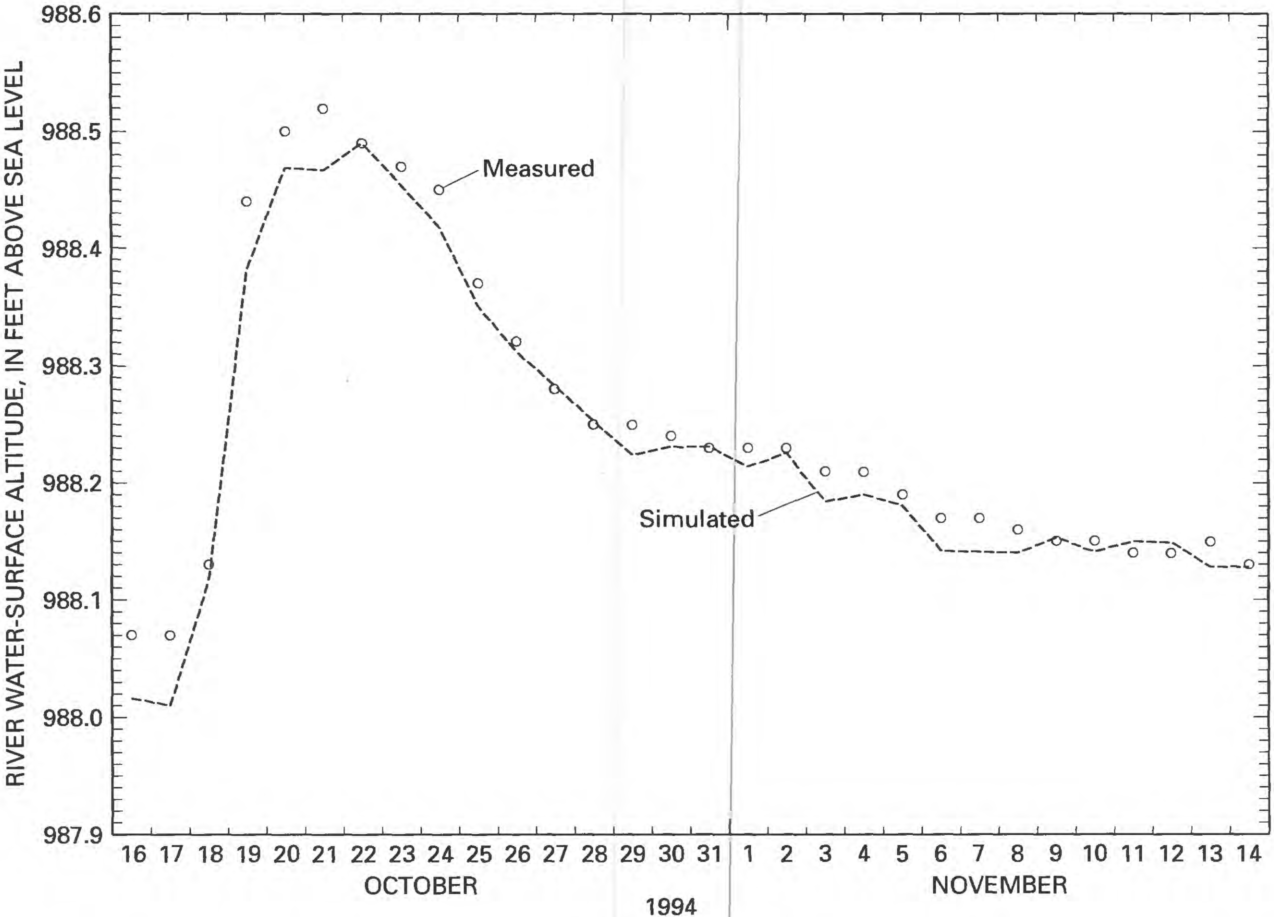


Figure 21. Measured and simulated water-surface altitudes in the Big Blue River at the Manhattan municipal well field, October 16 through November 14, 1994.

streamflow decrease and the induced infiltration were both 6.48 ft^3/s (fig. 23*B*), and intercepted base flow was zero. At the end of the simulation period, the cumulative net streamflow decrease for October 16 through November 14, 1994, caused by pumping was about 384 acre-ft, all of which consisted of induced infiltration from the Big Blue River (fig. 23*C*).

The simulated daily and monthly mean streamflow decrease for the Kansas River for without-pumping and with-pumping simulations (fig. 24*A*) shows that pumping slightly increased the amount of streamflow loss. The monthly mean streamflow decrease was about -0.68 ft^3/s without pumping and -0.49 ft^3/s with pumping. The negative values indicate that, on average, the stream gained water during both simulations but gained less with pumping. Figure 24*B* shows the net streamflow decrease and the induced infiltration and intercepted base flow resulting from pumping. The net monthly mean streamflow decrease was about 0.19 ft^3/s, and the mean monthly induced infiltration and intercepted base flow were about 0.03 and 0.16 ft^3/s, respectively. At the end of the simulation period, the cumulative net streamflow decrease for October 16 through November 14, 1994, caused by pumping was 11.3 acre-ft, of which induced infiltration was 1.6 acre-ft, or about 14 percent of the cumulative net streamflow decrease, and intercepted base flow was about 9.7 acre-ft, or about 86 percent of the cumulative net streamflow decrease (fig. 24*C*).

The combined net monthly mean streamflow decrease for the Big Blue and Kansas Rivers was 6.67 ft^3/s, and the combined monthly mean induced infiltration and intercepted base flow were 6.51 and 0.16 ft^3/s, respectively. At the end of the simulation period, the combined cumulative net streamflow decrease for October 16 through November 16, 1994, caused by pumping was about 395 acre-ft, of which induced infiltration was about 385 acre-ft, or about 97 percent of the combined cumulative net streamflow decrease, and intercepted base flow was about

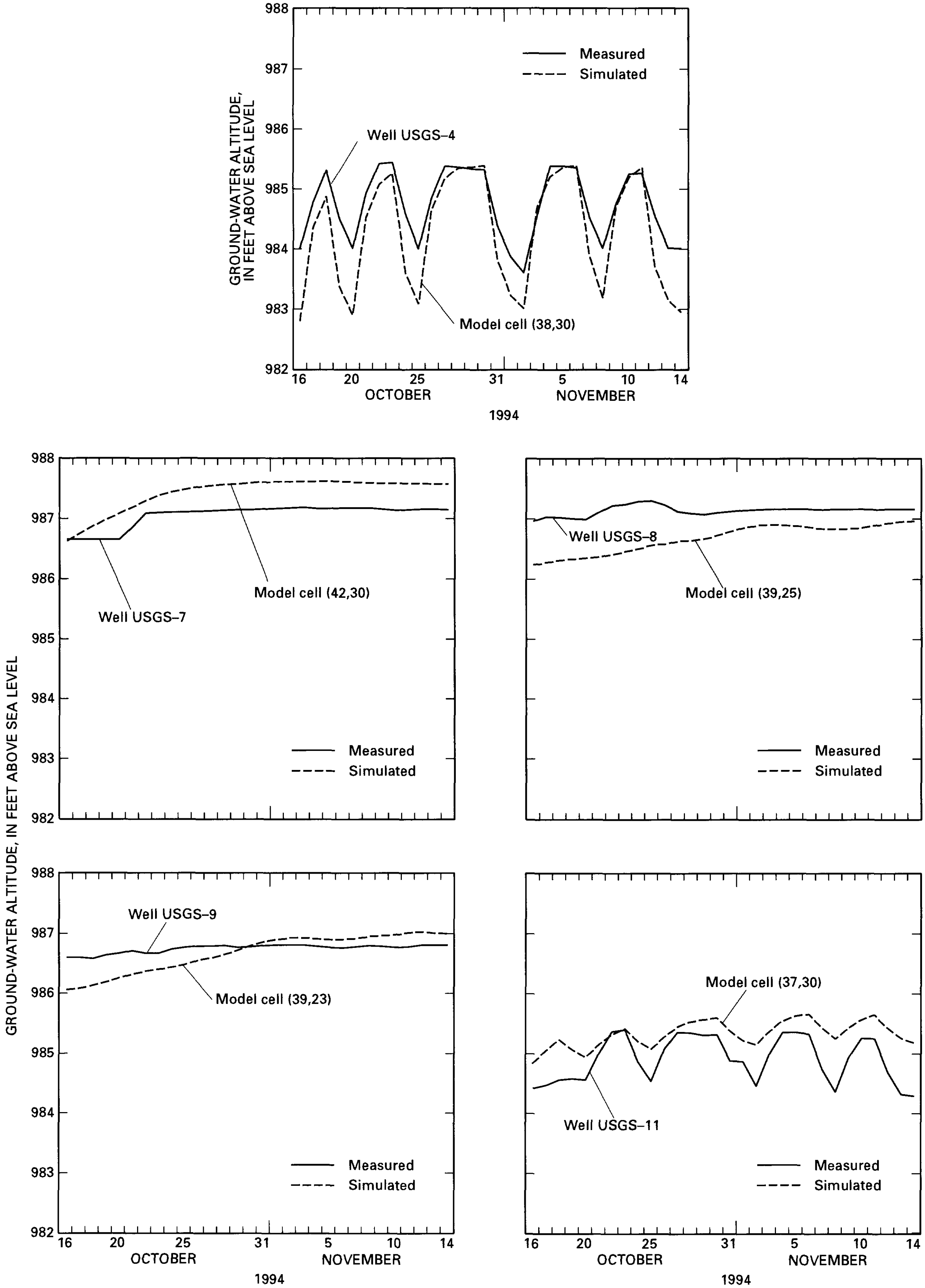


Figure 22. Measured and simulated ground-water altitudes for selected observation wells in model area, October 16 through November 14, 1994.

Table 9. Difference between selected measured and simulated ground-water altitudes for October 16 through November 14, 1994

[RMSE, root mean square error]

Well (fig. 2)	Model cell (row, column) (fig. 11)	Mean difference (feet)	Standard deviation of difference (feet)	RMSE of difference (feet)
USGS–4	38, 30	0.45	0.43	0.62
USGS–7	42, 30	-.38	.11	.39
USGS–8	39, 25	.46	.22	.51
USGS–9	39, 23	.07	.26	.27
USGS–11	37, 30	-.42	.25	.49

10 acre-ft or about 3 percent of the combined cumulative net streamflow decrease. Well-field pumpage for October 16 through November 14, 1994, was about 506 acre-ft, so about 76 percent of the total well-field pumpage was from induced infiltration and about 2 percent was from intercepted base flow, and the remainder of the pumpage (22 percent) came from decreased aquifer storage, decreased outflow from the aquifer, and increased recharge and inflow to the aquifer.

Figure 25 shows the simulated mean ground-water altitudes in the Manhattan municipal well field (fig. 12) and drawdown caused by pumping. The mean monthly simulated ground-water altitude was 987.6 ft without pumping and 986.5 ft with pumping (fig. 25*A*). The mean monthly drawdown caused by pumping was about 1.1 ft (fig. 25*B*).

Simulations of Hypothetical Conditions

In the actual stream-aquifer system, precipitation, and thus recharge, and streamflow discharge vary daily, seasonally, and yearly, so that the stream-aquifer system is in a state of quasi-equilibrium where hydraulic heads and flow between the stream and aquifer fluctuate about long-term average values. These long-term average values are approximated by the steady-state simulations.

The predictive capabilities of the calibrated model permit hypothetical conditions to be explored by changing data input to simulate various hydrologic conditions. A series of steady-state model simulations were made to compare ground-water altitudes and decrease in streamflow in the well-field area to different pumpage and streamflow conditions.

Hypothetical Conditions

Hypothetical conditions used for simulations were a combination of different precipitation, pumpage, and Big Blue and Kansas River streamflow. Precipitation values were determined by taking percentages of the long-term mean annual precipitation of 32.88 in. observed at Manhattan (National Oceanic and Atmospheric Administration, 1993–94). The percentages used were 0, 25, 50, and 100 percent, or, 0, 8.22, 16.44, and 32.88 in., respectively. The percentage of this precipitation that was assumed to be recharged to the alluvial aquifer was 15 percent, as determined during model calibration.

Five pumpage rates for Manhattan municipal wells were used in hypothetical simulations: (1) no pumpage, (2) the 1993 mean pumpage, (3) the maximum allowable pumpage, (4) 1.5 times the maximum allowable pumpage, and (5) 2.0 times the maximum allowable pumpage. The 1993 mean pumpage for Manhattan municipal wells was 7.8 ft^3/s, and the maximum allowable pumpage for these wells was 14.8 ft^3/s. The maximum allowable pumpage for non-Manhattan municipal, agricultural, and industrial wells of 3.3 ft^3/s was used for the 1993 mean pumpage.

Twenty-four hypothetical streamflows used in the simulations for the Big Blue River ranged from 100 to 10,000 ft^3/s. Four hypothetical streamflows used for the Kansas River ranged from 250 to 3,000 ft^3/s.

Results of Simulations

The different combinations of hypothetical conditions of precipitation, pumpage, and streamflow just discussed were used as the basis for 1,920 steady-state simulations. Figures 26–29 show the relations among simulated average and minimum ground-water altitudes for model cells within the Manhattan municipal well field boundary (fig. 12) for the various precipitation, pumpage, and streamflow rates. Given simulated precipitation, pumpage, and Kansas River streamflow rates, the Big Blue River streamflow that is needed to produce a desired ground-water altitude in the well field for a the selected pumping rate can be determined (figs. 26–29). For example, figure 26 shows that with zero precipitation, 1993 mean pumpage, and Kansas River streamflow between 250 and 3,000 ft^3/s

Table 10. Simulated water budget for the alluvial aquifer for the October 16 through November 14, 1994, transient model simulation and comparison of simulated and conceptual model differences between recharge and discharge

[Values are in cubic feet per second. +, recharge is greater than discharge; -, recharge is less than discharge]

Budget term	Simulated recharge to aquifer	Simulated discharge from aquifer	Simulated water-budget difference between recharge and discharge	Conceptual water-budget difference between recharge and discharge (table 2)
Recharge from precipitation	0.73	0	+0.73	+0.7
Subsurface inflow (recharge) and outflow (discharge)	2.73	0.93	+1.80	+1.3
Seepage for Big Blue and Kansas Rivers	17.38	3.00	+14.38	+14.1
Well pumpage	0	8.50	-8.50	-8.7
Aquifer storage	6.02	14.26	[1]-8.24	[1]-7.4
Total	**26.86**	**26.69**	**+.17**	**0**

[1]Shown as a negative number because addition of water to storage is considered to be a discharge from the digital and conceptual models.

(results are nearly identical for streamflows ranging from 250 to 3,000 ft^3/s), the average ground-water altitude in the well field would be about 988 ft, and the minimum ground-water altitude in the well field would be about 987 ft for a Big Blue River streamflow of 2,000 ft^3/s. The average ground-water altitude would be about 985 ft, and the minimum altitude would be about 983 ft for a Big Blue River streamflow of 100 ft^3/s. Thus, the streamflows required to maintain the ground-water altitudes in the well field at an operationally desirable altitude can be interpolated from the curves in figures 26–29.

Figures 30–33 show the relation among the simulated minimum ground-water altitudes in the well field and the simulated ground-water altitudes for model cell (39,25) (row 39, column 25), which corresponds to the location of observation well USGS–8. Well USGS–8 was selected for this comparison because it is located between the two groups of municipal wells in the old and new parts of the Manhattan municipal well field and could be measured in the future as an indication of the average ground-water altitude in the well field. Simulated ground-water altitudes in model cell (39,25) are about 1 to 8 ft higher than simulated minimum ground-water altitudes; larger simulated pumpage produced a larger difference between minimum ground-water altitude and simulated ground-water altitude in model cell (39,25). Simulated ground-water altitudes for model cell (39,25) are about 0.2 to 2.0 ft higher than the simulated average ground-water altitudes in the well-field area.

Figures 26–33 illustrate other aspects of the relations among simulated average ground-water altitudes in the well field and various hypothetical precipitation rates, pumpages, and streamflows. If the drawdown is defined as the difference between the altitude without pumping and with pumping, drawdown in the well field decreases as precipitation and streamflow increase. The drawdown in the municipal well field for all steady-state simulations using 1993 mean pumpage averaged 2.4 ft and ranged from 1.9 to 2.7 ft. This small range indicates that drawdown is not very sensitive to different precipitation or streamflow rates. Drawdown is a function primarily of well-field pumping.

Average and minimum ground-water altitudes rise as precipitation and streamflow increase. Average ground-water altitudes rise by about 0.13 in. for each inch of precipitation. Average ground-water altitudes also rise with stream stage as streamflow increases. This effect was insignificant for changes in Kansas River streamflow. Computed over the entire range of streamflow used in hypothetical simulations, average ground-water altitudes increase by about 0.013 ft for a Kansas River streamflow increase of 1,000 ft^3/s, whereas ground-water altitudes increase by about 1.18 ft for a Big Blue River streamflow increase of 1,000 ft^3/s. Ground-water altitudes in the well field probably are more sensitive to streamflow changes in

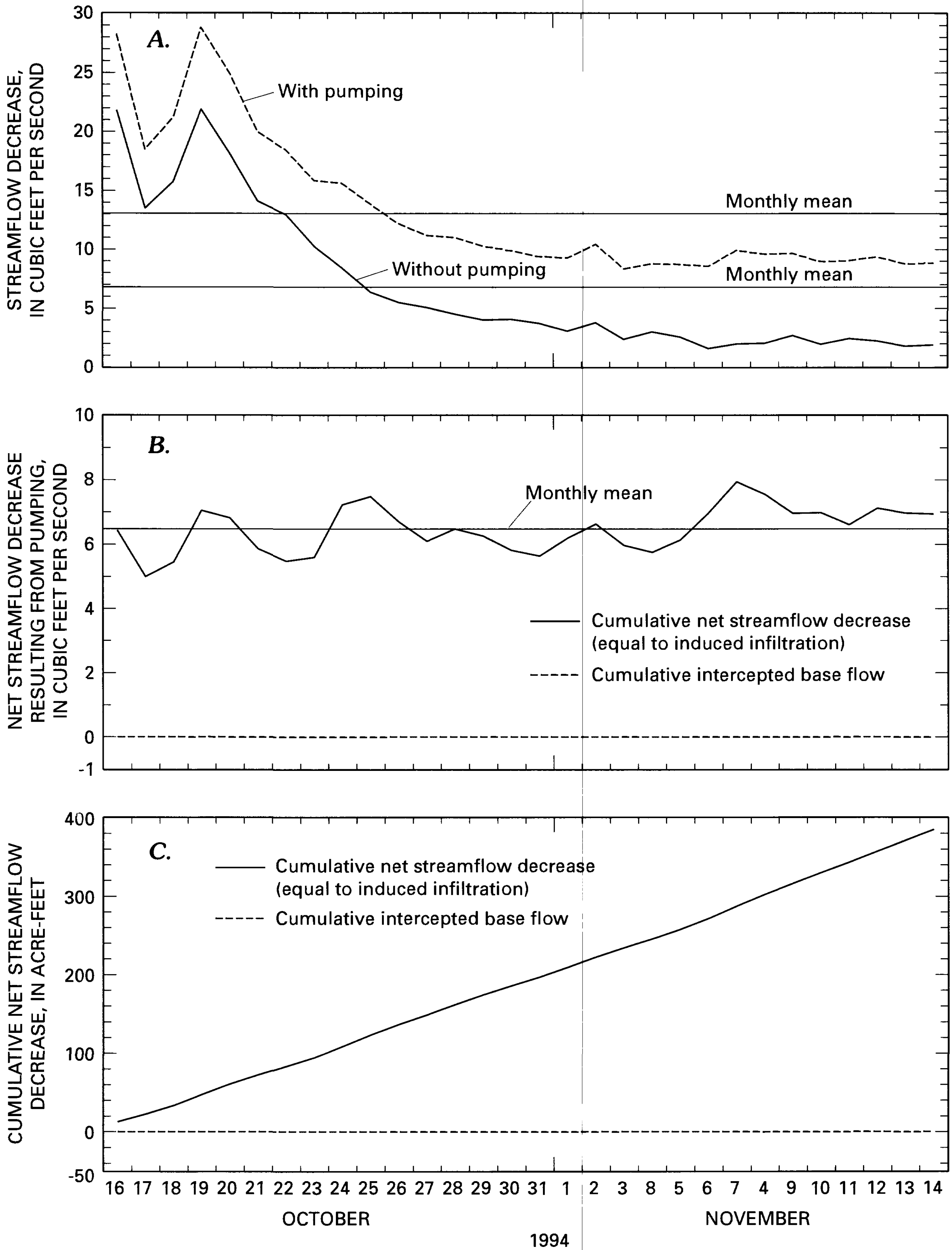


Figure 23. Simulated October 16 through November 14, 1994, (*A*) daily and monthly mean streamflow decrease from Big Blue River without and with pumping, (*B*) net streamflow decrease and stream- and ground-water contributions to net streamflow decrease caused by pumping, and (*C*) cumulative net streamflow decrease and stream- and ground-water contribution to net streamflow decrease caused by pumping.

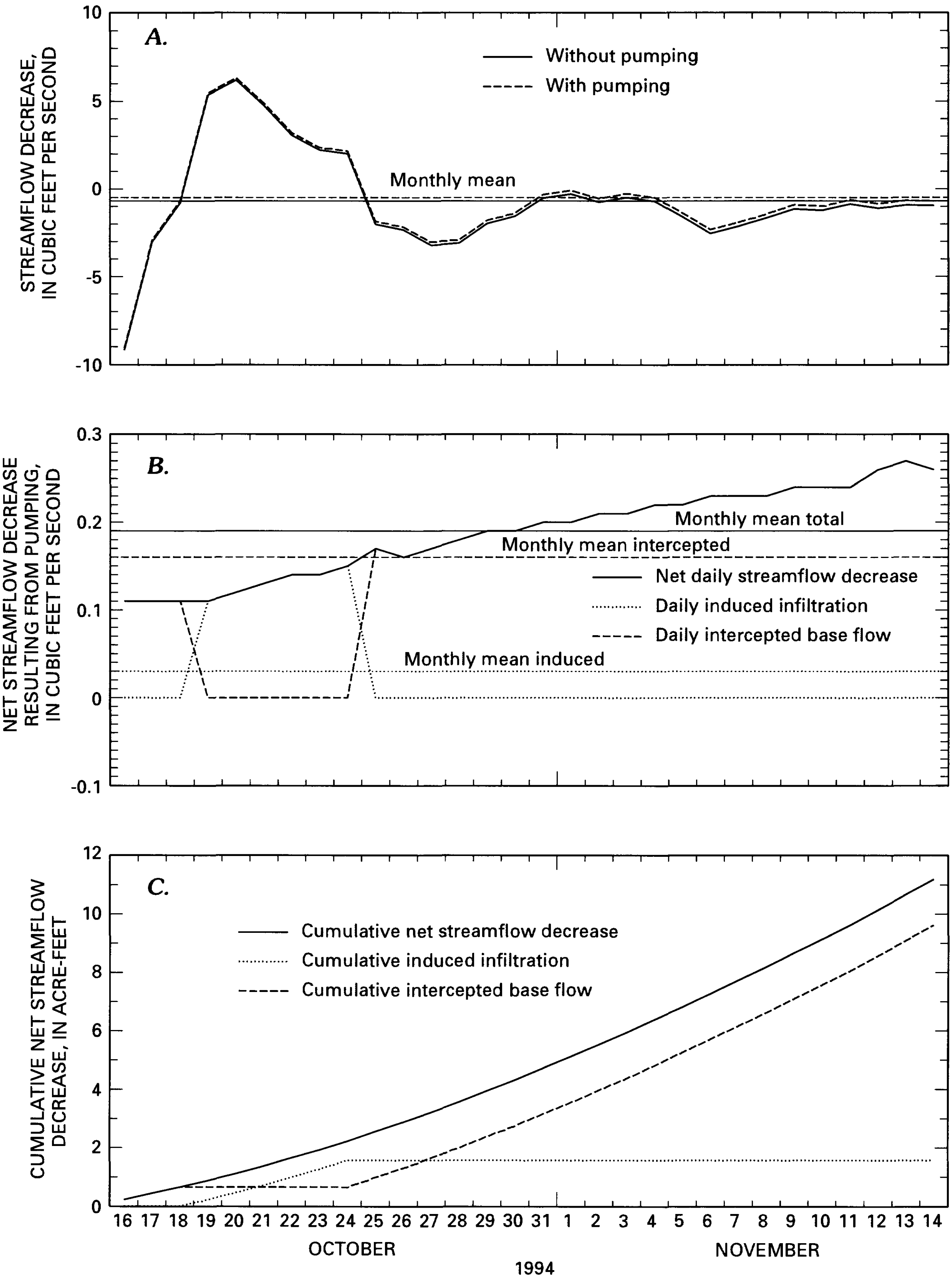


Figure 24. Simulated October 16 through November 14, 1994, (*A*) daily and monthly mean streamflow decrease from Kansas River without and with pumping, (*B*) net streamflow decrease and stream- and ground-water contributions to net streamflow decrease caused by pumping, and (*C*) cumulative net streamflow decrease and stream- and ground-water contributions to net streamflow decrease caused by pumping.

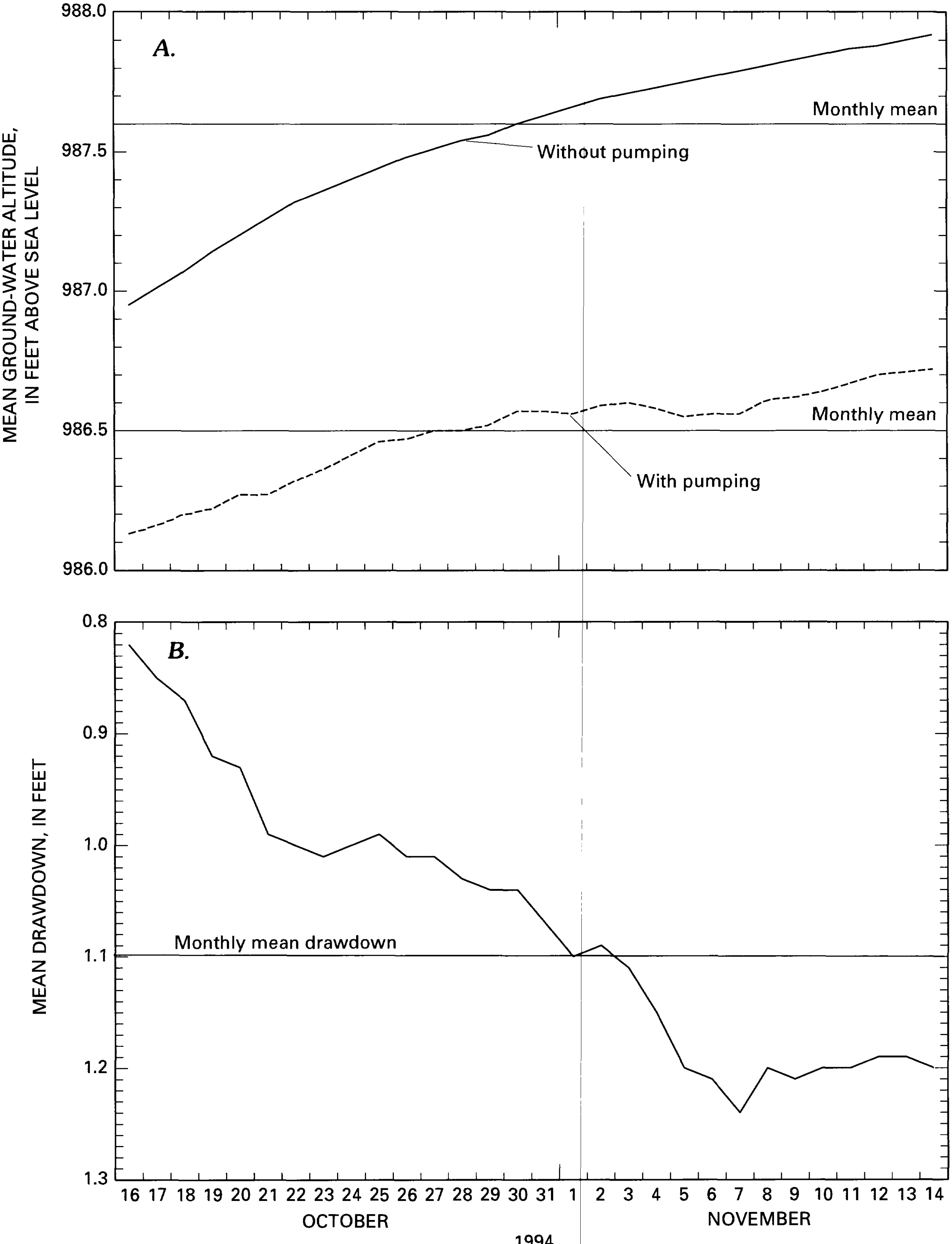


Figure 25. Simulated *(A)* daily and monthly mean ground-water altitudes and *(B)* daily and monthly mean drawdown caused by pumping in Manhattan municipal well field, October 16 through November 14, 1994.

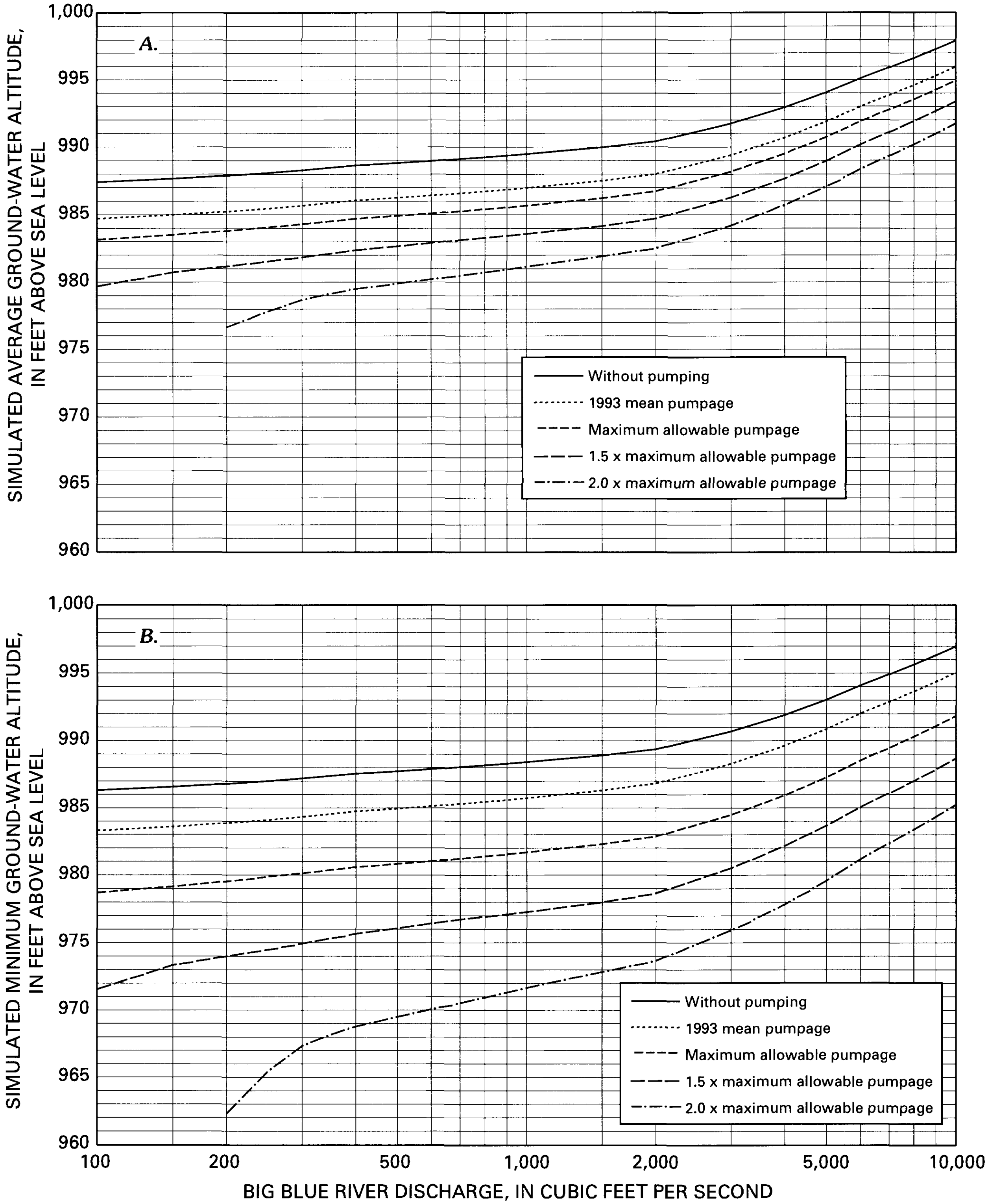


Figure 26. Relations among simulated (*A*) average and (*B*) minimum ground-water altitudes in the Manhattan municipal well field and stream discharge in the Big Blue and Kansas Rivers, with zero simulated precipitation and simulated streamflows in Kansas River from 250 to 3,000 cubic feet per second.

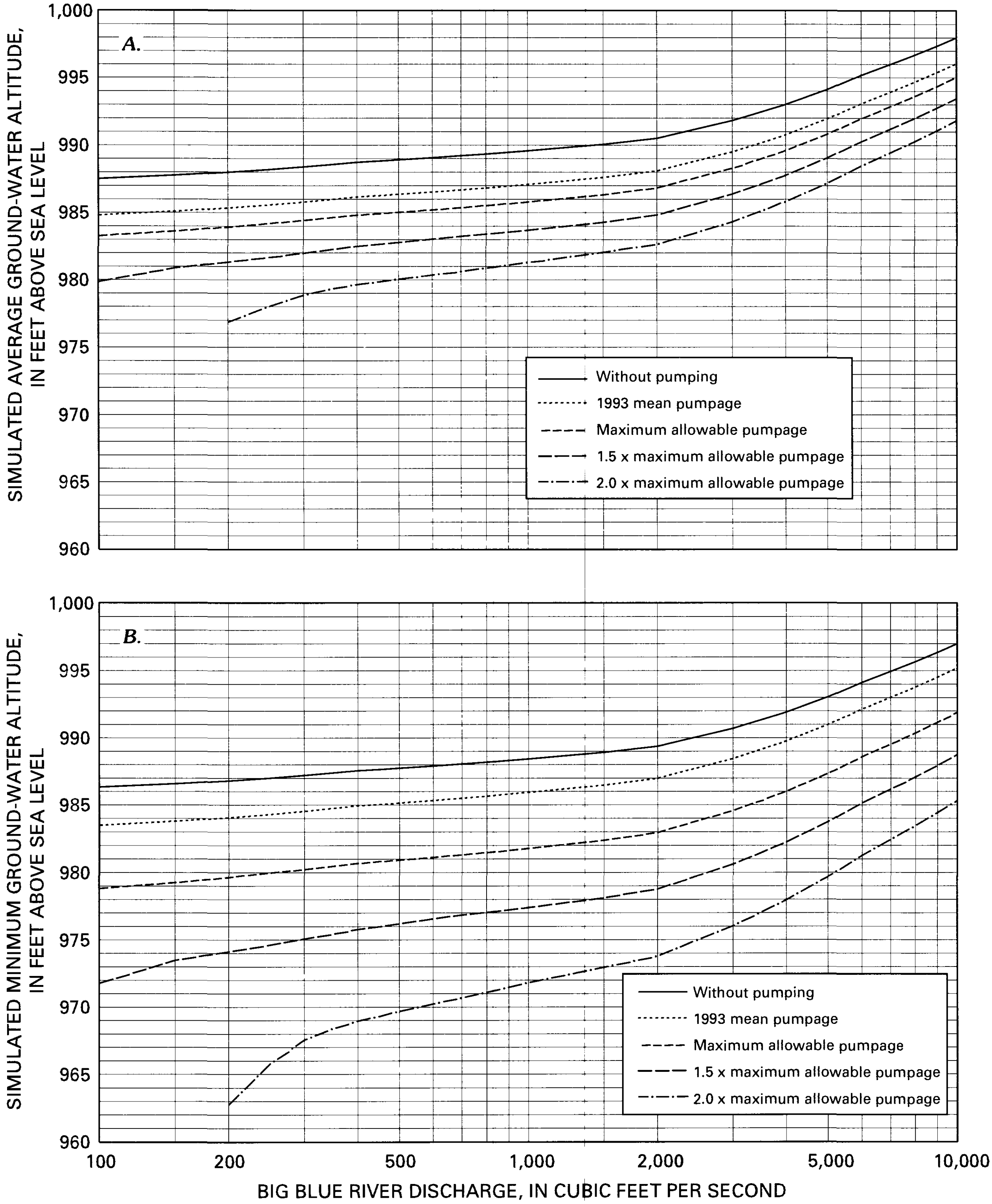


Figure 27. Relations among simulated (*A*) average and (*B*) minimum ground-water altitudes in the Manhattan municipal well field and stream discharge in the Big Blue and Kansas Rivers, with simulated precipitation 8.22 inches per year and simulated streamflows in Kansas River from 250 to 3,000 cubic feet per second.

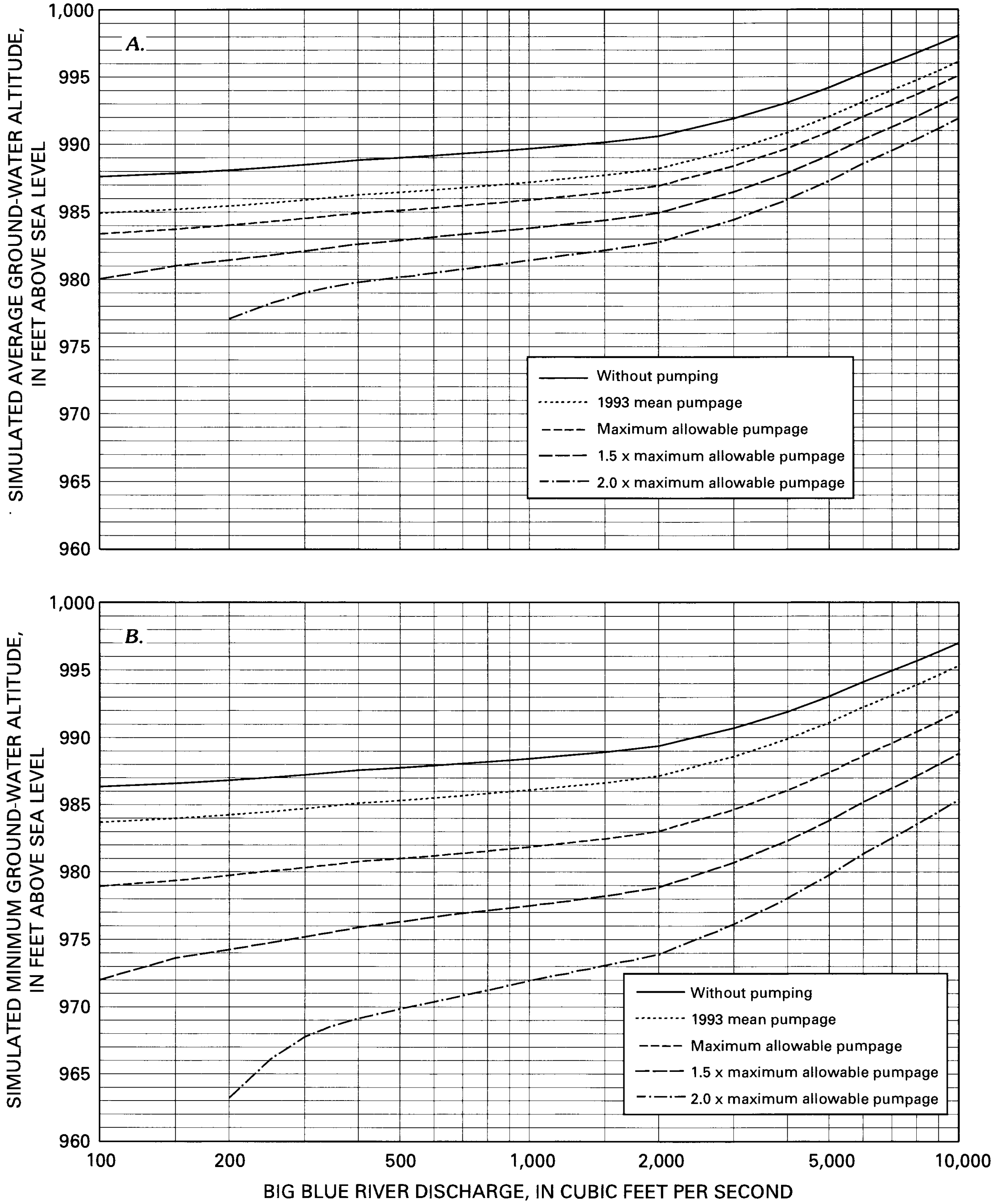


Figure 28. Relations among simulated (*A*) average and (*B*) minimum ground-water altitudes in the Manhattan municipal well field and stream discharge in the Big Blue and Kansas River, with simulated precipitation 16.44 inches per year and simulated streamflows in Kansas River from 250 to 3,000 cubic feet per second.

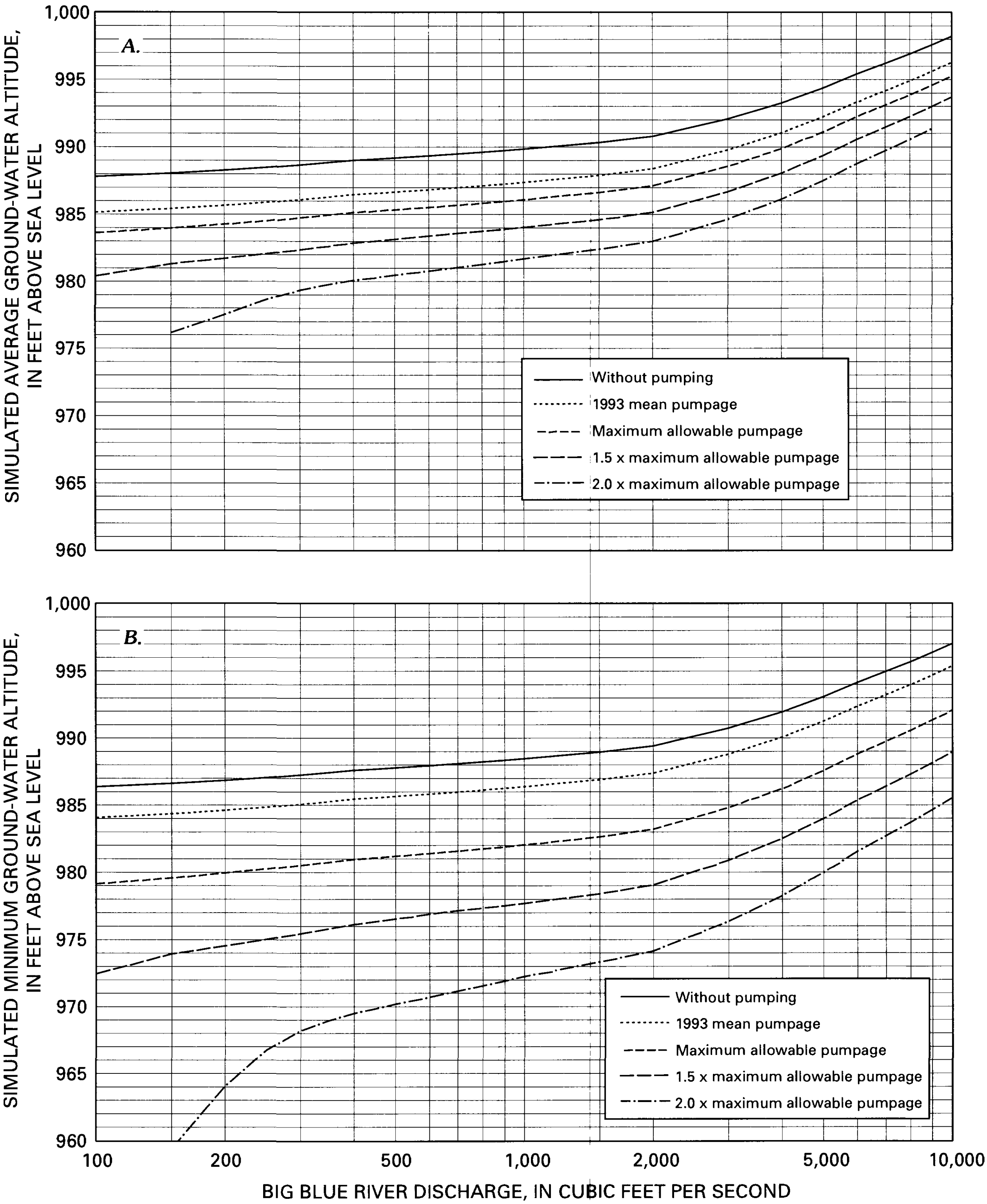


Figure 29. Relations among simulated (*A*) average and (*B*) minimum ground-water altitudes in the Manhattan municipal well field and stream discharge in the Big Blue and Kansas Rivers, with simulated precipitation 32.88 inches per year and simulated streamflows in Kansas River from 250 to 3,000 cubic feet per second.

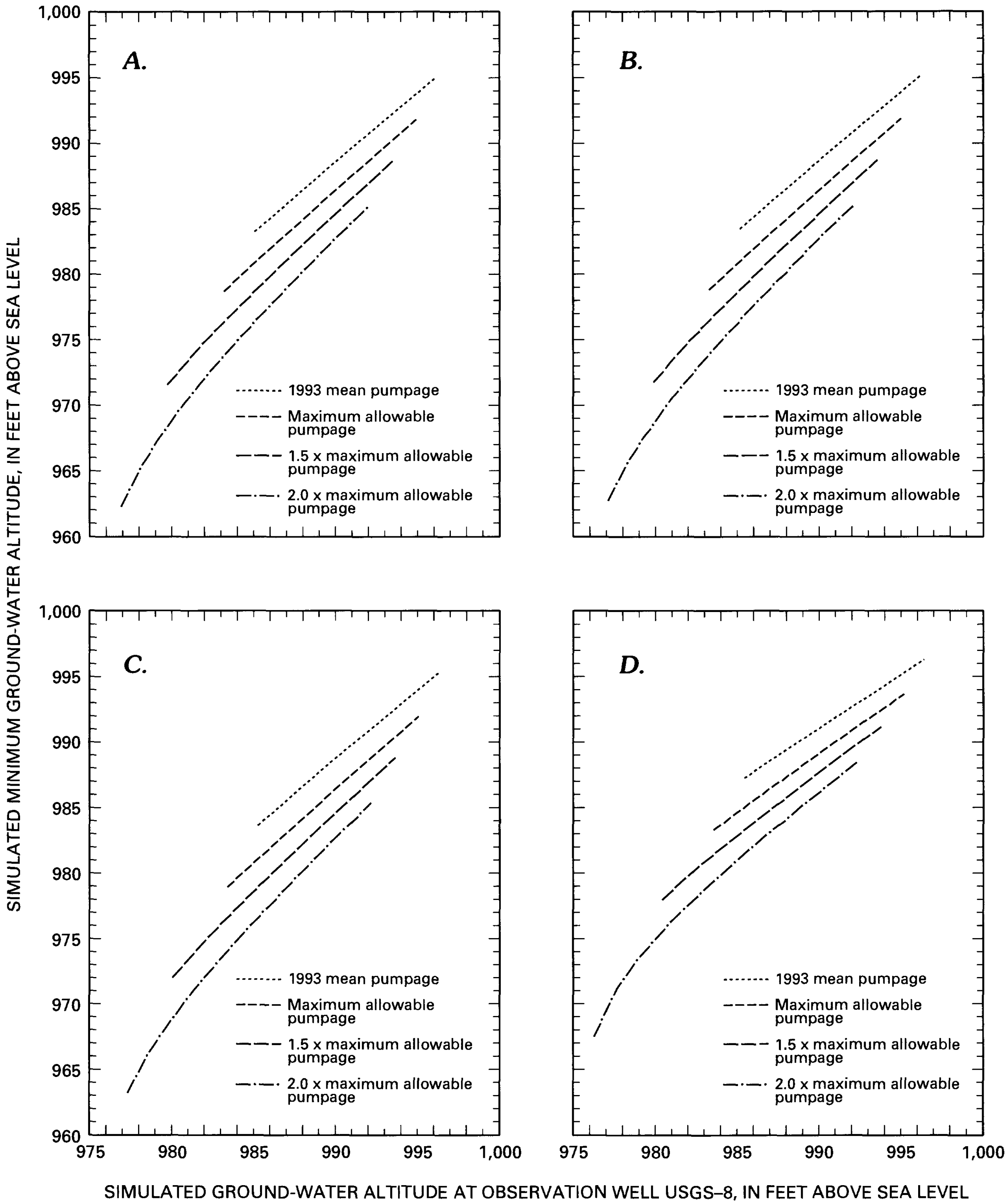


Figure 30. Relations among simulated ground-water altitudes at model cell (39,25) (observation well USGS–8) and simulated minimum ground-water altitudes in the Manhattan municipal well field for precipitation rates of (*A*) zero, (*B*) 8.22, (*C*) 16.44, and (*D*) 32.88 inches per year and simulated streamflow in Kansas River of 250 cubic feet per second.

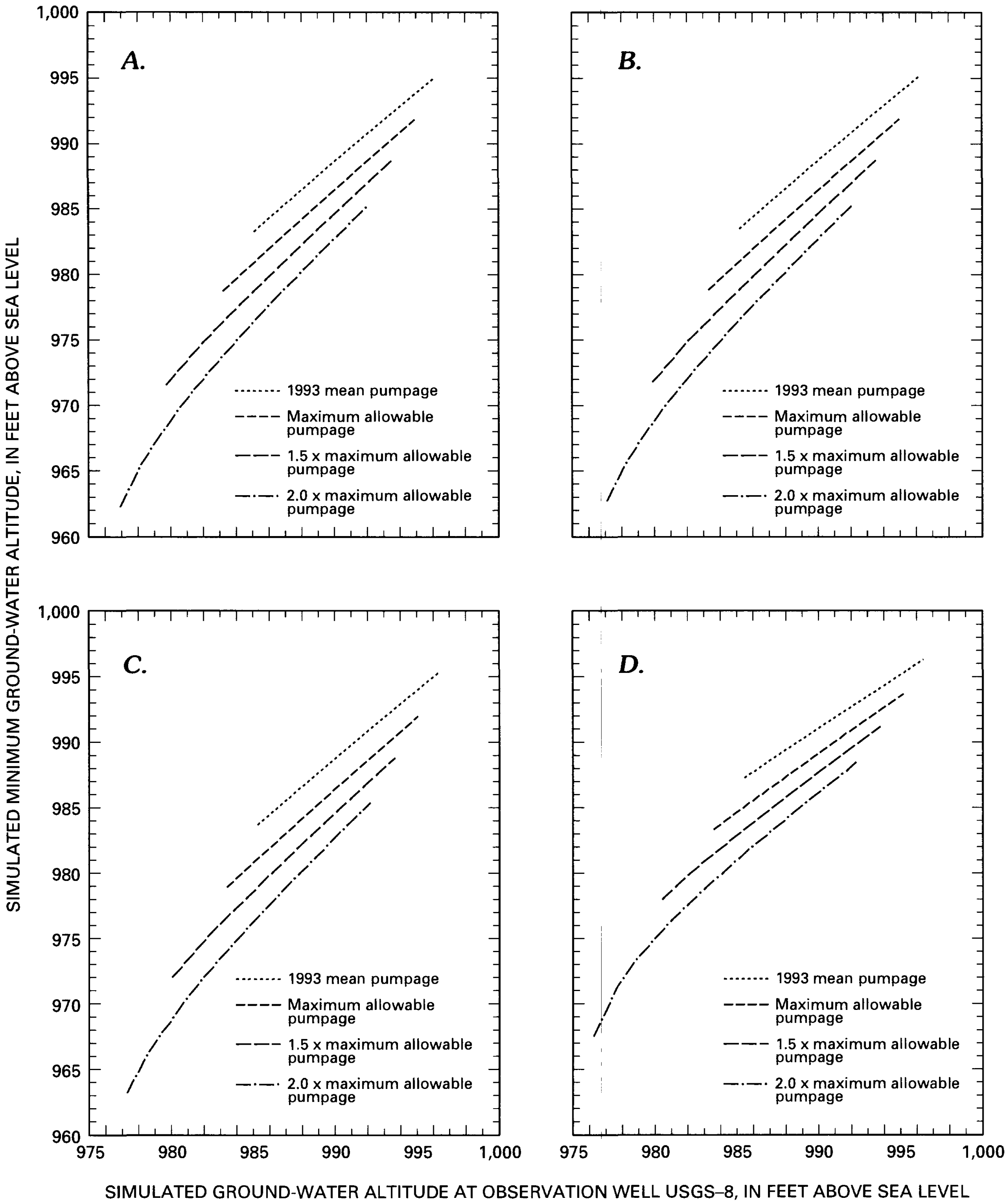


Figure 31. Relations among simulated ground-water altitudes at model cell (39,25) (observation well USGS–8) and simulated minimum ground-water altitudes in the Manhattan municipal well field for precipitation rates of (*A*) zero, (*B*) 8.22, (*C*) 16.44, and (*D*) 32.88 inches per year and simulated streamflow in Kansas River of 500 cubic feet per second.

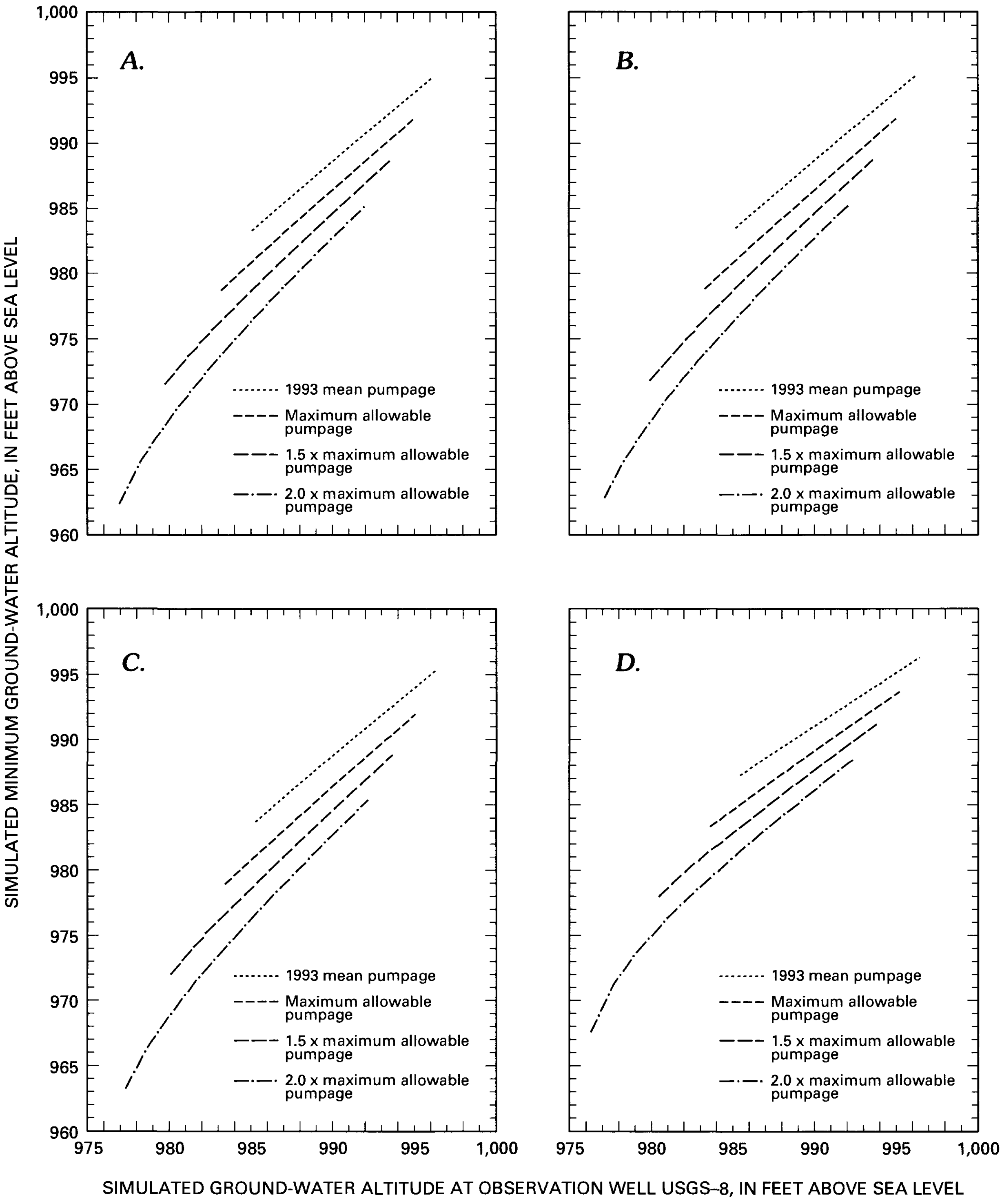


Figure 32. Relations among simulated ground-water altitudes at model cell (39,25) (observation well USGS–8) and simulated minimum ground-water altitudes in the Manhattan municipal well field for precipitation rates of (*A*) zero, (*B*) 8.22, (*C*) 16.44, and (*D*) 32.88 inches per year and simulated streamflow in Kansas River of 1,000 cubic feet per second.

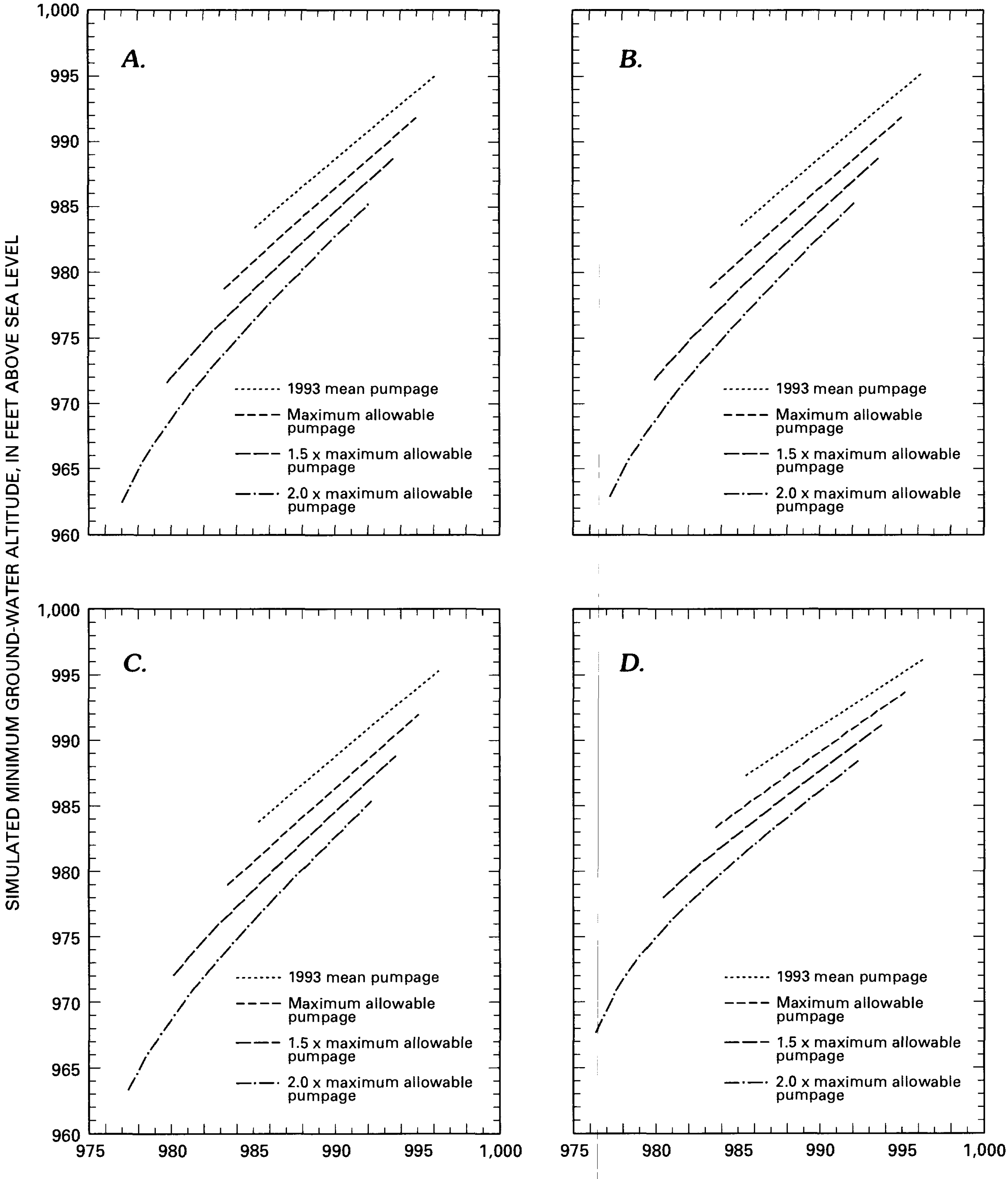


Figure 33. Relations among simulated ground-water altitudes at model cell (39,25) (observation well USGS–8) and simulated minimum and ground-water altitudes in the Manhattan municipal well field for precipitation rates of (*A*) zero, (*B*) 8.22, (*C*) 16.44, and (*D*) 32.88 inches per year and simulated streamflow in Kansas River of 3,000 cubic feet per second.

Table 11. Steady-state streamflow decrease in the Big Blue River

[Values, in cubic feet per second (ft^3/s), are the mean for all simulated Big Blue River streamflows from 100 to 10,000 ft^3/s]

Precipitation, in inches	Without pumping	1993 mean pumpage	Maximum allowable pumpage	1.5 x maximum allowable pumpage	2.0 x maximum allowable pumpage
Mean streamflow decrease in the Big Blue River for Kansas River streamflow of 250 ft^3/s					
0	-0.889	7.460	14.161	20.621	27.059
8.22	-1.455	6.894	13.597	20.060	26.499
16.44	-2.023	6.328	13.033	19.495	25.938
32.88	-3.149	5.205	11.906	18.375	24.783
Mean streamflow decrease in the Big Blue River for Kansas River streamflow of 500 ft^3/s					
0	-0.885	7.462	14.162	20.622	27.058
8.22	-1.451	6.897	13.599	20.060	26.498
16.44	-2.017	6.332	13.034	19.496	25.939
32.88	-3.144	5.208	11.908	18.377	24.782
Mean streamflow decrease in the Big Blue River for Kansas River streamflow of 1,000 ft^3/s					
0	-0.882	7.463	14.163	20.622	27.057
8.22	-1.448	6.897	13.599	20.059	26.497
16.44	-2.014	6.332	13.035	19.495	25.938
32.88	-3.142	5.210	11.910	18.378	24.788
Mean streamflow decrease in the Big Blue River for Kansas River streamflow of 3,000 ft^3/s					
0	-0.855	7.486	14.183	20.640	27.074
8.22	-1.423	6.920	13.621	20.080	26.516
16.44	-1.989	6.357	13.057	19.516	25.956
32.88	-3.115	5.234	11.932	18.398	24.802

the Big Blue River than to streamflow changes in the Kansas River because of the Big Blue River's closer proximity to the well field, narrower channel, and smaller slope. For equivalent streamflow increases in a narrow or a wide channel, stream stage would increase more in the narrow channel and thus would have more effect on ground-water altitudes in the adjacent aquifer. However, changes in Kansas River streamflow can affect Big Blue River stage when the Big Blue River exhibits a backwater condition.

For the steady-state simulations of hypothetical conditions, the magnitude of streamflow decrease in the Big Blue River at the Manhattan municipal well field generally was controlled by recharge from precipitation, well-field pumpage, and streamflow provided that stream-channel geometry and streambed hydraulic parameters remain unchanged. Differences in streamflow decreases in the municipal well field for different recharge rates are small but are larger for different pumping rates (table 11). Changes in well-field pumpage had the largest effect on streamflow decreases. Differences in streamflow decreases for various recharge rates are small because the Manhattan municipal well field is very close to the Big Blue River and because steady-state simulations assume that ground water in the aquifer is in equilibrium with recharge, pumping stresses, and streamflow. Under steady-state conditions, a specified recharge rate or streamflow will produce higher or lower hydraulic heads in the aquifer but, compared to the effect of different Manhattan municipal well pumpage rates, would produce only small differences in the amount of water flowing between the stream and aquifer in the well field (table 12). However, under transient conditions, changes in recharge or streamflow may produce large but transient changes in the amount of water flowing between the stream and aquifer, which will diminish with time and eventually approach steady-state values if recharge, pumpage, and streamflow remain constant.

The digital model is, by its nature, a simplification of the natural stream-aquifer system and can not reproduce the level of geologic or hydrologic detail

Table 12. Difference between simulated steady-state Big Blue River streamflow decrease for Big Blue River streamflows of 100 and 10,000 cubic feet per second

[Values are in cubic feet per second, ft^3/s.]

Precipitation, in inches	Difference without pumping	Difference with 1993 mean pumpage	Difference with maximum allowable pumpage	Difference with 1.5 x maximum allowable pumpage	Difference with 2.0 x maximum allowable pumpage
		Kansas River streamflow of 250 ft^3/s			
0	0.225	0.180	0.165	0.625	0.958
8.22	.230	.182	.167	.605	.931
16.44	.234	.179	.172	.573	.903
32.88	.239	.181	.174	.534	1.136
		Kansas River streamflow of 500 ft^3/s			
0	.237	.181	.160	.618	.958
8.22	.234	.181	.165	.600	.932
16.44	.246	.181	.174	.568	.905
32.88	.251	.185	.173	.532	1.134
		Kansas River streamflow of 1,000 ft^3/s			
0	.251	.188	.168	.605	.940
8.22	.252	.188	.170	.579	.917
16.44	.258	.187	.181	.553	.891
32.88	.275	.197	.178	.516	1.120
		Kansas River streamflow of 3,000 ft^3/s			
0	.264	.199	.177	.601	.930
8.22	.269	.200	.184	.579	.896
16.44	.266	.203	.183	.550	.891
32.88	.277	.198	.183	.509	1.106

present in the natural system. The digital model is limited in representing the natural stream-aquifer system by the accuracy of measurements of hydraulic conductivity, aquifer thickness, recharge, streamflow, and pumping and by the spatial and temporal discretization of these parameters in the model. Because of these limitations, the digital model may not accurately represent hydrologic stresses such as the location of cones of drawdown caused by pumping wells or the duration of transient stresses such as well pumping, changing streamflow, or precipitation. None-the-less, the digital model is a useful tool for projecting the average or long-term effects of hydrologic stresses, such as municipal well-field pumping, on the hydrologic system.

SUMMARY AND CONCLUSIONS

In 1992, a 3-year study was undertaken to determine the effects of pumping municipal wells in the alluvial aquifer at Junction City and Manhattan, Kansas, on streamflows in the Republican, Big Blue, and Kansas Rivers. This report presents the effects of known and hypothetical municipal well-field pumping at Manhattan on streamflow in the Big Blue and Kansas Rivers.

A network of observation wells, including wells drilled by the USGS during the study, was established for the purpose of collecting water-level and other hydrogeological data in and around the municipal well field. Eleven observation wells were equipped with water-level recording instruments; other wells in the network were measured about monthly with a steel tape. A stage-only surface-water-gaging station on the Big Blue River was established at the well field and was equipped with a water-level recording instrument. Geologic information was recorded while drilling, and gamma-ray logs were obtained from observation wells drilled to bedrock during the study. Water levels were used to construct potentiometric-surface maps for selected dates. An aquifer test was conducted during August 1994 using an irrigation well in the study area.

Alluvial and terrace deposits of the Big Blue and Kansas Rivers form the surficial materials in the study area. The alluvium is as much as 90-ft thick and generally consists of sand and gravel, coarse-to-fine sand, and silt, with some interbedded clay layers. The coarsest sediments generally are found near the bottom of the alluvial deposits. Terrace deposits consist of fining-upward sequences of gravel, sand, silt, and clay. Alluvial and terrace deposits are underlain by shale and limestone of Permian age.

Flow in the Big Blue and Kansas Rivers was largely unregulated until a series of dams were constructed during the 1960's for flood control and other purposes. Since 1962, streamflow in the Big Blue River downstream from Tuttle Creek Dam has been completely regulated.

Ground water in the alluvial aquifer is unconfined throughout the study area. Saturated thickness ranges from zero to about 70 ft. Potentiometric-surface maps for May 25–26, 1993, and December 7–8, 1994, show that ground water in the alluvial aquifer generally flows down the valley and either towards or away from the rivers. A depression in the water table has formed in the vicinity of the Manhattan municipal well field. Ground water in the vicinity of the well field flows towards the pumping wells. Water-level data collected during this study indicate that the Big Blue River and alluvial aquifer are an integrated system and that there is a strong correlation between river water-surface and ground-water altitudes.

Aquifer property data, gathered from various sources, indicates that hydraulic conductivity ranges from about 200 to 960 ft/d, specific yield ranges from 0.10 to 0.25, and the streambed hydraulic gradient in the Big Blue River streambed near the well field ranges from 0.03 to 0.39. Streambed hydraulic conductivity of the Big Blue and Kansas River streambeds is assumed to be about 1 ft/d.

The effects of pumping on streamflow depends on several factors, including the hydraulic conductivity of the streambed and aquifer, the saturated thickness and specific yield of the aquifer, the distance between the wells and river, and well-pumping rates. Pumping wells close to a stream affect streamflow sooner and to a greater extent than wells farther from the stream. A streamflow decrease because of well pumping may not consist entirely of water from the stream (induced infiltration) but may consist partially of ground water that would have become base flow in the stream under a nonpumping hydraulic gradient (intercepted base flow), or may consist entirely of intercepted base flow.

For the conceptual model of the stream-aquifer system, the alluvial aquifer was represented as an unconfined aquifer with boundaries, recharge, and discharge. Boundaries included relatively impermeable bedrock located under and surrounding the model area except for the upstream and downstream cross-sectional areas within the river valley. Recharge to the aquifer may result from precipitation, subsurface inflow to the aquifer, seepage from streams, and agricultural and urban water applications. Discharge from the aquifer may result from subsurface outflow, pumping, evapotranspiration, and seepage to rivers. Recharge from precipitation for May 1993 and October 16 through November 14, 1994, within the conceptual model area was estimated from precipitation data to be 16.3 and 0.7 ft^3/s, respectively. Subsurface inflow to the aquifer was estimated to be 17.3 and 2.3 ft^3/s for May 1993 and October 16 through November 14, 1994, respectively. Subsurface outflow from the aquifer was estimated to be 2.2 and 1.0 ft^3/s for May 1993 and October 16 through November 14, 1994, respectively. Seepage from streams during May 1993 was estimated to be 20.5 ft^3/s for the Big Blue River and 19.3 ft^3/s for the Kansas River. Seepage from streams during October 16 through November 14, 1994, was estimated to be 7.7 ft^3/s for the Big Blue River and 6.4 ft^3/s for the Kansas River. Municipal well discharges from the aquifer in the conceptual model area for May 1993 and October 16 through November 14, 1994, were 7.0 and 8.5 ft^3/s, respectively.

A finite-difference, ground-water flow model (MODFLOW) was used to simulate the stream-aquifer system. The one-layer, finite-difference grid consisted of 42 columns and 60 rows of cells. No-flow cells were used to represent the physical edge of the aquifer and ground-water divides. General cells represented active model cells. General-head cells were used to represent the hydraulic connection between the model and the laterally adjacent aquifer. Stream cells were used to represent the Big Blue and Kansas Rivers. Pumping cells were used to represent locations where water was pumped out of the aquifer. Aquifer properties used in the models were: hydraulic conductivity, 650 ft/d; specific yield, 0.20; and streambed vertical hydraulic conductivity, 1 ft/d. Stresses included in the model were recharge from precipitation, well pumpages, and streamflow.

The model was calibrated to May 1993 conditions and verified to October 16 through November 14, 1994, conditions. Calibration and verification involved a number of trial simulations in which values of aquifer properties were adjusted within reasonable ranges. Initial hydraulic heads for the May 1993 and October 16 through November 14, 1994, transient simulations were determined using steady-state model simulations of climatic, pumping, and streamflow conditions that existed during the month preceding May 1993 and during October 1–15, 1994, which preceded October 16 through November 14, 1994.

For the May 1993 calibration period, the maximum root mean square of the difference between measured and simulated ground-water altitudes at observation wells was 1.00 ft. Simulations of May 1993 conditions indicate that well-field pumping decreased simulated streamflow in the Big Blue and Kansas Rivers by 5.28 ft^3/s for the month, of which 3.22 ft^3/s was contributed from the stream (induced infiltration) and 2.06 ft^3/s was contributed from ground water that would have seeped to the stream if the wells had not been pumping (intercepted base flow). Total well-field pumpage for May 1993 was about 414 acre-ft. About 48 percent of the total well-field pumpage was from induced infiltration and about 31 percent was from intercepted base flow.

For the verification period, the maximum root mean square of the difference between measured and simulated ground-water altitudes at observation wells was 0.62 ft. Simulations of October 16 through November 14, 1994, conditions indicate that well-field pumping decreased simulated streamflow in the Big Blue and Kansas Rivers by 6.67 ft^3/s for the period, of which 6.51 ft^3/s was from induced infiltration and 0.16 ft^3/s was from intercepted base flow. Total well-field pumpage for October 16 through November 14, 1994, was about 506 acre-ft. About 76 percent of the total well-field pumpage was from induced infiltration, and about 2 percent was from intercepted base flow.

A series of 1,920 steady-state simulations of hypothetical conditions were conducted to compare ground-water altitudes in the Manhattan municipal well field to different precipitation, pumpages, and streamflows. Pumping rates used in these simulations were (1) no pumping, (2) the 1993 mean pumpage, (3) the maximum allowable pumpage, (4) 1.5 times the maximum allowable pumpage, and (5) 2.0 times the maximum allowable pumpage. Hypothetical Big Blue River streamflows used in the simulations ranged from 100 to 10,000 ft^3/s. Kansas River streamflows ranged from 250 to 3,000 ft^3/s. On the basis of the simulations, the streamflow required to produce a desired average ground-water altitude in the municipal well field for a selected pumpage rate can be determined. For example, given no precipitation, 1993 mean pumpage, and Kansas River streamflow between 250 and 3,000 ft^3/s, a Big Blue River streamflow of 2,000 ft^3/s is required to produce an average ground-water altitude in the well field of 988 ft. The drawdown in the well field for all 1,920 simulations, using 1993 mean pumpage, averaged about 2.4 ft and was not very sensitive to differences in precipitation or streamflow. For the steady-state simulations, differences in streamflow loss due to differences in precipitation or streamflow were small. The steady-state simulations approximate long-term average conditions.

The digital model is a simplification of the stream-aquifer system and is limited in simulating the natural system by the accuracy of data used to construct the model and by spatial and temporal discretization. None-the-less, the digital model is a useful tool for projecting the long-term effects of hydrologic stress on the hydrologic system.

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SUPPLEMENTARY INFORMATION

Table 13. Lithologic logs of wells drilled by U.S. Geological Survey and Kansas Water Office during this study
[Location of observation wells is shown in figure 2. All altitudes are referenced to sea level and are reported to the nearest 0.01 foot. Depth of well is reported in feet below land surface]

Observation well USGS–1—Drilled September 2–3, 1992.
Altitude of land surface, 1,010.48 feet.

	Thickness, in feet	Depth, in feet
Fill, brown, clay, silty, pieces of broken glass, concrete, and brick	6	6
Silt, light-tan to brown, clayey	6	12
Sand, orange, fine, mostly quartz	9	21
Sand, gray, fine, clayey	3	24
Sand and gravel, gray, medium-to-coarse, mostly quartz, feldspar, limestone, and chert	14	38
Sand and gravel, grayish-tan, coarse; comprised of quartz, feldspar, limestone, and chert; cobbles and boulders likely at 65 feet; some 0.75- to 1-inch-diameter material in auger flights; drilling stopped on hard bedrock	31	69

Observation well USGS–2—Drilled September 4, 1992.
Altitude of land surface, 1,009.38 feet.

	Thickness, in feet	Depth, in feet
Road fill, comprised of soil and gravel	1	1
Soil, brown, clayey to silty, fining upward	11	12
Silt, brown, sandy to clayey	4	16
Silt, gray, clayey; mud balls	4	20
Wood	1	21
Clay, gray, silty	4	25
Sand and gravel, comprised of quartz, feldspar, limestone, and chert; coarse gravel at 36 feet	40	65
Gravel and cobbles, very coarse; limestone, chert, and red quartzite; drilling stopped on hard bedrock	4	69

Observation well USGS–3—Drilled September 9, 1992.
Altitude of land surface, 1,007.77 feet.

	Thickness, in feet	Depth, in feet
Soil, brown, clayey to silty	5	5
Sand, orange, fine-to-medium	5	10
Sand and gravel, tannish-gray, medium-to-coarse; comprised of quartz, feldspar, limestone, and chert; clay layer at 10 to 15 feet; drilling stopped on hard bedrock	57	67

Observation well USGS–4—Drilled September 10, 1992.
Altitude of land surface, 1,008.61 feet.

	Thickness, in feet	Depth, in feet
Silt, tan	2	2
Soil, dark-brown, silty	9	11
Sand, tan, fine, clayey	1	12
Clay, brown, silty	2	14
Sand, tan, fine-to-medium, coarse sand at 18 feet	10	24
Sand and gravel, orange; comprised of quartz, feldspar, limestone, and chert; coarse gravel zones at 40, 45, and 50 to 67 feet; drilling stopped on hard bedrock	43	67

Observation well USGS–5—Drilled September 15, 1992.
Altitude of land surface, 1,009.00 feet.

	Thickness, in feet	Depth, in feet
Silt, tan,	4	4
Silt and fine sand, tan	2	6
Silt, tan	8	14
Silt, brown, clayey	3	17
Sand and gravel, orange; comprised of quartz, feldspar, limestone, and chert; some gravel 2 inches in diameter; drilling stopped in sand and gravel	21	38

Observation well USGS–6—Drilled September 15, 1992.
Altitude of land surface, 1,009.10 feet.

	Thickness, in feet	Depth, in feet
Silt, tan, hard	4	4
Silt and fine sand, tan	2	6
Silt, tan	7	13
Silt, brown, clayey	5	18
Sand and gravel, orange; comprised of quartz, feldspar, limestone, and chert; coarse gravel at 32 and 68 feet; drilling stopped on hard bedrock	50	68

Observation well USGS–7—Drilled September 17, 1992.
Altitude of land surface, 1,009.45 feet.

	Thickness, in feet	Depth, in feet
Soil, brown, clayey to silty	3	3
Sand, tan, fine	1	4
Silt, tan, clayey	4	8
Sand, orange, fine	2	10
Silt, tannish-gray, clayey	7	17
Sand and gravel, arkosic, and quartzose, with pieces of chert and limestone; coarse gravel at 27, 37, and 45 feet; drilling stopped in sand and gravel	33	50

Observation well USGS–8—Drilled October 6, 1992.
Altitude of land surface, 1,009.31 feet.

	Thickness, in feet	Depth, in feet
Soil, brown, clayey to silty	3	3
Silt, tan	4	7
Silt, brown, clayey	9	16
Sand, orange, medium-to-fine	14	30
Sand and gravel, abundant quartz and feldspar, with pieces of chert and limestone; coarse gravel at 45 feet and larger cobbles below 58 feet; drilling stopped on hard bedrock	36	66

Observation well USGS–9—Drilled October 6, 1992.
Altitude of land surface, 1,010.26 feet.

	Thickness, in feet	Depth, in feet
Soil, brown, clayey to silty	2	2
Silt, tan, clayey in lower part of interval	5	7
Sand, tan, fine, clayey	8	15
Silt and sand, brown, fine, clayey	7	22
Sand and gravel, comprised of quartz, feldspar, limestone, and chert; most material looks like gravel pack; coarse gravel at 25 feet and cobbles below 60 feet; drilling stopped on hard bedrock	44	66

Observation well USGS–10—Drilled October 6, 1992.
Altitude of land surface, 1,009.37 feet.

	Thickness, in feet	Depth, in feet
Soil, brown, clayey to silty	6	6
Silt, tannish-gray, brown, clayey	5	11
Silt and fine sand, tan	3	14
Sand, tan, fine	2	16
Sand, brown, clayey to silty	2	18
Sand, tan, fine	4	22
Clay, gray, silty	2	24
Sand and gravel, tannish-gray; comprised of quartz, feldspar, limestone, and chert; coarse gravel at 40, 42, 46, and 52 feet; coarse gravel at 66 feet	42	66
Shale; drilling stopped	0.5	66.5

Observation well USGS–11—Drilled April 30, 1993.
Altitude of land surface, 1,007.90 feet.

	Thickness, in feet	Depth, in feet
Soil, dark-brown, clayey	6	6
Silt, tannish-gray, slightly clayey	8	14
Silt, tannish-gray, clayey	8	22
Sand and gravel, comprised of quartz, feldspar, limestone, and chert; very coarse sand and gravel at 50 and 67 feet	45	67
Shale, green; drilling stopped	0.2	67.2

Observation well USGS–500E—Drilled April 27, 1993.
Altitude of land surface, 1,013.85 feet.

	Thickness, in feet	Depth, in feet
Soil and clay, brown, silty	6	6
Sand, tan, fine	1	7
Clay, tannish-brown, silty	3	10
Clay, tannish-brown, silty and sandy	5	15
Sand, tan, fine	5	20
Sand and gravel, comprised of quartz, feldspar, limestone, and chert; sand and gravel grading coarser at 30 and 50 feet	45	65
Shale, green, hard; drilling stopped	1.2	66.2

Observation well USGS–250E—Drilled April 28, 1993.
Altitude of land surface, 1,014.69 feet.

	Thickness, in feet	Depth, in feet
Soil, dark-brown, silty	4	4
Silt, tan, clayey	3	7
Sand, tan, fine	3	10
Silt, tan, clayey	1	11
Sand, tan, fine	14	25
Sand and gravel, comprised of quartz, feldspar, limestone, and chert; drills like coarse gravel at 55 feet and material looks like gravel pack below 65 feet	52	77
Sand, tan, fine	8.5	85.5
Shale, gray, weathered, clayey; drilling stopped	2.5	88

Observation well USGS–50E—Drilled April 28, 1993.
Altitude of land surface, 1,015.19 feet.

	Thickness, in feet	Depth, in feet
Soil, brown, silty	3	3
Silt, tan, slightly clayey	7	10
Silt, tan, clayey	3	13
Sand, tan, coarse; comprised of quartz, feldspar, limestone, and chert	17	30
Sand and gravel, orange; comprised of quartz, feldspar, limestone, and chert	47	77
Sand, tan to gray, fine; comprised of quartz	15.5	92.5
Shale, gray, weathered; drilling stopped	0.5	93

Observation well USGS–50W—Drilled May 17, 1993.
Altitude of land surface, 1,014.57 feet.

	Thickness, in feet	Depth, in feet
Soil, clayey, silty, brown	3	3
Silt and fine sand, tan, clayey	10	13
Sand, tan, fine	4	17
Sand, coarse, white shells; comprised of quartz, feldspar, limestone, and chert	19	36
Sand and gravel, orange; comprised of quartz, feldspar, limestone, and chert	31	67
Clay, blue-gray, sticky	3	70
Sand, gray, fine	10	80
Clay, blue-gray	2	82
Sand, gray, fine	9	91
Clay, gray	1	92
Sand, gray, fine; drilling stopped on hard bedrock at 94 feet	2	94

Observation well USGS–250W—Drilled May 4, 1993.
Altitude of land surface, 1,014.66 feet.

	Thickness, in feet	Depth, in feet
Soil, brown	2	2
Silt, tan, clayey	12	14
Sand, tan, fine	13	27
Sand and gravel, comprised of quartz, feldspar, limestone, and chert; lots of shells and chert at 40 feet	43	70
Clay, gray, silty	6	76
Sand, gray, fine, silty and clayey	18	94
Shale, gray, hard; drilling stopped	0.5	94.5

Observation well USGS–500W—Drilled May 18, 1993.
Altitude of land surface, 1,014.83 feet.

	Thickness, in feet	Depth, in feet
Soil, brown	3	3
Sand, tan, silty	5	8
Silt, tan, sandy	1	9
Sand, tan, fine	6	15
Sand, tan, fine, silty	3	18
Sand and gravel, comprised of quartz, feldspar, limestone, and chert; drilling stopped on hard bedrock, possibly limestone	32	50