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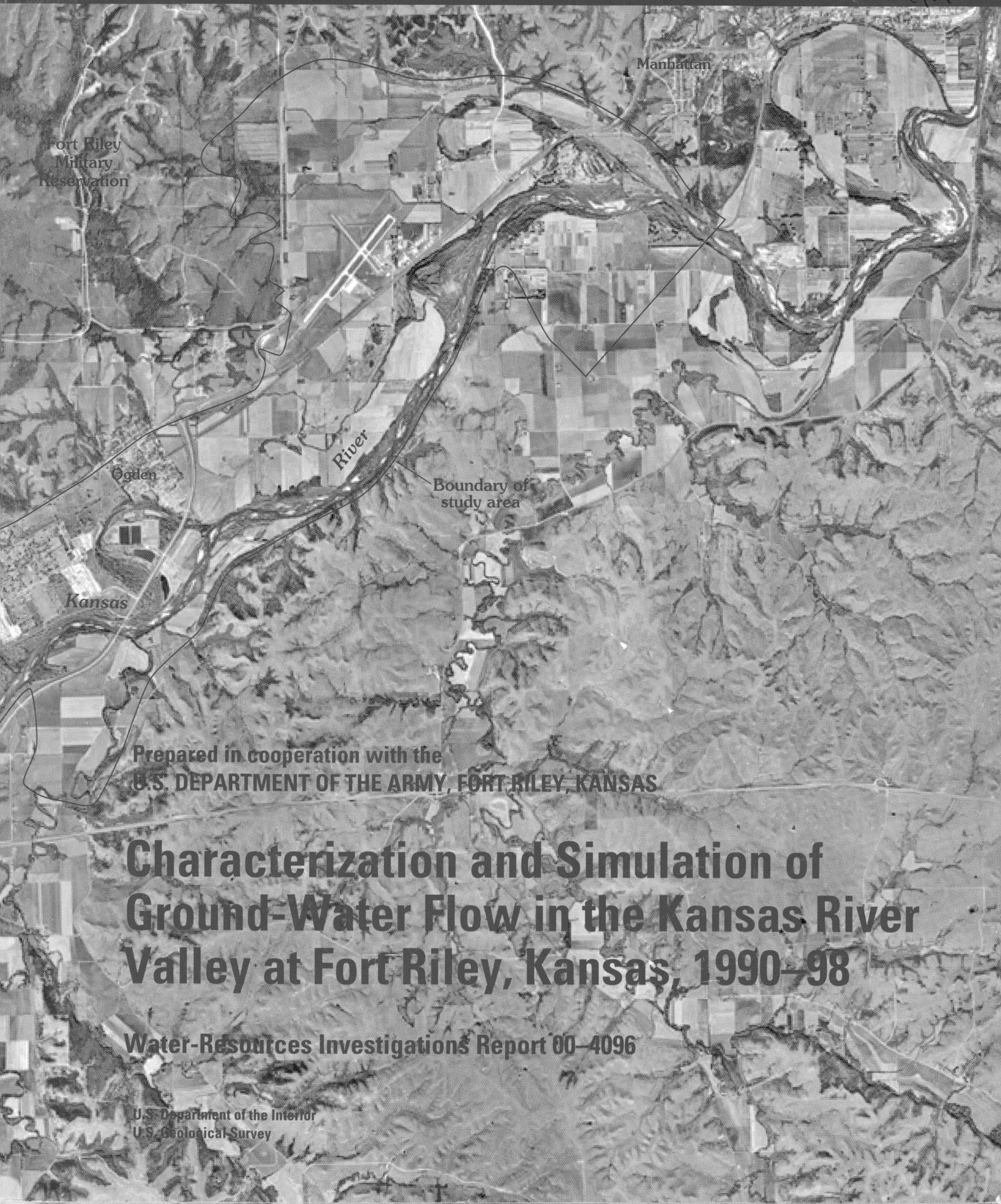

Prepared in cooperation with the
U.S. DEPARTMENT OF THE ARMY, FORT RILEY, KANSAS

Characterization and Simulation of Ground-Water Flow in the Kansas River Valley at Fort Riley, Kansas, 1990–98

Water-Resources Investigations Report 00–4096

U.S. Department of the Interior
U.S. Geological Survey

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By NATHAN C. MYERS

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U.S. DEPARTMENT OF THE ARMY, FORT RILEY, KANSAS

Lawrence, Kansas
2000

U.S. Department of the Interior

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
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 (ft/d)	0.3048	meter per day
foot per day (ft/d)	0.0003527	centimeter per second
foot per day-foot (ft/d-ft)	1.0	meter per day-meter
foot per day-foot (ft/d-ft)	1.0	centimeter per day-centimeter
foot per foot (ft/ft)	1.0	meter per meter
foot per second (ft/s)	0.3048	meter per second
foot squared per day (ft^2/d)	0.092903	meter squared per day
foot squared per day (ft^2/d)	929.03	centimeter squared per day
foot squared per second (ft^2/s)	0.092903	meter squared per second
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year
meter (m)	3.281	foot
mile (mi)	1.609	kilometer
millimeter (mm)	0.03937	inch
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C = 5/9\ (°F - 32)$$
$$°F = 9/5\ (°C) + 32.$$

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.

Conductance. A measure of the ease with which ground-water flows across some boundary or feature of interest. Mathematically, it is defined as $\frac{KA}{M}$, where K is the **hydraulic conductivity** of the material through which flow occurs, A is the area through which flow occurs, and M is the distance along which flow occurs. **Conductance** has units of cubic foot per day per foot [$(ft^3/d)/ft$]. This mathematical expression reduces to foot squared per day (ft^2/d).

Diffusivity. Equivalent to **transmissivity** divided by **storage coefficient**.

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

Hydraulic conductivity. The volume of water at the existing kinematic viscosity that will move in unit time under a unit **hydraulic gradient** through a unit area measured at right angles to the direction of flow. 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 flux. Volumetric rate of flow of water across an interface.

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

Hydraulic head. Height above a standard datum (such as sea level) of the surface of a water column that can be supported by the static water pressure at a given point in an **aquifer**.

Natural attenuation. The breakdown of a chemical compound over time resulting from microbial metabolic processes, chemical interactions, mixing with water that has smaller concentrations of the compound, and dispersion.

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**.

Porosity. The ratio of the volume of void spaces in sediment or rock to the total volume of the sediment or rock. **Porosity** is mathematically equivalent to the sum of **specific yield** plus **specific retention**.

Recharge. The processes involved in the addition of water to the saturated part of an **aquifer**.

Saturated thickness. The thickness of the zone in an **aquifer** that is saturated with water.

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

Specific retention. The ratio of the volume of water, which sediment or rock, after being saturated then drained, will retain against the pull of gravity to the total volume of the sediment or rock.

Specific storage. Volume of water that an **aquifer** releases from or takes into **aquifer storage** per unit volume of saturated **aquifer** material per unit change in **hydraulic head.**

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

Stage. The height of a water surface above an established datum plane.

Steady state. Condition under which there are no changes in **aquifer** storage, the magnitude and direction of ground-water flow velocities are constant with time, and water inflow to and outflow from the **aquifer** are equal and constant.

Storage coefficient. Volume of water that an **aquifer** releases from or takes into **aquifer** storage per unit surface area per unit change in **hydraulic head.**

Storativity. The capacity of an **aquifer** to transfer water to and from **aquifer** storage. **Storativity** is described by one or more of **specific storage, storage coefficient**, or **specific yield**.

Transient. Condition under which **aquifer** storage and the magnitude and direction of ground-water flow velocities may vary with time, and water inflow to 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).

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

Characterization and Simulation of Ground-Water Flow in the Kansas River Valley at Fort Riley, Kansas, 1990–98

By Nathan C. Myers

Abstract

Hydrologic data and a ground-water flow model were used to characterize ground-water flow in the Kansas River alluvial aquifer at Fort Riley in northeast Kansas. The ground-water flow model was developed as a tool to project ground-water flow and potential contaminant-transport paths in the alluvial aquifer on the basis of past hydrologic conditions. The model also was used to estimate historical and hypothetical ground-water flow paths with respect to a private- and several public-supply wells.

The ground-water flow model area extends from the Smoky Hill and Republican Rivers downstream to about 2.5 miles downstream from the city of Ogden. The Kansas River Valley has low relief and, except for the area within the Fort Riley Military Reservation, is used primarily for crop production.

Sedimentary deposits in the Kansas River Valley, formed after the ancestral Kansas River eroded into bedrock, primarily are alluvial sediment deposited by the river during Quaternary time. The alluvial sediment consists of as much as about 75 feet of poorly sorted, coarse-to-fine sand, silt, and clay, 55 feet of which can be saturated with ground water. The alluvial aquifer is unconfined and is bounded on the sides and bottom by Permian-age shale and limestone bedrock.

Hydrologic data indicate that ground water in the Kansas River Valley generally flows in a downstream direction, but flow direction can be quite variable near the Kansas River due to changes in river stage. Ground-water-level changes caused by infiltration of precipitation are difficult to detect because they are masked by larger changes caused by fluctuation in Kansas River stage.

Ratios of strontium isotopes Sr^{87} and Sr^{86} in water collected from wells in the Camp Funston Area indicate that the ground water along the northern valley wall originates, in part, from upland areas north of the river valley. Water from Threemile Creek, which flows out of the uplands north of the river valley, had Sr^{87}:Sr^{86} ratios similar to those in ground water from wells in the northern Camp Funston Area. In addition, comparison of observed water levels from wells CF90–06, CF97–101, and CF97–401 in the Camp Funston Area and ground-water levels simulated for these wells using floodwave-response analysis indicates that ground-water inflow from bedrock is a hydraulic stress that, in addition to the changing stage in the Kansas River, acts on the aquifer. This hydraulic stress seems to be located near the northern valley wall because the effect of this stress is greater for well CF97–101, which is the well closest to the valley wall.

Ground-water flow was simulated using a modular, three-dimensional, finite-difference ground-water flow model (MODFLOW). Particle tracking, used to visualize ground-water flow paths in the alluvial aquifer, was accomplished using MODPATH. Forward-in-time particle tracking indicated that, in general, particles released

near the Kansas River followed much more variable paths than particles released near the valley wall. Although particle tracking does not simulate solute transport, this increased path variability indicates that, near the river, ground-water contaminants could follow many possible paths towards the river, whereas more distant from the river, ground-water contaminants likely would follow a narrower corridor. Particle tracks in the Camp Funston Area indicate that, for the 1990–98 simulation period, contaminants from the ground-water study sites in the Camp Funston Area would be unlikely to move into the vicinity of Ogden's supply wells. Backward-in-time particle tracking indicated that the flow-path and recharge areas for model cells corresponding to Ogden's supply wells lie near the northern valley wall and extend into the northern Camp Funston Area. The flow-path and recharge areas for model cells corresponding to Morris County Rural Water District wells lie within Clarks Creek Valley and probably extend outside the model area.

Three hypothetical simulations, in which pumpage from Ogden's supply wells was increased by 2, 5, or 10 times 1997 pumping rates, indicate that further development of ground-water resources near Ogden could degrade the quality of water pumped from the city wells. Two hypothetical simulations in which hypothetical wells southeast of Ogden were pumped at 100 and 900 gallons per minute indicate that these hypothetical wells would obtain much of their water from the Camp Funston Area, but none of the flow-path areas for model cells corresponding to Ogden's wells or the hypothetical wells intersected the Southwest Funston Landfill. Although the hypothetical simulations indicate the general direction that ground-water contaminants would move under the simulated pumping and climatic conditions, the simulations do not indicate whether contaminants would actually reach pumping wells because the concentrations of many ground-water contaminants decrease over time as a result of naturally occurring processes such as chemical degradation, mechanical and chemical dispersion, and bacterial metabolic action.

INTRODUCTION

Background

Characterization of ground-water flow in the Kansas River Valley at the Fort Riley Military Reservation in northeast Kansas (figs. 1 and 2) is important for understanding the movement of ground-water contaminants and the source of ground water that is pumped from supply wells near Fort Riley. Site-specific studies of ground-water flow and quality, conducted by Fort Riley, at locations in the Kansas River Valley (fig. 3) have shown the presence of ground-water contamination at these sites and have indicated the potential for transport of these contaminants by ground water in the alluvial sediment of the Kansas River Valley. The local direction of ground-water flow at these sites generally is known from potentiometric-surface (water-table) maps constructed during the site-specific studies. However, the water-table maps only show the direction of ground-water flow for specific study sites at specific times when ground-water-level data were collected and do not fully characterize the variations in ground-water flow direction that are caused by water-level (stage) changes through time in the Kansas River and its tributaries.

The study described in this report began in 1995 and was designed to examine the effects of the Kansas River and its tributaries on ground-water movement in both space and time and to provide a comprehensive characterization of ground-water flow in the Kansas River Valley at and near Fort Riley (figs. 1 and 2). This study was conducted by the U.S. Geological Survey (USGS) in cooperation with the U.S. Department of the Army, Fort Riley, and was done in support of the U.S. Department of the Army's Installation Restoration Program (IRP) at Fort Riley. The ground-water flow model described herein can be used as the basis for development of site-specific models at Fort Riley. The characterization of ground-water flow and the flow model can be used to project ground-water movement in relation to supply wells at and outside of Fort Riley. This work is relevant nationwide to studies of stream-aquifer relationships in settings similar to the Kansas River Valley where changes in stream stage have significant effects on ground-water movement.

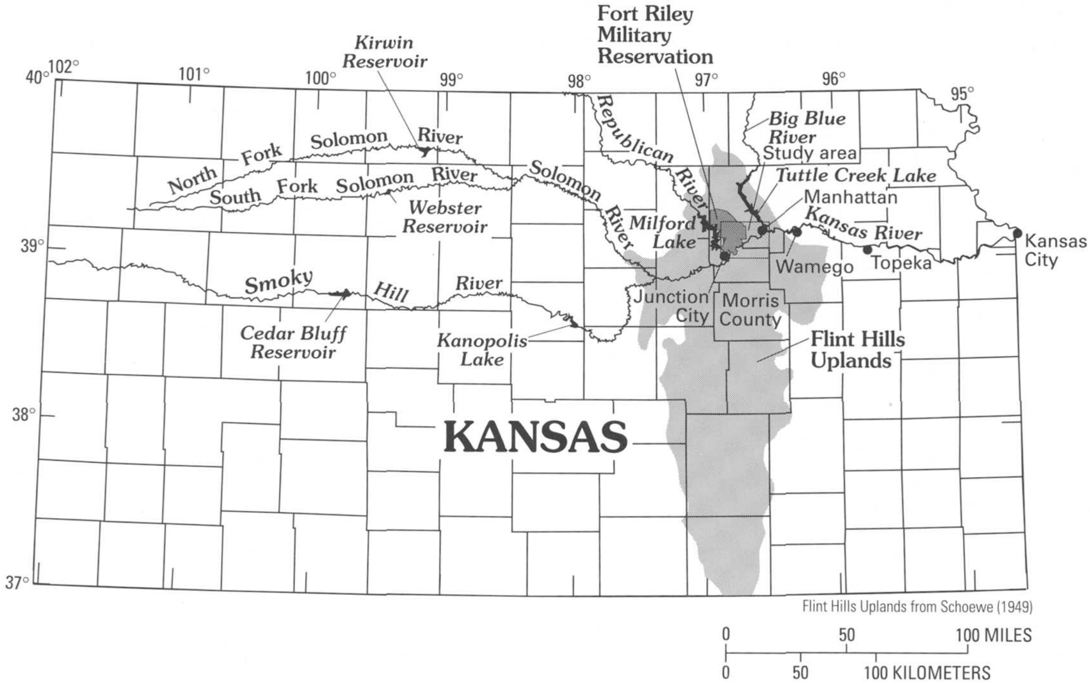


Figure 1. Location of study area at Fort Riley in northeastern Kansas.

Purpose and Scope of Report

The purpose of this report is to characterize ground-water flow in the Kansas River Valley at Fort Riley, to document a ground-water flow model developed to simulate ground-water flow in the valley, and to describe the results of 1990–98 historical and hypothetical simulations of ground-water flow using the model. This report includes descriptions of the geology and hydrology of the Kansas River Valley at Fort Riley, descriptions of aquifer characteristics incorporated into the ground-water flow model, development of the ground-water flow model, a presentation of ground-water flow and particle-tracking simulations for 1990–98, and the results of five hypothetical supply-well pumping scenarios.

Description of Study Area

The study area is located in the Kansas River Valley from Junction City to near Manhattan, Kansas (fig. 2), and includes the southernmost part of Fort Riley. Fort Riley is located in northeastern Kansas in the Flint Hills Uplands physiographic division (Schoewe, 1949), which is a prominent upland area in Kansas (fig. 1) characterized by rolling topography and deep stream valleys with steep valley walls. Near Junction City, the Republican and Smoky Hill Rivers join to form the Kansas River (fig. 2). The Kansas River Valley is characterized by landforms of low relief such as alluvial terraces near the valley walls and abandoned river channel (oxbow) lakes that were cut off from the main channel over time as the river periodically changed course.

Except for the part within the Fort Riley Military Reservation, much of the Kansas River Valley is used for crop production. Riparian zones along the Kansas River and its tributaries generally are forested or in grassland and provide important wildlife habitats. Upland areas away from the river generally serve as pasture for livestock production.

The cities nearest the southern part of Fort Riley are Junction City, Grandview Plaza, and Ogden (fig. 2). The city of Manhattan is about 7 mi northeast of southern Fort Riley along the Kansas River. All of these cities are in or border the Kansas River Valley. Ground water in the valley serves as an important source of water for these cities, for Fort Riley, and for other communities that lie in the uplands north and south of the valley. Ground water also is used for crop irrigation in the valley.

Fort Riley has served as an Army post since 1854. Its original mission was to protect pioneers and railroad trains. Over the years parts of the Kansas River Valley at Fort Riley have been used for troop housing and training (calvary and infantry), vehicle and

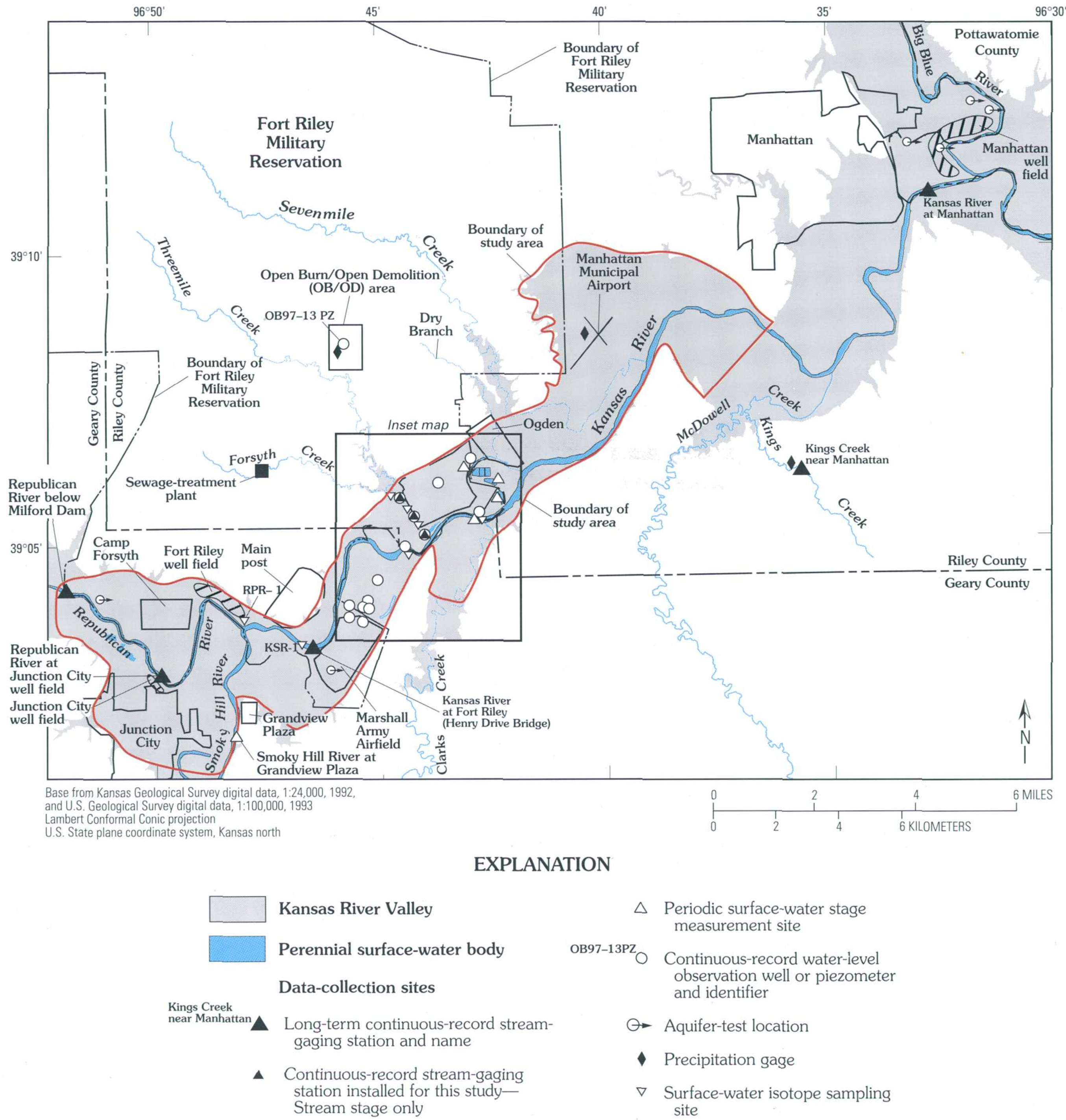


Figure 2. Kansas River Valley from Junction City to Manhattan and location of data-collection sites.

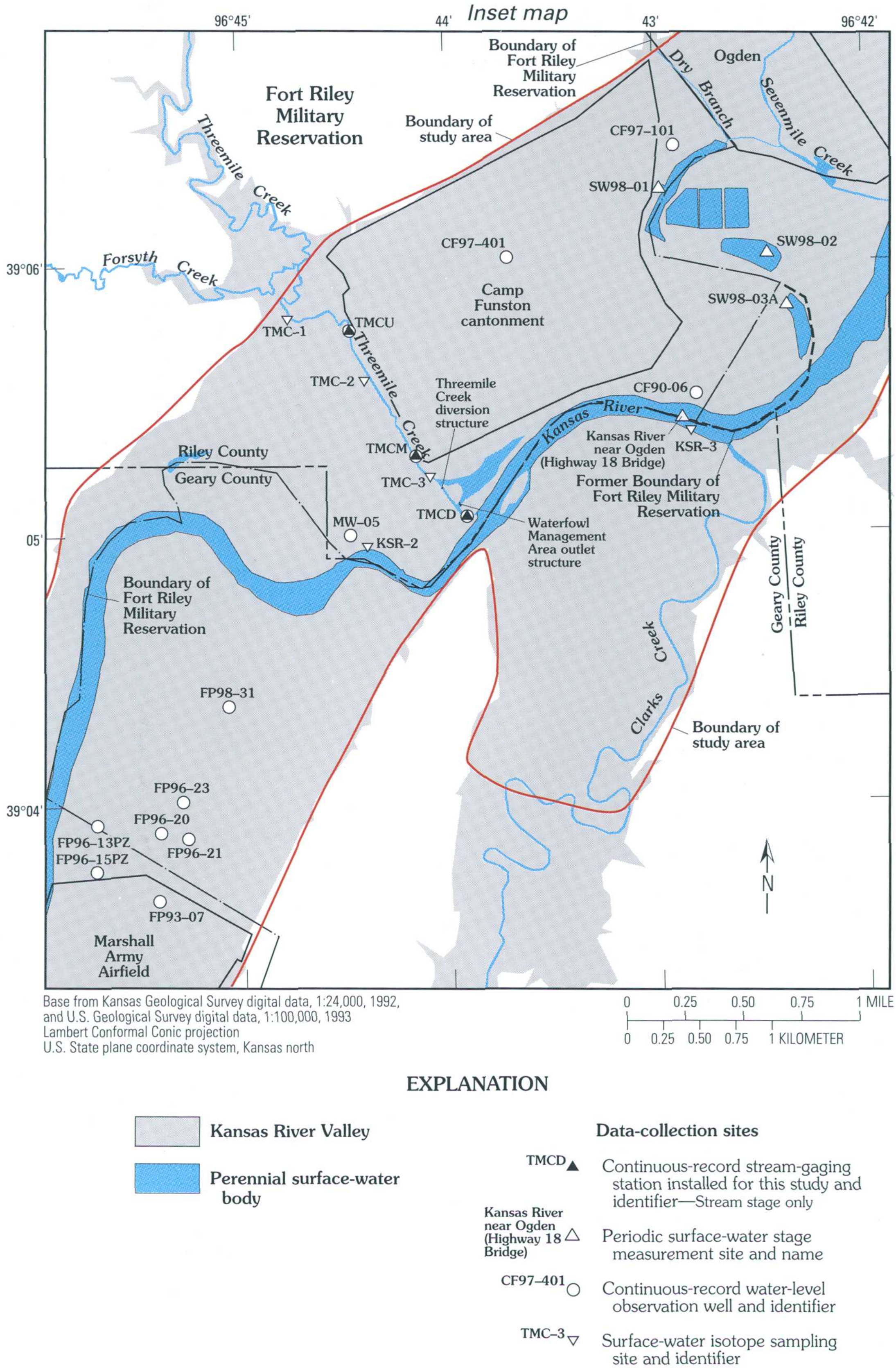


Figure 2. Kansas River Valley from Junction City to Manhattan and location of data-collection sites—Continued.

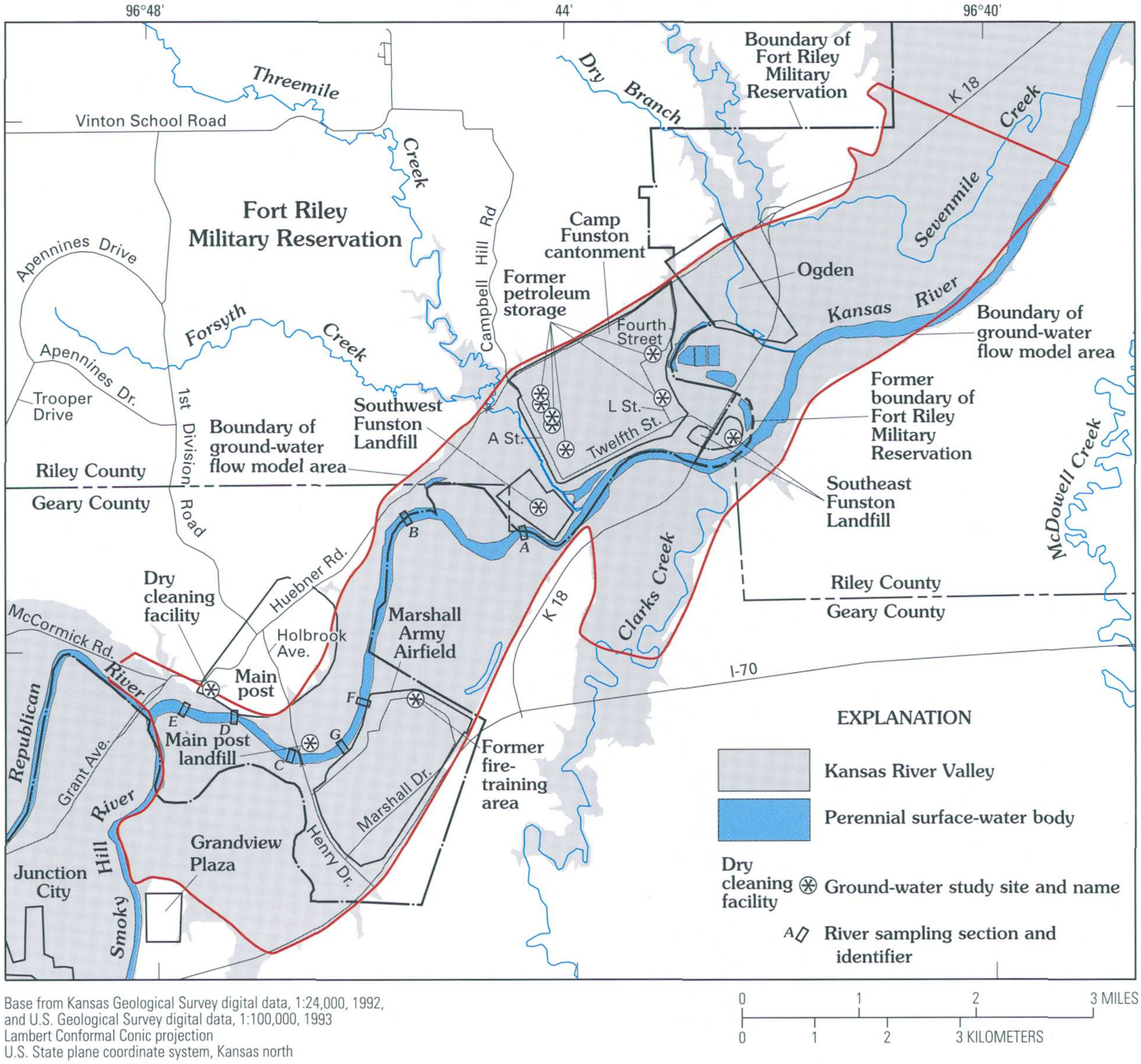


Figure 3. Location of ground-water flow model area, previous ground-water study sites, and Kansas River sampling sections in Kansas River Valley at Fort Riley.

equipment maintenance, railcar loading and unloading, warehousing of goods, clothing laundering and dry cleaning, and disposal of wastes in sanitary landfills. Some of these activities have resulted in ground-water contamination at specific sites (fig. 3) within the valley.

The ground-water flow model area covers part of the study area. It extends from the Smoky Hill River down the valley to about 2.5 mi downstream from Ogden and is wholly contained within the Kansas River Valley (fig. 3).

Well and Surface-Water Site-Identification System

Hydrogeologic studies have been done at Fort Riley by different organizations. Consequently, several different well-identification systems have been used. In 1996 Fort Riley standardized its well-identification system. Tables 12 through 15 in the "Supplemental Information" section list wells that are referenced in this report. Table 1 explains the abbreviations used in well identifiers. Wells installed on Fort Riley for the

Table 1. Explanation of abbreviations used in monitoring-well, piezometer, and surface-water-measurement or sampling-site identifiers

Abbreviation	Explanation	Abbreviation	Explanation
CF	Camp Funston Area well	PLG	Well has been plugged
D	Observation well for aquifer test at Marshall Army Airfield	PZ	Piezometer
FP	Fire training area well (Marshall Army Airfield)	RPR	Republican River sampling site
FR	Fort Riley supply well	SEFL	Southeast Funston Landfill well
GP	Grandview Plaza supply well	SFL	Southwest Funston Landfill well
IR	Irrigation well	SW	Surface-water-level measurement site
KSR	Kansas River	TMCD	Threemile Creek Downstream gaging station
MC	Morris County Rural Water District supply well	TMCM	Threemile Creek Middle gaging station
MPL	Main Post Landfill well	TMCU	Threemile Creek Upstream gaging station
MW	Southwest Funston Landfill closure well	USGS	U.S. Geological Survey observation well
OG	Ogden supply well	WMA	Waterfowl Management Area piezometers
OB	Open Burn/Open Demolition (OB/OD) area well or piezometer	WR	Well drilled for wash rack operation but never used for that purpose
P	Private-supply well		

purpose of measuring ground-water levels and collecting ground-water samples for chemical analysis are termed "monitoring wells" by Fort Riley. Wells installed for the primary purpose of measuring ground-water levels are termed "observation wells" and "piezometers." In this report monitoring wells also are called observation wells. Wells installed outside of Fort Riley were assigned identifiers by the USGS during the course of this study. Fort Riley supplies water for military and civilian use on Fort Riley from wells in the Fort Riley well field (fig. 2). In addition, the cities of Junction City and Ogden and the Morris County Rural Water District operate supply wells that provide water for public use. The city of Grandview Plaza operated supply wells until late 1990.

Observation-well identifiers generally are structured to identify an associated building or former building, the general well location, the year the well was installed, a sequence number, and a relative depth indicator. For example, well 1915CF92–03 (fig. 4) is an observation well near former building 1915, is located in the Camp Funston Area (Southwest Funston Landfill, Camp Funston cantonment, and Southeast Funston Landfill), was drilled in 1992, and is the third well drilled that year at that location, but has no relative depth indicator (last of ending three digits or letters). Observation wells not associated with buildings have identifiers that begin with the general well location. Wells with no depth indicator in their identifier generally are shallow wells whose well screen intersects the water table. Only wells in clusters of two or more have well identifiers with relative depth indicators. Well clusters at Fort Riley consist of two or more wells drilled at one location. Typically, the well screens (well intakes) of monitoring wells in a cluster are set at different depths to allow water-level and water-quality data to be collected at these various depths. Examples of well identifiers with relative

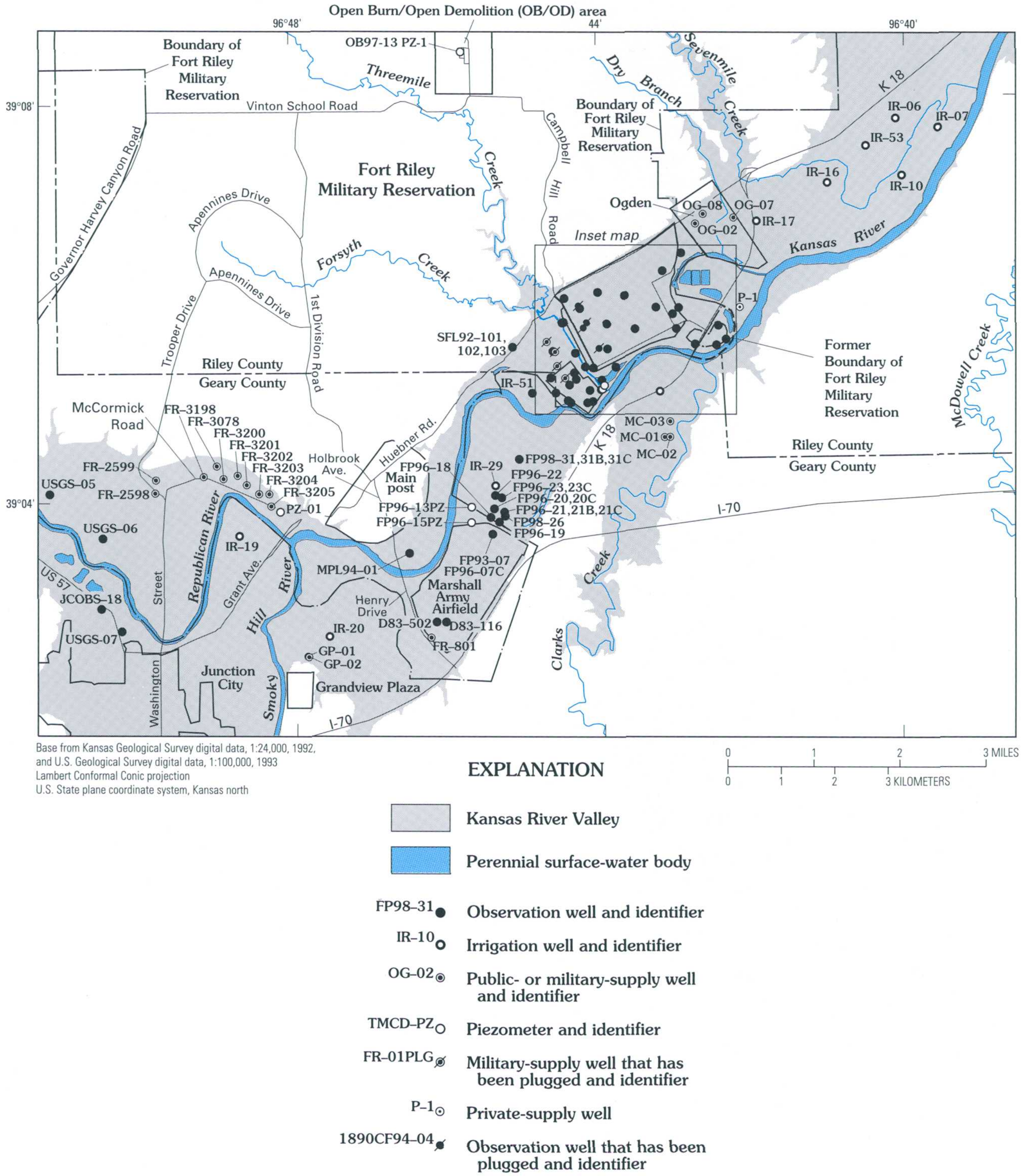


Figure 4. Location of observation, irrigation, and public-supply wells and piezometers referenced in this report.

Inset map

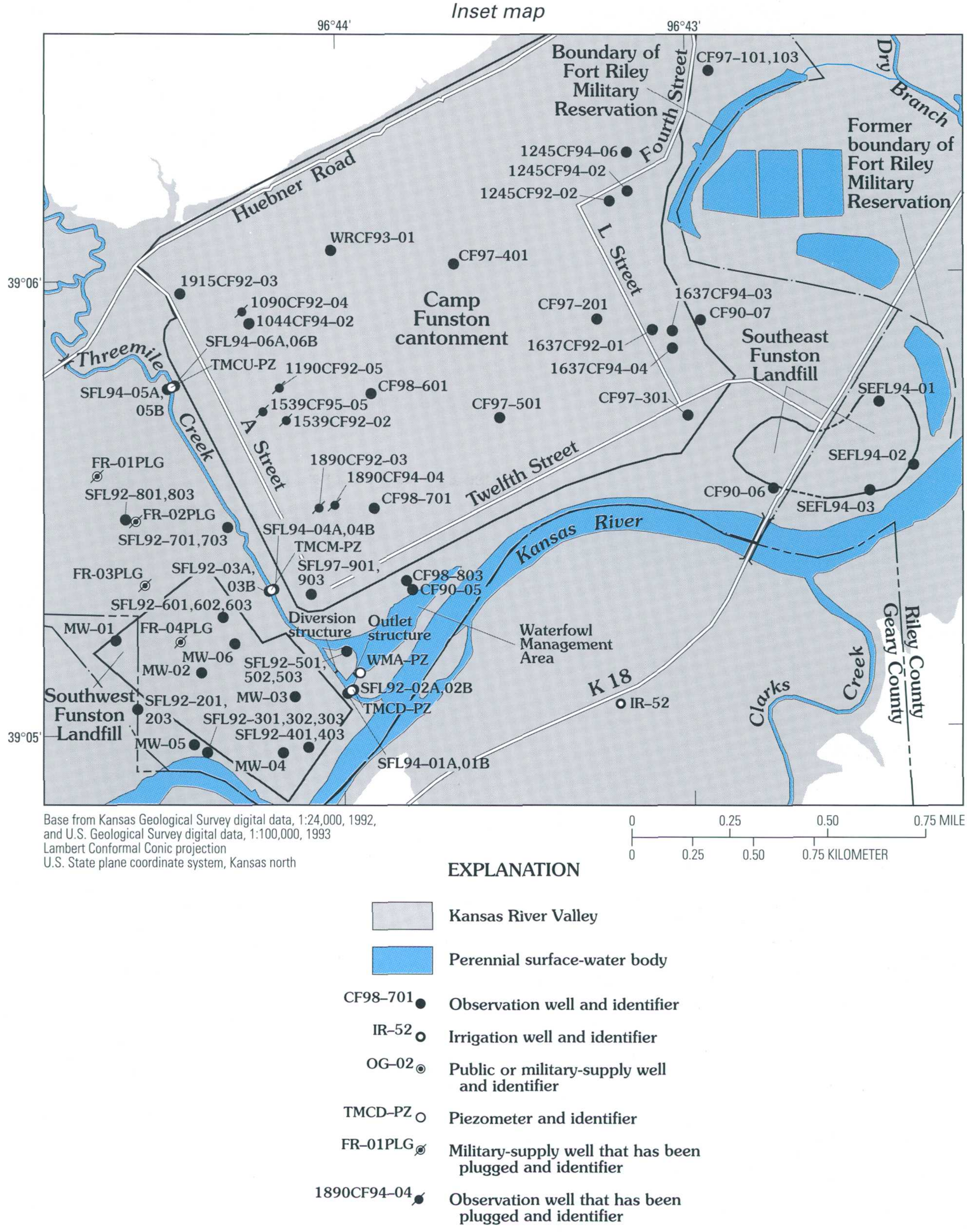


Figure 4. Location of observation, irrigation, and public-supply wells and piezometers referenced in this report—Continued.

depths are wells SFL92–101, SFL92–102, and SFL92–103 (fig. 4). These wells are located at or near the Southwest Funston Landfill, were drilled in 1992, and have well screens set at shallow (101), intermediate (102), and deep (103) depths, respectively. Wells SFL94–01A and SFL94–01B (fig. 4) are located at or near the Southwest Funston Landfill, were drilled in 1994, and have well screens set at shallow (01A) and deep depths (01B), respectively.

Observation wells and piezometers referenced in this report are listed in the "Supplemental Information" section (table 13). The identifiers for these wells generally consist of an agency or location identifier followed by a sequence number. Wells MW–01 through MW–05 were installed in 1983 at the Southwest Funston Landfill as part of the landfill closure process. Piezometers TMCD–PZ through WMA–PZ were installed along Threemile Creek (TMC) or at the Waterfowl Management Area (WMA) in 1997. Outside Fort Riley, irrigation wells (IR) were assigned sequence numbers during this study (table 14).

Wells within the study area that are used to supply water to Fort Riley or the public (fig. 4) are listed in the "Supplemental Information" section (table 15). Formerly used Fort Riley supply wells FR–01PLG through FR–04PLG have been identified in earlier reports using a "FUN" prefix (LAW Engineering and Environmental Services, 1994). These wells were plugged (PLG) and abandoned in 1990. The identifiers of Fort Riley supply wells begin with "FR" and end with a three- or four-digit number that is the Fort Riley well-house building number. Public-supply wells operated by the city of Ogden have identifiers that start with "OG" and end with a sequence number assigned by the city. Formerly used public-supply wells at Grandview Plaza have identifiers that begin with "GP" and end with a sequence number assigned for this study. Morris County Rural Water District well identifiers begin with "MC" and end with a sequence number assigned for this study.

Surface-water-measurement or sampling-site identifiers generally incorporate the name of the surface-water body or begin with "SW" ("Supplemental Information" section, table 16). Site identifiers beginning with "TMC" are surface-water stage-measurement or surface-water-sampling sites located along Threemile Creek (fig. 2). Site identifiers beginning with "KSR" or "RPR" are surface-water sampling sites located along the Kansas or Republican Rivers, respectively.

Previous Studies

Several studies provide background information for understanding the hydrogeology of the Kansas River Valley. Jewett (1941) discussed the geology of Riley and Geary Counties, and established the geologic framework for the area. Frye and Leonard (1952) discuss the Pleistocene geology of Kansas, including the nature and timing of deposition of sediment in the Kansas River Valley. Latta (1949) described ground-water conditions in the Smoky Hill Valley, including the Junction City area.

Fader's (1974) report is an important source of hydrologic information. The report describes ground-water conditions in the Kansas River Valley from Junction City to Kansas City and provides data on aquifer thickness, aquifer permeability, and ground-water storage capacity. Data from Fader's (1974) report is presented in the "Aquifer Characteristics" section of this report. Widmer Engineering Company (1941a, b) drilled numerous test holes, installed observation wells, and developed a water-table contour map of the Kansas River Valley at Fort Riley.

Three reports describe ground-water modeling studies for various parts of the Kansas River Valley. Wolf and Helgesen (1993) developed a ground-water flow model to simulate ground- and surface-water interaction between Wamego and Topeka, Kansas. Myers and others (1996) and Jian and others (1997) developed ground-water flow models to simulate the effects of ground-water pumping in municipal well fields at Junction City and Manhattan, respectively, on streamflow in adjacent rivers. The last two models were limited in extent and did not extend up or down the Kansas River Valley far enough to merge. Thus, the Kansas River Valley, from the confluence of the Republican and Smoky Hill Rivers to Manhattan has not been included previously in a ground-water flow model.

Acknowledgments

The U.S. Army Corps of Engineers (USACE) has been instrumental in providing data and logistical support for this study.

APPROACH

Tasks identified to support ground-water flow characterization and simulation for the Kansas River Valley at Fort Riley were:

- Develop a geographic information system (GIS) data base of map features, geology, hydrology, and ground-water quality;
- Use geologic, hydrologic, and water-quality data to characterize ground-water flow; and
- Develop a ground-water flow model that can be used to simulate historic ground-water flow, simulate ground-water flow for selected hypothetical conditions, simulate the effects of the Kansas River and tributary creeks on ground-water flow, and delineate ground-water flow-path and recharge areas for supply wells.

Activities supporting these tasks are detailed in the following paragraphs.

Many of the basic map features of Fort Riley, such as roads, buildings, fences, levees, utilities, topographic contours, hydrography, elevation points, and boundaries, were available in digital form from Fort Riley. Features not available in digital form (changes to existing features and new features) were added to the GIS data base by digitizing from paper maps or by entering feature coordinates. Basic map features for areas outside of Fort Riley were obtained from USGS 1:100,000 digital line graph files available from the Earth Resources Observation Systems (EROS) Data Center in Sioux Falls, South Dakota. This map data included roads, railroads, and streams. Topographic data for Fort Riley were obtained from Fort Riley in digital form. Topographic data for areas outside of Fort Riley were obtained from USGS hypsographic data sets (Juracek and Hansen, 1995). The X-Y coordinates and measuring-point altitudes of observation wells and piezometers were determined by USACE or surveyors contracted by USACE. These coordinates and altitudes were available in electronic and paper formats. Coordinates for wells outside of Fort Riley were determined using a global positioning system (GPS) receiver that was accurate to within about 300 ft. Measuring-point altitudes for wells outside of Fort Riley were estimated from a USGS 1:24,000-scale topographic map with a contour interval of 2.5 m (about 8.2 ft). The accuracy of these measuring-point altitudes was one-half of the contour interval or 1.25 m (about 4.1 ft).

Data from observation-well and piezometer construction (borehole depth, lithology, well depth, and screen interval) were available primarily in paper form and were manually entered into the GIS data base. Ground-water-level data were obtained in paper and electronic forms. Ground-water-level data were collected periodically by the USACE or its consultants at times of ground-water sampling (July and November 1992; February, May, and October 1993; October 1994; December 1995; May and November 1996; June and November 1997; May and December 1998; and June 1999). These water levels were measured to the nearest 0.01 ft using an electric tape.

Periodic ground-water-level data also were collected in April and September 1997 and April 1998 by the USGS from wells in the Kansas River Valley between Junction City and Manhattan, including wells at Fort Riley (fig. 4). Ground-water levels obtained from wells outside of Fort Riley were measured to the nearest 0.01 ft using a steel tape or an electric tape. Ground-water levels obtained from wells at Fort Riley were measured to the nearest 0.01 ft using an electric tape.

In addition, hourly ground- and surface-water levels were obtained by the USGS from selected Fort Riley wells that were equipped with electronic instruments to continuously measure, record, and transmit water levels. Manual measurements of water levels were made about every 8 weeks to ensure the quality of the electronic data. Wells or surface-water sites equipped with continuous-record water-level recorders are shown in figure 2. Some of these sites were instrumented as early as February 1995 and some as recently as January 1999. The manual and continuous-record water levels were measured to the nearest 0.01 ft.

Water samples from Fort Riley monitoring wells have been collected and analyzed by the U.S. Army, the USACE, and consulting firms using methods described in U.S. Army Corps of Engineers (1994) (sampling and analysis prior to 1994 may not have adhered to these methods). The USGS did not collect or analyze samples for this study. Water-quality data from the Camp Funston Area monitoring wells were obtained in electronic and paper forms. These data were entered into a GIS data base and were checked for errors against copies of the original laboratory analysis reports.

Characterization of ground-water flow in the Kansas River Valley focused on the Camp Funston Area to determine the potential for ground-water flow from ground-water study sites (fig. 3) to Ogden's supply wells. Also, an understanding of the effect of Threemile Creek on ground-water flow is important to assess the potential for ground-water flow from the Southwest Funston Landfill into the Camp Funston cantonment. Early in the study (1995), it was hypothesized that if Threemile Creek had a significant effect on ground-water flow then it could prevent the movement of ground-water contaminants from the Southwest Funston Landfill to the Camp Funston cantonment.

Information used to construct the ground-water flow model included geologic, hydraulic property, well-pumping, precipitation, streamflow, and stream-stage data. Geologic information was obtained from published reports including Jewett (1941), Latta (1949), and Frye and Leonard (1952). Geologic information also was obtained from records of boreholes drilled on and near Fort Riley, which were available from reports provided to Fort Riley by consultants. Hydraulic property information was obtained from published reports, such as Latta (1949) and Fader (1974), and from data collected during this study. Well pumping data were obtained from the Kansas Department of Agriculture, Division of Water Resources (DWR) (Topeka, Kansas). Pumping data obtained from DWR were for public-supply and irrigation wells for 1990–97. Pumpage volumes for 1997 were used for 1998 model simulations because, at the time of model development, pumpage data for 1998 were not available. Precipitation data were obtained from the USGS National Water Information System (NWIS) data base for a stream-gaging station on Kings Creek (fig. 2, Kings Creek near Manhattan). Precipitation data from the Kings Creek stream-gaging station were used because, at the time of model development, data from the Manhattan precipitation gage (fig. 2) were not available for the last 3 months of 1998. Precipitation data from the Kings Creek long-term stream-gaging station were compared to precipitation data from the Manhattan Municipal Airport gage and found to be similar. Streamflow and stream-stage data were obtained from the USGS NWIS data base.

GEOLOGY AND HYDROLOGY OF STUDY AREA

Geology

The Kansas River Valley was formed as the ancestral Kansas River eroded the bedrock surface (fig. 5) during Pleistocene and Holocene time (Frye and Leonard, 1952). At the bottom of the bedrock valley a narrow river channel about 20 ft deep was carved into bedrock (fig. 6). This channel does not necessarily occupy the center of the present-day river valley (Fader, 1974) but meanders back and forth across the bedrock surface.

The bedrock surface consists of Permian shale and limestone from the upper part of the Council Grove Group (Jewett, 1941). The upper part of the Council Grove Group includes, in ascending order, the Bader Limestone, Easly Creek Shale, Crouse Limestone, Blue Rapids Shale, Funston Limestone, and Speiser Shale (fig. 7). Because bedrock dips northwest in the study area and because the altitude of the bedrock surface in the valley decreases in the downstream direction (Fader, 1974), rocks at the bedrock surface would be progressively older downstream.

Surficial, unconsolidated, sedimentary deposits in the Kansas River Valley consist primarily of alluvium with some Newman terrace deposits (fig. 8) of Quaternary age. The alluvium consists primarily of coarse- to-fine sand with interbedded layers of silt and clay (Fader, 1974). The alluvium was deposited as fluvial sediment in the river channel or on the flood plain. This sediment tends to be coarser near the bottom and finer near the top of the alluvium (fig. 9) and is generally poorly sorted (table 17 in "Supplemental Information" section). The alluvium ranges in thickness from less than 1 ft near the valley walls to about 75 ft (Fader, 1974) and occupies the width and depth of the valley. The alluvium in the Kansas River Valley is bounded laterally and along the bottom by shale and limestone bedrock.

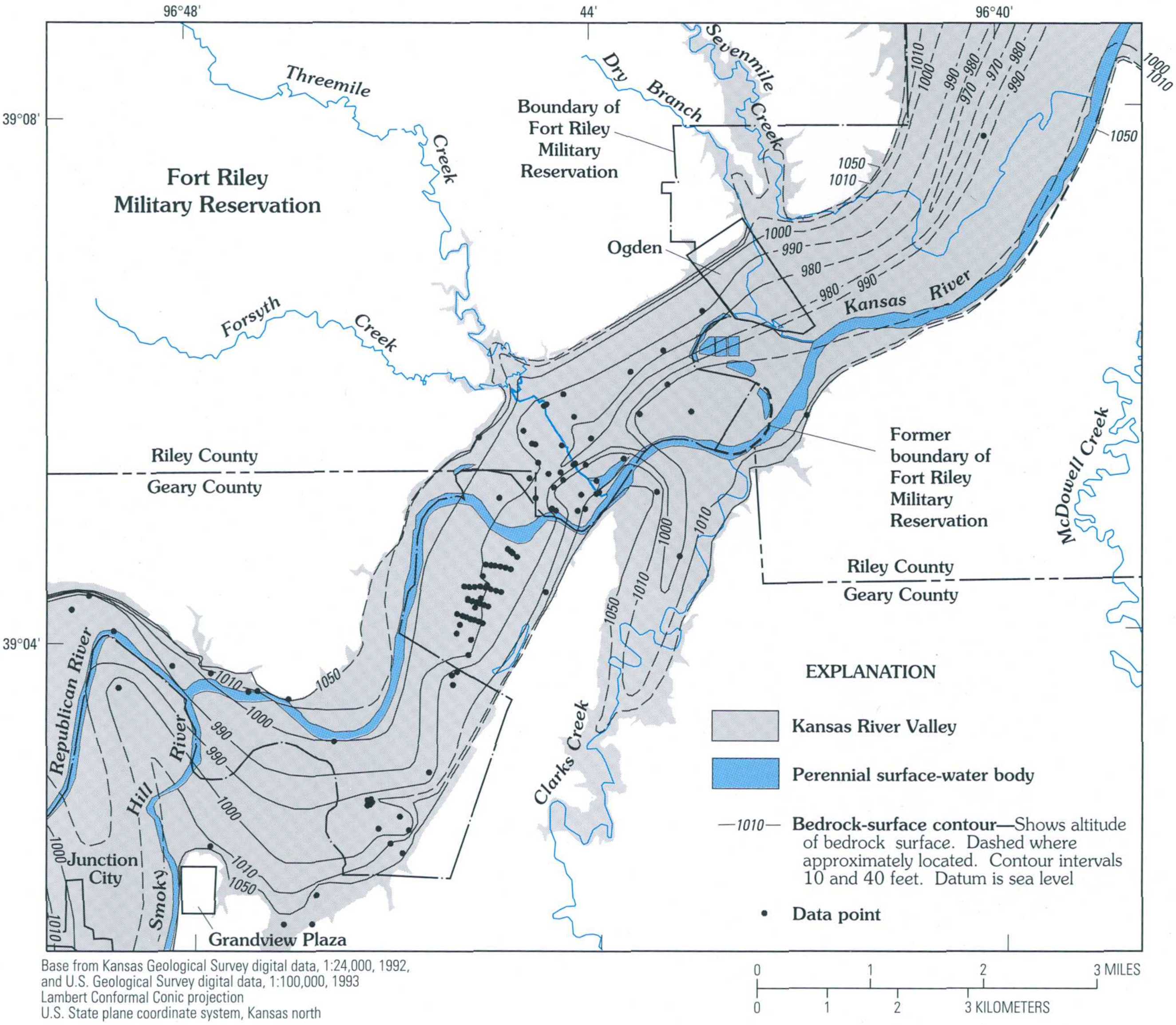


Figure 5. Configuration of bedrock surface in Kansas River Valley in study area (data on file with U.S. Geological Survey, Lawrence, Kansas).

Newman terrace deposits consist of fining-upward sequences of gravel, sand, silt, and clay (Fader, 1974). Newman terrace deposits generally are 10 to 15 ft thick and occur near the valley walls.

Fluvial deposits, such as the Kansas River alluvium, typically consist of a layered sequence of fining-upward sedimentary units, each of which may be truncated by erosion. Each sedimentary unit may represent all or part of a sequence of depositional environments such as, from bottom to top, river-channel environment (gravel-lag or fining-upward point-bar deposits), flood-plain environment (thinly laminated sand, silt, and clay deposited during floods), and abandoned river-channel environment (silt and clay deposits in channels abandoned because of changes in river course). The geometry and orientation of each of these sedimentary units are variable. As a river meanders across its valley, it typically leaves a fining-upward sedimentary unit that eventually may occupy the width of the river valley. As the river meanders and reworks the surficial deposits, fine-grained sediment (clay and silt) tends to be preferentially removed from the alluvium leaving the coarser sediment behind.

Newman terrace deposits (fig. 8), occurring near the edge of the valley (Fader, 1974), were deposited during a period of time when the surface of the Kansas

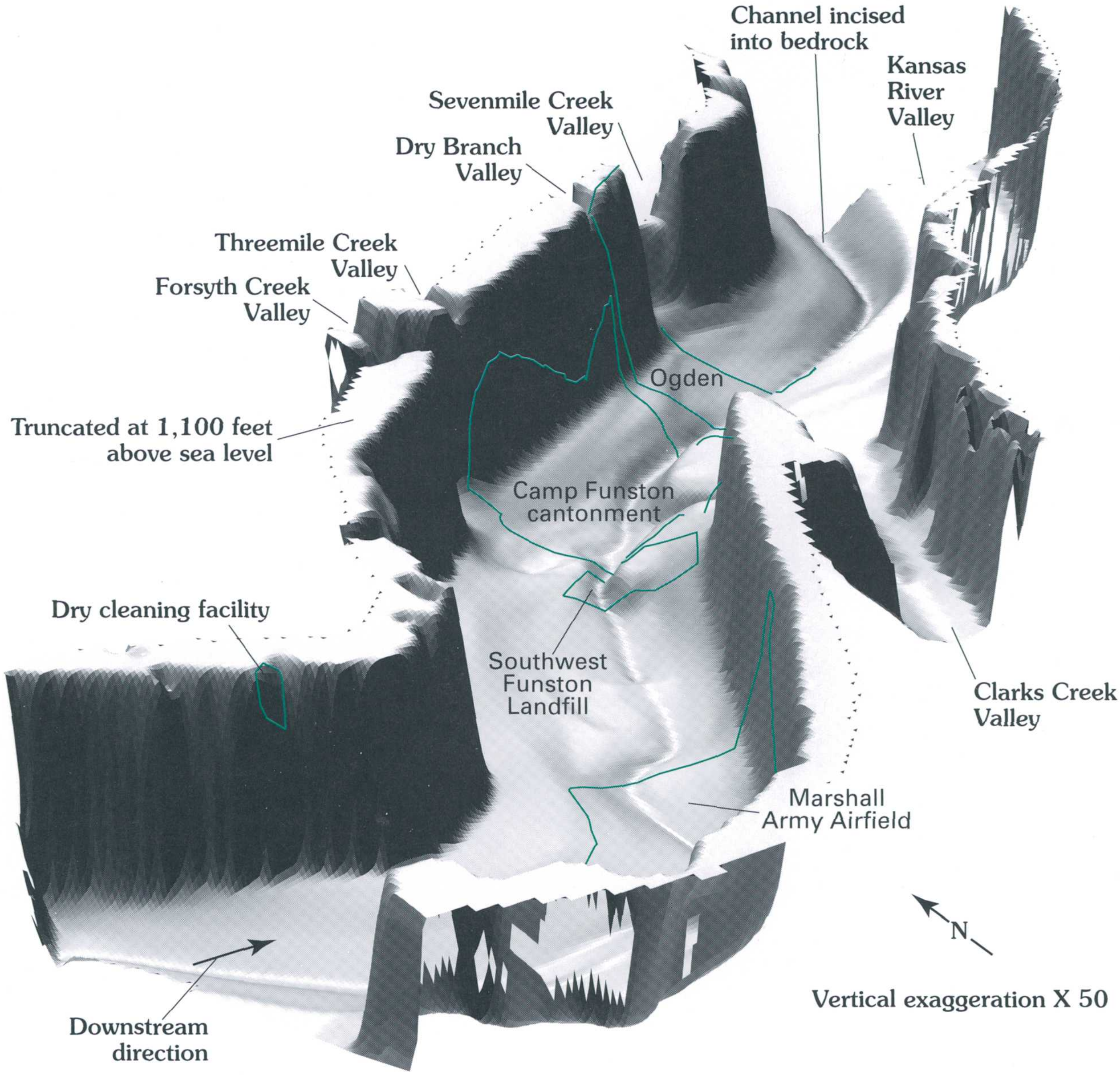


Figure 6. Shaded relief of bedrock surface in Kansas River Valley in study area. Alluvial sediment has been removed. Map is based on bedrock-surface contours shown in figure 5.

River Valley was at a higher altitude than at the present time. Newman terrace deposits are defined as occurring from the first topographic escarpment near the edge of the river valley to the next higher or second escarpment (Fader, 1974).

Precipitation and Surface Water

The mean annual precipitation at the Manhattan Municipal Airport during 1961–90 [the National Weather Service's current (2000) long-term averaging period] was 33.82 in. (fig. 10*A*) (National Oceanic and Atmospheric Administration, 1998). Annual precipitation during this averaging period ranged from 15.52 in. in 1966 to 51.48 in. in 1973 (fig. 10*A*) (National Climatic Data Center, 1999). About 70 percent (23.81 in.) of the mean annual precipitation occurred during the warm-season months of April through September, whereas about 30 percent (10.01 in.) occurred during the cool-season months of October through March. During 1990–98, mean annual precipitation was 36.23 in., which is about 7.1 percent above the

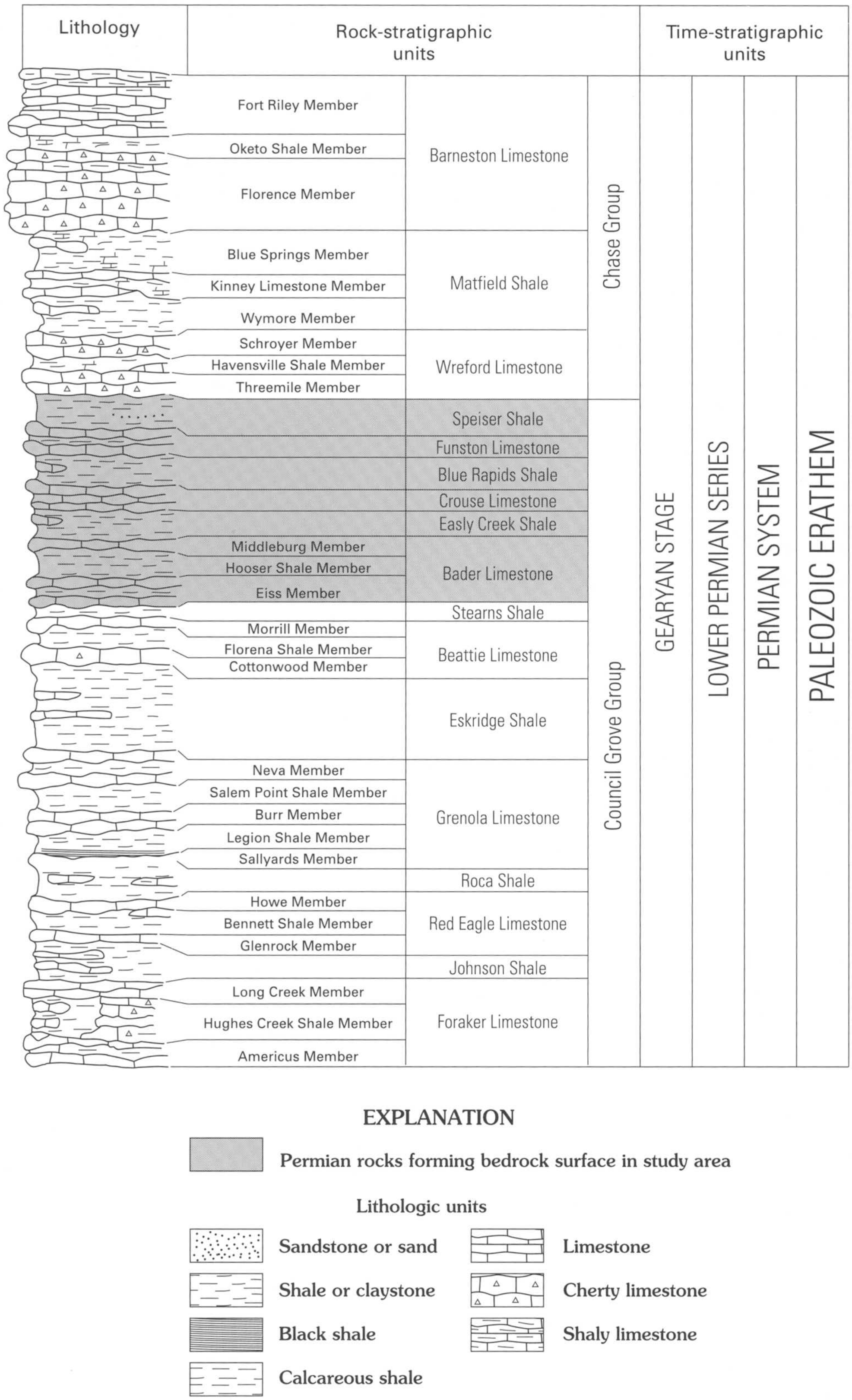


Figure 7. Stratigraphic column showing position and lithology of Permian rocks forming bedrock surface in study area (modified from Zeller, 1968).

long-term mean, and ranged from 26.33 in. in 1991 to 55.78 in. in 1993 (fig. 11*A*) (National Climatic Data Center, 1999). Because of the large amount of precipitation in 1993, the stream gage at the Kansas River at Fort Riley (Henry Drive Bridge) (fig. 2) recorded an instantaneous peak streamflow on July 26 of 87,600 ft^3/s. This peak streamflow is the largest ever recorded since this stream-gaging station began operation in 1964 (Geiger and others, 1994).

Streamflow in the Kansas River Basin was unregulated until the late 1950's and early 1960's when dams on the Smoky Hill, Solomon, and Republican Rivers (fig. 1) were completed. These dams were built to provide flood control and other beneficial uses. Since dam completion, streamflow in the Kansas River (figs. 10*B* and 11*B*) has been related to precipitation to the extent that the undammed reaches of the Kansas River and its tributaries contribute to streamflow and in that reservoir outflows generally are matched to reservoir inflows. During cool-season months and periods of significant drought, streamflows are maintained by reservoir releases and are not necessarily related to precipitation.

Since the completion of the Milford Lake dam in

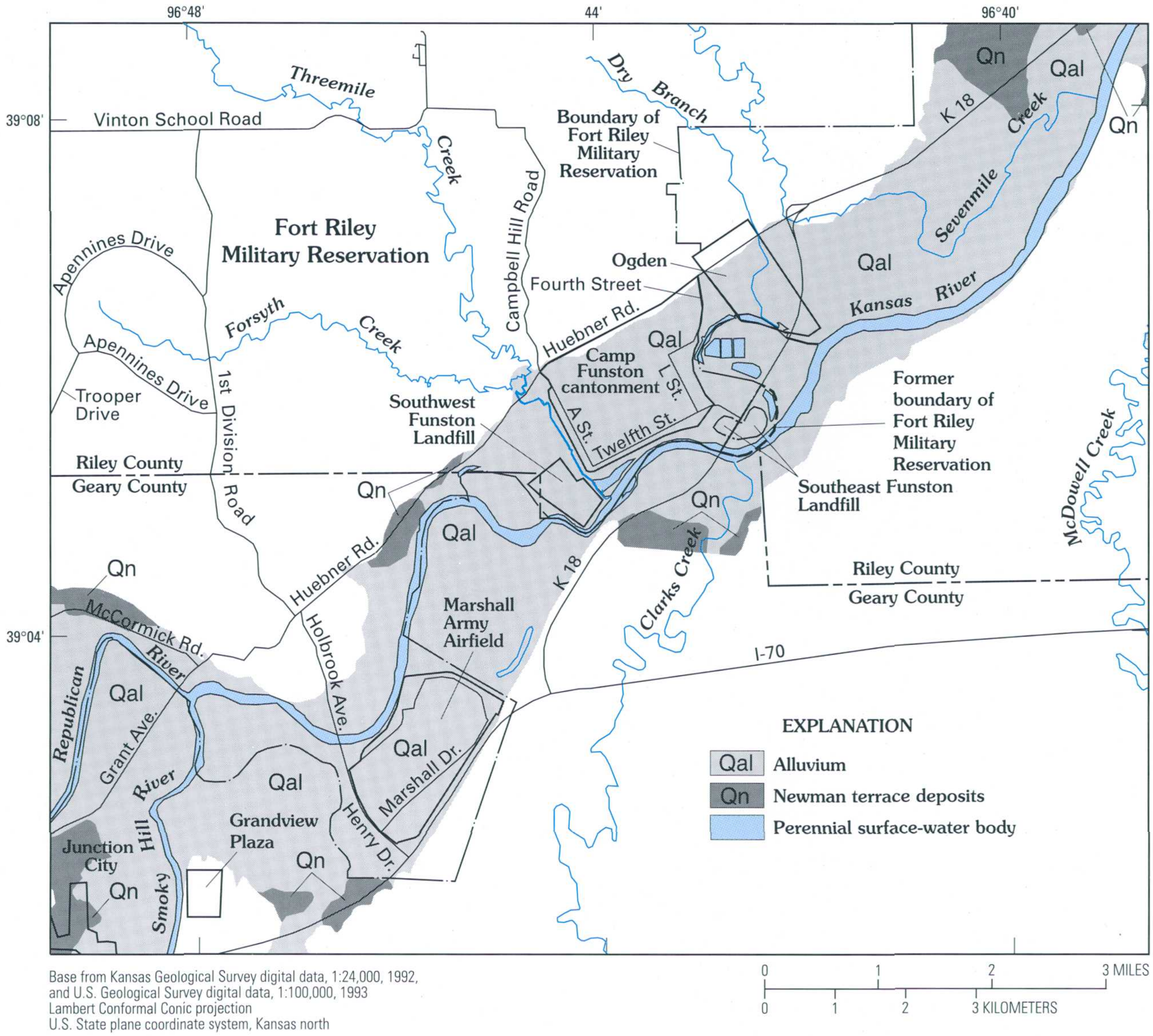


Figure 8. Surficial deposits in Kansas River Valley in study area (modified from Fader, 1974).

August 1967, sediment transported in the Republican River has been trapped in Milford Lake. As a result, the Republican River channel at the Republican River below Milford Lake stream-gaging station (fig. 2) degraded (deepened) by about 9 ft between 1967 and 1993 (Myers and others, 1996). At the Kansas River at Fort Riley (Henry Drive Bridge) stream-gaging station, the river channel degraded by about 3 ft between 1967 and 1993 and subsequently has aggraded about 0.5 ft (fig. 12). Major episodes of Kansas River channel degradation at the Kansas River at Fort Riley (Henry Drive Bridge) gaging station occurred in 1973, 1987, and 1993 in conjunction with flooding (fig. 12). After the 1987 and 1993 floods, some channel aggradation occurred but not enough to restore the channel bed to its former level (fig. 12).

Within the study area, large streamflows and high stream stages in the Smoky Hill, Republican, and Kansas Rivers create backwater conditions in tributaries. Backwater conditions exist where water from a stream backs up into and raises the water level in a tributary above the level that normally would result from the amount of streamflow in the tributary. Because streamflow in the Republican River is controlled by Milford Dam, streamflow and stream stage can be very different in the Republican and Smoky Hill Rivers. These differences in stream stage can result in backwater conditions in the Smoky Hill or Republican Rivers.

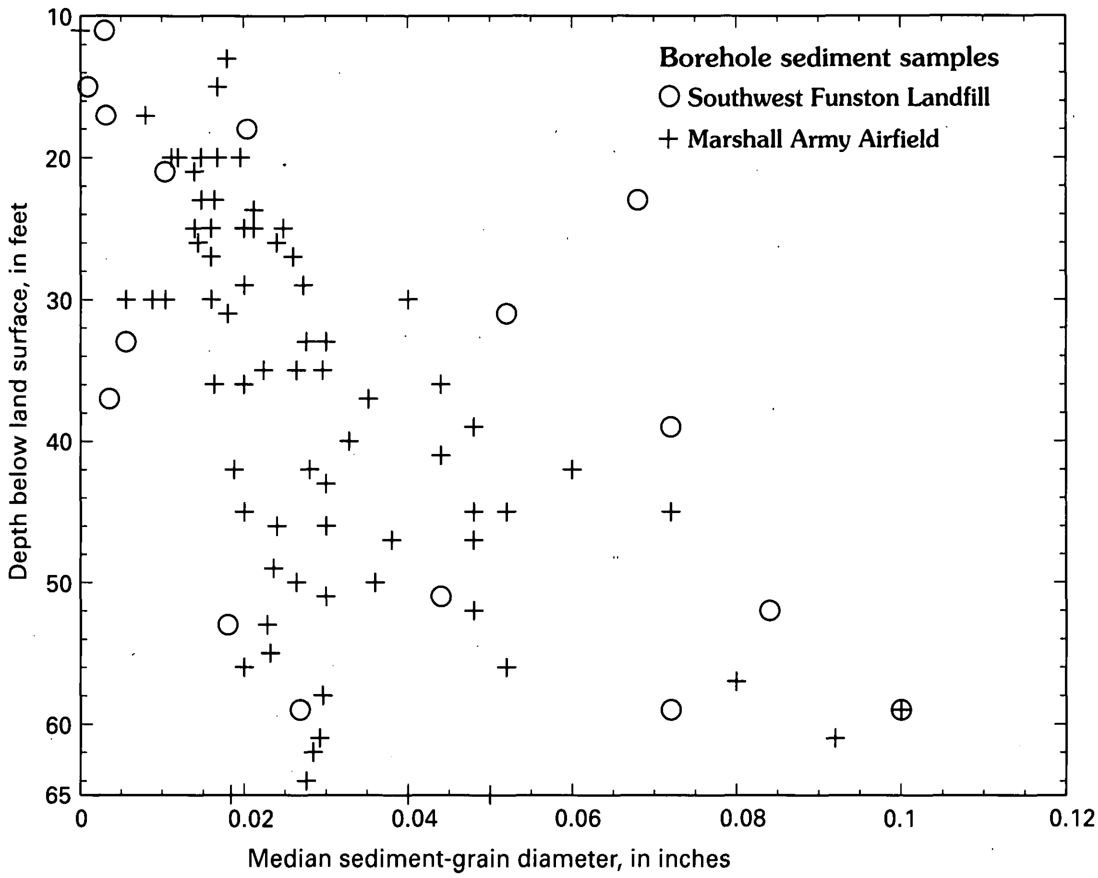


Figure 9. Variation in median sediment-grain diameter with depth below land surface in borehole sediment samples from Southwest Funston Landfill and Marshall Army Airfield (table 17 in "Supplemental Information" section).

Ground-Water Flow and Ground-Water/ Surface-Water Interaction

Although the following discussion focuses on the interaction of ground water and the Kansas River, similar processes probably occur also near the Republican and Smoky Hill Rivers. The alluvial aquifer is that part of the alluvium below the water table in the Kansas River Valley. Water-table maps indicate that the direction of ground-water flow in the alluvial aquifer generally is down the valley but can be quite variable near the Kansas River (figs. 13*A*, 13*B*, and 13*C*; figs. 42–49 in "Supplemental Information" section). Ground-water levels in the alluvial aquifer are affected primarily by the stage of the Kansas River and to a lesser extent by the stage of tributaries, ponds, lakes, and by infiltration from precipitation (Myers and others, 1999). The correlation between Kansas River stage and ground-water levels in the alluvial aquifer is strongest near the river and is weaker farther from the river (fig. 14). Ground-water-level changes caused by infiltration of precipitation in the study area generally are difficult to detect because they are masked by larger ground-water-level changes caused by changes in Kansas River stage.

Ground-water flow upward from bedrock underlying the alluvium probably is minimal because of the relatively impermeable nature of the shale that is interbedded with limestone in the bedrock beneath the alluvium. However, lateral inflow of ground water from adjacent bedrock probably contributes a small but important component of ground water to the alluvial aquifer at the valley walls. As discussed in the following paragraphs, lateral inflow from adjacent bedrock is indicated by strontium-isotope data and by analysis of well hydrographs in the Camp Funston cantonment.

Median strontium-isotope ratios (Sr^{87}:Sr^{86}) for ground-water samples collected from May 1996 through November 1997 indicate a zone in the alluvial aquifer along the northern Kansas River Valley wall where median Sr^{87}:Sr^{86} values generally were smaller than in most of the rest of the Camp Funston Area

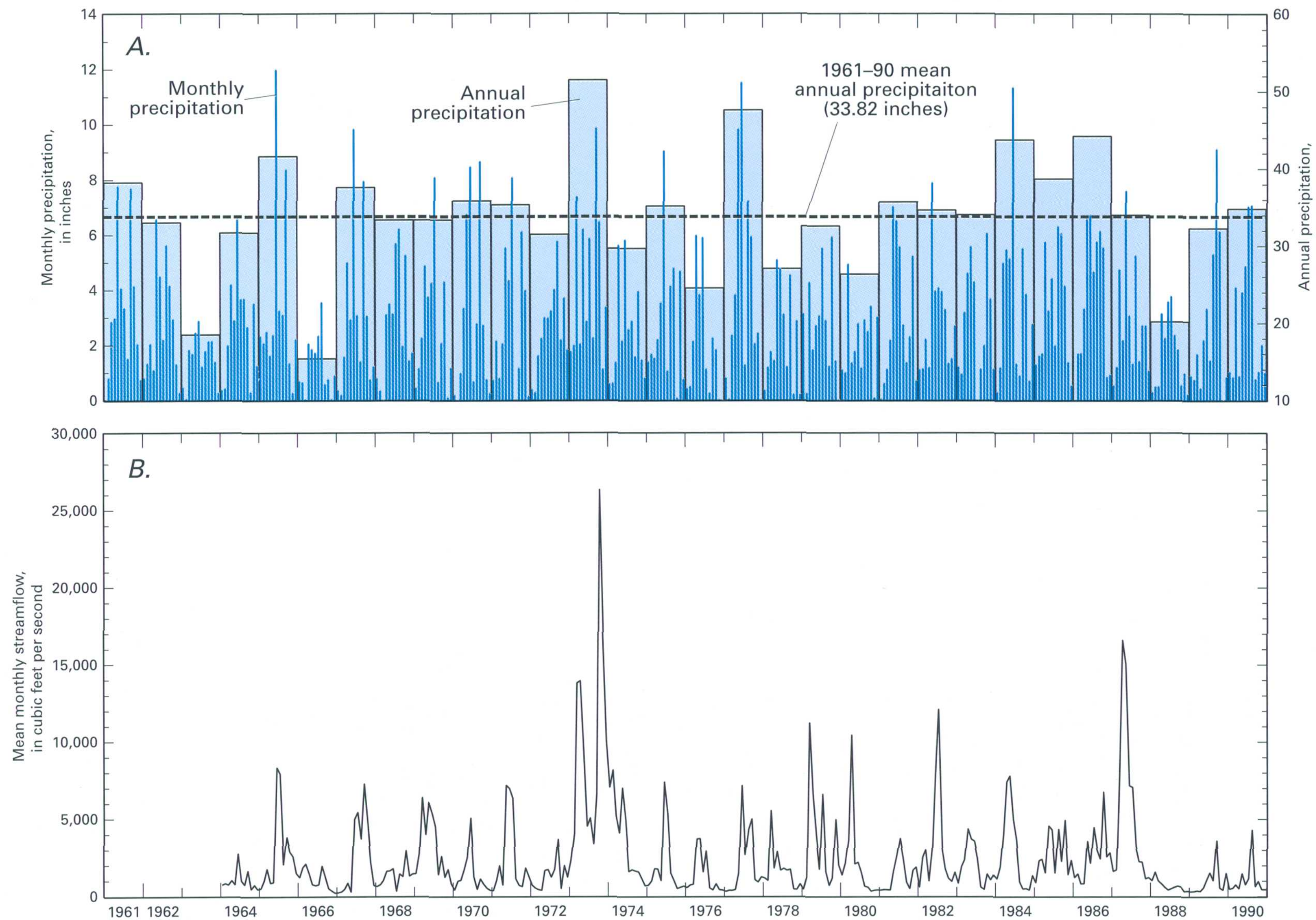


Figure 10. Relation between *(A)* monthly and annual precipitation and 1961–90 mean annual precipitation at Manhattan Municipal Airport, and *(B)* mean monthly streamflow for Kansas River at Fort Riley (Henry Drive Bridge), 1964–90 (streamflow data on file with U.S. Geological Survey, Lawrence, Kansas; precipitation data from National Oceanic and Atmospheric Administration, 1998, and National Climatic Data Center, 1999).

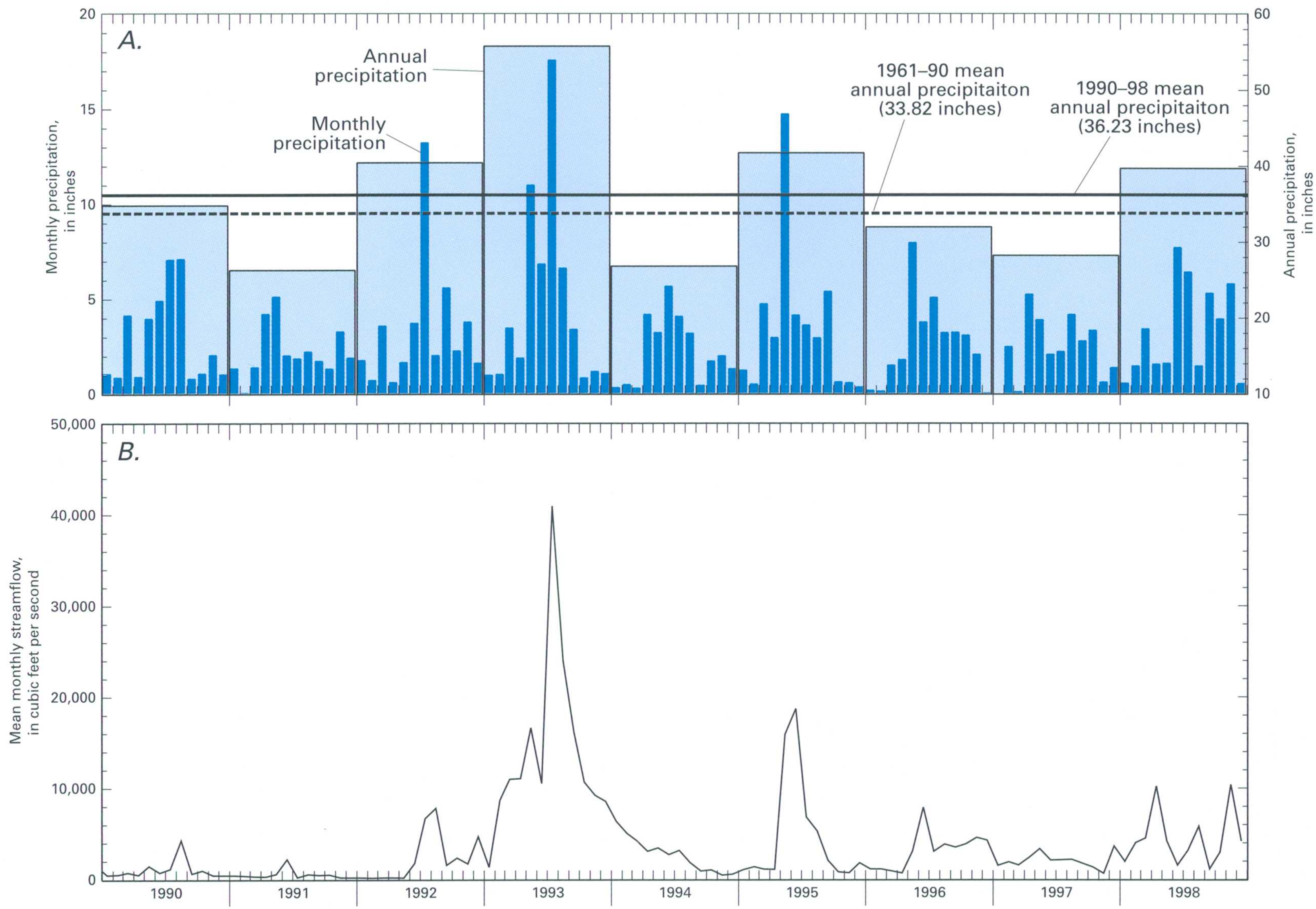


Figure 11. Relation between *(A)* monthly and annual precipitation, 1990–98, and 1961–90 and 1990–98 mean annual precipitation at Manhattan Municipal Airport, and *(B)* mean monthly streamflow for Kansas River at Fort Riley (Henry Drive Bridge), 1990–98 (streamflow data on file with U.S. Geological Survey, Lawrence, Kansas; precipitation data from National Oceanic and Atmospheric Administration, 1998, and National Climatic Data Center, 1999).

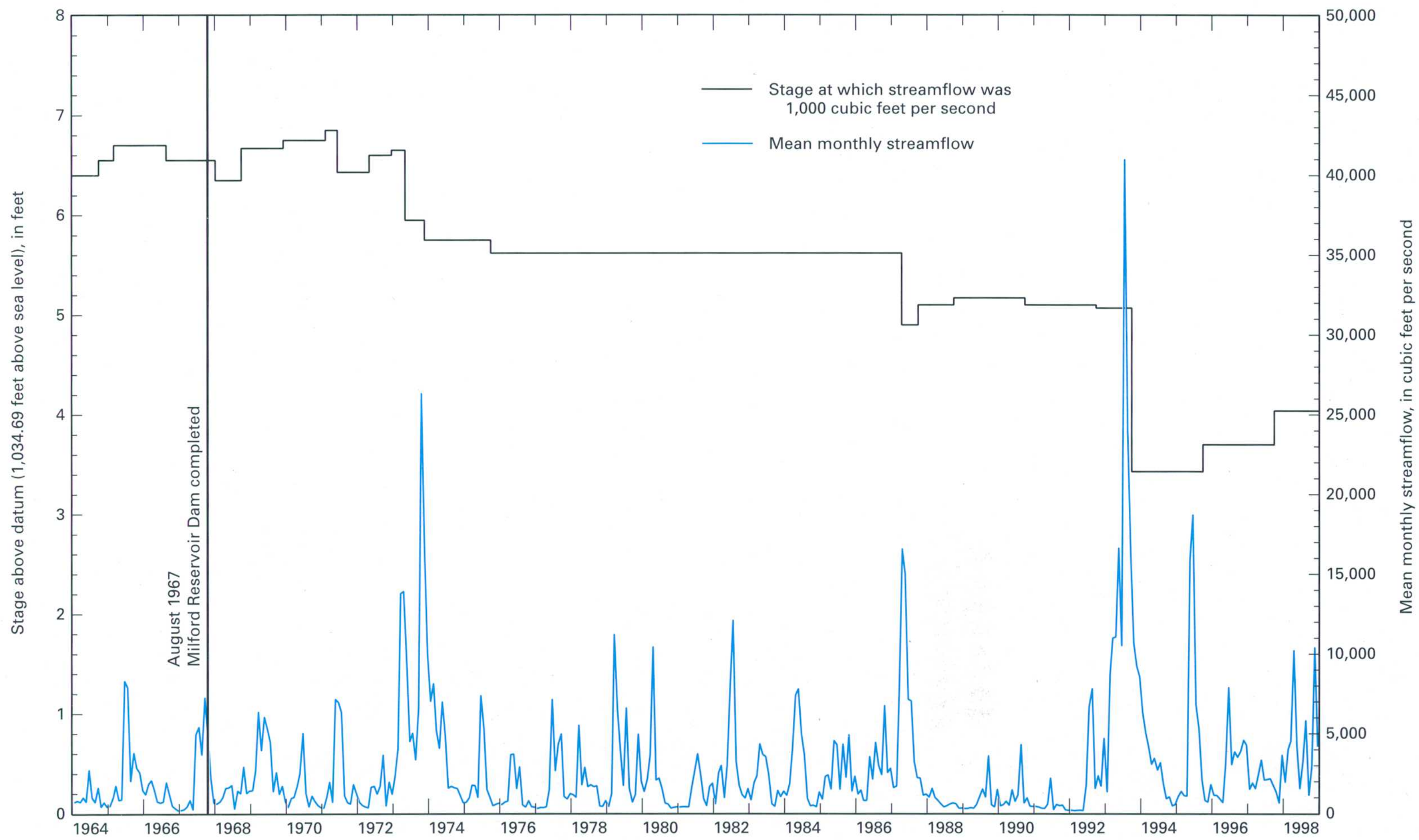
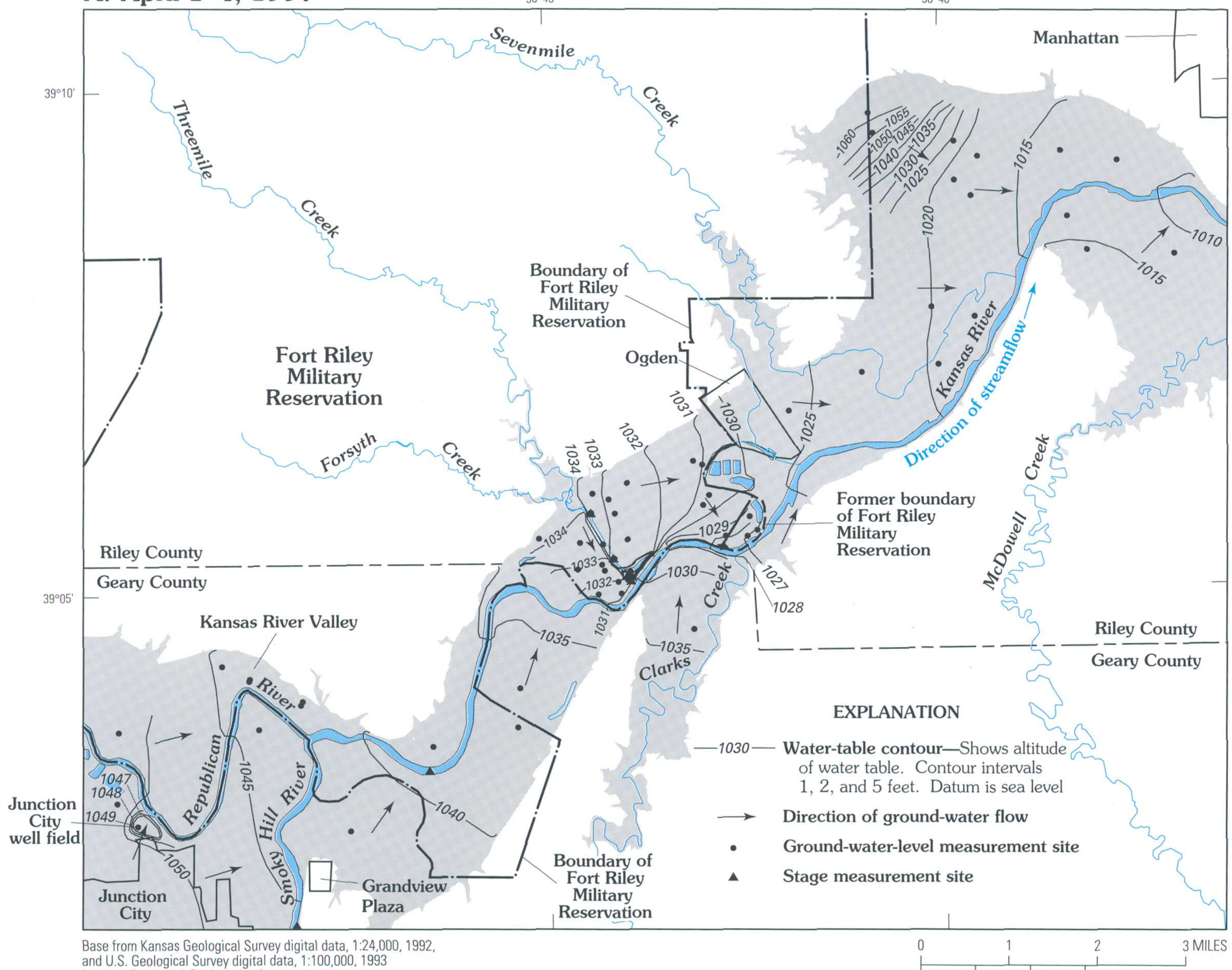


Figure 12. Changes in stage at which streamflow was equal to 1,000 cubic feet per second and mean monthly streamflow for Kansas River at Fort Riley (Henry Drive Bridge), 1964–98 (data on file with U.S. Geological Survey, Lawrence, Kansas).

A. April 1–4, 1997



Base from Kansas Geological Survey digital data, 1:24,000, 1992, and U.S. Geological Survey digital data, 1:100,000, 1993
Lambert Conformal Conic projection
U.S. State plane coordinate system, Kansas north

Figure 13. Water-table surface in Kansas River Valley in study area, *(A)* April 1–4, 1997, *(B)* September 7–9, 1997, and *(C)* April 1–3, 1998 (J.D. Breedlove and others, U.S. Geological Survey, written commun., 1998).

B. September 7–9, 1997

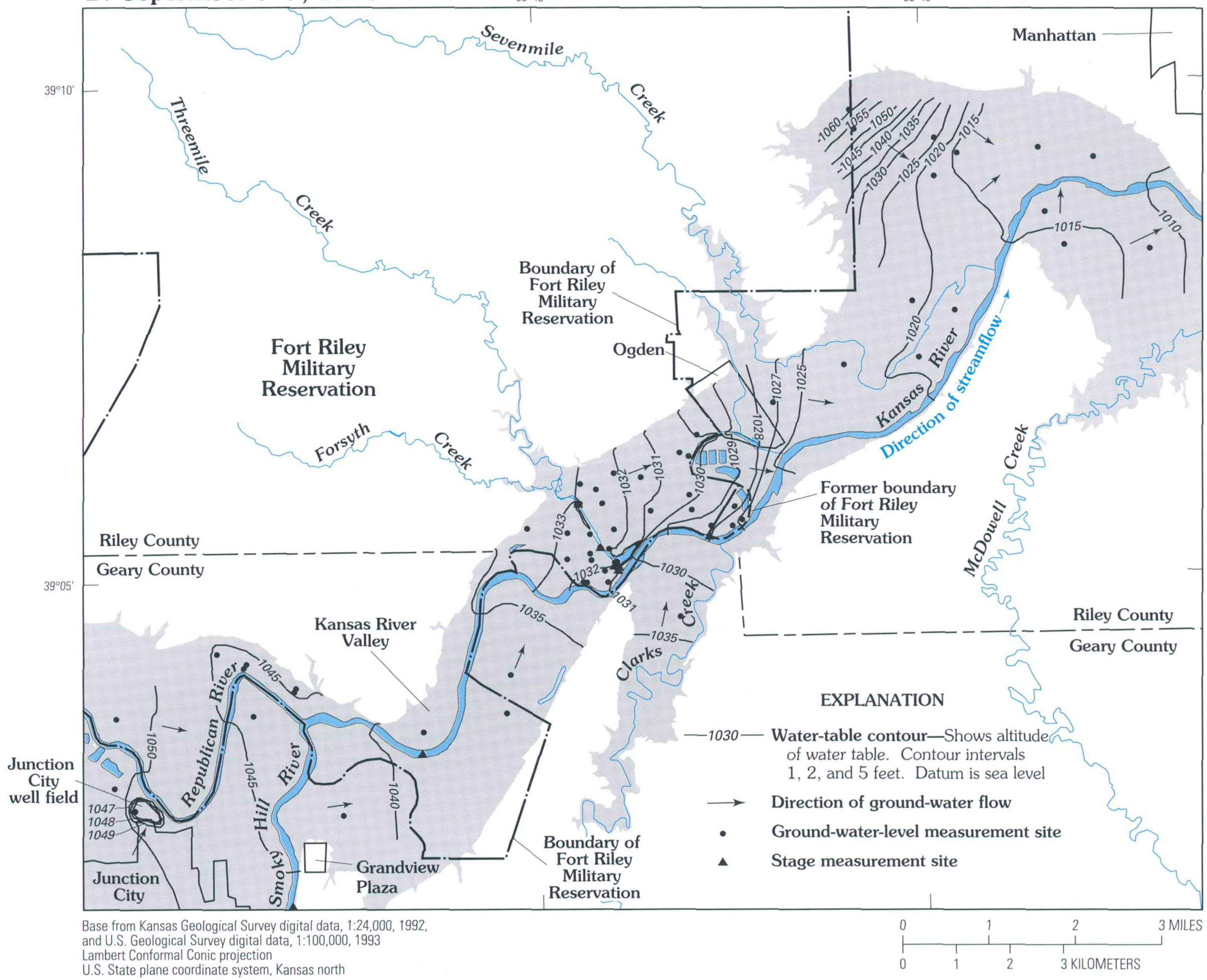
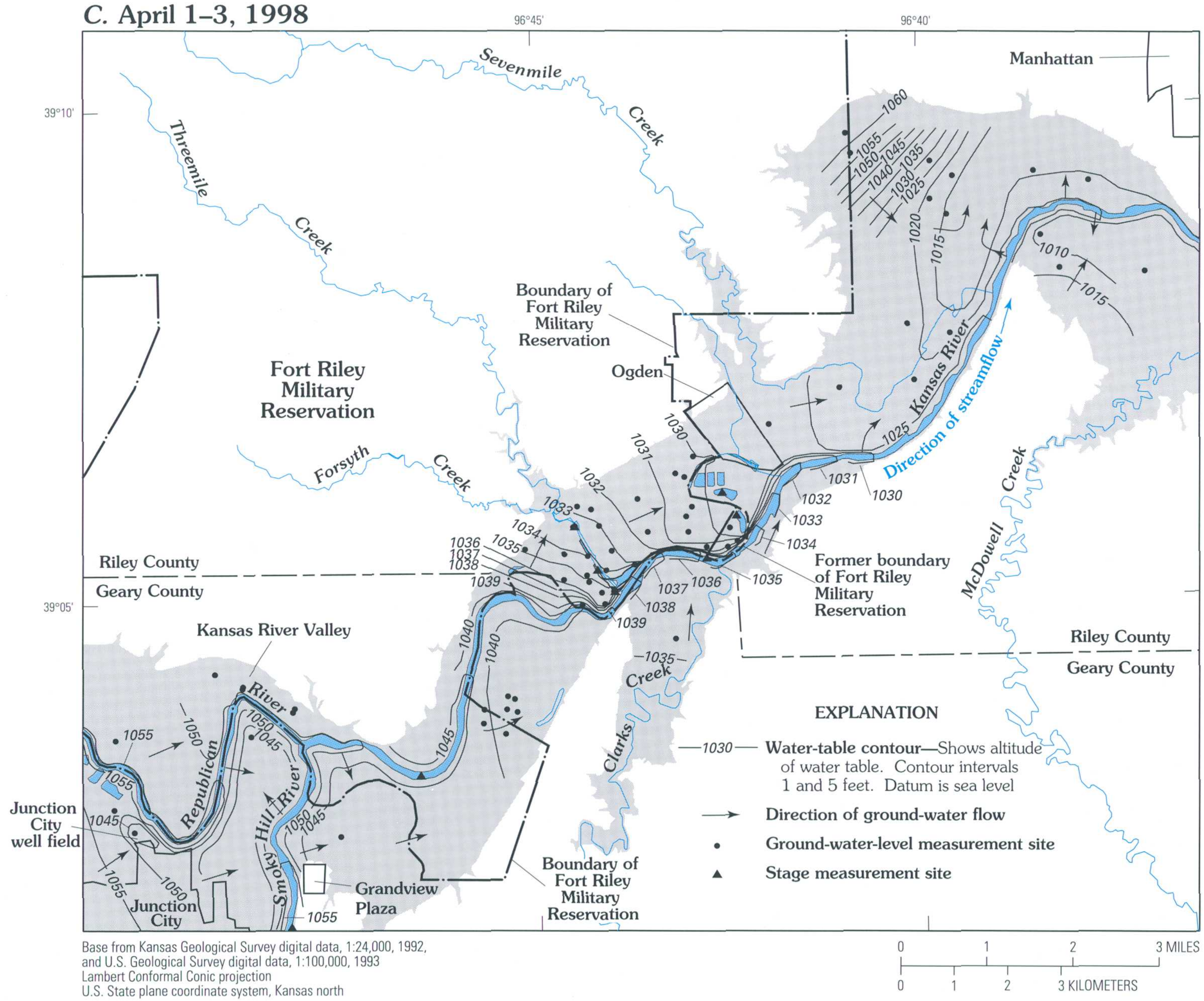


Figure 13. Water-table surface in Kansas River Valley in study area, *(A)* April 1–4, 1997, *(B)* September 7–9, 1997, and *(C)* April 1–3, 1998 (J.D. Breedlove and others, U.S. Geological Survey, written commun., 1998)—Continued.

C. April 1–3, 1998



Base from Kansas Geological Survey digital data, 1:24,000, 1992, and U.S. Geological Survey digital data, 1:100,000, 1993
Lambert Conformal Conic projection
U.S. State plane coordinate system, Kansas north

Figure 13. Water-table surface in Kansas River Valley in study area, *(A)* April 1–4, 1997, *(B)* September 7–9, 1997, and *(C)* April 1–3, 1998 (J.D. Breedlove and others, U.S. Geological Survey, written commun., 1998)—Continued.

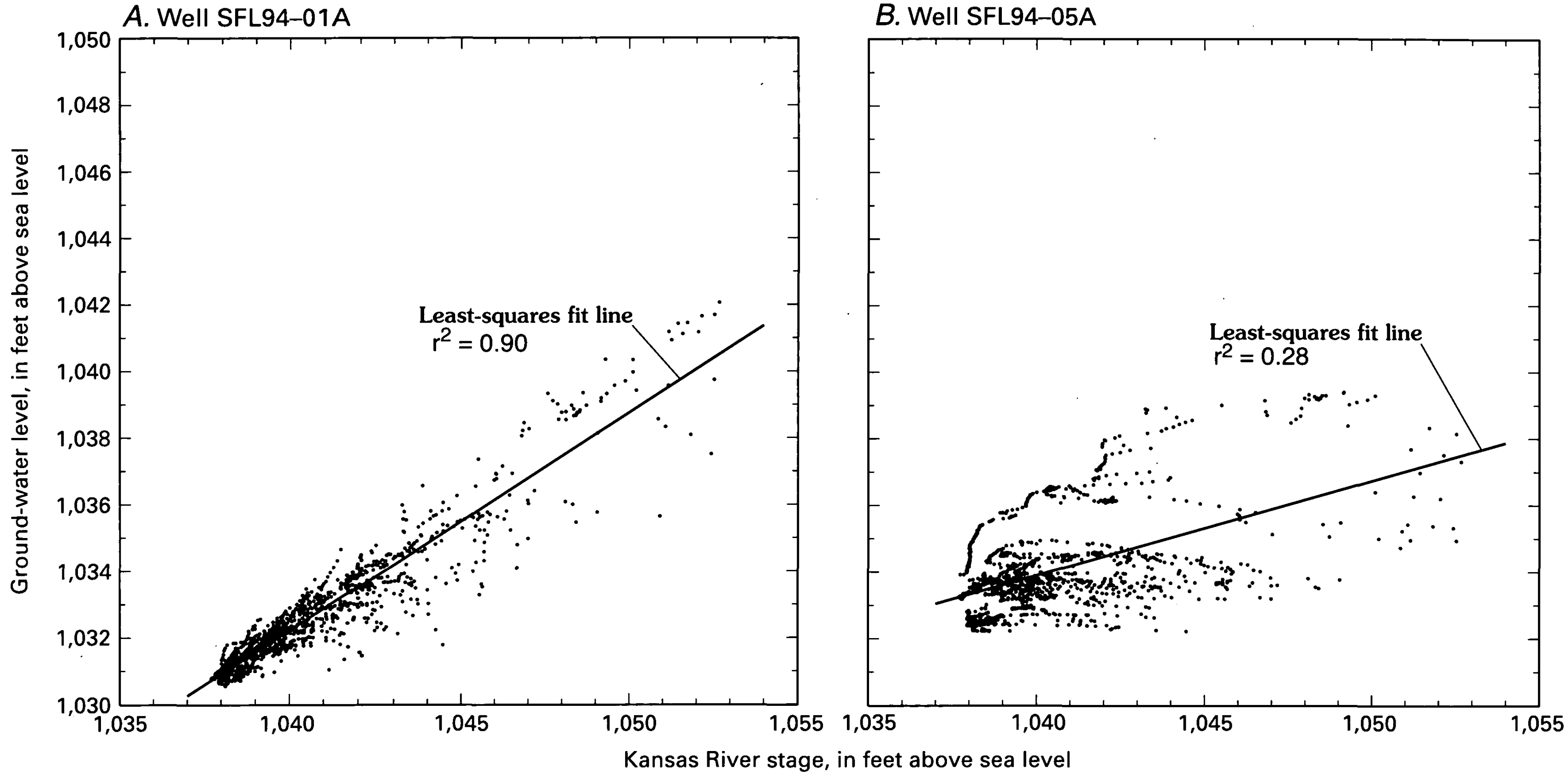


Figure 14. Correlation between daily mean stage of Kansas River at Fort Riley (Henry Drive Bridge) and daily mean ground-water levels in wells *(A)* close to river (well SFL94–01A) and *(B)* farther from river (well SFL94–05AA), February 1995–December 1998 (location of wells shown in figure 4; data on file with U.S. Geological Survey, Lawrence, Kansas).

(Chaudhuri, 1999) (fig. 15). Water in Threemile Creek, derived from runoff or ground-water seepage in the uplands north of the Kansas River Valley, had median $Sr^{87}:Sr^{86}$ ratios that were similar to those for ground water from wells (SFL92–103, SFL94–05A and 05B, SFL94–06A and 06B, 1915CF92–03, 1044CF94–02, WRCF93–01, CF97–401, 1245CF94–06, CF97–103, OG–02, and OG–07) near the northern valley wall (fig. 16). The similarity of $Sr^{87}:Sr^{86}$ ratios in water from Threemile Creek and from wells near the valley wall indicates that the ground water, in part, originated from the uplands north of the Kansas River Valley. In contrast, ground water in the central and southern Camp Funston Area had larger $Sr^{87}:Sr^{86}$ ratios. Kansas and Republican River water generally had $Sr^{87}:Sr^{86}$ ratios that were larger than those from Threemile Creek (fig. 16). Generally, $Sr^{87}:Sr^{86}$ ratios similar to those found in the Kansas and Republican Rivers were found in ground water from wells closer to the river (fig. 16).

Analyses of hydrographs from wells CF90–06, CF97–101, and CF97–401 in the Camp Funston Area (fig. 17) also indicate that ground-water inflow from bedrock may be occurring. By using a technique called the floodwave-response method (Pinder and others, 1969; Grubb and Zehner, 1973; Reynolds, 1987), the response of ground-water levels to changes in hydraulic stresses, such as stream stage, can be computed. At a given point in an aquifer, the ground-water-level response to changes in stream stage can be computed by using the following equation:

$$h_p = \sum_{m=1}^{p} \sum_{n=1}^{\infty} (-1)^{(n-1)} \Delta H_m \left[erfc\left(0.5U\left(\frac{\frac{2n-2}{\frac{X}{L}} + 1}{\sqrt{p-m}}\right)\right) + erfc\left(0.5U\left(\frac{\frac{2n}{\frac{X}{L}} - 1}{\sqrt{p-m}}\right)\right)\right], \quad (1)$$

where

$$U = \frac{X}{\sqrt{\left(\frac{T}{S}\right)\Delta t}}, \quad (2)$$

and

h_p is the total hydraulic head at a distance $(L - X)$ from the river at time $p\Delta t$, where p is the total number of time intervals for the simulation, in feet;

ΔH_m is the instantaneous rise in river stage at time $t = m\Delta t$, where m is an integer representing a number of time intervals, in feet;

$erfc$ is the complementary error function;

X is the distance from the point where the aquifer response is observed to an impermeable boundary (valley wall), in feet;

L is the distance from the river to the impermeable boundary (valley wall), in feet;

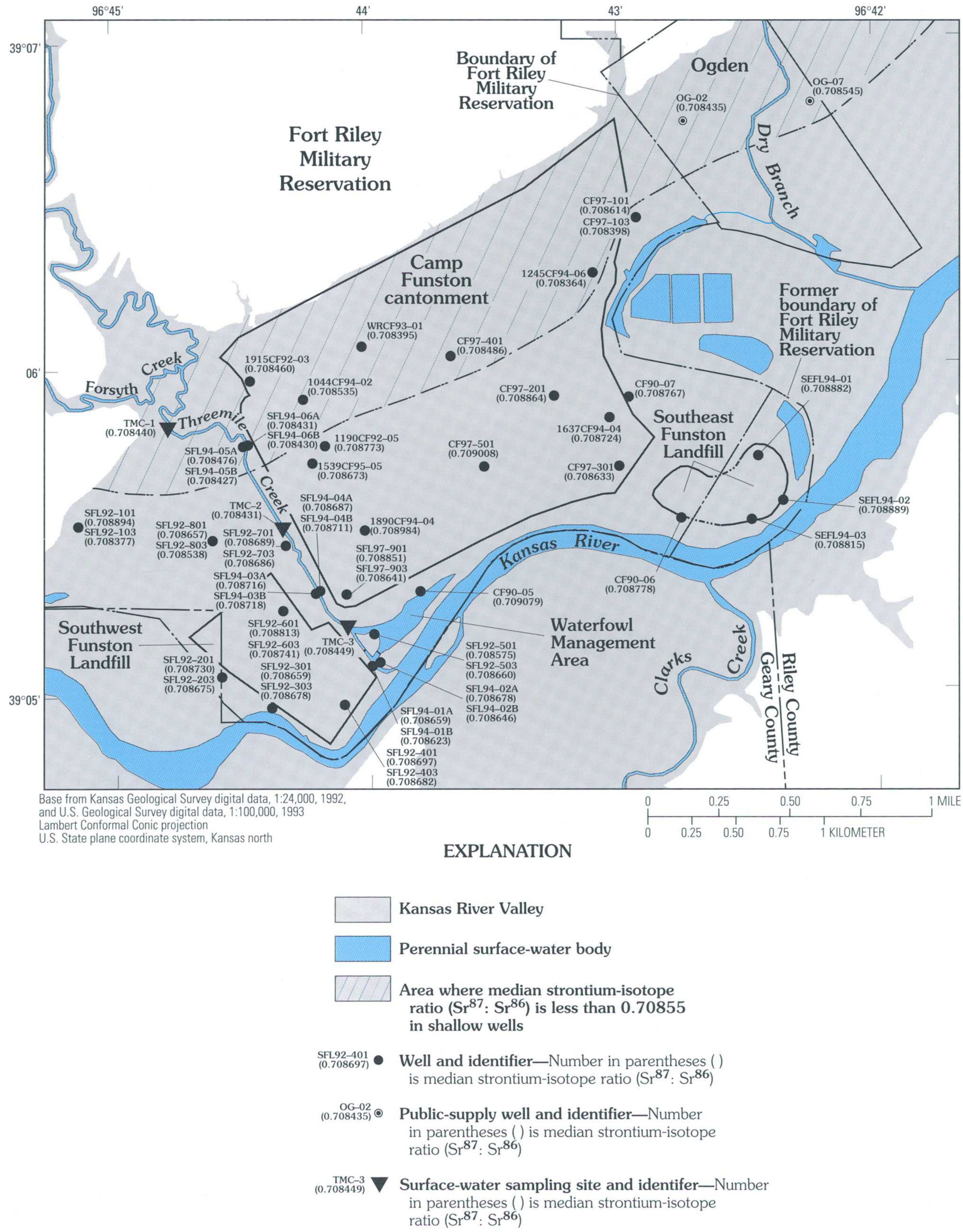


Figure 15. Median strontium-isotope ratios for water from wells and surface-water sampling sites in Camp Funston Area, May 1996–November 1997 (Chaudhuri, 1999).

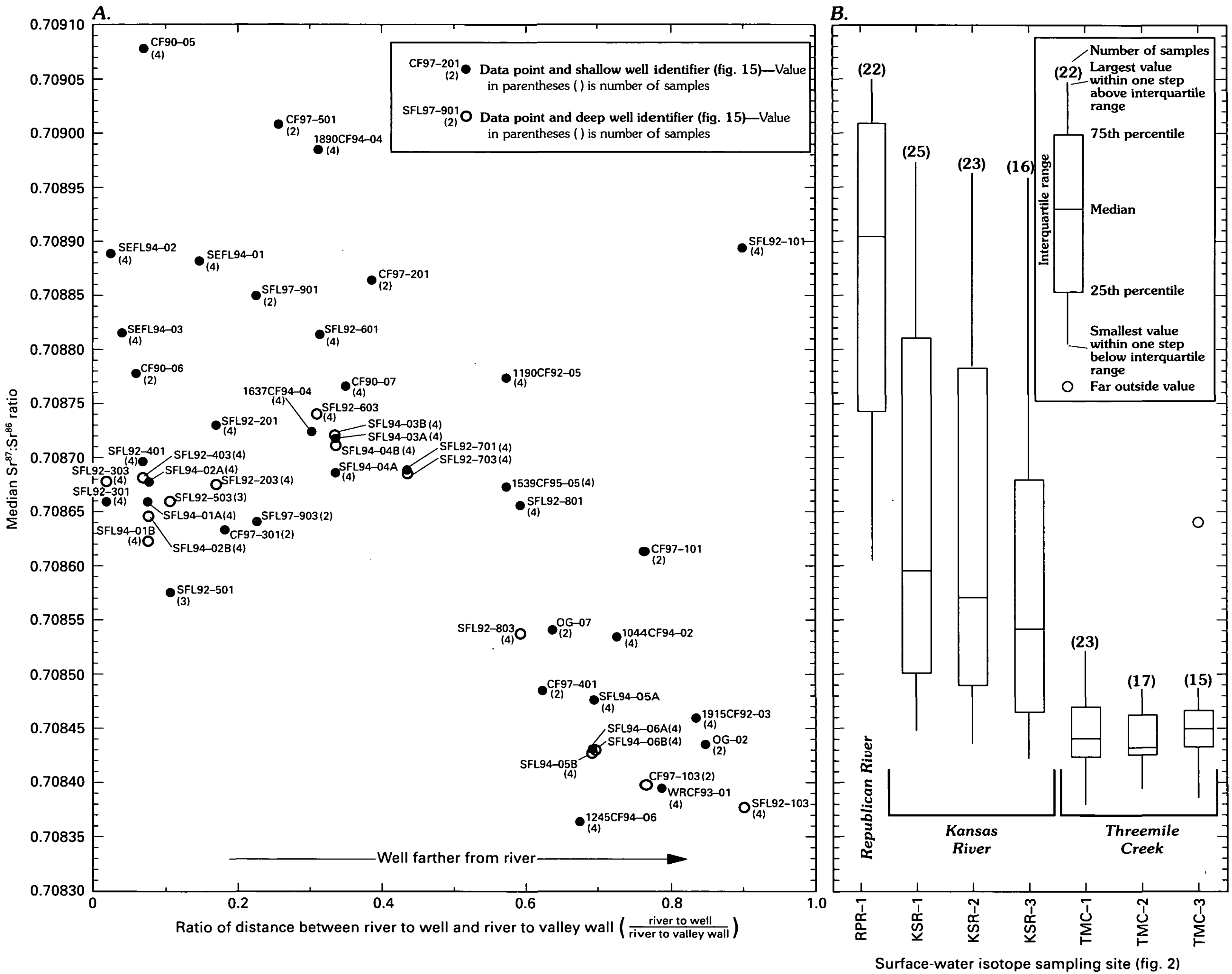


Figure 16. Relation between median *(A)* strontium-isotope ratios ($Sr^{87}:Sr^{86}$) in ground water and distance to Kansas River, and *(B)* strontium-isotope ratios ($Sr^{87}:Sr^{86}$) in water from Republican and Kansas Rivers and Threemile Creek, May 1996–November 1997 (Chaudhuri, 1999).

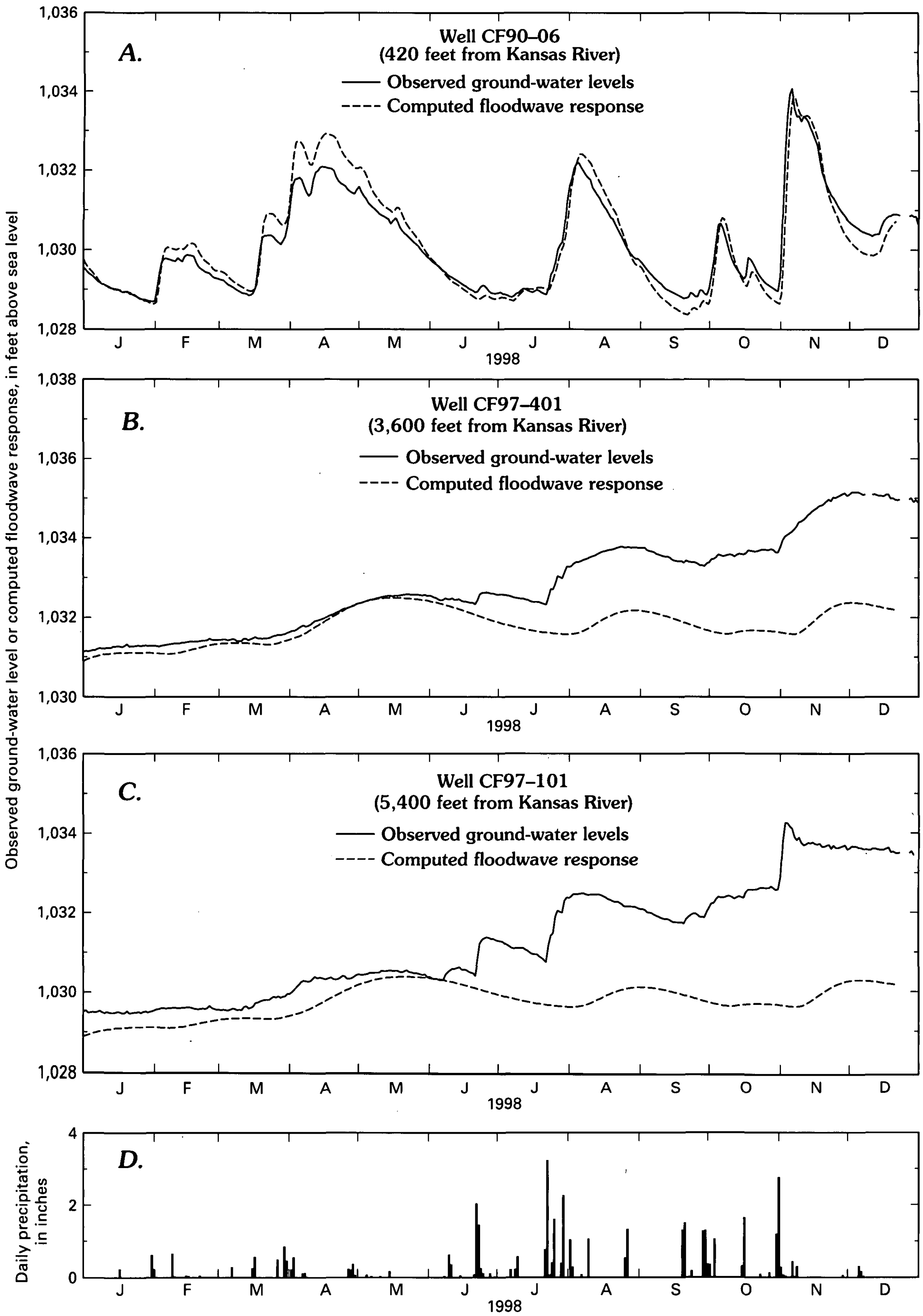


Figure 17. Observed ground-water-level and computed floodwave response to changes in Kansas River stage for *(A)* well CF90–06, *(B)* well CF97–401, and *(C)* well CF97–101, and *(D)* precipitation at OB/OD area (fig. 2), January–December 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas).

$\frac{T}{S}$ is the diffusivity of the aquifer (transmissivity divided by storage coefficient), in feet squared per day; and

Δt is the unit time-step duration, in days.

Equation 1 is best solved using a computer program such as that documented in Desimone and Barlow (1999) that solves the equation for successive time steps and sums the resulting values to yield changes in total hydraulic head over time.

This method for computing ground-water-level response assumes that the diffusivity of the aquifer and the distance between the river and valley wall are constant. If these assumptions are satisfied, then the response of ground water to a change in stream stage is a function of the distance from the river to an observation point in the aquifer. Figure 18 shows an example of how the computed ground-water-level response to an increase and decrease in Kansas River stage varies with the distance of the well from the river. These curves were computed assuming a diffusivity of 175,000 ft^2/d and a river-to-valley-wall distance of 7,200 ft. Note that the amplitude of the ground-water-level response is smaller with increasing distance from the river. Also, the time lag between peak river stage and peak ground-water level increases with increasing distance from the river. Thus, the effects of hydraulic stresses, such as changes in river stage, on ground-water levels are smaller and occur later in time with increasing distance from the hydraulic stress.

If changes in river stage were the only hydraulic stress being placed upon an alluvial aquifer, then observed ground-water levels would be similar to computed response curves. However, if other hydraulic stresses, such as episodic recharge from precipitation or changes in ground-water levels in adjacent bedrock, are present, then the observed ground-water levels will depart from the computed response curve.

Ground-water-response curves were computed for three wells in the Camp Funston Area (fig. 17). In

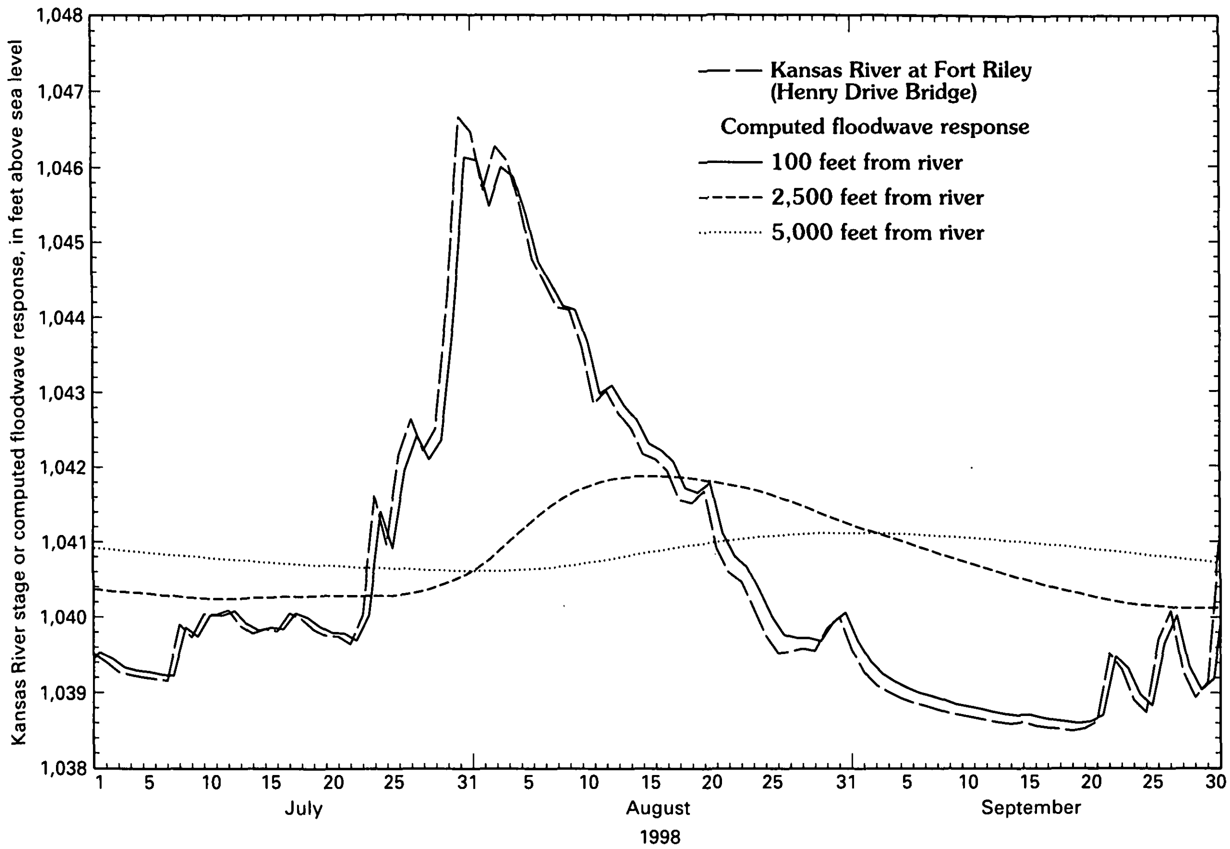


Figure 18. Example of computed floodwave response of ground-water levels at 100, 2,500, and 5,000 feet from river to changes in Kansas River stage at Fort Riley (Henry Drive Bridge), July–September 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas).

order of increasing distance, well CF90–06 is about 420 ft, well CF97–401 is about 3,600 ft, and well CF97–101 is about 5,400 ft from the Kansas River. Observed ground-water levels and computed ground-water-level responses to changes in Kansas River stage for well CF90–06 are very similar, indicating that at this well ground-water levels are affected substantially by river stage (fig. 17*A*). Farther from the river, at wells CF97–401 and CF97–101, the observed ground-water-level and computed ground-water-level response curves are similar from January through early June (figs. 17*B* and 17*C*) but then diverge as precipitation amounts increase in mid-June (fig. 17*D*). The divergence of the observed ground-water levels in wells CF97–101 and CF97–401 from the computed ground-water-level responses indicates that, in addition to the Kansas River, there is another source of recharge that places an episodic hydraulic stress on the aquifer. This episodic hydraulic stress seems to originate near the valley wall because the effect of this stress is greater for well CF97–101, which is closer to the valley wall, than for well CF97–401 (figs. 14*B* and 14*C*). The fact that the divergence of the observed curve from the computed curve occurred when precipitation increased in mid-June is an indication that this valley-wall hydraulic stress is related to precipitation. Precipitation falling on and recharging limestone aquifers in the uplands adjacent to the river valley would cause higher water levels in the limestone and lateral flow from the limestone aquifers to the alluvium. Also, some of the precipitation may run off the uplands as overland flow, then infiltrate into the alluvial aquifer at the edge of the valley, contributing to the observed valley-wall hydraulic stress.

The Kansas River has such a dominant effect on ground-water flow that it is important to quantify streamflow gains or losses between the river and the aquifer. A series of streamflow measurements were conducted July 26–28, 1999 (table 2), in conjunction with river-water sampling at five locations on the Kansas River (fig. 3, river-sampling sections A–E). These measurements were obtained using an acoustic doppler current profiler (ADCP), which uses sonar to measure stream depth and current velocity and accumulates measurements across the stream to produce a final value.

The variations in the measured streamflow values and comparison to streamflow values from the Kansas River at Fort Riley (Henry Drive Bridge) stream-gaging station indicate that measurement error was too large to quantify seepage gains or losses in this short (4.9-mi) river reach. The ADCP streamflow measurements, obtained during a period of 3 days, ranged from 2,600 to 2,970 ft^3/s but did not show a consistent increase or decrease of streamflow either through time or along the river channel (table 2). Streamflow data from the Kansas River at Fort Riley (Henry Drive Bridge) stream-gaging station, located between the C and B sampling sections, indicate that for the times of measurement there was a streamflow increase of

Table 2. Measured streamflow at Kansas River sampling sections and streamflow at Kansas River at Fort Riley (Henry Drive Bridge) stream-gaging station, July 26–28, 1999

[Data on file with U.S. Geological Survey, Lawrence, Kansas]

Sampling section, in downstream order (fig. 3)	Date and time (24-hour) of measurement	ADCP-[1] measured streamflow (cubic feet per second)	Streamflow at time of measurement at Kansas River at Fort Riley stream-gaging station (cubic feet per second)	ADCP-[1] measured streamflow corrected for changes in streamflow at Kansas River at Fort Riley stream-gaging station (cubic feet per second)
E	July 28, 1999, at 1145	2,600	2,680	2,921
D	July 27, 1999, at 1540	2,905	2,880	3,026
C	July 27, 1999, at 1030	2,693	3,100	2,594
B	July 26, 1999, at 1530	2,970	3,150	2,821
A	July 26, 1999, at 1100	2,662	3,001	2,662

[1]Acoustic doppler current profiler.

149 ft^3/s on July 26 then a streamflow decrease of 470 ft^3/s during the next 2 days. Even when the ADCP-measured streamflow values are corrected for the changes in streamflow observed at the Kansas River at Fort Riley (Henry Drive Bridge) gaging station, there is not a consistent increase or decrease of streamflow through time or along the river channel (table 2).

To quantify streamflow gains or losses in a longer river reach, streamflows measured at the Kansas River at Fort Riley (Henry Drive Bridge) (fig. 2) and the Kansas River at Wamego (fig. 1) stream-gaging stations were compared. In the river reach between Fort Riley and Wamego, the two largest tributaries, Clarks Creek and the Big Blue River, had or have stream-gaging stations near their junctions with the Kansas River from 1957–65 and 1951–present (2000), respectively. The Kansas River at Fort Riley (Henry Drive Bridge) and the Kansas River at Wamego stream-gaging stations have streamflow data beginning in December 1963 and January 1919, respectively. Therefore, the period of concurrent records for these four stream-gaging stations is December 19, 1963, through September 30, 1965. To minimize the effects of inflow from ungaged tributaries and of evapotranspiration along the river, which would be a factor during the growing season, a low-flow period of December 1, 1964, through February 20, 1965, was selected for analysis. For this period, the mean streamflow gain from the aquifer was about 70 ft^3/s or about 1.67 ft^3/s per river mile for this 42-mi river reach. For the computed mean streamflow of 780 ft^3/s at the Kansas River at Wamego stream-gaging station during this time period, the 5-percent measurement error, 39 ft^3/s, is considerably less than the mean streamflow gain.

In the interim between 1965 and the present (2000), changes in river-channel elevation (discussed in "Precipitation and Surface Water") have occurred. The changes in river-channel elevations also would cause changes in ground-water levels in the alluvial aquifer. In the short term there may be more ground-water outflow into a degraded channel (less into an aggraded channel) until the water table reaches a new quasi-equilibrium with the river. However, over the long term, inflows to and outflows from the alluvial aquifer will be equal, and ground-water flow to or from the river should remain more or less constant. Therefore, the preceeding analysis of seepage to the Kansas River should be applicable to present (2000) conditions.

Stream-stage and backwater conditions in tributaries can have a direct effect on ground-water flow in areas near the tributaries. Of particular interest to this study was the effect of Threemile Creek on ground-water flow. Because Threemile Creek separates the Southwest Funston Landfill from the Camp Funston cantonment, it could have an effect on the rate and direction of ground-water flow under the landfill.

Evaluations of ground- and surface-water levels, seepage surveys along the creek, and ground-water-quality data indicate that Threemile Creek interacts with shallow ground water but probably does not prevent ground-water flow under the creek. Ground-water hydrographs for shallow well SFL94–03A and deep well SFL94–03B show that ground-water levels in these wells respond to changes in Threemile Creek stage (fig. 19*A*). Increases in creek stage cause Threemile Creek water to seep into the alluvial aquifer when creek stage is higher than the adjacent ground-water level (fig. 19*A*). The small ground-water-level changes (fig. 19*A*, March–April) were not caused by changes in Kansas River stage, considering that the river-stage increases occurred after the ground-water-level changes were observed (fig. 19*A*, late March). Although the March 1995 ground-water-level changes could have been affected by infiltrating precipitation, comparison of figures 19*A* and 19*B* indicate that the late-April ground-water change is a response to a change in Threemile Creek stage and not precipitation. The ground-water-level response in shallow well SFL94–03A is larger and sharper than the response in deep well SFL94–03B (fig. 19*A*). This is consistent with the deep well's screen being farther (vertically) from the creek bed than the shallow well's screen.

Six seepage surveys conducted between April 16, 1997, and July 7, 1998, indicated that Threemile Creek was gaining water from or losing water to the alluvial aquifer (fig. 20). Seepage surveys are measurements of streamflow made during a short-time period at selected points along a stream. Between the Huebner Road Bridge (fig. 4) and the Threemile Creek Upstream gaging station (TMCU, fig. 2), the creek was both gaining water from and losing water to the alluvial aquifer. However, these gains or losses are within or very similar to measurement error (table 3) and, therefore, may not be reliable. Between the Threemile Creek Upstream gaging station and the diversion and Waterfowl Management Area outlet structures (fig. 4), the creek generally was losing water

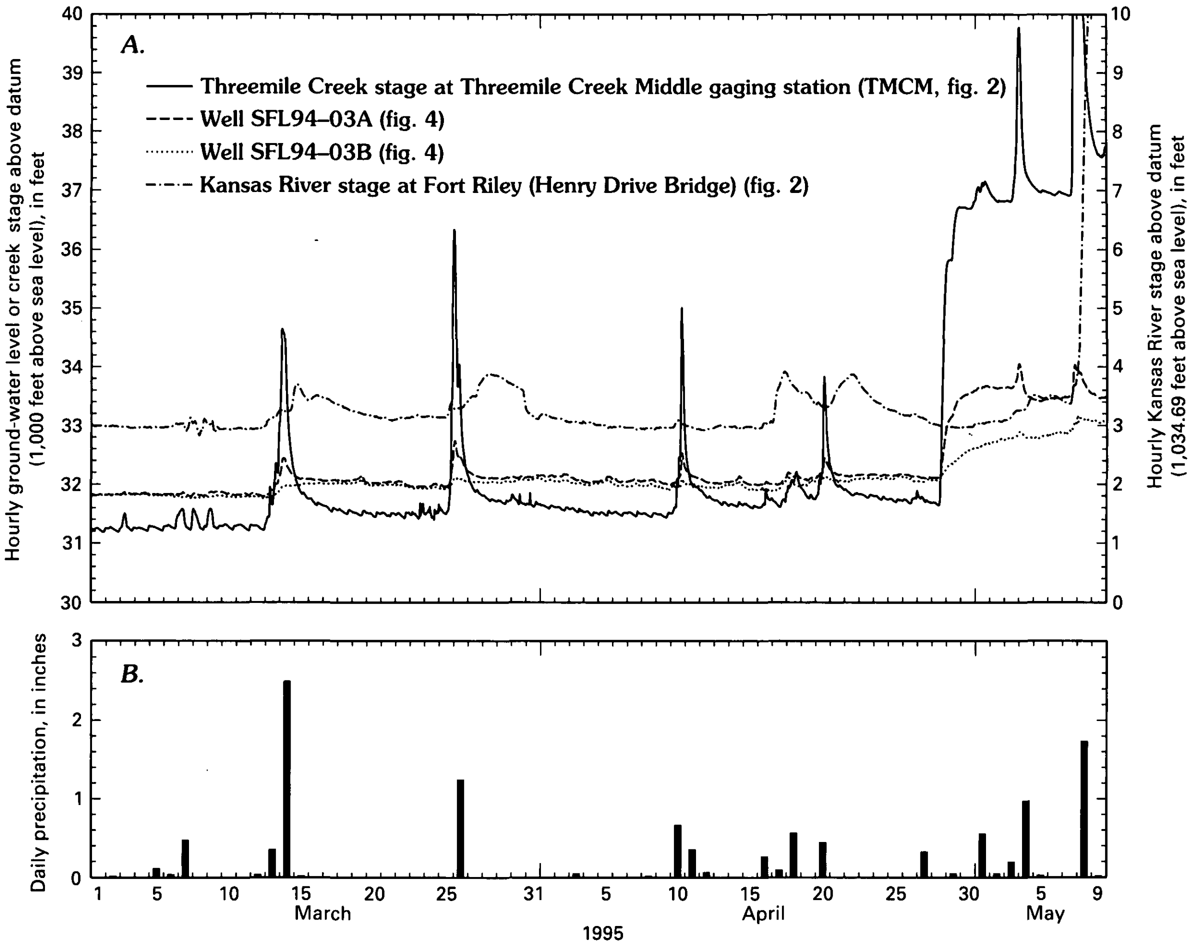


Figure 19. Relation among *(A)* Threemile Creek Middle gaging station and Kansas River stages, ground-water levels in wells SFL94–03A and SFL94–03B, and *(B)* precipitation at OB/OD area (fig. 2), March 1–May 9, 1995 (data on file with U.S. Geological Survey, Lawrence, Kansas).

to the aquifer, and these losses were greater than measurement error (table 3).

Water-quality data collected for a long-term ground-water monitoring program (U.S. Army Corps of Engineers, 1998) from wells at the Southwest Funston Landfill and from wells along Threemile Creek indicate that creek water interacts with ground water. Ground-water samples from wells collected and reported by Law Engineering and Environmental Services (1992; 1993a–d; 1995) and Louis Berger and Associates (1996a–b; 1997a–b; 1998a–b) were analyzed for volatile organic compounds (VOC's). VOC's have been detected consistently in shallow and deep wells west of Threemile Creek (except well SFL94–03A), but only in deep wells east of Threemile Creek (except well SFL94–02A) (fig. 21). This pattern of VOC detections indicates that VOC concentrations in shallow ground water are naturally attenuated by chemical or biological interaction with recharging creek water or that the influx of creek water into the alluvial aquifer deflects contaminated ground-water flow deeper into the aquifer as it flows under the creek.

Although most surface- and ground-water flow in the study area is natural, recent construction has caused some changes. During April 1995, a diversion structure was constructed in Threemile Creek in preparation to divert creek water into the Waterfowl Management Area (fig. 21). The diversion structure impounded water in the creek prior to and after the opening of the inlet channel to the Waterfowl Management Area in December 1995. As a result of impoundment, stream stage in the creek rose about 5 ft at the Threemile Creek Middle gaging station (TMCM in fig. 21). The diversion and outlet structures have created a condition whereby, upstream from the structures, the creek stage is almost always higher than adjacent ground-water levels. This condition extends

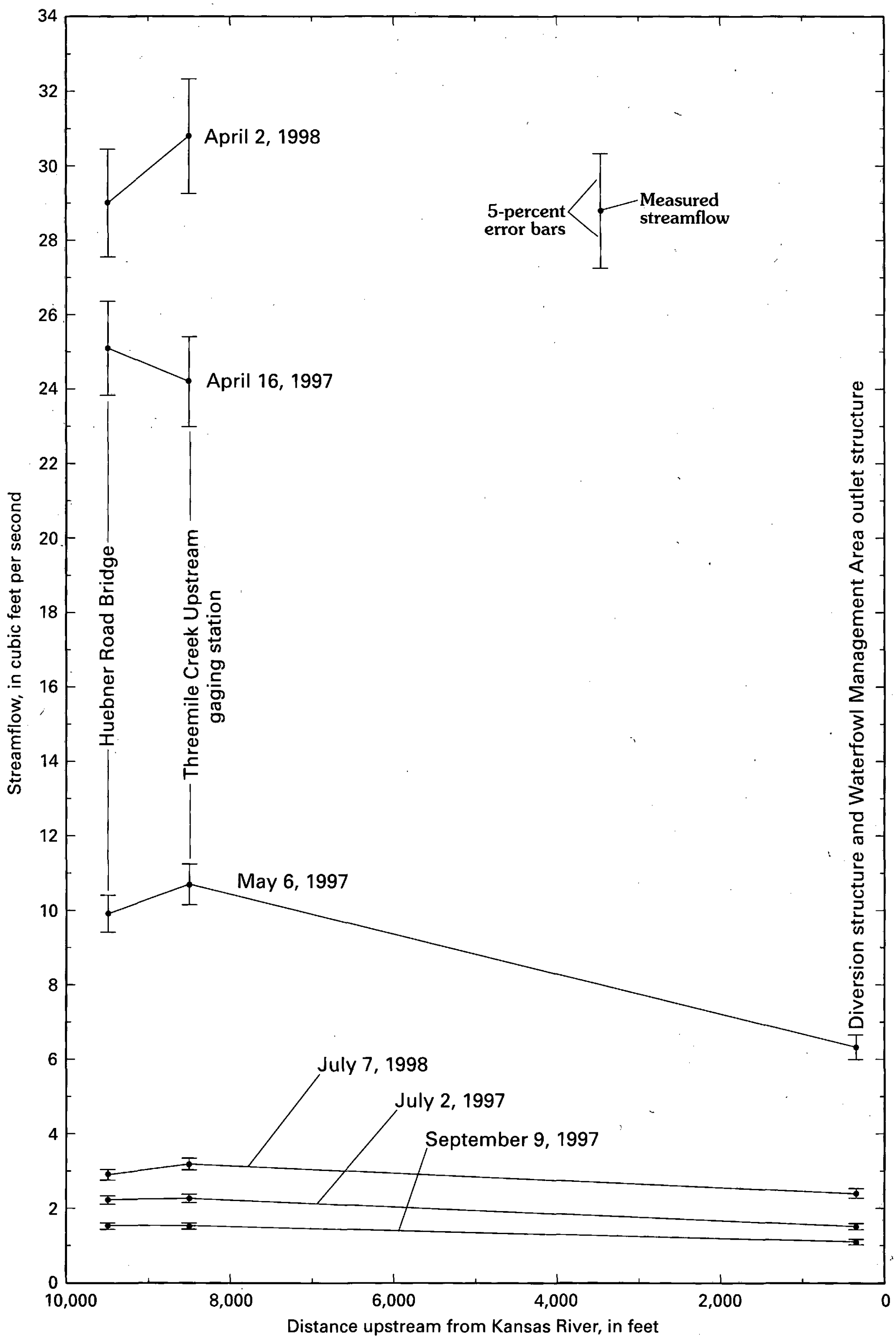


Figure 20. Results of six Threemile Creek seepage surveys conducted between April 16, 1997, and July 7, 1998 (data on file with U.S. Geological Survey Survey, Lawrence, Kansas).

Table 3. Results of six Threemile Creek seepage surveys conducted between April 16, 1997, and July 7, 1998

{Data on file with U.S. Geological Survey, Lawrence, Kansas. --, no data]

Measurement location or stream reach (figs. 2 and 4)	Streamflow and 5-percent measurement error (±), in cubic feet per second					
	April 16, 1997	May 6, 1997	July 2, 1997	Sept. 9, 1997	April 2, 1998	July 7, 1998
Huebner Road Bridge	25.1 ±1.25	9.91 ±0.50	2.23 ±0.11	1.53 ±0.076	29.0 ±1.45	2.90 ±0.14
Gain (+) or loss (-) in reach from Huebner Road Bridge to Threemile Creek Upstream gaging station	-.9	+.79	+.03	-.01	+1.8	+.28
Threemile Creek Upstream gaging station	24.2 ±1.21	10.70 ±0.54	2.26 ±0.11	1.52±0.076	30.8 ±1.54	3.18 ±0.16
Gain (+) or loss (-) in reach from Threemile Creek Upstream gaging station to diversion structure and Waterfowl Management Area outlet structure	--	-4.38	-.75	-.42	--	-.79
Diversion structure and Waterfowl Management Area outlet structure	--	6.32 ±0.32	1.51 ±0.076	1.10 ±0.06	--	2.39 ±0.12

upstream but does not affect Threemile Creek at the upstream gaging station (TMCU in fig. 2). Thus, upstream from the diversion and outlet structures, the higher water levels in Threemile Creek cause creek seepage losses to the aquifer and shallow ground-water flow away from the creek. Downstream from the diversion structure, ground-water levels probably are higher than Threemile Creek water levels, although the difference would diminish in the downstream direction, so that shallow ground-water flow generally would be towards the creek.

Aquifer Characteristics

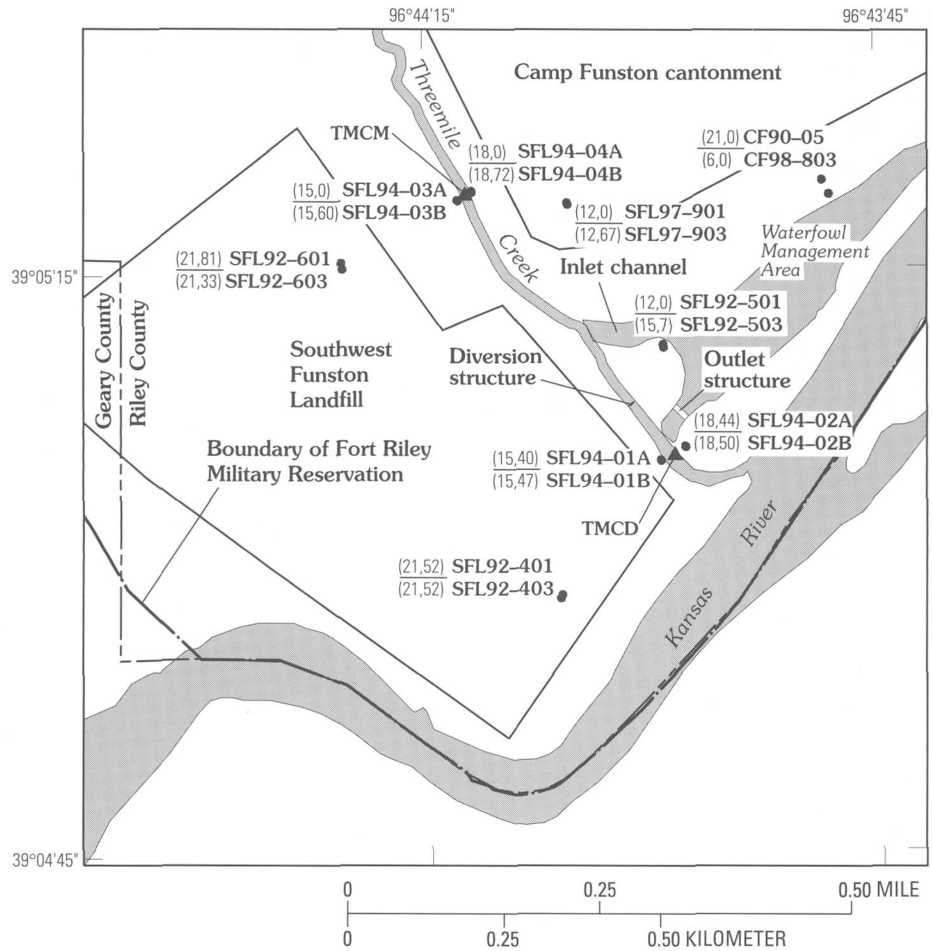
Geometry

Saturated thickness of the alluvial aquifer is the difference between the water-table altitude (fig. 13) and the bedrock-surface altitude (fig. 5) and ranges from less than 1 ft at the valley edges to about 55 ft in the thickest part of the aquifer. The depth to ground water below land surface generally is about 20 ft. The width of the river valley in the study area generally ranges from 1.5 to 2 mi. In a cross-sectional view oriented perpendicular to the length of the valley, the bedrock surface below the alluvial sediment forms a U-shape that is defined by steep walls and a fairly broad bottom (fig. 6).

Properties

The alluvial aquifer is unconfined. A general review of borehole logs from site-specific studies at Fort Riley and information provided by contractors to Fort Riley does not indicate the presence of widespread or laterally extensive fine-grained layers (Mike Greene, U.S. Army Corps of Engineers, oral commun., November 10, 1999). This absence of widespread confining units and the generally sandy nature of the alluvial sediment result in good hydraulic conductivity from top to bottom in the aquifer.

The alluvial aquifer from Junction City to Kansas City has been the subject of many aquifer tests. From aquifer tests in which water levels are observed in wells near a pumping well (pumping test), the horizontal and sometimes the vertical hydraulic conductivity, specific yield, and specific storage of an aquifer



EXPLANATION

Perennial surface-water body

(21,52) SFL92–401 • (21,52) SFL92–403 **Monitoring wells and identifiers**—First number in each parentheses ( ) is total number of analyses done for benzene, 1,2-dichloroethylene, and vinyl chloride, and second number is percentage of analyses in which benzene, 1,2-dichloroethylene, or vinyl chloride were detected. Identifiers are grouped at each location, with shallow well on top and deep well on bottom

Figure 21. Percentage of ground-water-sample analyses in which benzene, 1,2-dichloroethylene, or vinyl chloride were detected in wells near Threemile Creek, December 1995–December 1998 (Law Engineering and Environmental Services, 1992, 1993a–d, 1995; Louis Berger and Associates, 1996a–b, 1997a–b, 1998a–b).

can be determined. From aquifer tests where water levels are observed in the pumping well only (specific-capacity test), the hydraulic conductivity can be estimated. Hydraulic conductivity estimated from a specific-capacity test is less reliable than hydraulic conductivity calculated from a pumping test. As used in this report, the term hydraulic conductivity refers to horizontal hydraulic conductivity. The results of aquifer tests relevant to the Fort Riley area are summarized as follows:

- Of the 18 pumping tests reported by Fader (1974), the three closest to Fort Riley were done at Manhattan, Kansas (fig. 2). Hydraulic conductivity determined from these three tests ranged from 720 to 940 ft/d, with a median of about 760 ft/d. These pumping tests were done in the Big Blue River alluvium close to the junction of the Big Blue and Kansas Rivers.
- During April and May 1975, the USACE conducted a pumping test in the Republican River alluvium at Fort Riley about 1.5 mi northwest of Junction City (fig. 2). This test indicated that hydraulic conductivity ranged from 460 to 1,030 ft/d, with a median of 933 ft/d (U.S. Army Corps of Engineers, 1975).
- Another pumping test conducted by the USACE at Marshall Army Airfield in March 1983 (fig. 2) indicated a hydraulic conductivity of about 700 ft/d (U.S. Army Corps of Engineers, 1983).
- During July and August 1994, the USGS conducted a pumping test near Manhattan, Kansas, in the alluvium of the Big Blue River, a tributary to the Kansas River. Results of this test indicated a

hydraulic conductivity of about 450 ft/d (Jian and others, 1997).

The median hydraulic-conductivity value from all the preceding pumping tests is 730 ft/d.

- Myers and others (1996) reported the results of five specific-capacity tests of municipal wells in the Junction City well field (fig. 2). Estimated hydraulic conductivity ranged from 230 to 622 ft/d, with a median of about 307 ft/d.
- For this study, hydraulic conductivity was estimated from data for several supply wells at Fort Riley—two wells near Camp Forsyth, four wells near the Main Post, and four wells near Camp Funston (now plugged and abandoned). Hydraulic conductivity was estimated from specific-capacity data for these wells that were reported by Latta (1949, tables 7 and 15, wells numbered 14, 15, and 21–28). Hydraulic conductivity was estimated using the following equations (Lohman, 1979):

$$T_c = 2.3\frac{Q}{4\Pi s}\log\left(\frac{2.25tT_e}{r^2S_y}\right), \qquad (3)$$

where

T_c is computed transmissivity, in feet square per day;

Q is well discharge, in cubic feet per day;

s is drawdown of the water level in the well, in feet;

t is the length of the test, in days;

T_e is estimated transmissivity, in feet squared per day;

r is the radius of the well, in feet; and

S_y is specific yield, dimensionless, estimated to be 0.2;

and

$$K = \frac{T_c}{b} \qquad (4)$$

where

K is hydraulic conductivity, in feet per day; and

b is saturated thickness, in feet.

Equation (3) is solved iteratively for successive estimates of T_e until T_c converges on the value used for T_e. Estimated hydraulic conductivity at Fort Riley

Table 4. Estimated hydraulic conductivity at Fort Riley supply wells

[Hydraulic conductivity estimated from specific-capacity data reported by Latta (1949)]

Well (fig. 4)	Latta's (1949) well number	Well discharge (cubic feet per day)	Drawdown (feet)	Length of test (days)	Well radius (feet)	Saturated thickness (feet)	Estimated hydraulic conductivity (feet per day)
FR–2599	14	188,700	25.3	0.333	2.17	56	88
FR–2598	15	192,500	18.0	.333	2.17	54	137
FR–3202	21	96,300	8.0	.417	1.50	44	215
FR–3203	22	96,300	6.0	.417	1.50	43	303
FR–3204	23	96,300	5.0	.417	1.50	45	354
FR–3205	24	327,300	15.7	.333	2.17	51	306
FR–01PLG	25	192,500	6.0	.250	2.17	45	544
FR–02PLG	26	196,400	6.2	.333	2.17	48	519
FR–03PLG	27	196,400	7.2	.333	2.17	43	491
FR–04PLG	28	196,400	5.5	.333	2.17	45	633

supply wells, shown in table 4, ranges from 88 to 633 ft/d, with a median of 330 ft/d. In general, hydraulic conductivity estimated from specific-capacity tests is subject to more error than hydraulic conductivity estimated from pumping tests. Errors may arise from inaccuracies in reported pumping rates, length of test, well construction, and well-screen fouling over time.

Vertical hydraulic conductivity generally is smaller than horizontal hydraulic conductivity. This is especially true because of a preferential horizontal orientation of plate-shaped clay minerals and also because of the layered nature of alluvial sediment (Freeze and Cherry, 1979, p. 32 and 148). Estimates of vertical-to-horizontal hydraulic-conductivity ratios, estimated using a method developed by Neuman (1975), were 0.12 and 0.48 for the July and August 1994 pumping test near Manhattan, Kansas (data on file with USGS, Lawrence, Kansas). These different values, estimated for groups of observation wells west and east of the pumped well, may be indicative of the natural variability and (or) the potential error associated with the analysis.

The storage term defined for unconfined aquifers is specific yield. Water is released from storage in an unconfined aquifer as pore spaces are drained. Specific-yield data relevant to this study are listed below:

- Fader (1974) reported that the specific yields determined from the three pumping tests near Manhattan ranged from 0.13 to 0.20, with a median of 0.16.
- Specific yield from the pumping test conducted by the USACE in the Republican River alluvium was reported to be 0.20 (U.S. Army Corps of Engineers, 1975).
- Specific yield from the pumping test conducted by the USACE at Marshall Army Airfield was reported to be about 0.17 (U.S. Army Corps of Engineers, 1983).
- Specific yields from the pumping test conducted by the USGS near Manhattan, Kansas, in July and August 1994 were computed to be 0.16 and 0.27 for groups of wells west and east of the pumped well (data on file with USGS, Lawrence, Kansas).

The median specific yield from the preceding pumping tests is 0.185.

Porosity is an aquifer property that is inversely related to the velocity of ground-water flow. Porosity is related to specific yield by:

$$n = S_y + S_r, \qquad (5)$$

where

n	is porosity, dimensionless;
S_y	is specific yield, dimensionless; and
S_r	is specific retention, dimensionless.

Specific retention is a measure of the amount of water that is retained in the aquifer, adhered to the surface of grains of sediment upon dewatering. Specific retention generally is smaller for coarser, well-sorted sediment than for finer, poorly sorted sediment because, for a given volume of sediment, there is less surface area in a coarse-grained, well-sorted sediment than in a fine-grained, poorly sorted sediment. Grain-size analyses of sediment obtained from borings in and near the Southwest Funston Landfill and Marshall Army Airfield indicate that Kansas River alluvial sediment generally is poorly sorted ("Supplemental Information," table 17). Poorly sorted sand typically has specific retention of 5 to 10 percent (Davis and DeWiest, 1966). Thus, for a specific yield of 0.20 and a specific retention of 0.05, the porosity would be 0.25.

Hydraulic Boundaries

Hydraulic boundaries are places within the aquifer or at its edges where external hydraulic stresses or changes in aquifer characteristics significantly affect the movement of ground water. Stress-induced hydraulic boundaries occur along the courses of the Republican, Smoky Hill, and Kansas Rivers. These rivers are hydraulic boundaries because they are well connected hydraulically to the alluvial aquifer; the large conductance of the streambeds allows unimpeded interchange of water between the river and the aquifer. Because river stage is almost always higher or lower than ground-water levels near the river (fig. 22), the river acts as a water source or a sink, and ground water on either side of the river flows away from or toward the river accordingly. There are no extensive fine-grained layers in the alluvial aquifer to prevent the river from affecting ground-water flow from top to bottom of the aquifer. Thus, although the river does not fully penetrate the aquifer, ground-water generally does not flow beneath this hydraulic boundary. However, a significant hydraulic stress near the river, such

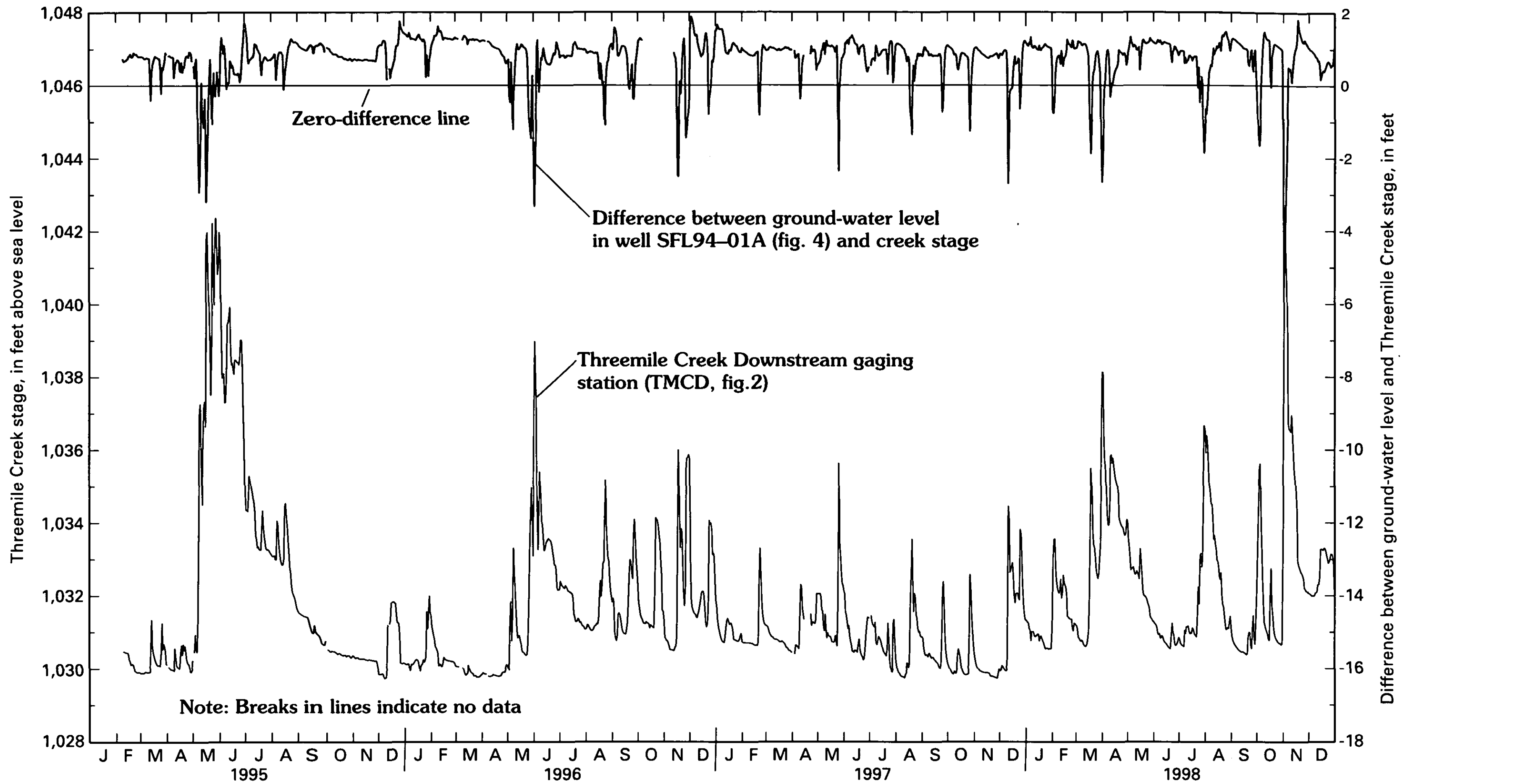


Figure 22. Stage at Threemile Creek Downstream gaging station and difference between ground-water level in well SFL94–01A and Threemile Creek stage, 1995–98. Threemile Creek stage at downstream gaging station is the same as Kansas River stage at mouth of Threemile Creek. Values above the zero-difference line indicate that the ground-water level is higher than the river stage and that ground-water flow is toward the river. Values below the zero-difference line indicate that the river stage is higher than the ground-water level and that ground-water flow is away from the river (data on file with U.S. Geological Survey, Lawrence, Kansas).

as a large-capacity supply well, can induce ground-water flow beneath the river.

Variations in aquifer properties, such as hydraulic conductivity within an aquifer or at the edge of an aquifer, also can create hydraulic boundaries. Within the Kansas River alluvial aquifer, widespread, fine-grained sediment layers have not been observed. Fine- and coarse-grained sediment layers that are present in the alluvial aquifer cause local variations in hydraulic conductivity but do not create widespread hydraulic boundaries. At the edges and bottom of the alluvial aquifer, however, the change from alluvial sediment to rock composed of layers of shale and limestone indicates a distinct difference in hydraulic conductivity that is present along the length of the river valley. Hydraulic conductivity of shale typically is less than 0.0003 ft/d (Freeze and Cherry, 1979). Hydraulic conductivity typical of limestone ranges from about 0.0002 to 1.0 ft/d; limestone with well-developed solution cavities and caves (karst features) can have a hydraulic conductivity of 5,500 ft/d (Freeze and Cherry, 1979).

The limestone along the Kansas River Valley at Fort Riley is fractured and exhibits some solution features but does not have well-developed karst features. Ground-water flow vertically upward through bedrock would be limited by the shale units along the bottom of the alluvial aquifer. However, lateral ground-water flow from limestone units can occur and could be significant where the limestone is fractured. The rate of this flow would be a function of the difference between hydraulic head in the limestone and in the alluvial aquifer. The larger the difference, the larger the flow. Hydraulic head in the limestone generally is related to precipitation (fig. 23).

Ground-Water Use

Ground water in the study area is used primarily as a water supply for public and irrigation purposes.

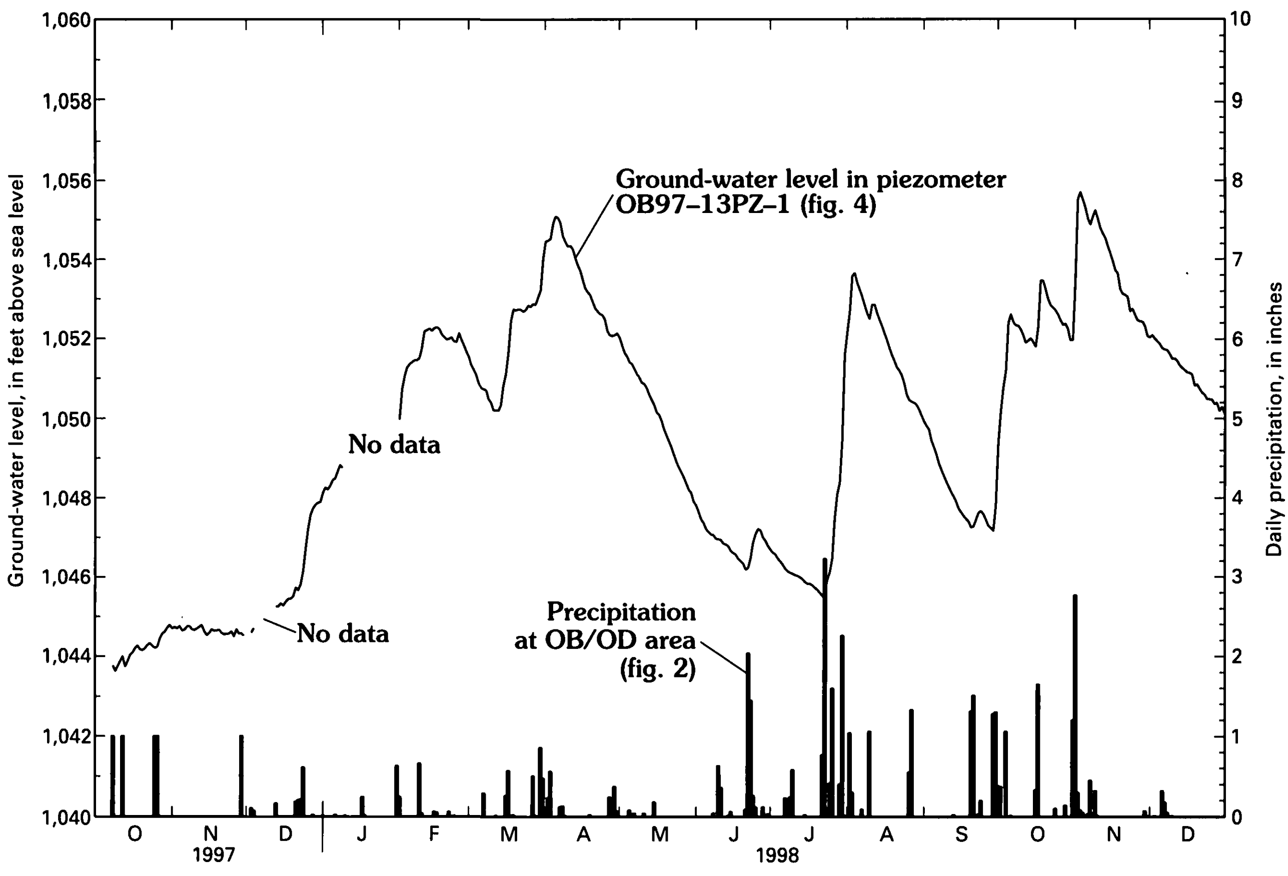


Figure 23. Relation between precipitation and ground-water level in piezometer OB97–13PZ–1 in upland limestone, October 1997–December 1998. Precipitation data for winter months of December through February probably do not accurately represent frozen precipitation but indicate when frozen precipitation melted and activated the tipping-bucket rain gage (data on file with U.S. Geological Survey, Lawrence, Kansas).

Wells presently (2000) used for public-water supply include Ogden wells located in the city of Ogden and Morris County Rural Water District wells located in the Clarks Creek Valley (fig. 4). Until the end of 1990, the city of Grandview Plaza operated wells in the Kansas River Valley but began using water from Junction City in 1991. Fort Riley wells, located near the north bank of the Republican River, are used to supply water for military (and related civilian) uses. Water use for public and military supply occurs year around.

Large pumping-capacity wells scattered throughout the Kansas River Valley are used to supply water for agriculture—primarily for irrigation of crops. Irrigation water use is seasonal and occurs mostly during the summer months of June through August.

Table 5 shows reported public, military, and irrigation water use for 1990–97. Fort Riley water use is shown for the years for which data were available. Water-use data were reported by well owners to DWR. Irrigation wells generally are not metered, whereas public-water supply wells are metered. Fort Riley does not report water use to DWR but keeps daily records of water pumped from each well. At the time of model development, water-use data were not available for 1998.

Estimated Water Budget for Aquifer

A ground-water budget was estimated on the basis of concepts of geology, geometry, and aquifer characteristics of the alluvial aquifer as described in previous sections. Components of inflow to and outflow from the alluvial aquifer were estimated for the water-budget area, an area approximately the same as the ground-water model area (fig. 3), which extends eastward from the confluence of the Smoky Hill and Republican Rivers to about 2.5 mi downstream from the city of Ogden, or about a 10-mi stretch of the valley.

Major inflows to the alluvial aquifer in the water-budget area consist of (1) precipitation recharge, (2) lateral ground-water flow from adjacent bedrock (valley walls), (3) subsurface ground-water flow down the valley from alluvial sediment, (4) seepage from the Republican, Smoky Hill, and Kansas Rivers to the aquifer, and (5) decreases in aquifer storage. Major outflows from the alluvial aquifer in the water-budget area consist of (1) subsurface ground-water flow down the valley to alluvial sediment, (2) seepage from the aquifer to the Republican, Smoky Hill, and Kansas Rivers, (3) supply-well pumpage, and (4) increases in aquifer storage. Some evapotranspiration from the aquifer probably occurs in riparian areas along creeks and rivers, but the water table in the remainder of the study area probably is below the root zone of most vegetation; therefore, evapotranspiration is considered to be a negligible part of the water budget for the aquifer.

Each of these components of inflow and outflow are discussed in the following paragraphs and are included as a water-budget item in table 6. Water-supply-well pumpage values were computed on the basis of reported annual pumpage values. Subsurface inflow and outflow and seepage from rivers were computed for selected times for which ground- and surface-water levels and a water-table map were available. These water-table maps were selected to represent dry conditions (fig. 13*A*) and wet conditions (fig. 13*C*) to provide a range of hydrologic conditions for budget computations. The water-table configuration in figure 13*A* reflects conditions of relatively low stream stage and little precipitation during the 4 months prior to April 1997, whereas the water-table configuration in figure 13*C* reflects conditions of higher stream stage and more precipitation during the 4 months prior to April 1998 (fig. 24).

The amount of precipitation that infiltrates to the water table (recharges the aquifer) is equal to total precipitation minus runoff, evaporation to the atmosphere, transpiration by plants, and the amount of moisture captured and stored in the unsaturated zone above the aquifer. The percentage of total precipitation that recharges the aquifer also is a function of the rate of rainfall, terrain, vegetation type, and climatic factors such as temperature, humidity, and wind. Direct measurement of precipitation recharge generally is not possible. However, mean annual precipitation recharge simulated by Dugan and Peckenpaugh (1985) for an area in south-central Kansas ranged from 0.44 to 8.27 in. depending on vegetation, terrain, and soil type. Vegetation in the Kansas River Valley includes crops (mostly corn and soybeans), woodland, and grassland. The terrain generally is flat, and soil types range from silty clay loam to loamy fine sand (Bidwell, 1960; Jantz and others, 1975). Simulated precipitation recharge for similar vegetation, terrain, and soil type (native grassland, flat terrain, and silty clay loam to loamy sand) ranged from 3.14 to 6.73 in/yr (Dugan and Peckenpaugh, 1985). These recharge rates were determined on the basis of a mean annual precipitation of 30.77 in. Thus, 3.14 to 6.73 in. represent 10 to

Table 5. Reported public, military, and irrigation water use in study area, 1990–97

[Data obtained from the Kansas Department of Agriculture, Division of Water Resources. NA, not available]

Water use	Water use, in acre feet per year							
	1990	1991	1992	1993	1994	1995	1996	1997
Ogden (public supply)	412.1	438.0	348.7	332.9	385.7	409.9	390.0	440.9
Grandview Plaza (public supply)	[1]79.5	0	0	0	0	0	0	0
Morris County (public supply)	0	0	0	[2]4.6	69.1	117.2	121.4	132.7
Fort Riley (military supply)	NA	NA	NA	3,600	NA	2,646.8	2,196.9	NA
Irrigation (agricultural)	278.0	591.1	111.1	[3]3.6	406.5	358.1	489.0	574.2

[1]Grandview Plaza wells not used after 1990.

[2]Morris County wells first used in 1993.

[3]Little water used for irrigation during this flood year.

Table 6. Estimated water budget for alluvial aquifer in water-budget area

Water-budget item	Aquifer recharge (+) or discharge (-) (cubic feet per second)	
	Dry conditions (April 1–4, 1997)	Wet conditions (April 1–3, 1998)
Recharge from precipitation	[1]+4.23	[1]+9.32
Lateral ground-water inflow (recharge) from adjacent bedrock	[1]+2.57	[1]+5.66
Subsurface ground-water inflow (recharge) from alluvial sediment	+.17	0
Subsurface ground-water outflow (discharge) to alluvial sediment	-1.96	-1.68
Seepage from Republican River[2]	-.69	+7.23
Seepage from Smoky Hill River[2]	-3.27	+34.30
Seepage from Kansas River[2]	-20.29	+212.61
Public-supply-well pumpage	[3]-1.42	[3]-.47
Subtotal (recharge - discharge)	**-20.66**	**+266.97**
Inflow from (+) or outflow to (-) aquifer storage	**+20.66**	**-266.97**

[1]Values estimated on the basis of recharge rate of 10 (dry conditions) and 22 (wet conditions) percent of mean annual precipitation.

[2]Positive value indicates seepage from the river to aquifer; negative value indicates seepage from aquifer to river.

[3]Values estimated on the basis of reported annual pumpage for dry (1991) and wet (1993) years.

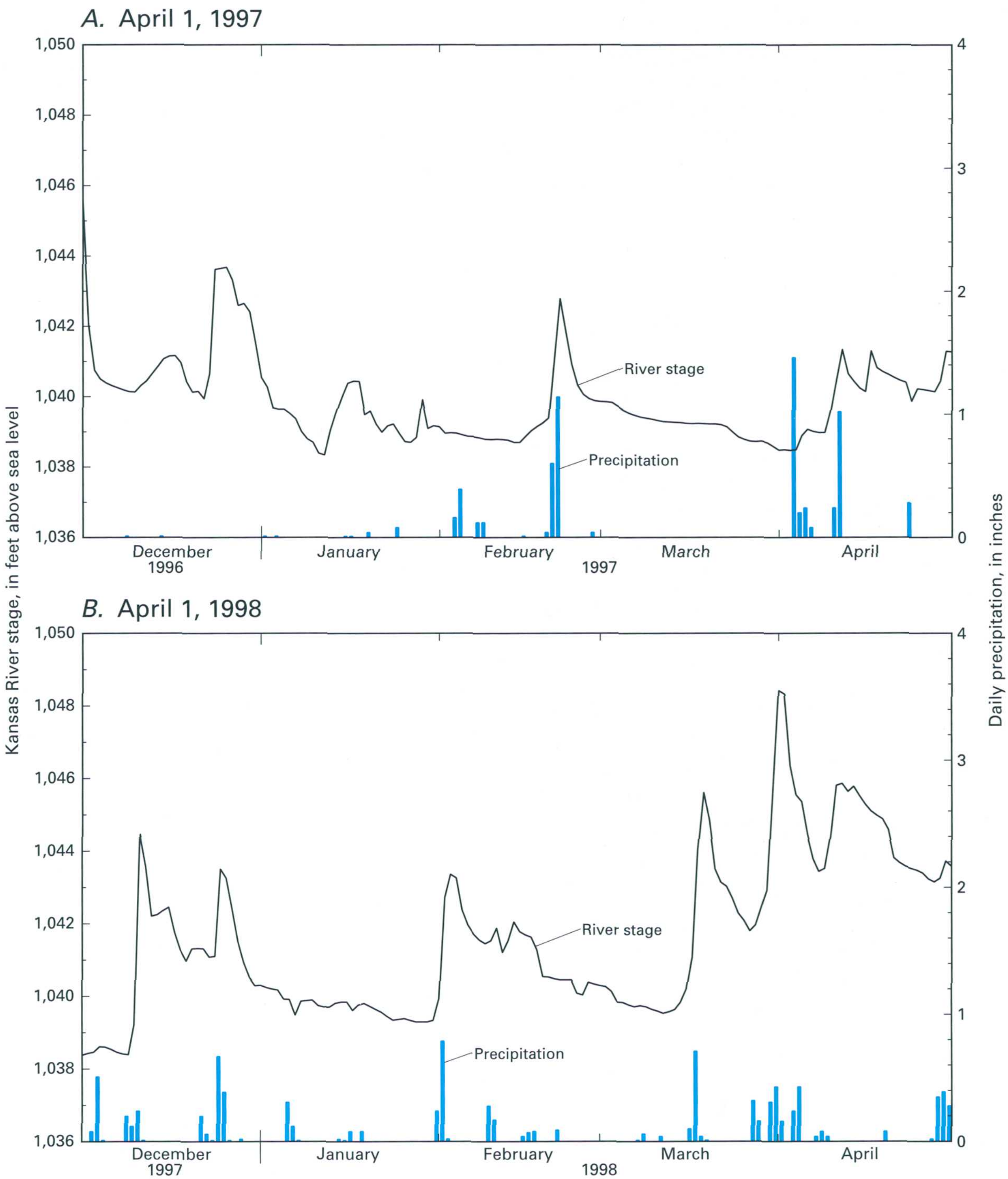


Figure 24. Kansas River stage at Fort Riley (Henry Drive Bridge) and precipitation at OB/OD area during 4 months prior to *(A)* April 1, 1997, and *(B)* April 1, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas).

22 percent of the mean annual precipitation in the Dugan and Peckenpaugh (1985) study. Therefore, at the Manhattan Municipal Airport precipitation gage where the 1961–90 mean annual precipitation was 33.82 in., 10 to 22 percent represents 3.38 to 7.44 in. The surface area of the alluvial aquifer within the model area is about 17 mi^2. Thus the volumetric rate of mean annual precipitation recharge was estimated to be in the range of 4.23 to 9.32 ft^3/s. Although these precipitation recharge values are based on mean annual precipitation, the range of values reflects dry and wet conditions observed prior to April 1997 and April 1998, respectively.

Lateral ground-water inflow from adjacent bedrock probably is related directly to precipitation. Ground-water levels in the upland limestone increase after precipitation (fig. 23) and decline as ground-water discharges to creeks and seeps along stream valleys. Much of the ground water in limestone discharges to perennial and ephemeral creeks, but it is likely that some discharges directly from bedrock to the alluvial aquifer or runs off the uplands and infiltrates into the alluvial aquifer near the edge of the Kansas River Valley. The assumption for this study was that precipitation within a given drainage basin would discharge to the creeks flowing through that basin. However, isolated upland areas (fig. 25) adjacent to the Kansas River Valley that slope toward the valley would discharge to the Kansas River alluvium. The amount of ground-water discharging from isolated upland areas directly to the alluvium would be proportional to the isolated upland surface area and to the amount of recharge. Combined, the isolated upland (fig. 25) surface area is about 10 mi^2. Soil permeability is smaller in upland areas than in the Kansas River Valley (Jantz and others, 1975), and thus precipitation recharge also would be smaller. However, runoff from the isolated upland areas flows toward the Kansas River Valley where it can infiltrate in the more permeable soil of the river valley. Thus, recharge in the isolated upland areas was assumed to be the same as in the river valley, 3.38 to 7.44 in/yr. Lateral ground-water inflow from adjacent isolated upland bedrock to the alluvial aquifer was estimated to be in the range of 2.57 to 5.66 ft^3/s.

Subsurface inflow and outflow from adjacent upstream and downstream alluvial deposits were estimated using Darcy's law:

$$Q = -KAi, \qquad (6)$$

where

Q is the flow, in cubic feet per second;

K is hydraulic conductivity, in feet per second;

A is the cross-sectional area of the aquifer, in square feet; and

i is the hydraulic gradient, in feet per foot (i is negative when the gradient slope is directed into the aquifer and positive when directed out of the aquifer in water-budget area).

Subsurface ground-water inflow from alluvial deposits to the water-budget area occurs between the Republican River and the northern valley wall. Across the rest of the river valley, the Republican and Smoky Hill Rivers were assumed to act as hydraulic boundaries that intercept subsurface ground-water flow. A hydraulic conductivity of 500 ft/d (about 0.0058 ft/s) was assumed for this estimate of inflow between the Republican River and the northern valley wall. The average aquifer thickness between the Republican River and the northern valley wall is about 40 ft, and the width of the valley from the river to the valley wall is about 1,500 ft, giving a cross-sectional area of about 60,000 ft^2. For April 1–4, 1997, the hydraulic gradient was about 0.0005 ft/ft (fig. 13*A*); for April 1–3, 1998, there was virtually no flow down the valley at this location, so the gradient was assumed to be zero (fig. 13*C*). Using these values, subsurface inflow was estimated to range from 0.17 to 0 ft^3/s for dry and wet conditions, respectively.

Subsurface ground-water outflow to alluvial deposits occurs at the downstream edge of the water-budget area. A hydraulic conductivity of 0.0058 ft/s also was assumed for this outflow area. The average aquifer thickness between the valley walls is about 50 ft at the downstream edge of the water-budget area, and the width about 9,700 ft, giving a cross-sectional area of about 458,000 ft^2. Hydraulic gradients for April 1–4, 1997, and April 1–3, 1998, were 0.0007 and 0.0006 ft/ft, respectively. Thus, the subsurface outflow was estimated to range from 1.96 to 1.68 ft^3/s for dry and wet conditions, respectively.

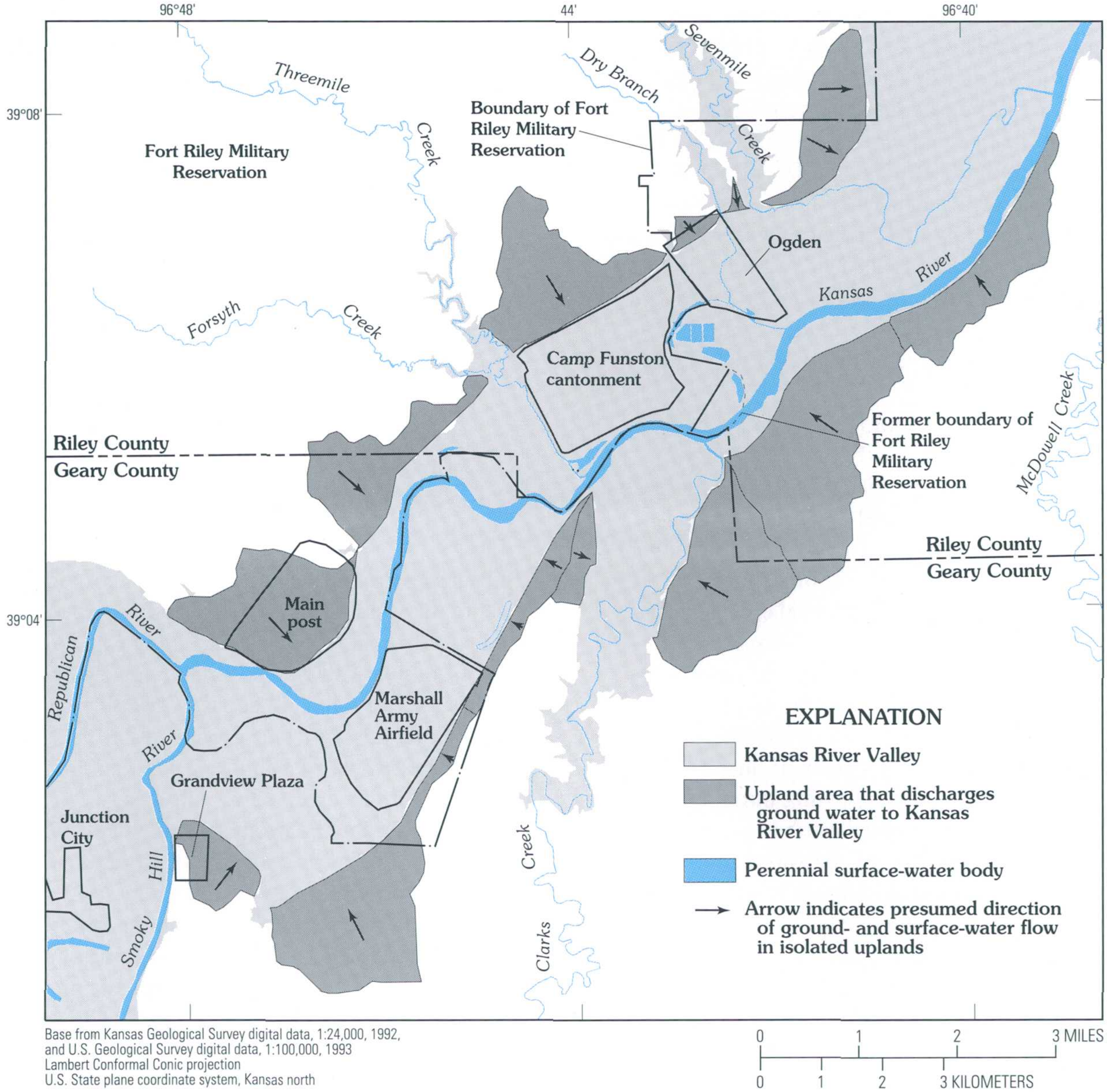


Figure 25. Isolated upland areas that discharge ground water to Kansas River Valley. Boundaries of upland areas are surface-drainage divides determined from U.S. Geological Survey topographic maps.

Seepage to or from the Republican, Smoky Hill, and Kansas Rivers was estimated using Darcy's law and ground-water-level measurements in well CF90–06 (fig. 4) and surface-water-level measurements of the Kansas River near Ogden (K 18 Bridge) (fig. 2) obtained April 1, 1997, and April 2, 1998. The distance from well CF90–06 to the river is about 20 times as great as the saturated thickness of the aquifer in this area. Therefore, ground-water flow between the river and well CF90–06 was assumed to be primarily horizontal. The horizontal hydraulic conductivity was assumed to be 0.0058 ft/s, and the cross-sectional area was estimated using the saturated thickness of the aquifer for each measurement date and the lengths of the river channels in the water-budget area (table 7).

Ground-water gradients for each measurement date were computed as the difference between water levels in well CF90–06 and the Kansas River near Ogden (K 18 Bridge) divided by the ground-water flow-path distances from the well to the river's edge (table 7). Ground-water flow-path lines and distances

Table 7. Values used in Darcy's law computation of Republican, Smoky Hill, and Kansas Rivers' seepage into or out of alluvial aquifer in water-budget area, April 1, 1997, and April 2, 1998

[A positive value indicates that the ground-water gradient is directed toward the river; a negative value indicates that the gradient is directed toward the aquifer.]

	April 1, 1997	April 2, 1998
Ground-water altitude in well CF90–06 (feet above sea level)	1,028.40	1,031.17
Surface-water altitude at Kansas River near Ogden (K 18 Bridge) (feet above sea level)	1,027.82	1,035.83
Hydraulic conductivity (feet per second)	.0058	.0058
Estimated saturated thickness (feet)	25	30
Republican River channel length (feet)	2,050	2,050
Smoky Hill River channel length (feet)	9,730	9,730
Kansas River channel length (feet)	60,310	60,310
Total cross-sectional area (square feet)	1,802,250	2,162,700
Ground-water flow-path length (feet)	500	460
Ground-water gradient (foot per foot)	.00116	-.01013

were determined on the basis of water-table maps for April 1–4, 1997, and April 1–3, 1998 (figs. 13*A* and 13*C*). For each measurement date, the same values of saturated thickness and hydraulic gradient were used for all three rivers because of their similarities and proximities to each other. Although saturated thickness does change along the river channels, these changes probably would be offset by corresponding but opposite changes in the ground-water gradient—smaller ground-water gradients where saturated thickness is larger and larger ground-water gradients where saturated thickness is smaller. Because seepage to or from the rivers occurs on both the north and south sides of the rivers, the seepage computed using the values shown in table 7 was doubled to represent the total seepage to or from the rivers.

The resulting seepage estimates (table 6) indicate that ground water was flowing from the aquifer to the rivers at a combined rate of 24.25 ft^3/s (about 1.78 ft^3/s per river mile) on April 1, 1997, and was flowing from the rivers to the aquifer at a combined rate of 254.14 ft^3/s (about 18.69 ft^3/s per river mile) on April 2, 1998 (table 6). The seepage estimate (1.78 ft^3/s per river mile) for dry conditions is nearly the same as that (1.67 ft^3/s per river mile) calculated for the 42 mi of the Kansas River from Fort Riley to Wamego (see "Ground-Water Flow and Ground-Water/Surface Water Interaction").

Supply-well pumpage in the water-budget area for dry and wet conditions was estimated on the basis of water-use data (table 5). In 1991, when dry conditions prevailed, 438 acre-ft of water was pumped for public-supply use, and 591.1 acre-ft was pumped for irrigation use. On an annual basis, these combined pumpages amount to an average of 1.42 ft^3/s. If the 1997 pumpage from the Morris County wells is added (as a better estimate of pumping in future dry years), the average use for dry periods is 1.60 ft^3/s. In 1993, a very wet year, 337.5 acre-ft was pumped for public-supply use, and 3.6 acre-ft was pumped for irrigation use. On an annual basis, these combined pumpages would average 0.47 ft^3/s.

In table 6, the subtotals indicate that during dry periods the aquifer loses water at a rate of 20.66 ft^3/s and during wet periods it gains water at a rate of 266.97 ft^3/s. The water lost from the aquifer comes from storage in the aquifer causing a decrease of water levels, and water gained by the aquifer goes into storage in the aquifer causing an increase of water levels. Thus, the subtotal and aquifer-storage values in table 6 are equal but opposite in sign.

The dry and wet condition water budgets in table 6 indicate that seepage from the rivers by far dominates the inflow to and outflow from the aquifer. Recharge from precipitation and subsurface inflow and outflow are about one to two orders of magnitude smaller than river seepage. Thus, the rivers are the dominant factor in determining the direction and volumetric rate of ground-water flow.

SIMULATION OF GROUND-WATER FLOW

A modular, three-dimensional, finite-difference, ground-water flow model (MODFLOW) (McDonald and Harbaugh, 1988) was used to simulate ground-water flow in the alluvial aquifer. MODFLOW represents the aquifer by using cells of user-specified length (x dimension), width (y dimension), and thickness (z dimension). Aquifer properties are uniform within a cell but may vary in value from cell to cell. Multiple layers of cells may be used to simulate three-dimensional ground-water flow. MODFLOW iteratively determines the hydraulic head for each cell by solving a finite-difference, ground-water flow equation that accounts for ground-water flow between model cells and between model cells and external sources or sinks of water (hydraulic stresses), such as model boundaries, streams, wells, precipitation recharge, and evapotranspiration. The solution process is repeated for all the model cells until the difference between successive hydraulic-head values in any one cell is less than a user-specified value.

MODFLOW models may be used for steady-state or transient simulations. For steady-state simulations, the hydraulic-head configuration (and thus direction of ground-water flow), aquifer storage, and stresses are constant with time. For transient simulations, hydraulic head, aquifer storage, and stresses are allowed to change at the beginning of each stress period. A stress period is a user-defined time period during which hydraulic stresses (precipitation recharge, boundary conditions, well pumpage, and streamflows or stream stages) in the model are held constant. It is common practice to use a steady-state simulation to condition hydraulic heads and aquifer storage for the beginning of a transient simulation.

The Department of Defense Groundwater Modeling System (GMS) version 2.1 was used to prepare data for MODFLOW simulations and to process MODFLOW output. GMS was developed as a cooperative effort among the Department of Defense, Department of Energy, U.S. Environmental Protection Agency, Cray Research, and 20 academic partners (U.S. Army Corps of Engineers Waterway Experiment Station, 1999). GMS provides an integrated and comprehensive computational environment for simulating subsurface ground-water flow.

As will be discussed in detail in later sections, several steady-state and transient simulations were conducted. Steady-state simulations were conducted to condition the starting hydraulic heads and aquifer storage for transient simulations . Transient simulations of September 7, 1997, through April 2, 1998, conditions were conducted for model calibration and sensitivity determinations, and simulations of January 1, 1990, through December 31, 1998, conditions were conducted for historical simulation of ground-water flow. The historical simulations were used as the basis for five hypothetical simulations testing the effects of varying Ogden supply-well and hypothetical well pumping.

Description of Model

The Kansas River alluvial aquifer at Fort Riley was represented by three layers of cells. Each layer of cells forms a grid consisting of 224 columns by 100 rows (fig. 26*A*, 26*B*, and 26*C*). The grid was oriented so that the rows generally parallel the long axis of the Kansas River Valley and the columns parallel Threemile Creek at the Camp Funston cantonment (fig. 26*A*). All of the cells, except those near Threemile Creek, are uniformly 250 ft in length and width. Because the effect of Threemile Creek on ground-water flow was of interest in this study, it was important to more closely simulate the true width of the creek. Accordingly, cells near Threemile Creek are 62.5 ft in length (fig. 26*A*) where the creek parallels the western edge of the Camp Funston cantonment. Cells 125-ft long were placed on either side of the 62.5-ft long cells to provide a smoother transition from the 250-ft to the 62.5-ft cells.The length and width (x and y dimensions) of each cell in all three layers are the same as the cell above or below.

The thickness of model cells, which varies from cell to cell and from layer to layer, was determined using GRID tools in ARC/INFO (ESRI, 1997). ARC/INFO is a geographic information system (GIS) program that can be used to manipulate geographic features and data attributed to those features (coverages). GRID, a subprogram of ARC/INFO, allows the user to discretize coverages into a grid of cells with user-defined dimensions. Data values assigned to each cell are interpolated from a data attribute of the discretized coverage. This grid of data values then represents some aspect of the discretized coverage, such as bedrock elevation. The data values

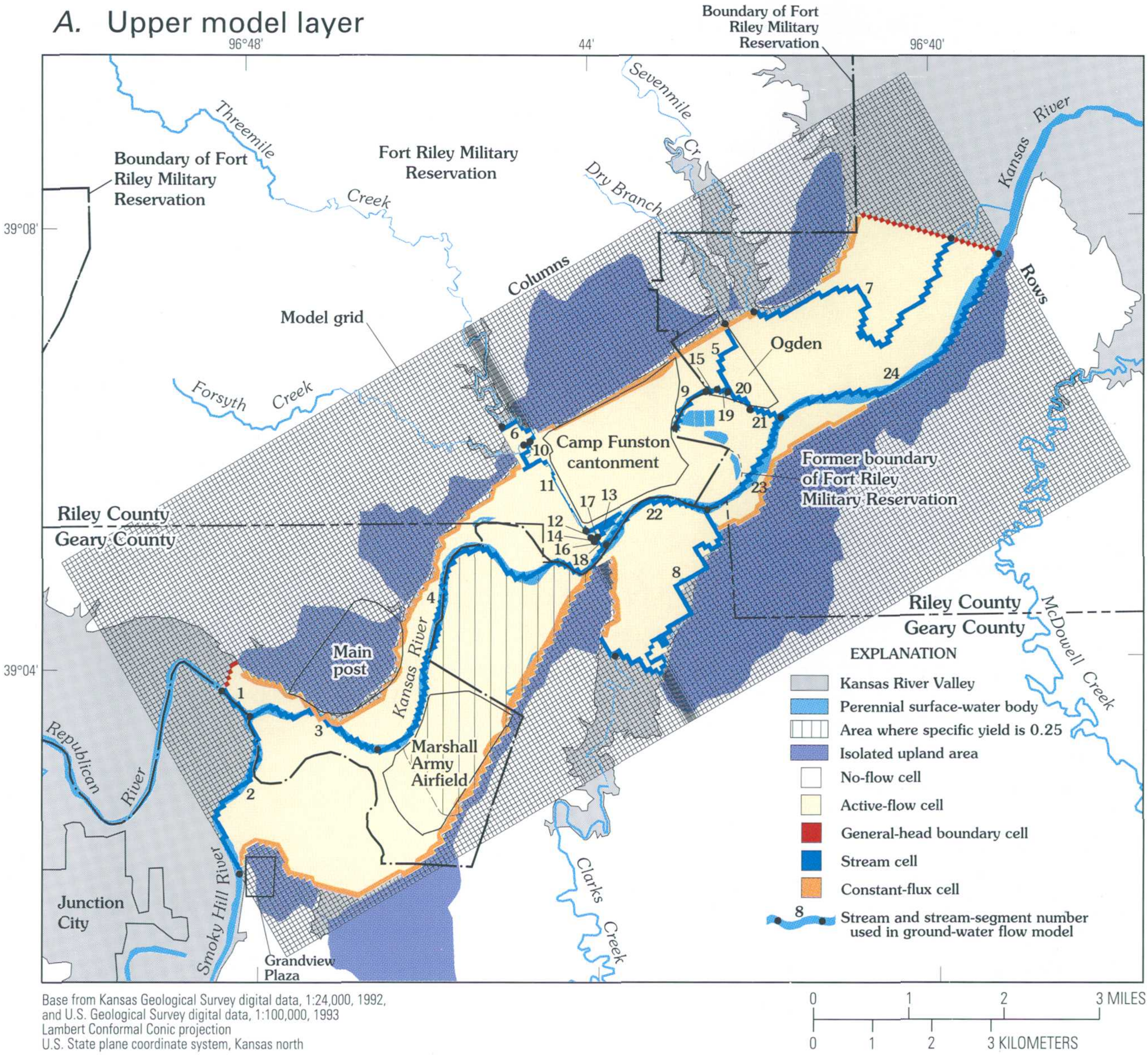


Figure 26. Model grid and model cells for *(A)* upper, *(B)* middle, and *(C)* lower model layers.

can be manipulated by applying mathematical operations to individual cells, to the whole grid, or by combining two or more grids.

The bedrock surface (fig. 5) was discretized using GRID, and values representing the altitude of the bedrock surface were assigned to each cell of the grid. Next, two grids representing planar surfaces were constructed such that they lay horizontally across the valley but sloped down the valley parallel to the slope of the bedrock (fig. 27). The surfaces were used to define the boundaries between the lower and middle, and middle and upper layers. These boundaries were placed 15 and 35 ft higher than the axis of the bedrock low, respectively. The vertical placements of the model layers were chosen such that the screens of observation wells at Marshall Army Airfield would be contained completely within a single model layer. This was to facilitate the development and use of a solute-transport model that is based on the ground-water flow model developed for this study. Thus, three model layers were created with thicknesses ranging from 15 ft or less for the lower layer and 20 ft or less for the middle layer. The thickness of the upper layer generally was 20 ft or less but varied in space and time because the top of the upper layer is defined by the altitude of the water table and not by the altitude of the land surface. The layers are fairly uniform in thickness except where they pinch out against the valley walls.

B. Middle model layer

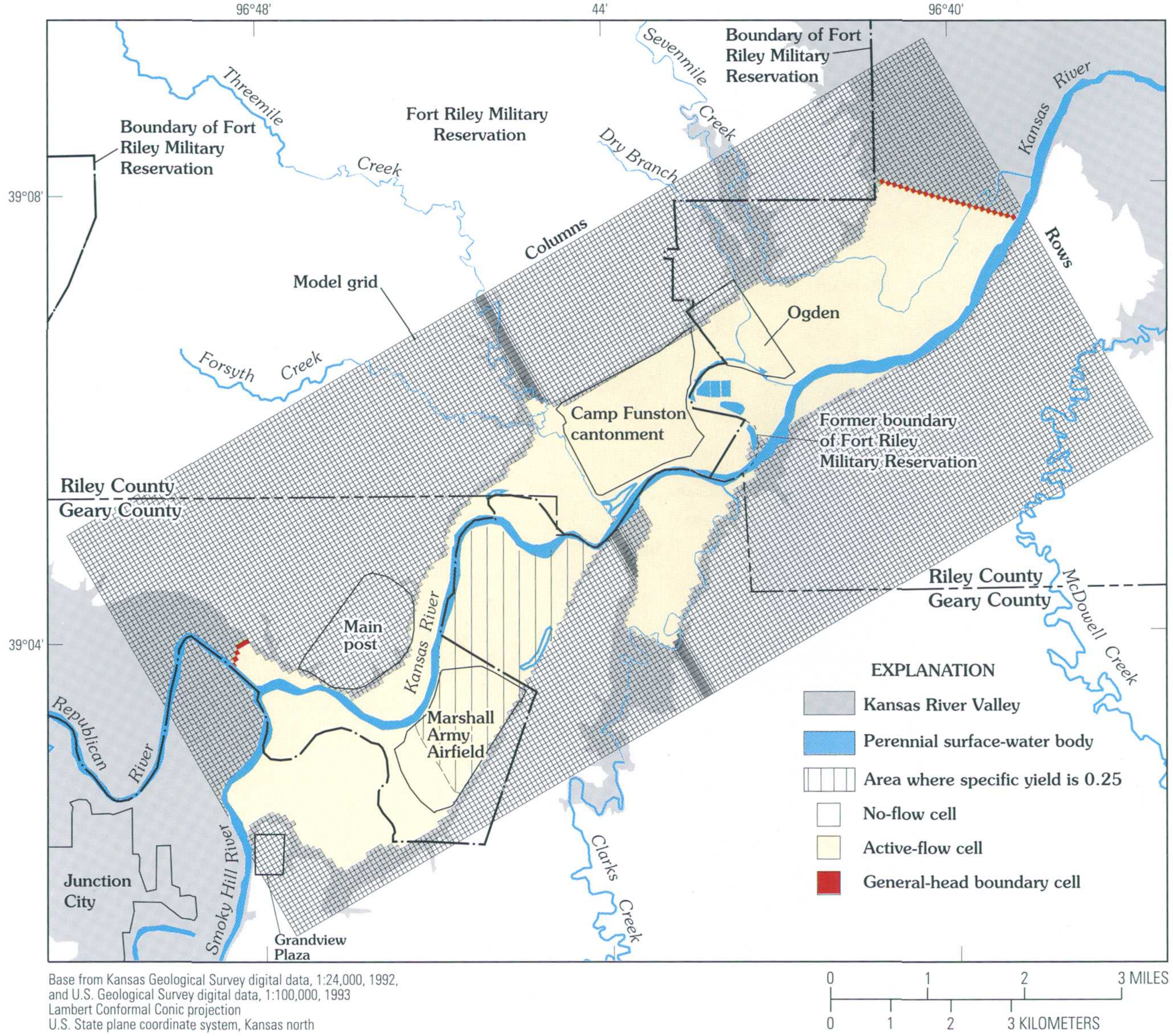


Figure 26. Model grid and model cells for *(A)* upper, *(B)* middle, and *(C)* lower model layers—Continued.

The three model layers vary in width with the upper model layer the widest and the lower layer the narrowest (fig. 26). This is a result of the U-shaped geometry of the bedrock surface in the river valley (fig. 27).

Where possible, model boundaries were made to coincide with natural hydrologic boundaries (table 8). Most of the upstream model boundary, corresponding to the Republican and Smoky Hill Rivers, was simulated using stream cells in the upper model layer (fig. 26*A*). The northern and southern model boundaries, corresponding to the northern and southern edges of the Kansas River Valley, were simulated using constant-flux cells (fig. 26*A*). The bottom of the model, corresponding to the contact between the bottom of alluvial deposits and bedrock, was simulated using implicit no-flow cells that exist at all margins of the model grid. Part of the upstream model boundary and all of the downstream model boundary, simulated using general-head cells (figs. 26*A*, 26*B*, 26*C*), do not correspond to natural hydrologic boundaries. Each of these types of boundaries are discussed in the following paragraphs.

Stream cells were used to represent rivers and creeks in the study area. For each stream cell, MODFLOW computes a flux in or out of the aquifer on the

C. Lower model layer

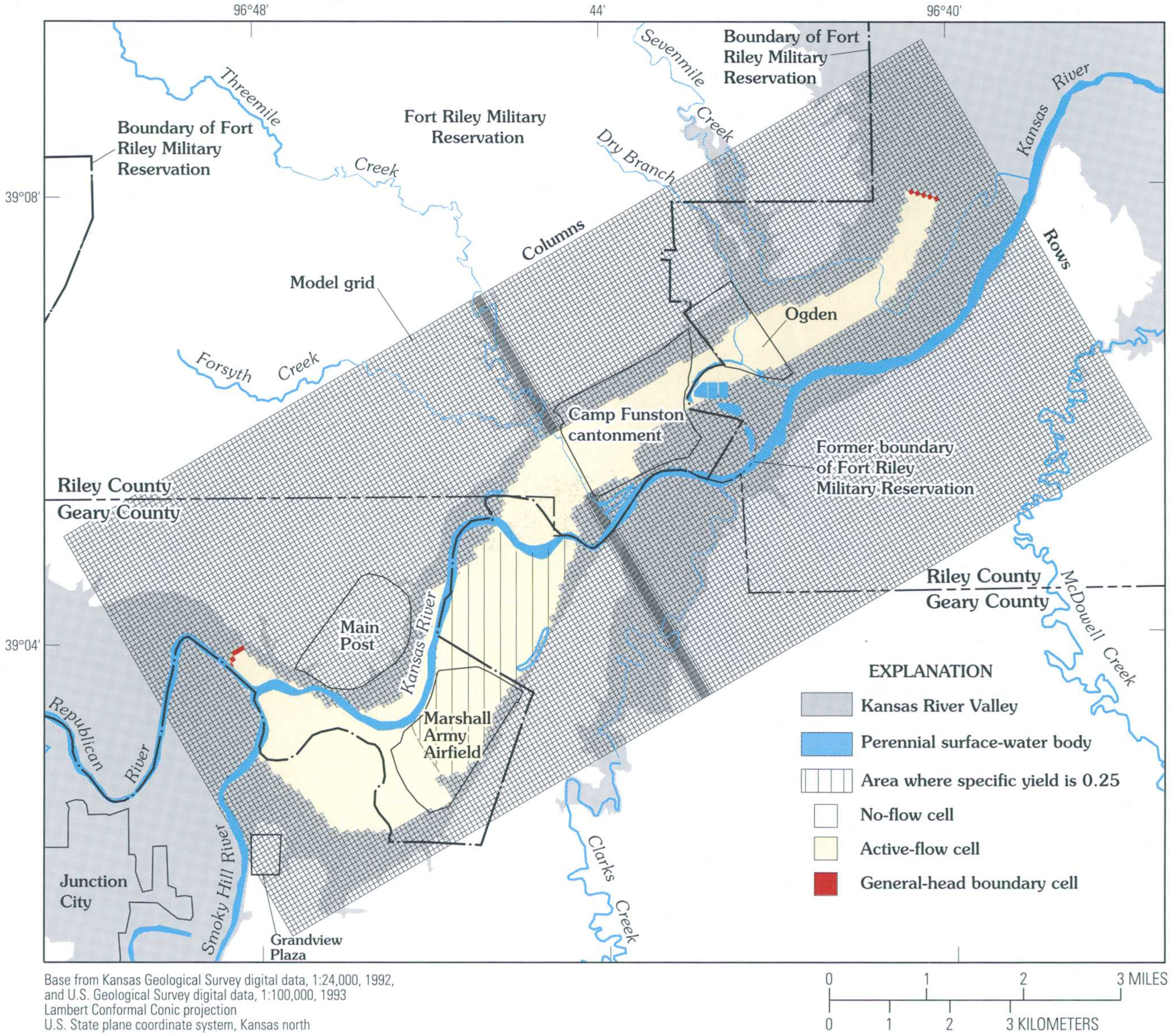


Figure 26. Model grid and model cells for *(A)* upper, *(B)* middle, and *(C)* lower model layers—Continued.

basis of the hydraulic head in the stream, the hydraulic head in the aquifer, and the conductance of the streambed. The user can choose to specify hydraulic head in the stream or to specify streamflow at the upstream-most stream cells and let MODFLOW compute the hydraulic head in the stream. MODFLOW computes hydraulic head in the stream (stream stage relative to sea level) on the basis of streamflow and the slope, roughness, and width of the stream channel. Large streams, such as the Republican, Smoky Hill, and Kansas Rivers, with effective hydraulic connection (large values of streambed conductance) with an aquifer with large vertical hydraulic conductivity, effectively dominate ground-water flow. Relative to hydraulic heads in the adjacent aquifer, lower (or higher) hydraulic heads in these large streams cause a vertical boundary to form below the streambed along the course of the stream across which ground water does not flow. Smaller streams, such as Clarks, Forsyth, Threemile, and Sevenmile Creeks, and Dry Branch have smaller streambed conductances and may interact with ground water but generally do not transmit enough water between the stream and aquifer

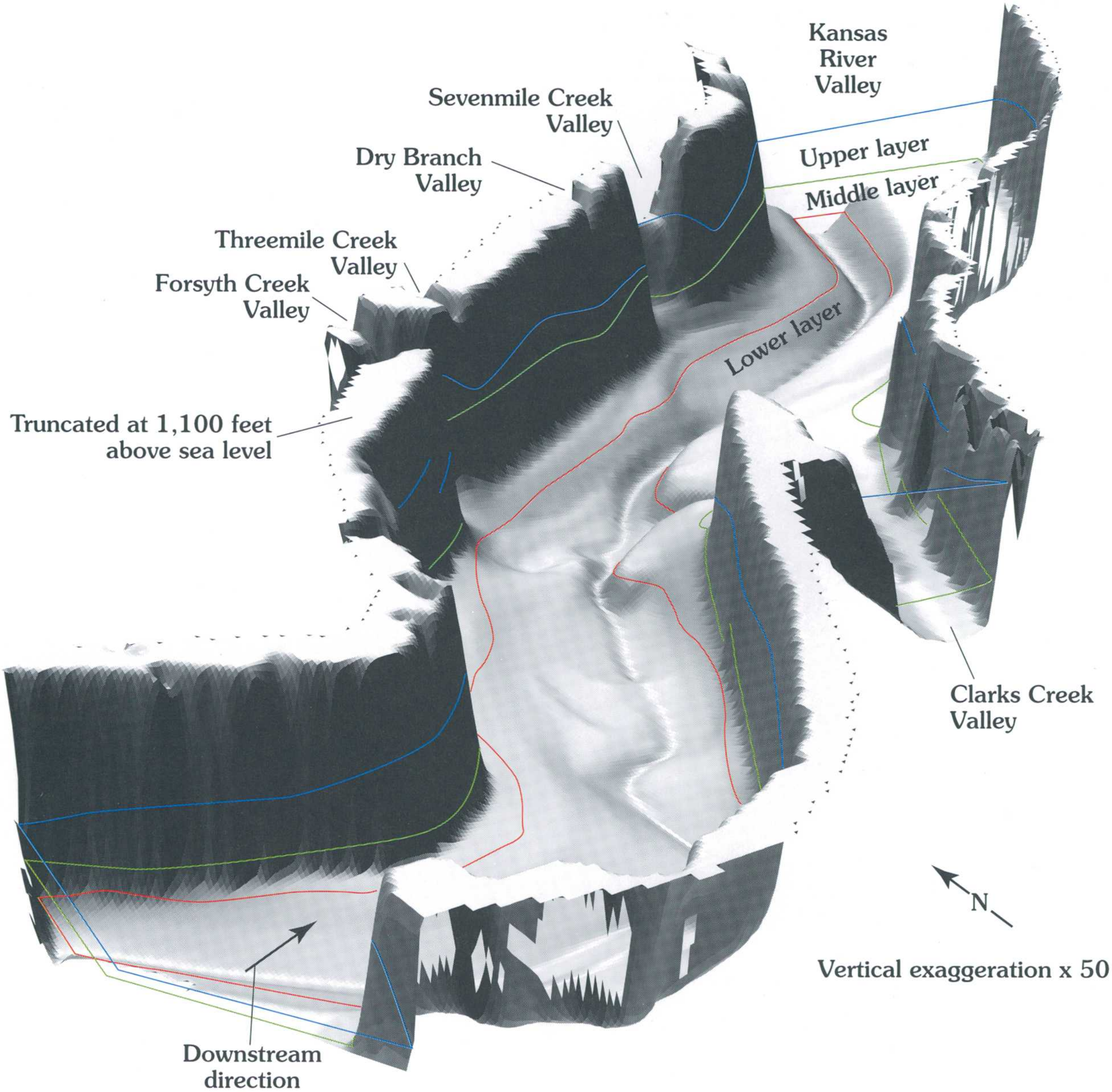


Figure 27. Shaded relief of bedrock surface in Kansas River Valley with superimposed traces of upper, middle, and lower model-layer boundaries. Alluvial sediment has been removed. Map is based on bedrock-surface contours shown in figure 5.

to create boundary conditions in a system where larger rivers exist.

Constant-flux cells were used to represent lateral ground-water inflow from bedrock to the alluvial aquifer along the northern and southern model boundaries (fig. 26*A*). The flux was held constant for each MODFLOW stress period but differed in successive stress periods on the basis of precipitation. The flux was applied to cells in the upper model layer using MODFLOW's recharge package. This flux was applied in addition to the precipitation recharge applied over all of the active model cells. Bedrock-derived recharge was not specified for the middle and lower model layers to simplify the model; vertical hydraulic conductivity is large enough that the addition of bedrock-derived recharge to only the upper layer did not cause significant simulation inaccuracies.

At the bottom of the lower layer, no-flow cells represent the contact between alluvial deposits and

Table 8. Natural hydrologic boundaries, hydrologic processes, simulated model boundaries, and types of model cells used to simulate boundaries

Natural		Simulated	
Hydrologic boundary	**Hydrologic process**	**Model boundary**	**Type of model cell**
Republican and Smoky Hill Rivers	Seepage to and from rivers	Most of the upstream model boundary	Stream cell
Kansas River	Seepage to and from river	Boundary internal to model	Stream cell
Edge of the Kansas River Valley where alluvial deposits contact bedrock	Lateral ground-water inflow from bedrock	Northern and southern model boundaries	Constant-flux cell
Contact between the bottom of the alluvial deposits and bedrock	No vertical ground-water flow	Bottom of the lower model layer	Implicit no-flow cell
No natural hydrologic boundary	Subsurface ground-water inflow from alluvial aquifer upstream from model boundary	Northern part of the upstream boundary	General-head cell
No natural hydrologic boundary	Subsurface ground-water outflow to alluvial aquifer downstream from model boundary	Downstream boundary	General-head cell

bedrock. In MODFLOW, no-flow boundaries implicitly surround the sides and bottom of the model grid.

General-head cells were used to represent subsurface ground-water inflow from the alluvial aquifer upstream from the model boundary and to represent subsurface ground-water outflow to the alluvial aquifer downstream from the model boundary. General-head cells were specified for all three layers at part of the upstream boundary and all of the downstream boundary (figs. 26*A*, 26*B*, 26*C*). General-head cells allow the user to specify a hydraulic head at some distance upstream or downstream from the model boundary that will be used to determine the direction (in or out of the simulated aquifer) and volume of ground-water flow. These heads are held constant for each MODFLOW stress period but can differ in successive stress periods.

The direction of ground-water flow is computed by MODFLOW on the basis of the user-specified general head and the simulated head in the boundary model cell. If the user-specified general head is larger than the simulated head in the boundary model cell, simulated ground water will flow into the model, and if it is smaller, simulated ground water will flow out of the model. The volume of simulated ground water flowing in or out of the model is dependent on the general-head hydraulic conductivity, distance from the model boundary to the user-specified general head, and the width and thickness of the model cell.

Because ground-water flow across general-head boundaries is affected by stresses simulated in the model, boundaries of this type usually are located some distance from the area of interest in the model. The upstream general-head boundary in this model is located about 0.75 mi upstream from one area of interest—the dry cleaning facility (fig. 3). The boundary was not extended farther upstream because doing so would have necessitated simulating ground-water pumpage in the Fort Riley well field and because farther upstream a longer general-head boundary would have been required. The downstream general-head boundary was located about 2.5 mi downstream from the city of Ogden because the source of ground water supplying Ogden public-supply wells was of interest in this study. Although three irrigation wells are present outside of and near the downstream boundary, these wells, at their maximum combined reported pumpages for 1991–95, yielded 29.3 acre-ft of water per year or about 0.04 ft^3/s on an annual basis. This is about 2 percent of the estimated subsurface outflow to alluvial sediment (table 6). Therefore, these wells are not likely to affect ground-water flow at Ogden to a measurable extent.

Representation of Aquifer Properties and Hydraulic Stresses

Aquifer Properties

Aquifer properties represented in the steady-state and transient models included hydraulic conductivity, vertical conductance between layers, and, in the transient model, aquifer storage. The specification of each of these properties is discussed in the following paragraphs.

Values of hydraulic conductivity were uniformly specified for each model layer—600, 800, and 900 ft/d for the upper, middle, and lower model layers, respectively. The vertical increases of hydraulic conductivity were used to represent the general downward coarsening of the alluvial sediment. These hydraulic-conductivity values were determined through the model-calibration process. There were not enough measurements of hydraulic conductivity across the model area to justify varying hydraulic conductivity within a layer.

Vertical conductance was determined through the use of a conductance equation (McDonald and Harbaugh, 1988, p. 5–13, eq. 51). In the equation, vertical conductance between model layers is computed using the hydraulic conductivity of the adjacent layers and a user-specified vertical hydraulic-conductivity value. A vertical hydraulic conductivity of 1/10 of the horizontal hydraulic conductivity was used uniformly for all cells in the model. The 1/10 value was determined to be a reasonable value on the basis of a pumping test near Manhattan, Kansas, where estimates of the vertical-to-horizontal hydraulic conductivity were 0.12 to 0.48 (data on file with USGS, Lawrence, Kansas). No other vertical hydraulic-conductivity values were reported for other pumping tests. Vertical conductance computed between the upper and middle layers was 3.4 ft/d-ft and between the middle and lower layers was 4.8 ft/d-ft.

For transient-model simulations, MODFLOW requires the user to specify primary aquifer-storage (storativity) values for each layer. For confined layers, MODFLOW requires the user to specify primary and secondary storativity values for each layer. These values can differ from layer to layer depending on whether a layer is defined as confined or unconfined. Storativity for confined aquifers generally is several orders of magnitude less than that for unconfined aquifers. This is because water released from storage in confined aquifers comes from expansion of water and decompression of the aquifer material, whereas water released from storage in unconfined aquifers comes from draining pore spaces in the aquifer material. In this model, the upper layer was defined as being unconfined and was assigned a primary storativity value, whereas the middle and lower layers were defined as being confined and were assigned primary and secondary storativity values. The layers are defined in this way because the releases of water from unconfined storage can occur only at the water table. The lower two model layers never would have releases of water from unconfined storage unless the water table declined below the bottom of the upper layer. MODFLOW uses primary and secondary storativity values to allow for the possibility of the water table declining below the bottom of the upper layer. Primary storativity (specific yield) values of 0.20 and 0.25 were used for the upper model layer. Primary storativity values of 0.001 and 0.005 and secondary storativity values of 0.20 and 0.25 were used in the middle and lower layers. As discussed in "Calibration of Transient Ground-Water Flow Model," the 0.20 and 0.001 values were used for most of the model area, whereas the 0.25 and 0.005 values were used in the Marshall Army Airfield area.

Hydraulic Stresses

Hydraulic stresses simulated in the ground-water flow model include recharge from precipitation; ground-water seepage from adjacent bedrock to the alluvial aquifer, or from or to the alluvial aquifer upstream or downstream from the model boundary; streamflow; and well pumpage. These stresses are discussed in the following paragraphs.

Recharge

The MODFLOW recharge package was used uniformly to apply precipitation recharge to all active model cells in the upper layer. At the time of model development, a complete set of preciptation data from the Manhattan Municipal Airport (fig. 2) was not available. Thus, the volumetric rate of recharge applied to the model, arrived at through calibration, was 22 percent of the daily precipitation recorded at the Kings Creek precipitation gage. A comparison of monthly precipitation at the Manhattan Municipal Airport and the Kings Creek gages for 1990–98 shows that, in general, precipitation amounts were similar, but that there is more variability during the warm

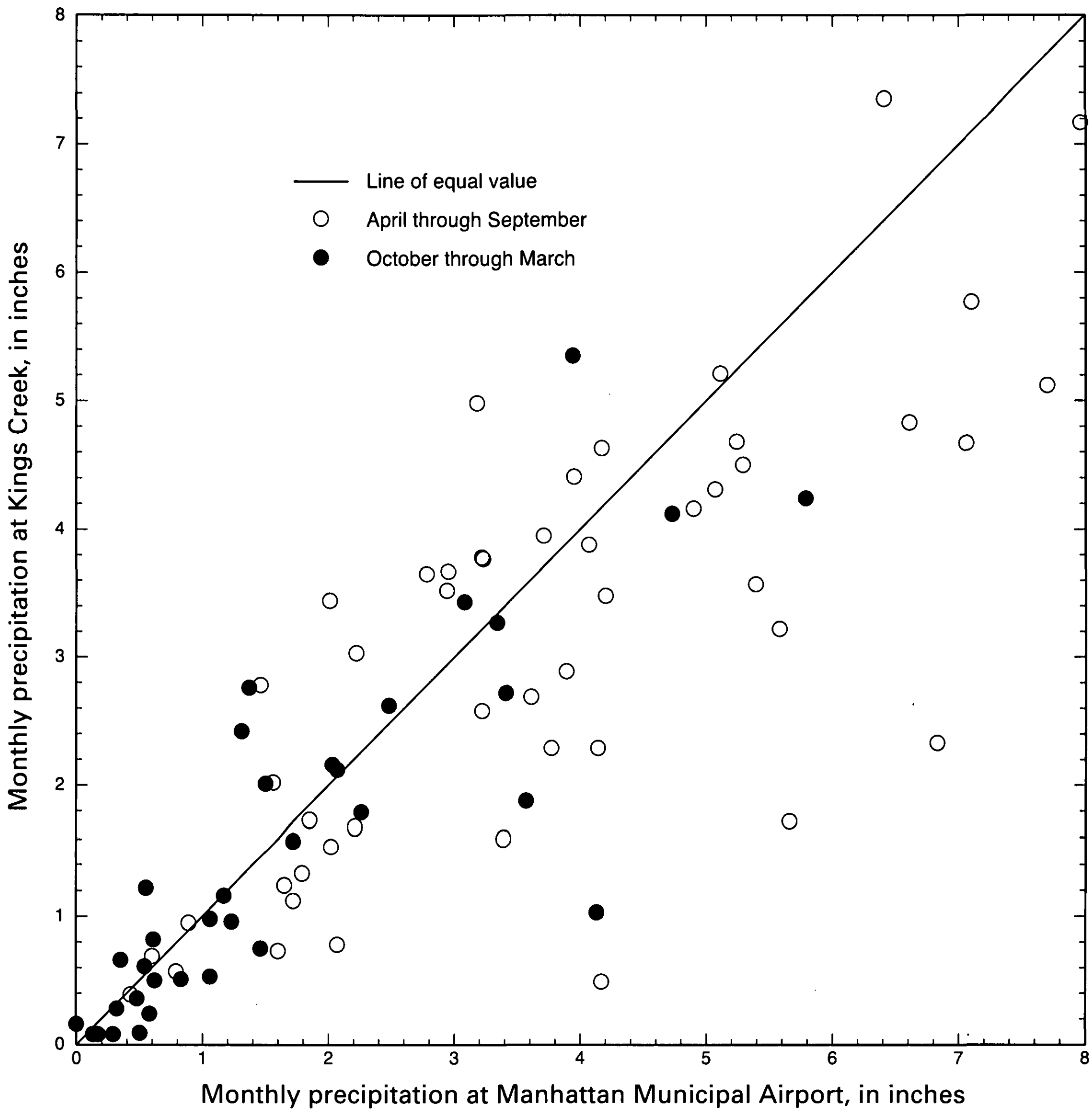


Figure 28. Comparison of monthly precipitation at Manhattan Municipal Airport to monthly precipitation at Kings Creek, 1990–98 (Manhattan Municipal Airport precipitation data from National Climatic Data Center, 1998, and National Oceanic and Atmospheric Administration, 1999; Kings Creek data on file with U.S. Geological Survey, Lawrence, Kansas).

season (April–September) than during the cool season (October–March) during which precipitation generally is much more widespread (fig. 28). In addition, Manhattan Municipal Airport appears to be a somewhat more likely to receive larger warm-season rainfall amounts than Kings Creek (fig. 28). The reasons for these differences may include geographic location of the precipitation gages, differences in measuring and reporting procedures, and random variability of precipitation. In the MODFLOW recharge package, recharge was specified in units of feet per day. The volume of water recharged to each model cell is computed by MODFLOW using the area of the cell and the recharge specified for that cell. The percentage of recharge was not adjusted seasonally. Recharge was represented as being added to the upper model layer during the same stress period as the precipitation occurred; MODFLOW does not simulate percolation of water through the unsaturated zone and so does not account for the delay between the precipitation event and infiltration to the water table.

Ground-Water Inflow and Outflow

Lateral ground-water inflow from adjacent bedrock to the alluvial aquifer was simulated using the MODFLOW recharge package. Lateral inflow was applied as recharge to constant-flux cells in the upper layer along the edges of the model (fig. 26*A*). The amount of recharge applied was computed on the basis of the surface area of an isolated upland area, the surface area of the adjacent model cells to which the recharge was applied, and the amount of daily precipitation at the Kings Creek precipitation gage. For example, if the surface area of an isolated upland area was 100,000 ft^2 and the surface area of adjacent model cells was 10,000 ft^2, then the amount of recharge applied to the adjacent model cells was increased 10 times over the amount of recharge that was applied normally. For any given precipitation event, 22 percent of the precipitation was assumed to recharge the isolated upland areas.

Subsurface inflow to or outflow from the alluvial aquifer upstream or downstream from the model boundary was simulated using the MODFLOW general-head package. This seepage was applied to general-head cells in all three layers for parts of the upstream end of the model and for all of the downstream end of the model. For the general-head package, the user specifies a conductance and a hydraulic head at some distance from the model boundary. Simulated water flows into the model at general-head model boundaries if the user-specified hydraulic head is larger than the simulated hydraulic head in the boundary cell. Simulated water flows out of the model at general-head boundaries if the user-specified hydraulic head is smaller than the simulated hydraulic head in the boundary cell. The volumetric rate of simulated water that flows into or out of the model is governed by the specified conductance. The conductance is computed as:

$$C = K\frac{A}{L}, \qquad (7)$$

where

C is conductance, in feet squared per day;

K is hydraulic conductivity, in feet per day;

A is the cross-sectional area through which ground water flows, in square feet; and

L is the horizontal distance over which ground water flows, in feet.

Thus, if all other variables are held constant, an increase in conductance would increase the rate of ground-water flow in or out of boundary cells. The conductance term was varied in the model to aid in calibration. The floodwave response, as described in the section "Ground-Water Flow and Ground-Water/Surface-Water Interaction," was used to compute hydraulic-head values for general-head cells on the basis of streamflow in the Kansas River at Fort Riley (Henry Drive Bridge) stream-gaging station. For each layer a set of hydraulic-head values (one value for each stress period) was computed for the general-head cells closest and farthest from the Kansas River at the upstream and downstream model boundaries; thus, 12 sets of hydraulic-head values were computed. These sets of hydraulic-head values were entered into GMS, which then was used to interpolate hydraulic-head values for the general-head cells between the cells closest and farthest from the Kansas River.

Streamflow

Streamflow for the major rivers was obtained from stream-gaging stations on the Republican and Kansas Rivers (fig. 2). Streamflow for the Smoky Hill River was computed as the difference between Republican River and Kansas River streamflow. These streamflows were converted to units of cubic feet per day and used in the MODFLOW stream package.

Streamflow for the creeks in the model area was determined on the basis of measured streamflow at stream-gaging stations in drainage basins of similar size and topography (fig. 29 and table 9). Streamflow at the Mill Creek near Paxico stream-gaging station was used as an analog for Clarks Creek streamflow. Streamflow from the Soldier Creek near Soldier stream-gaging station was used as an analog for streamflow in Threemile and Sevenmile Creeks. Streamflow from the Kings Creek near Manhattan stream-gaging station was used as an analog for streamflow in Dry Branch. Although the Soldier Creek Basin is in a different physiographic division (fig. 29) with generally less topographic relief, the rolling-hill

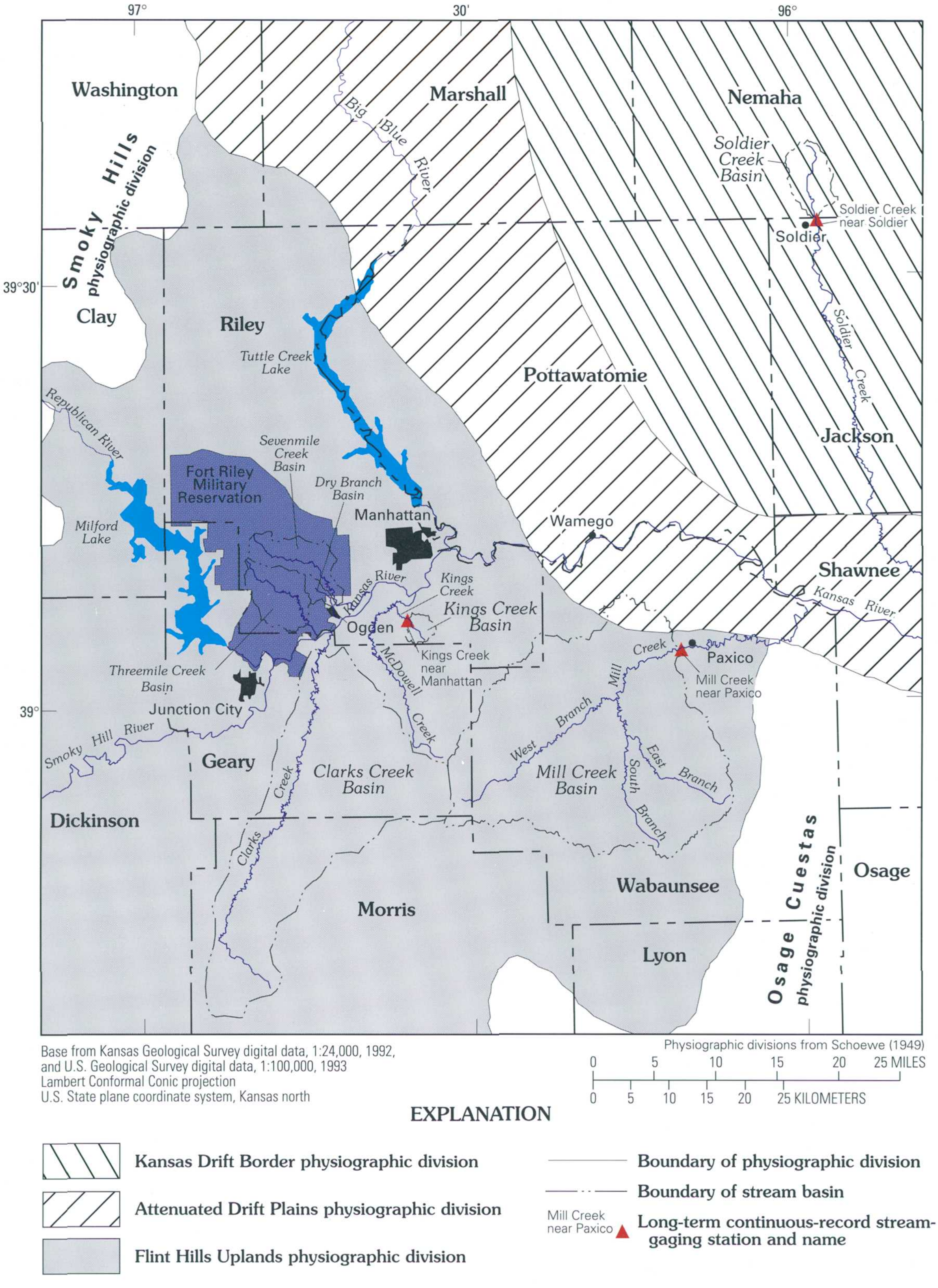


Figure 29. Physiographic divisions and location of stream basins at Fort Riley and basins used as analogs for developing streamflow data for ground-water flow model.

Table 9. Creeks in model area, analog creek and stream-gaging stations, and ratios of drainage-basin areas

[Data on file with U.S. Geological Survey, Lawrence, Kansas. mi^2, square miles]

Creek in model area (fig. 29)	Analog creek and stream-gaging station (fig. 29)	Drainage-basin area ratio of creek in model area to analog creek
Clarks Creek	Mill Creek near Paxico	$247.77\ mi^2 / 321.87\ mi^2 = 0.77$
Threemile Creek	Soldier Creek near Soldier	$21.49\ mi^2 / 17.01\ mi^2 = 1.26$
Sevenmile Creek	Soldier Creek near Soldier	$19.65\ mi^2 / 17.01\ mi^2 = 1.16$
Dry Branch	Kings Creek near Manhattan	$3.36\ mi^2 / 4.48\ mi^2 = 0.75$

topography of the basin is similar to that of basins in the study area. Forsyth Creek also was included in the model because a Fort Riley sewage-treatment plant (fig. 2) discharges about 2.3 ft^3/s of treated water to the creek (LAW Engineering and Environmental Services, 1994); however, Forsyth Creek is part of the Threemile Creek drainage basin, and its precipitation-related streamflow was computed as part of the streamflow for Threemile Creek.

Assuming that the amount of streamflow in a creek would be proportional to the drainage-basin size for similar size basins, drainage-basin area ratios were computed for the creeks in the model area and their analog creeks (table 9). Mean daily streamflows for model simulation periods were obtained for each analog basin and were multiplied by the drainage-basin area ratios to estimate streamflow for creeks in the model area. This approach probably introduces error into the timing and volume of warm-season streamflows because of the very localized nature of summertime thunderstorms in Kansas. Less error would occur for cool-season storms during which precipitation generally is much more widespread.

In the ground-water flow model, the hydraulic head (stage) in the streams was computed first by specifying streamflow, slope, roughness, and width (table 18 in "Supplemental Information" section), and letting MODFLOW compute the hydraulic head in the streams. Second, the MODFLOW-computed hydraulic head in streams was recomputed using step-backwater computations. Step-backwater computations were necessary because large stage differences between the Republican and Smoky Hill Rivers or between the Kansas River and its tributaries caused significant inaccuracies in MODFLOW's computed stream stages. The step-backwater method solves the streamflow energy equation by determining the energy at an upstream stream section that balances the previously computed energy at an adjacent downstream stream section. In the model each stream cell was used to represent a stream section. Step-backwater computations proceeded from downstream to upstream in the model.

The streamflow energy equation (Shearman, 1976) is:

$$WSU + VHU = WSD + VHD + HF + HE \quad , (8)$$

where

WSU and WSD are the water-surface elevations (total hydraulic heads) at the upstream and downstream sections, respectively, in feet above sea level;

VHU and VHD are the velocity hydraulic heads at the upstream and downstream sections, respectively, in feet;

HF is the frictional energy loss between the upstream and downstream sections, in feet; and

HE is the eddy energy loss between the upstream and downstream sections, in feet.

For this study, stream channels were assumed to have rectangular cross sections so that wetted area could be calculated by multiplying water depth by channel width and wetted perimeters could be calculated by adding two times the water depth plus the channel width. With these assumptions, the energy equation can be expanded to:

$$[sb_u + d_u] + \left[\frac{\alpha_u\left(\frac{Q_u}{d_u w_u}\right)^2}{2g}\right] = [sb_d + d_d] + \left[\frac{\alpha_d\left(\frac{Q_d}{d_d w_d}\right)^2}{2g}\right] +$$

$$\left[\frac{LQ_m^2}{\left[\left(\frac{1.49}{n}d_u w_u\left(\frac{d_u w_u}{2d_u + w_u}\right)^{\left(\frac{2}{3}\right)}\right)\left(\frac{1.49}{n}d_d w_d\left(\frac{d_d w_d}{2d_d + w_d}\right)^{\left(\frac{2}{3}\right)}\right)\right]}\right] + \left[k_e\left(\frac{\alpha_u\left(\frac{Q_u}{d_u w_u}\right)^2}{2g} - \frac{\alpha_d\left(\frac{Q_d}{d_d w_d}\right)^2}{2g}\right)\right], \qquad (9)$$

where

sb_u and sb_d are the elevations of the streambed at the upstream and downstream sections, respectively, in feet above sea level;

d_u and d_d are the depths of water in the stream at the upstream and downstream sections, respectively, in feet;

α_u and α_d are the kinetic-energy correction factors at the upstream and downstream sections, respectively, in feet;

Q_u and Q_d are the streamflows at the upstream and downstream sections, respectively, in cubic feet per second;

w_u and w_d are the channel widths at the upstream and downstream sections, respectively, in feet;

g is the acceleration due to gravity, 32.15 feet squared per second;

L is the distance along the stream channel between the upstream and downstream sections, in feet;

Q_m is the mean of the streamflows at the upstream and downstream sections, in cubic feet per day;

n is Manning's streambed roughness coefficient, dimensionless; and

k_e is eddy loss coefficient, dimensionless, and is 0.5 for an expanding channel and is 0 for a contracting channel between the upstream and downstream sections.

Each part of equation 9 in square brackets [ ] corresponds to a term in equation 8. Calculation of the kinetic-energy correction factors (α_u and α_d) requires detailed water depth and width measurements for subsections within each stream section. Except at the Kansas River at Fort Riley (Henry Drive Bridge) stream-gaging station, this information was not available for the streams in the study area. For stream sections lacking subsection data, the value of the kinetic-energy correction factor was assumed to be equal to 1 (Davidian, 1984, p. 15). The kinetic-energy correction factor was introduced into the energy equation to account for variations in streamflow velocity across the width of a channel (Davidian, 1984, p. 24). The effect of assuming α_u and α_d are equal to 1 is to make the value of the eddy-loss term (HE in equation 8, last set of square brackets in equation 9) smaller than if the kinetic-energy correction factor was computed.

Ground-Water Pumpage

Ground-water pumpage was simulated by using the MODFLOW well package. In the well-package input file, the user specifies, for each model stress period, well-pumpage rates and the model cell (layer, row, and column) from which the water is pumped. Historic well-pumpage rates obtained from DWR were used for wells in the model. Public-, military-, and irrigation-supply wells generally penetrate and pump water from the full thickness of the aquifer. Therefore, the pumping for each stress period was divided among the three model layers in proportion to their transmissivity. In areas where the alluvial aquifer was too thin to allow definition of the lower and (or) middle model layers (fig. 26), the pumpage was divided among the active layers.

Steady-State Ground-Water Flow Model

A steady-state ground-water flow model was constructed for the purpose of providing reasonable starting hydraulic-head values for the transient calibration, historical, and hypothetical simulations using the model. The steady-state model simulations provided starting hydraulic-head conditions that incorporated the same aquifer parameters and geometry as their respective transient model simulations, except storage. Some changes in hydraulic-head values because of the inclusion of storage are expected at the beginning of transient model simulations. Steady-state and transient models were assigned the same aquifer parameters except that change in aquifer storage was not simulated in the steady-state model. Hydraulic stresses for the steady-state model were chosen to represent the initial conditions in the respective transient model simulations.

Steady-state model simulations were conducted to provide the starting-head configurations for the transient model calibration simulation of September 7, 1997, through April 2, 1998 (steady-state model calibration simulation), for the transient historical simulation of January 1, 1990, through December 31, 1998 (steady-state model historical simulation), and for the hypothetical simulations (steady-state model hypothetical simulation). These steady-state model simulations are discussed in the following paragraph.

Hydraulic stresses for the steady-state model calibration simulation were defined on the basis of hydrologic conditions on or leading up to September 7, 1997. A mean annual recharge of 22 percent of the mean annual precipitation (33.82 in.) or about 0.0017 ft/d was specified for all active upper layer cells. The same recharge was assumed for the isolated upland areas adjacent to the modeled area and was applied to constant-flux cells along the northern and southern edges of the modeled area. Hydraulic-head values for general-head boundaries were determined as described above. The heads determined for the starting stress period of the transient model calibration simulation were used at the upstream and downstream model general-head boundaries in the steady-state model simulation. The streamflows specified for the starting stress period of the transient model calibration simulation were used in the steady-state model. Well pumpage was specified only for public- and military-supply wells because irrigation wells generally are not used in September. The pumpages specified in the steady-state model were the mean daily pumpage rates for 1997. Similar hydraulic stresses were used for the steady-state model historical and hypothetical simulations except that streamflows for January 1, 1990 (specified for the starting stress period of the transient model historical simulation), and mean daily pumping rates for 1990 were specified for the steady-state model historical and hypothetical simulations.

The hydraulic-head values computed in the steady-state model calibration simulation and used as the starting head distribution of the transient model calibration simulation were compared to ground-water-level measurements obtained on September 11, 1997 (fig. 30*A*). The well-to-nearest model-cell differences (fig. 30*A*) indicated a reasonable match (root mean square error of 0.83 ft) between these observed and simulated ground-water levels.

A. September 11, 1997

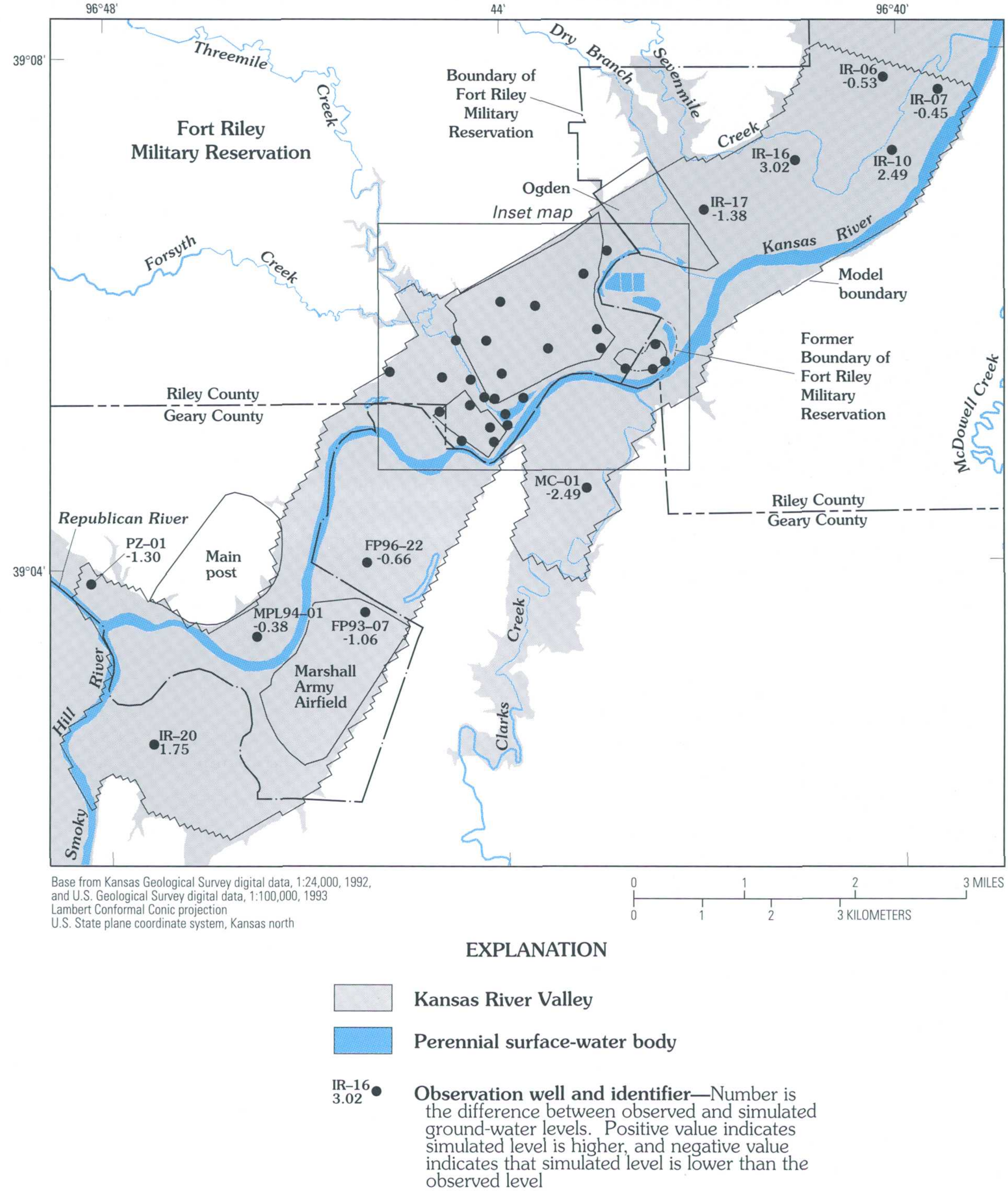


Figure 30. Differences between observed and simulated ground-water levels for *(A)* September 11 and *(B)* November 10, 1997, and *(C)* April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas).

A. September 11, 1997—Continued

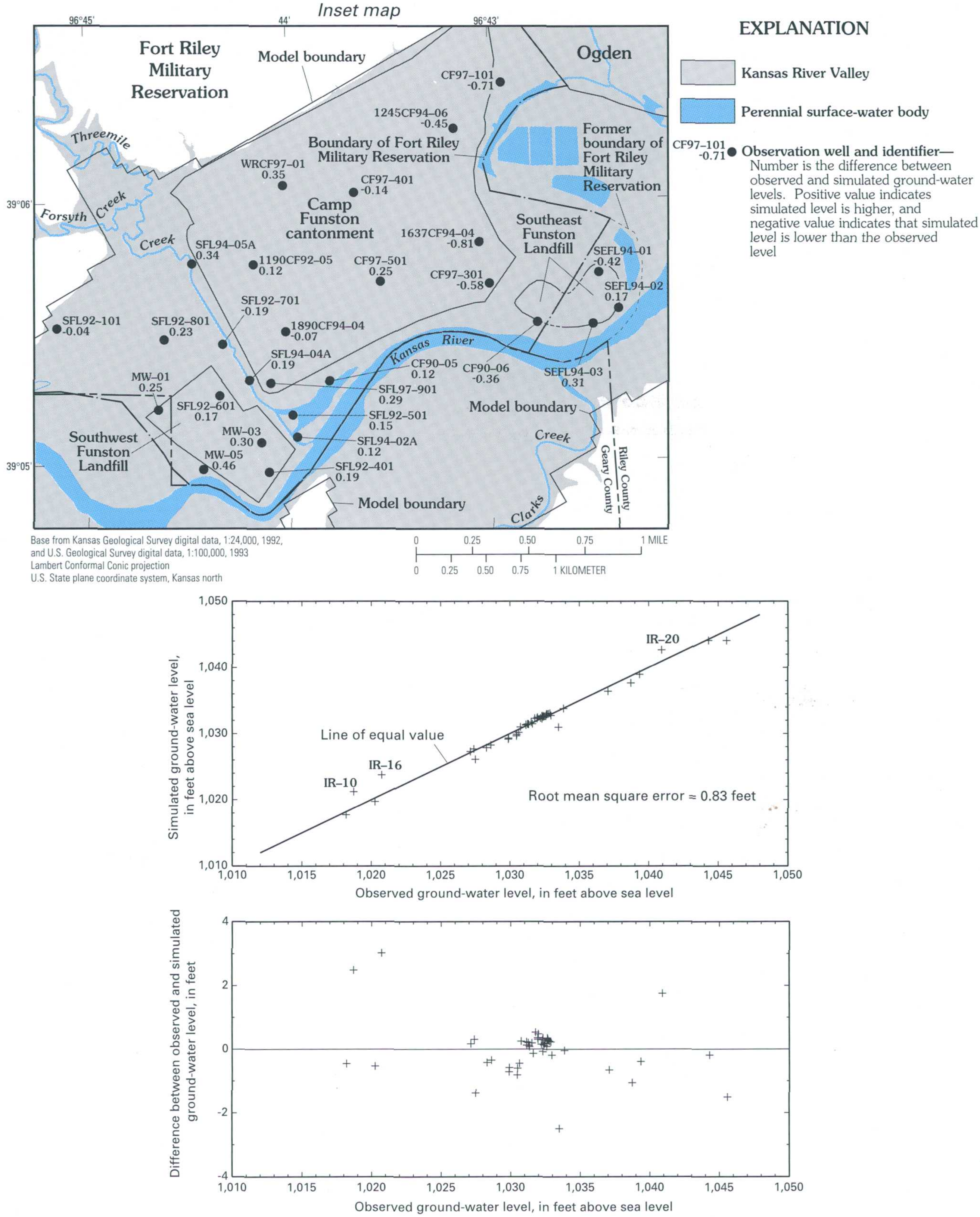
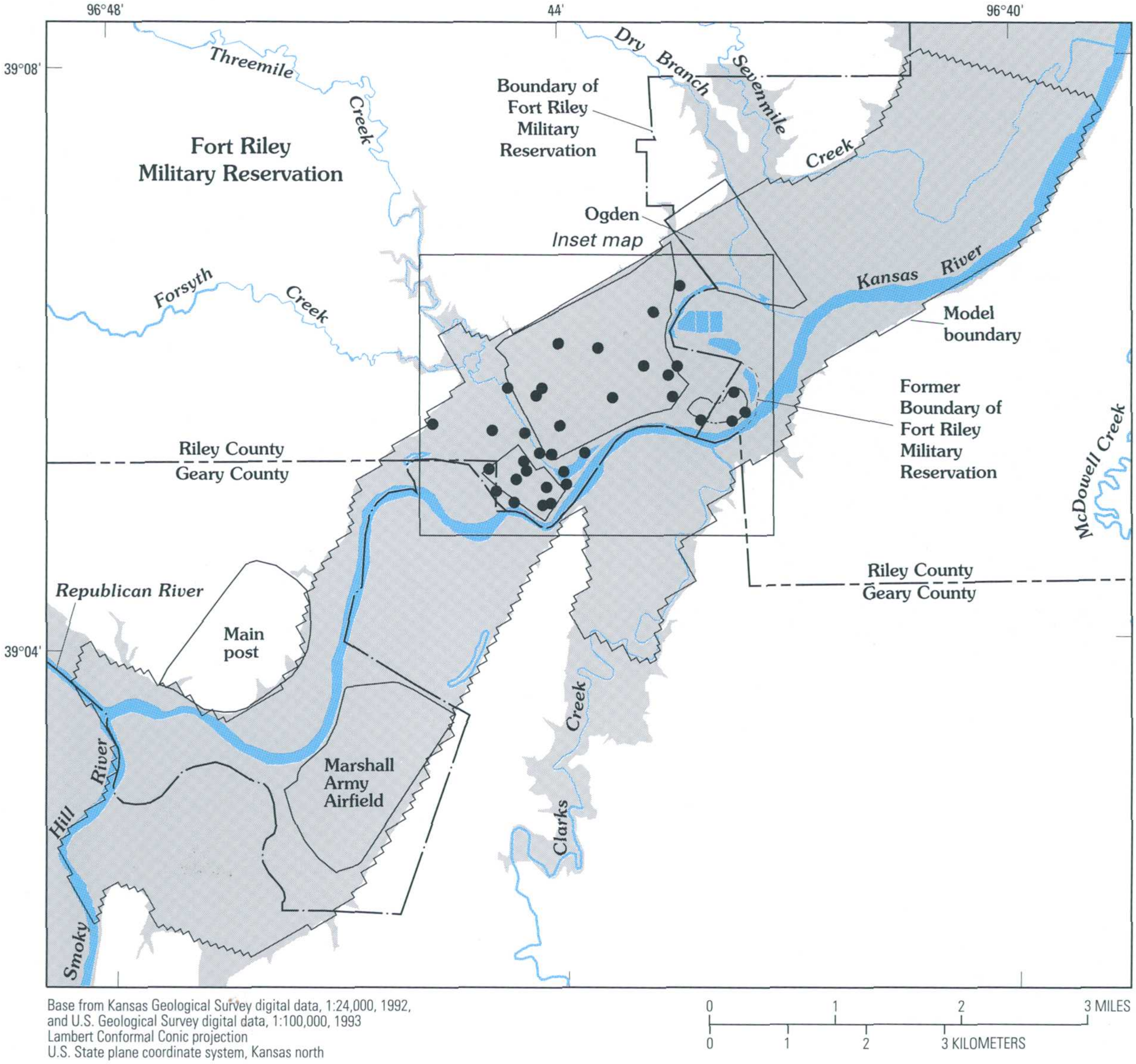


Figure 30. Differences between observed and simulated ground-water levels for *(A)* September 11 and *(B)* November 10, 1997, and *(C)* April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

B. November 10, 1997



EXPLANATION

- Kansas River Valley
- Perennial surface-water body
- ● Observation well

Figure 30. Differences between observed and simulated ground-water levels for *(A)* September 11 and *(B)* November 10, 1997, and *(C)* April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

B. November 10, 1997—Continued

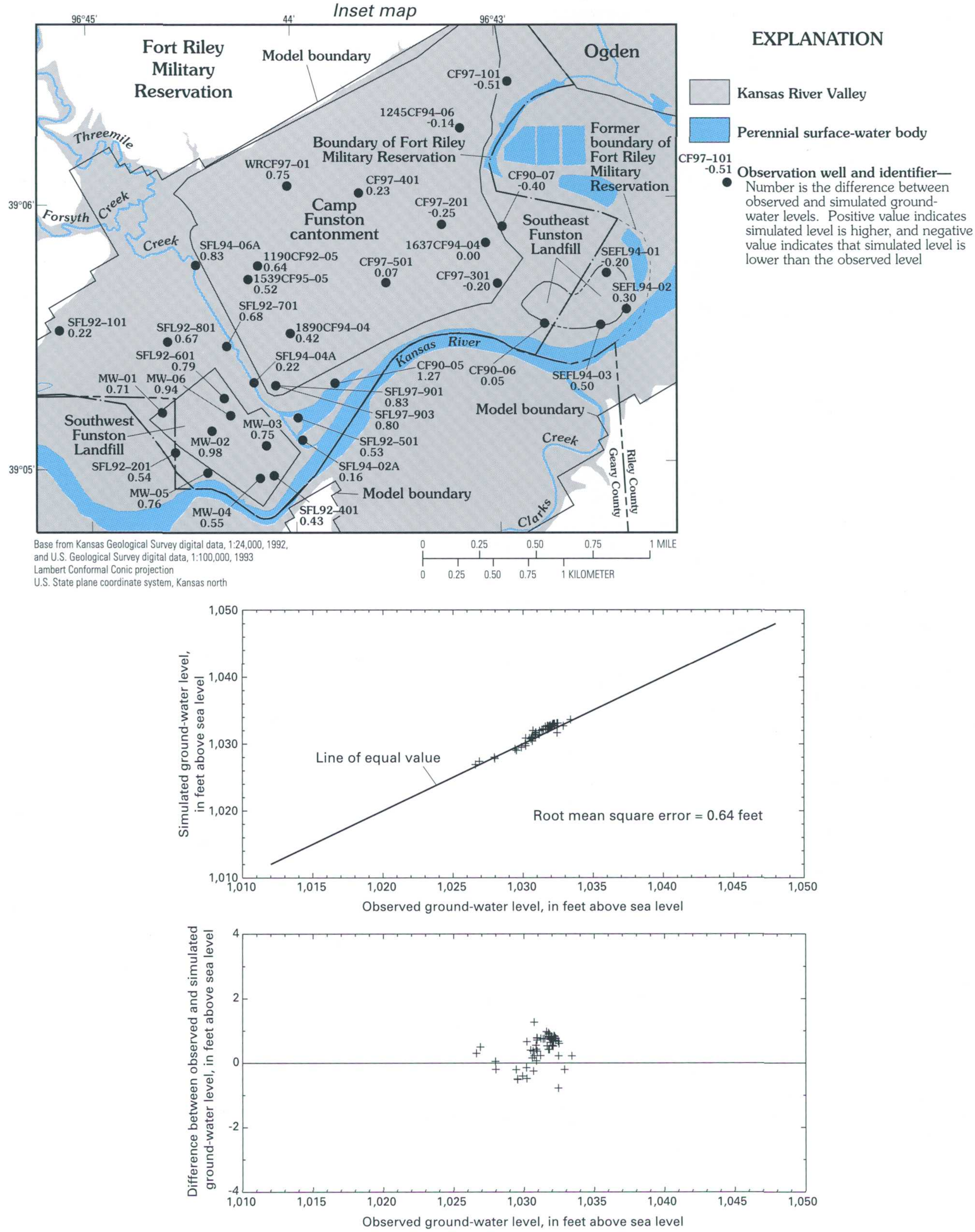


Figure 30. Differences between observed and simulated ground-water levels for *(A)* September 11 and *(B)* November 10, 1997, and *(C)* April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

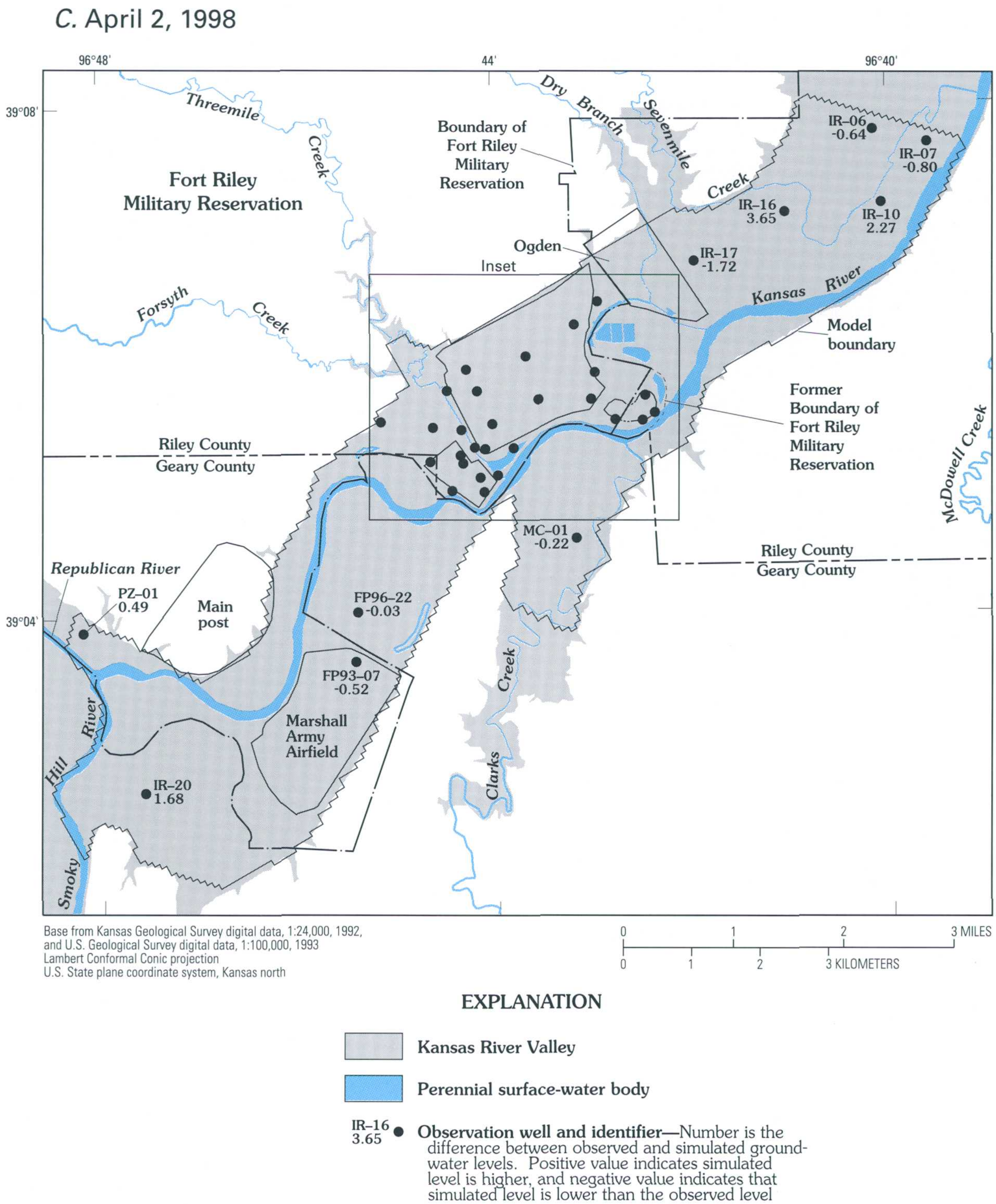


Figure 30. Differences between observed and simulated ground-water levels for *(A)* September 11 and *(B)* November 10, 1997, and *(C)* April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

C. April 2, 1998—Continued

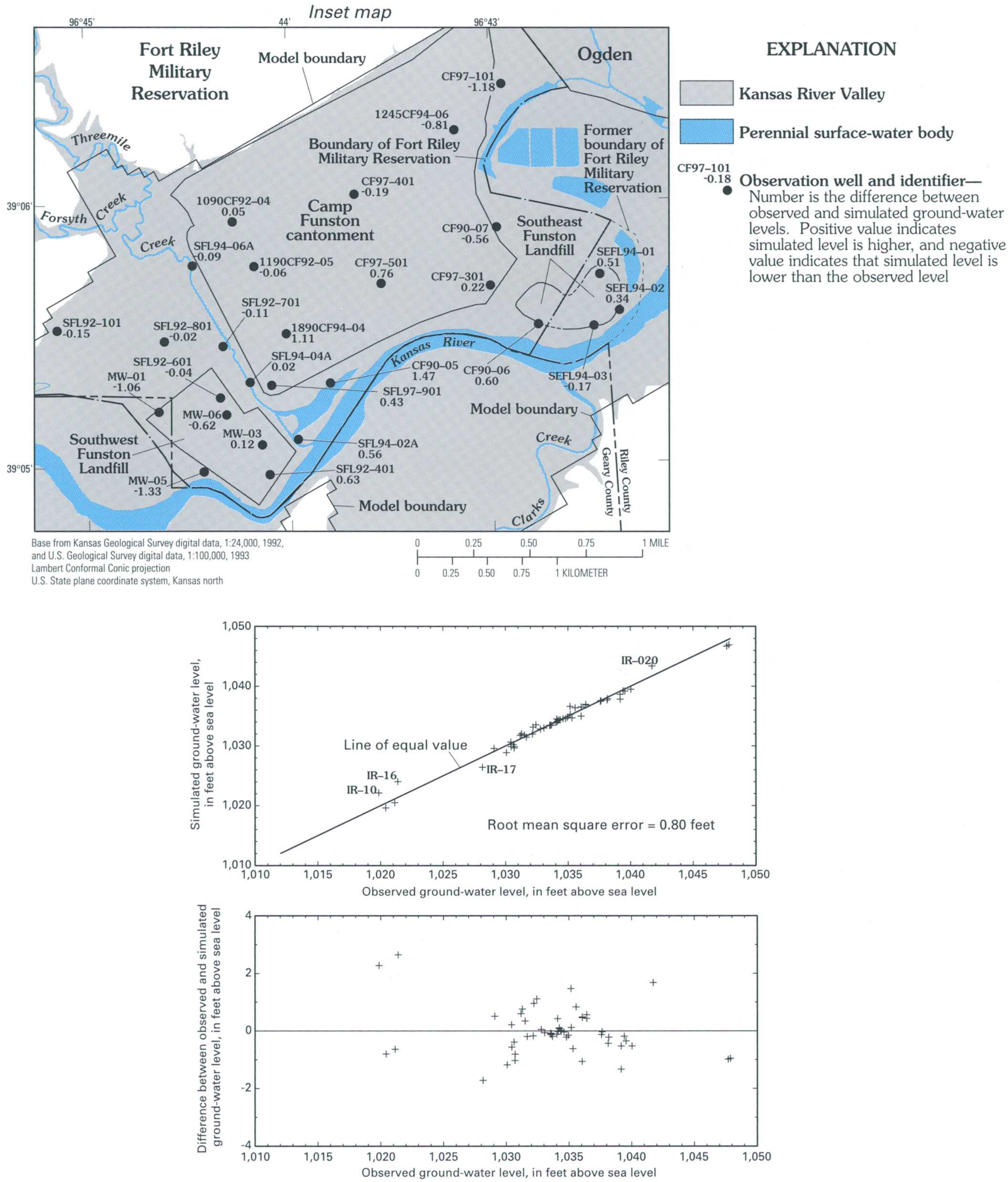


Figure 30. Differences between observed and simulated ground-water levels for *(A)* September 11 and *(B)* November 10, 1997, and *(C)* April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

Calibration of Transient Ground-Water Flow Model

Because the steady-state model did not simulate changes in storage, some changes in hydraulic head were expected at the beginning of the transient model simulations. Therefore, the transient model calibration simulation was run first from September 7 through November 9, 1997, to allow the expected storage adjustment to take place. Data comparisons to achieve calibration then were made for November 10, 1997, through April 2, 1998. For the calibration simulation, each stress period represented 1 day. Observed or computed mean daily values of streamflow were used to specify streamflow and to define general-head boundary conditions. Recharge for each stress period was specified as 22 percent of the daily precipitation measured at the Kings Creek near Manhattan precipitation gage (fig. 2). Mean daily pumpage rates were computed for public-supply wells on the basis of the pumpages reported to DWR for 1997. Irrigation-well pumpage was set to zero because irrigation wells generally are not used from September through April. Additional recharge was applied at the edges of the active model to simulate lateral ground-water inflow from the isolated upland areas bordering the Kansas River Valley. Isolated upland recharge was specified as 22 percent of the daily precipitation measured at the Kings Creek near Manhattan precipitation gage multiplied by the ratio of the area of an adjacent upland to the adjacent model area over which that recharge was applied.

The transient ground-water flow model was calibrated using several comparisons: (1) observed water levels from wells were compared to simulated water levels from the model cells nearest to those wells for September 11 and November 10, 1997, and April 2, 1998; (2) observed mean daily water levels from wells equipped with water-level recorders were compared to simulated water levels from model cells nearest those wells; (3) measured seepage to or from Threemile Creek was generally compared to simulated seepage; (4) observed Kansas River stage at the Fort Riley gaging station (Henry Drive Bridge) and Threemile Creek stage near the mouth of the creek (TMCD gaging station) were compared to river and creek stages computed using the step-backwater method; and (5) simulated inflow and outflow water budgets were compared to those estimated for the water-budget area (table 6).

Comparisons of observed and simulated ground-water levels for November 10, 1997 (fig. 30*B*), and April 2, 1998 (fig. 30*C*) were used to adjust, within reasonable ranges, hydraulic-conductivity and recharge values used in the transient model. For November 10, 1997, the root mean square error between observed and simulated values was 0.64 ft, and for April 2, 1998, it was 0.80 ft. For November 10, 1997, ground-water-level measurements outside of the Camp Funston Area were not available. The largest positive error for the November 10, 1997, comparison of observed and simulated ground-water levels was 1.27 ft (simulated was higher) at well CF90–05 near the Waterfowl Management Area (fig. 30*B*). The largest negative error was -0.51 ft at well CF97–101. For the April 2, 1998, comparison of observed and simulated ground-water levels, the largest positive error was 3.65 ft at well IR–16 (fig. 30*C*). The largest negative error was -1.72 ft at well IR–17. Some of the error for these wells may be the result of using a topographic map with a 2.5-m contour interval to assign their land-surface altitudes. In general, observed and simulated ground-water levels were similar and plot near their lines of equal value (graphs in figs. 30*A*, 30*B*, and 30*C*).

Hydraulic-conductivity adjustments were made to minimize the root mean square error between observed and simulated ground-water levels for November 10, 1997, and April 2, 1998. Initially, hydraulic-conductivity values of 500, 600, and 700 ft/d were used for the upper, middle, and lower model layers, respectively. Through trial and error, values of 600, 800, and 900 ft/d for the upper, middle, and lower model layers were found to give the smallest root mean square error. The mean of these hydraulic-conductivity values, weighted by their respective layer thickness of about 20, 20, and 15 ft, is about 755 ft/d, which is similar to the 730 ft/d median hydraulic conductivity computed for pumping tests, exclusive of specific-capacity tests, reported in the "Properties" section of this report.

Daily mean water levels observed in wells and piezometers equipped with continuous water-level recorders were compared to simulated water levels in the model cell nearest each of these wells for November 10, 1997, through April 2, 1998. Differences between the observed and simulated values, observed and simulated water-level trends, and water-level response to river-stage changes were used to adjust the value of specific yield used in the Marshall

Army Airfield area and to adjust the amount of recharge applied to the model from adjacent upland areas. Figure 31*A* shows hydrographs of observed and simulated water levels in wells FP93–07, FP96–20, FP96–21, and FP96–23, and piezometers FP96–13PZ and FP96–15PZ (locations shown in fig. 4). These wells and piezometers are located on or near the Marshall Army Airfield. In initial transient model simulations, the difference between observed and simulated values was less than 1 ft in both wells and piezometers, but the vertical fluctuations in the simulated hydrographs generally were larger than in the observed hydrographs. These fluctuations primarily result from changes in Kansas River stage and, to a minor extent, precipitation recharge. Changing the specific yield in an area within and near the Marshall Army Airfield from 0.20 to 0.25 (fig. 26) decreased the magnitude of vertical fluctuations in the hydrographs for the final transient model simulations (fig. 31*A*).

In the Camp Funston Area, comparisons of observed and simulated hydrographs for wells along Threemile Creek, wells CF90–06, CF97–101, CF97–401, and MW–05, were used to adjust the amount of upland recharge applied along the edges of the model. Ground-water altitudes for simulated hydrographs generally were within 1 ft of observed water levels (fig. 31*B*). In initial transient model

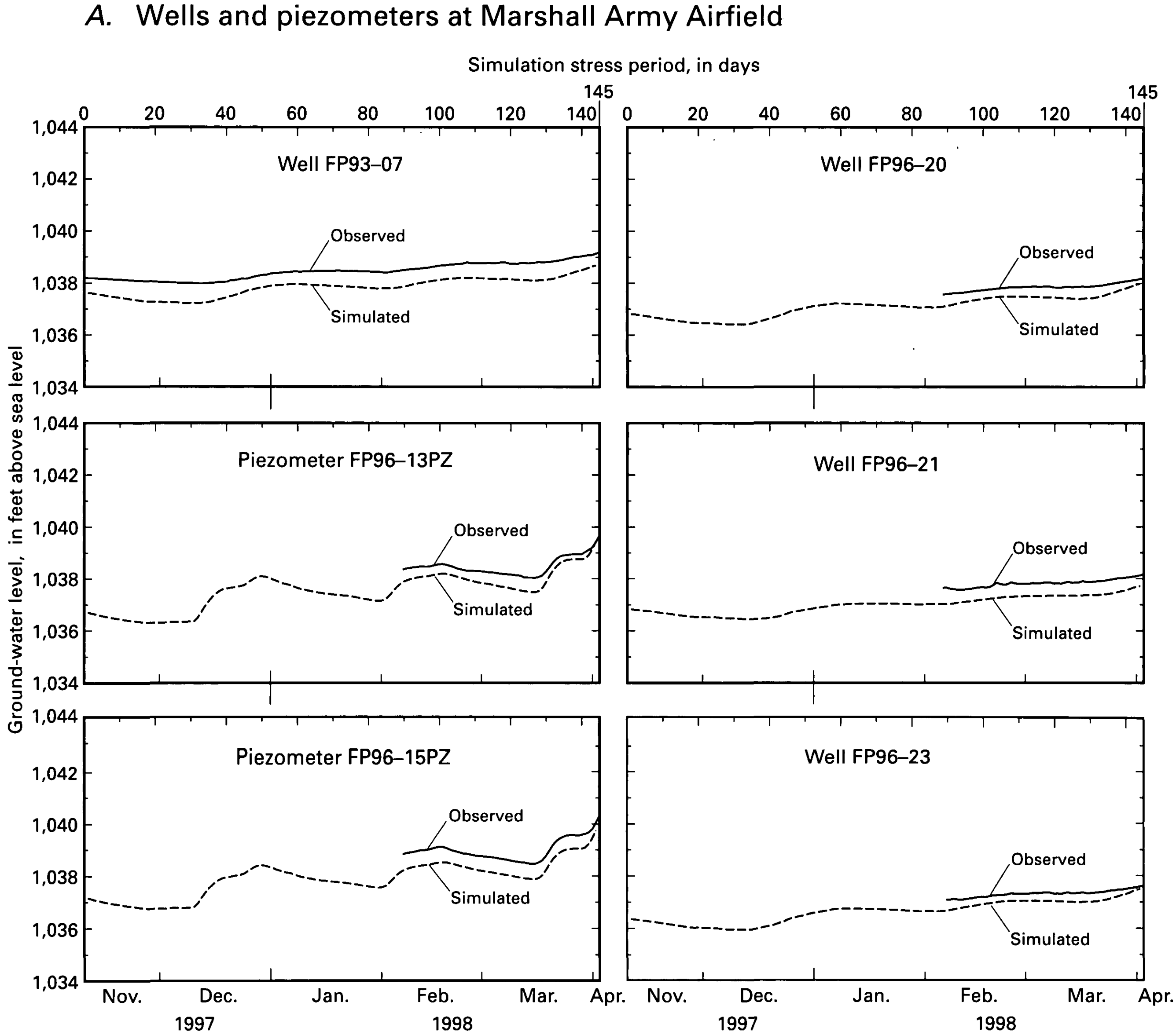


Figure 31. Observed and simulated water levels in wells and piezometers (locations shown in fig. 4) equipped with continuous water-level recorders at *(A)* Marshall Army Airfield and in *(B)* Camp Funston Area, November 10, 1997, through April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas).

B. Wells at Camp Funston Area

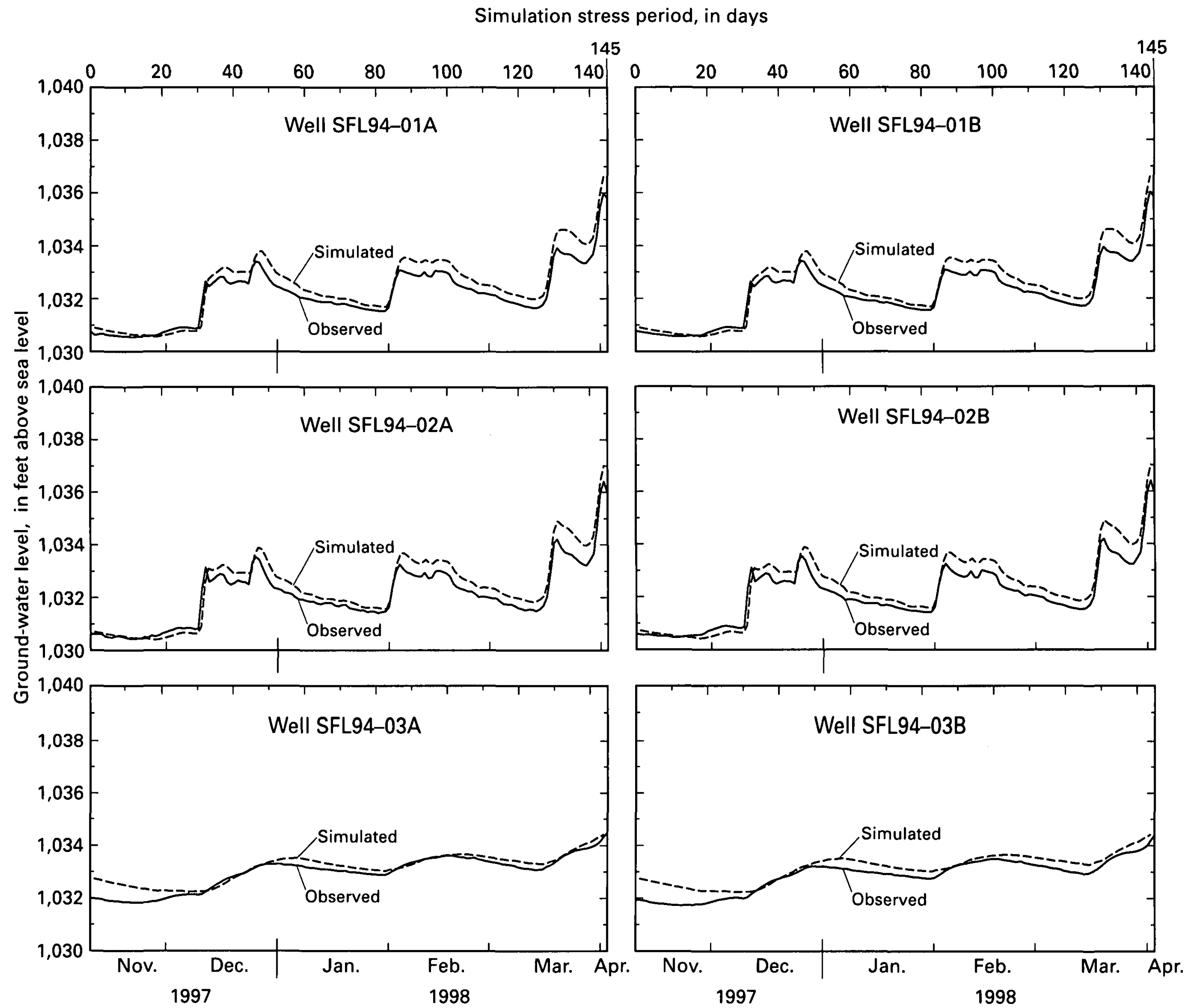


Figure 31. Observed and simulated water levels in wells and piezometers (locations shown in fig. 4) equipped with continuous water-level recorders at *(A)* Marshall Army Airfield and in *(B)* Camp Funston Area, November 10, 1997, through April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

simulations, the simulated hydrographs for wells CF97–101 and CF97–401 diverged downward from the observed hydrographs, an indication that recharge from upland sources should be included in the simulations. After upland recharge was included in the simulations, hydrographs from the final transient model simulations hydrographs more closely matched the observed hydrographs (fig. 31*B*). Although some divergence of the final observed and simulated hydrographs is evident for well CF97–101 (fig. 31*B*), further increases in the amount of upland recharge were found to have little effect on this divergence.

Comparisons between Threemile Creek seepage measurements and simulated seepage to or from the creek are shown in table 10. Because of high water, seepage measurements were not obtained downstream of the TMCU stream-gaging station (fig. 2) in early April 1998. Therefore, observed seepage values for dry and wet conditions were compared to simulated seepage for November 10, 1997 (dry), and April 1, 1998 (wet), conditions (table 10). Observed and simulated seepage values are reasonably similar.

Comparisons of observed and simulated Kansas River stage at the Kansas River at Fort Riley (Henry

B. Wells in Camp Funston Area—Continued

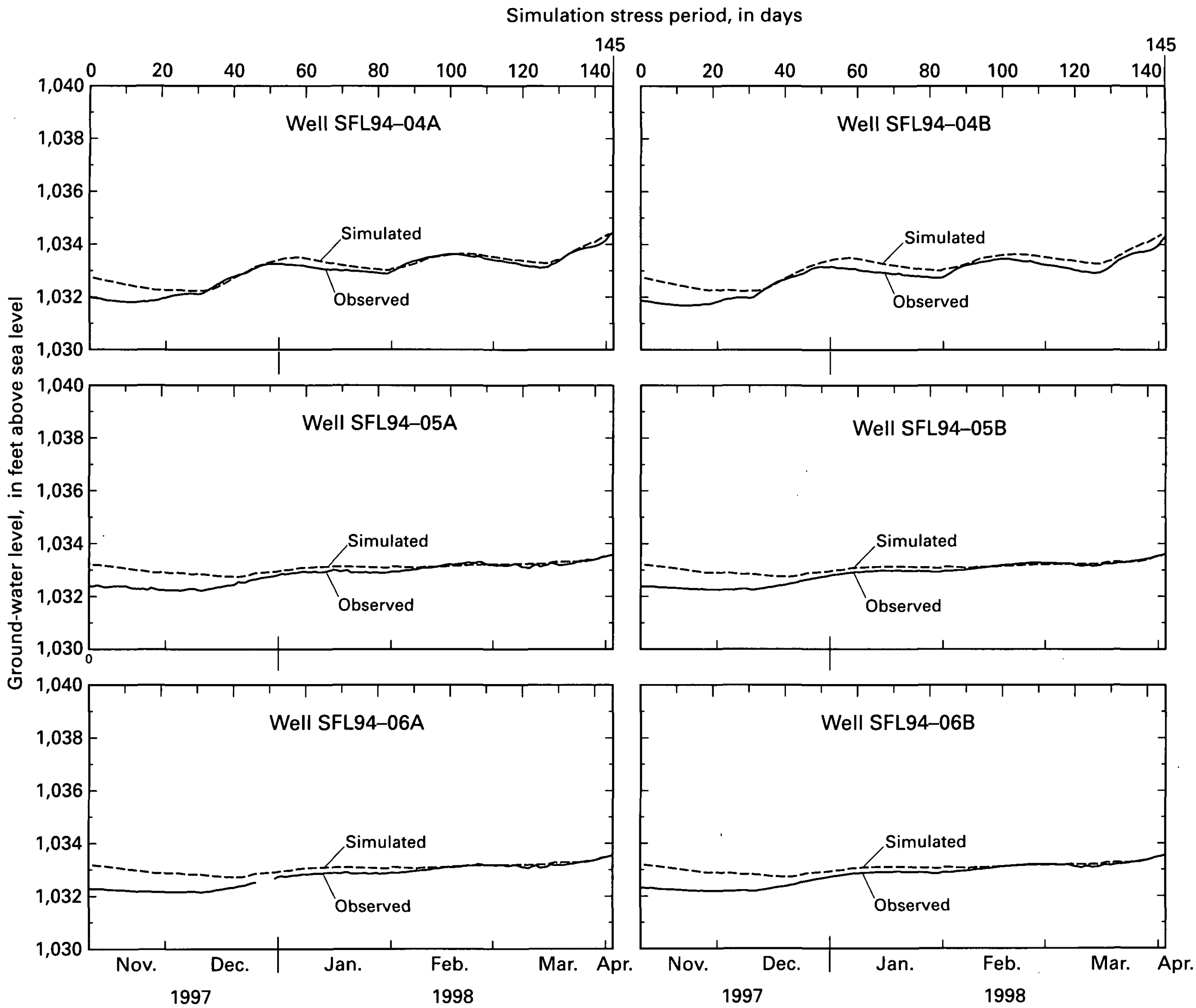


Figure 31. Observed and simulated water levels in wells and piezometers (locations shown in fig. 4) equipped with continuous water-level recorders at *(A)* Marshall Army Airfield and in *(B)* Camp Funston Area, November 10, 1997, through April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

Drive Bridge) stream-gaging station and Threemile Creek stage at the downstream gaging station (TMCD) are shown in figure 32. Simulated Kansas River stage generally was within 0.2 ft of the observed stage. Simulated Threemile Creek stage generally was within 0.5 ft of the observed stage. The differences between observed and simulated river and creek stages probably resulted from model assumptions as to channel widths and roughness coefficients.

Simulated water inflow and outflow budgets were compared to those estimated for the water-budget area (table 11). Simulated values are reasonably similar to the estimated values. Estimated recharge and pumpage values are annual averages, whereas simulated recharge and pumpage are based on the values estimated for the indicated date. The largest differences between estimated and simulated water budgets were for seepage from the Kansas, Smoky Hill, and Republican Rivers (table 11). These differences probably are due to the difficulty of estimating stream seepage for the rivers.

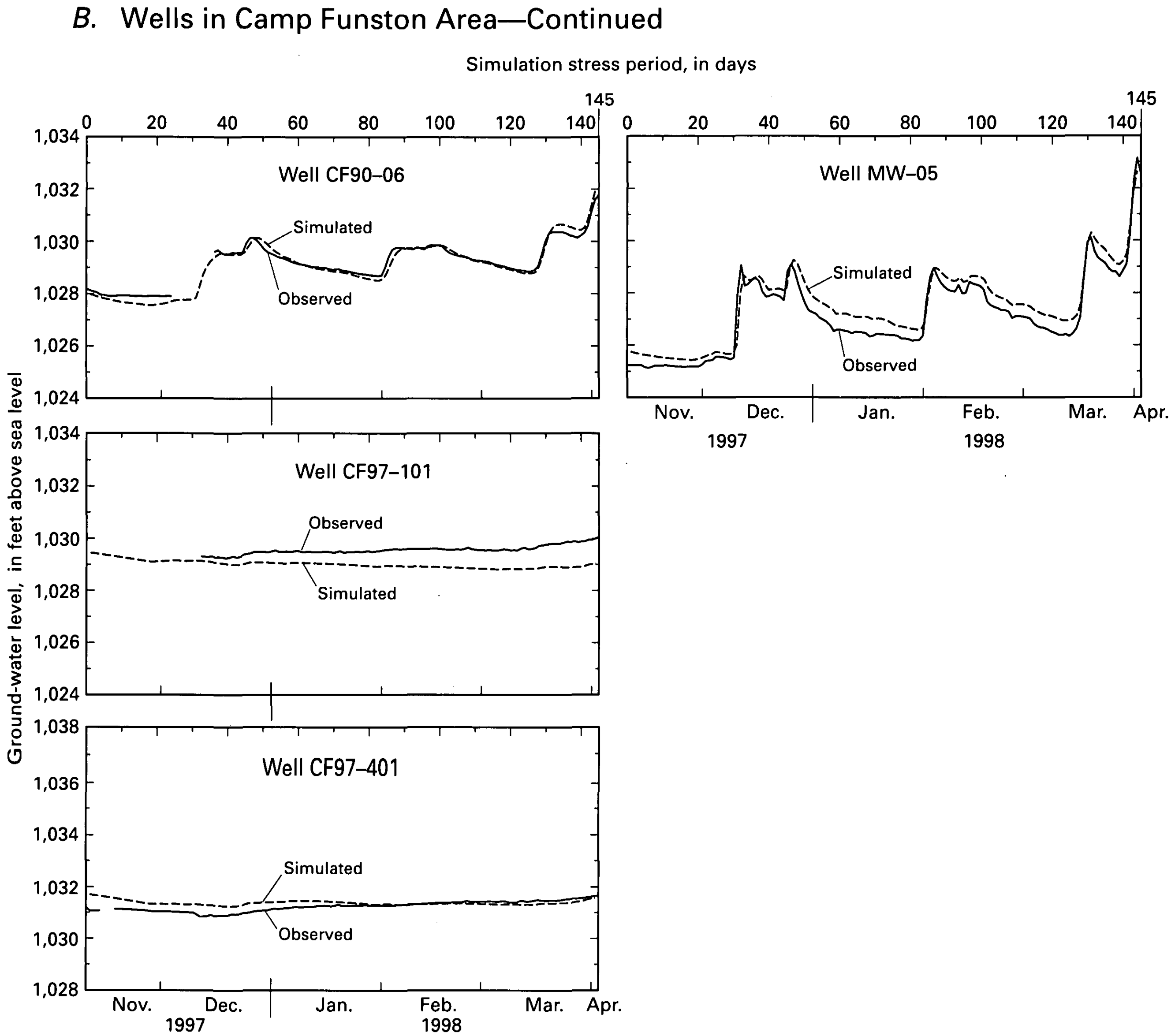


Figure 31. Observed and simulated water levels in wells and piezometers (locations shown in fig. 4) equipped with continuous water-level recorders at *(A)* Marshall Army Airfield and in *(B)* Camp Funston Area, November 10, 1997, through April 2, 1998 (data on file with U.S. Geological Survey, Lawrence, Kansas)—Continued.

Sensitivity Analyses

Sensitivity analyses of the calibrated model were done to determine the sensitivity of model-computed ground-water levels to changes in model parameters. Sensitivity analyses helped quantify the uncertainty in the calibrated transient model and were used to test whether the calibrated model minimized the error between observed and simulated ground-water levels.

For sensitivity analyses, the transient calibration model parameters that were changed were hydraulic conductivity, storativity, and recharge from precipitation. Each of these parameters was changed from 50 percent less to 100 percent greater than the calibrated values. This established, for each parameter, six data sets with values ranging from one-half to twice the calibrated value. Only one parameter value was varied at a time; other parameters were held at their calibrated values.

For changes of 0 to 50 percent less than the calibrated values, simulated ground-water levels were most sensitive to decreases in hydraulic conductivity and storativity and less sensitive to decreases in recharge from precipitation (fig. 33). For changes of 0 to 100 percent greater than the calibrated values, simulated ground-water levels were most sensitive to

Table 10. Observed and simulated seepage values for Threemile Creek

Measurement reach	Streamflow gain (+) or loss (-) (cubic feet per second)			
	Dry period		Wet period	
	Observed for September 9, 1997	Simulated for November 10, 1997	Observed for May 6, 1997	Simulated for April 1, 1998
Huebner Road Bridge to Threemile Creek Upstream gaging station	[1]-0.01	-0.03	[2]+0.79	-1.61
Threemile Creek Upstream gaging station to diversion structure and Waterfowl Management Area outlet structure	[3]-.42	-.10	[4]-4.38	-2.85

[1]A 5-percent error in the upstream and downstream measurements means that the actual value of streamflow gain or loss is in the range of -0.16 to +0.14 ft^3/s.

[2]A 5-percent error in the upstream and downstream measurements means that the actual value of streamflow gain or loss is in the range of -0.25 to +1.83 ft^3/s.

[3]A 5-percent error in the upstream and downstream measurements means that the actual value of streamflow gain or loss is in the range of -0.56 to -0.28 ft^3/s.

[4]A 5-percent error in the upstream and downstream measurements means that the actual value of streamflow gain or loss is in the range of -5.33 to -3.52 ft^3/s.

increases in recharge from precipitation and storativity and less sensitive to increases in hydraulic conductivity (fig. 33). The sensitivity analyses indicate that there is a fairly large range of values that satisfy a calibration criteria of having the root mean square error be less than 1.0 ft. This probably reflects the dominant effect that the Kansas River has on ground-water levels and the fact that the alluvial aquifer is constrained between less-permeable bedrock valley walls.

Changes in model parameters can cause changes in ground-water levels, ground-water flow velocity, inflow to and outflow from the model, and streamflow gains and losses.

Decreases in hydraulic conductivity cause:

- Increases in ground-water levels,
- Decreases in the velocity of ground-water flow,
- Decreases in subsurface ground-water inflow to and outflow from the model, and
- Decreases in streamflow gains and losses.

Decreases in storativity cause:

- More rapid increases and decreases in ground-water levels,
- Greater amplitude of ground-water-level fluctuations,
- Decreases in streamflow losses and gains, and
- Decreases in subsurface ground-water inflow to and outflow from the model.

Decreases in recharge from precipitation cause:

- Decreases in ground-water levels,
- Increases in subsurface ground-water inflow to the model,
- Decreases in subsurface ground-water outflow from the model,
- Decreases in streamflow gains, and
- Increases in streamflow losses.

Increases in hydraulic conductivity, storativity, and recharge from precipitation will have effects opposite to those noted above.

Historical Simulations, 1990–98

The calibrated transient model and a particle-tracking program were used as the basis for transient historical simulations of ground-water flow for 1990–98. These simulations were done so that the recent flow patterns and movement of ground water could be shown in relation to known areas of ground-water contamination and to estimate flow-path and recharge areas for public-supply wells. The flow patterns and ground-water movement were mapped using a particle-tracking program.

Threemile Creek was simulated differently in the 1990–95 transient simulations than for 1996–98 to account for construction and initial use of the Threemile Creek diversion structure and the Waterfowl Management Area in December 1995. In the 1990–95 simulations, Threemile Creek flowed directly to the

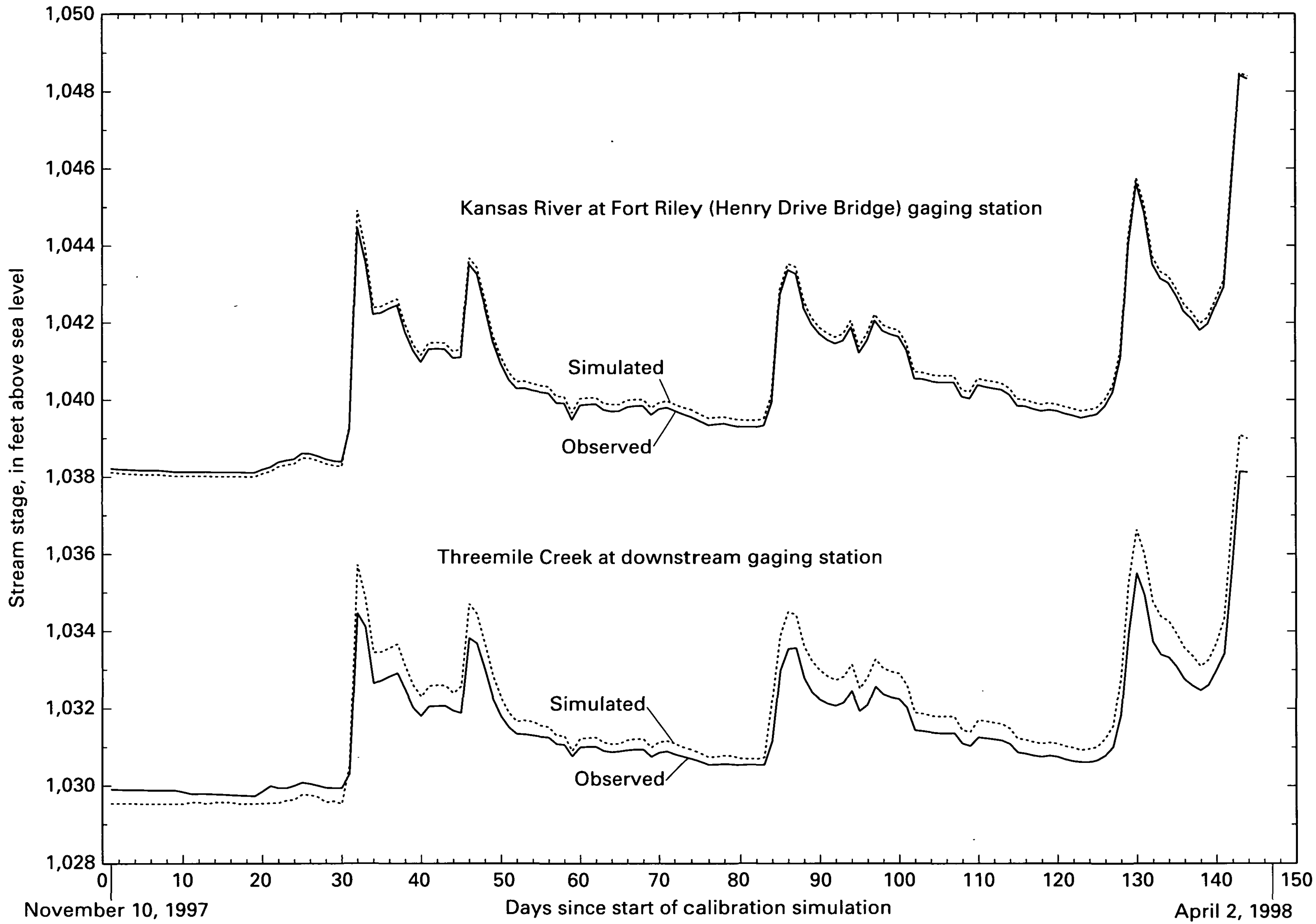


Figure 32. Comparison of observed and simulated Kansas River stage at Kansas River at Fort Riley (Henry Drive Bridge) stream-gaging station and observed and simulated Threemile Creek stage at downstream gaging station (TCMD, fig. 2) (data on file with U.S. Geological Survey, Lawrence, Kansas).

Table 11. Comparison of water budgets estimated for water-budget area and simulated for transient calibration model

[NE, not estimated]

Water-budget item	Aquifer recharge (+) or discharge (-) (cubic feet per second)			
	Dry period		Wet period	
	Estimated for April 1–4, 1997	Simulated for November 10, 1997 (stress period 1)	Estimated for April 1-3, 1998	Simulated for April 1, 1998 (stress period 143)
Recharge from precipitation	[1]+4.23	0	[1]+9.32	+12.12
Lateral ground-water inflow (recharge) from adjacent bedrock	[1]+2.57	0	[1]+5.66	+5.21
Subsurface ground-water inflow (recharge) from alluvial sediment	+.17	+1.13	0	-.18
Subsurface ground-water outflow (discharge) to alluvial sediment	-1.96	-3.13	-1.68	-2.81
Seepage from Republican River[2]	-.69	-1.01	+7.23	+9.77
Seepage from Smoky Hill River[2]	-3.27	-.98	+34.30	+24.89
Seepage from Kansas River[2]	-20.29	-26.58	+212.61	+340.65
Seepage from creeks[2]	NE	+1.46	NE	+11.28
Public-supply well pumpage	[3]-1.42	-.79	[3]-.47	-.79
Subtotal (recharge - discharge)	**-20.66**	**-29.89**	**+266.97**	**400.14**
Inflow (+) from or outflow (-) to aquifer storage	**+20.66**	**+29.86**	**-266.97**	**-400.38**
Error	**0**	**-.03**	**0**	**-.24**

[1]Values estimated on the basis of recharge rates of 10 (dry period) and 22 (wet period) percent of mean annual precipitation.

[2]Positive value indicates seepage from the river to alluvial aquifer; negative value indicates seepage from alluvial aquifer to river.

[3]Values estimated on the basis of reported annual pumpage for dry and wet years.

Kansas River without going through the Waterfowl Management Area. Also, the hydraulic conductivity of the streambed upstream from the diversion structure was increased to a value similar to that of Threemile Creek downstream from the diversion structure in the 1996–98 simulations (table 18 in "Supplemental Information" section). The hydraulic conductivity of that part of Threemile Creek upstream from the diversion structure was decreased in the transient calibrated and post-1995 models to account for the accumulation of 2 or more feet of fine-grained sediment upstream from the diversion structure.

The 1990–98 historical simulation had stress periods of 1 week in length. A starting hydraulic-head distribution was constructed using the steady-state model with January 1–7, 1990, mean streamflow. Mean weekly streamflow and precipitation values were computed from observed records and were used to prepare input data sets of stream and creek discharge, upstream and downstream general-head boundary heads, and recharge. During 1993, the Kansas River rose out of its banks and flooded much of the river valley. However, no modification of the model was prepared to account for the wider channel. The effect of not simulating the wider 1993 flood channel probably was to underrepresent the magnitude of ground-water-level fluctuations and velocity near the edges of the observed flood channel.

A particle-tracking program allows the user to tag hypothetical particles of ground water and then to trace their movement through the aquifer over time. Particles are simulated to move with ground-water flow, but their movement can be terminated if they are intercepted by rivers, wells, or other points of discharge from the model. Although particle-tracking methods can be used to estimate the path that a

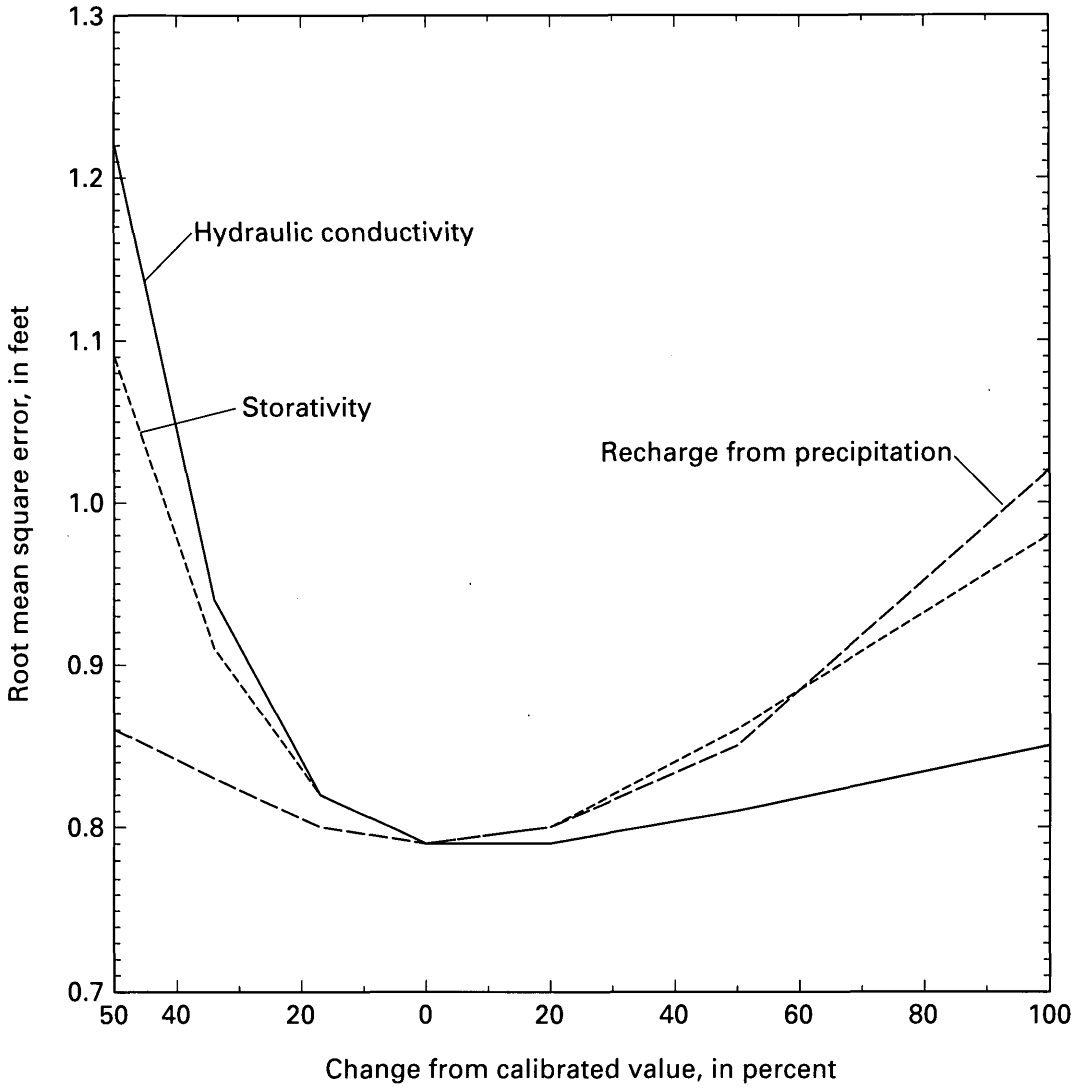


Figure 33. Root mean square error between observed and simulated ground-water levels resulting from changes in hydraulic-conductivity, storativity, and recharge-from-precipitation values.

ground-water contaminant might follow, particle tracking is not the same as solute transport modeling. Particle tracking cannot be used to estimate contaminant concentration and does not account for dispersion, retardation, or natural attenuation of contaminants.

Particle tracking was done using version 3 of the MODPATH computer program (Pollock, 1994). MODPATH version 3 allows transient particle tracking in multilayer models. In addition to the model parameters needed for MODFLOW, porosity is needed for MODPATH. Porosity is used in MODPATH to compute the velocity of ground-water flow. Ground-water flow and thus particle velocity are related to porosity by:

$$\bar{v} = \frac{Ki}{n}, \tag{10}$$

where $\bar{v}$ is the mean ground-water velocity, in feet per day;

K is the hydraulic conductivity, in feet per day;

i is the hydraulic gradient, in feet per foot; and

n is the porosity (dimensionless).

From equation 10, it is evident that changes in porosity have an inversely proportional effect on ground-water particle velocity.

Porosity was set equal to specific yield plus specific retention, or 0.25 for most of the model and 0.30 for the Marshall Army Airfield area. These values were used for all three layers.

Hypothetical ground-water particles were placed in the model near selected ground-water study sites where contaminants are present in ground water and other areas of hydrologic interest to estimate the direction and velocity of travel and to evaluate the variability of paths of particles starting from the same location (fig. 34). This particle tracking does not simulate solute transport. In figure 34, ground-water particles were released from each starting point at the beginning of 1990 and 1993 and were tracked until 1998. At most locations, a single particle was placed at the water table. In several locations, however, a particle was placed in the center of each model cell in each layer for a given model row and column. These multiple-particle locations generally were near the Kansas River. In general, particles moved towards the Kansas River and were terminated at the river if they traveled that far (fig. 34). Ground-water particles also moved generally deeper into the aquifer, as indicated by the color of the path lines on maps and cross sections in figure 34, until they reached the vicinity of the Kansas River, at which point they moved upward towards the river. The particle positions along each path in figure 34 indicate 1 year of travel from the previous year's starting point. At the Southwest Funston Landfill, ground-water particles generally moved to the east-southeast (fig. 34, inset A). Of the six particles released in 1990 and 1993 in the upper, middle, and lower layers of the model in the north part of the Southwest Funston Landfill, five discharged to Threemile Creek in 1993, 1994, and 1995. Only one particle, released in the lower model layer in 1990, moved under Threemile Creek and discharged to the Kansas River (fig. 34, inset A). Particles released in the Camp Funston cantonment show the movement of ground water away from the valley wall and towards the river. These particle paths indicate that during 1990–98 ground-water contaminants present at ground-water study sites in the Camp Funston Area would have been unlikely to move into the vicinity of Ogden's supply wells. The two particles released farthest from the river at Marshall Army Airfield moved to the northeast but did not reach the river within the 9 years of this simulation. Ground-water particles released closer to the river moved towards and discharged to the river in 3 to 4 years (fig. 34, inset B). Ground-water particles released south of the main post (fig. 34, inset C) moved northeast from near one reach of the Kansas River to another. The particles took about 7 to 8 years to travel from their starting point to the Kansas River. Ground-water particles released in the vicinity of the dry cleaning facility in 1990 generally traveled to the southeast and took 3 years to reach the river (fig. 34, inset D). A particle released farther northwest, along section D–D', in 1990 took 9 years to reach the Kansas River, whereas a particle released in 1993 took 5 years to reach the river. This difference resulted from the different paths the particles followed and the timing of hydraulic stresses during their travel. Particles released near Grandview Plaza and about halfway between Grandview Plaza and the main post traveled towards and discharged to the Kansas River near the main post (fig. 34, inset E).

To assess the variability of the particle paths over time, ground-water particles were released from the same starting point at the beginning of 1990 and 1993 (fig. 34). Every particle released was tracked for the duration of the simulation. In general, ground-water particles released near the Kansas River follow much more variable paths than particles released near the valley wall (fig. 34). Although particle tracking does not simulate solute transport, the increased path variability near the river indicates that, near the river, ground-water contaminants could follow many possible paths, making consistent detection difficult in water from a single monitoring well. In addition, multiple potential ground-water contaminants in an area near the river could lead to a confusing pattern of changing contaminant detections for wells that are sampled infrequently (once or twice a year). More distant from the river, contaminants likely would follow a narrower corridor (fig. 34).

Particle tracking also can be done backwards in time. This is useful for estimating the points of origin and pathways that ground-water particles have followed to reach a certain point in the aquifer. In this way recharge and flow-path areas for model cells corresponding to supply wells can be estimated. For backward particle tracking, 500 ground-water particles were placed in each model cell in each model layer penetrated by Ogden's supply wells, the Morris County Rural Water District wells, and one private-supply well (fig. 35). For the purposes of the following discussion, these model cells will be called well cells. These particles were released at the end of each year from 1990–98 and were tracked backwards for the

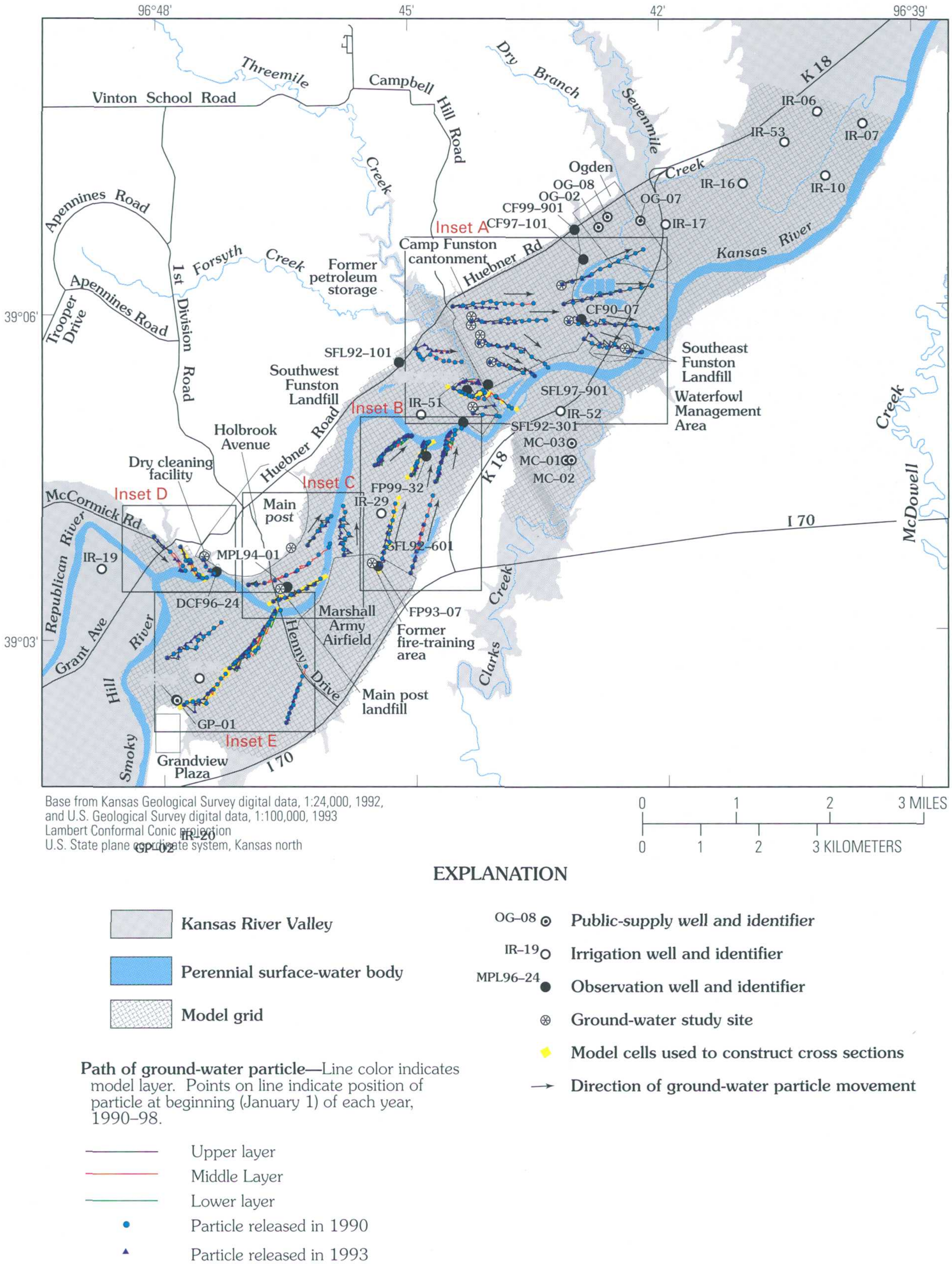


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998.

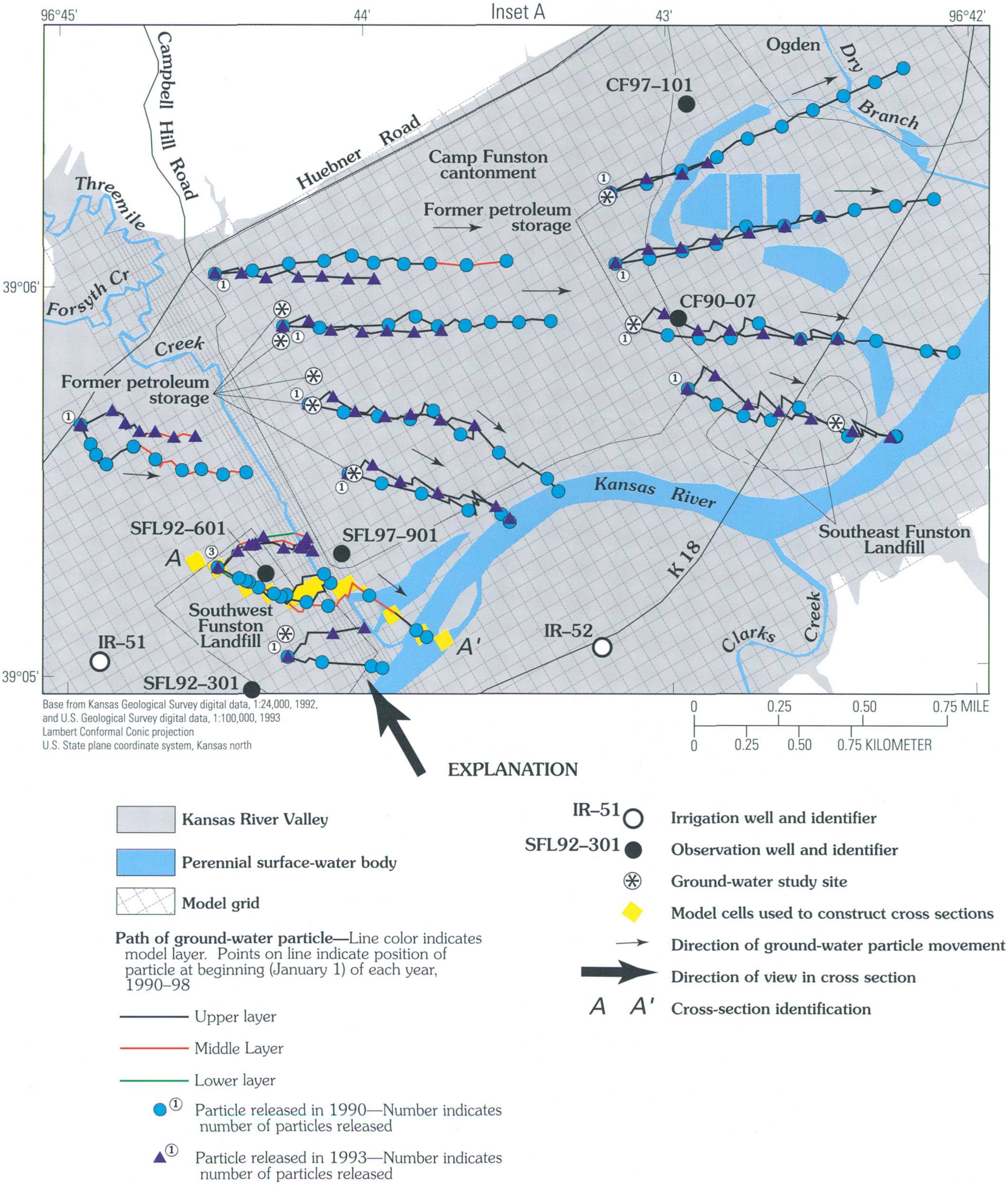


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

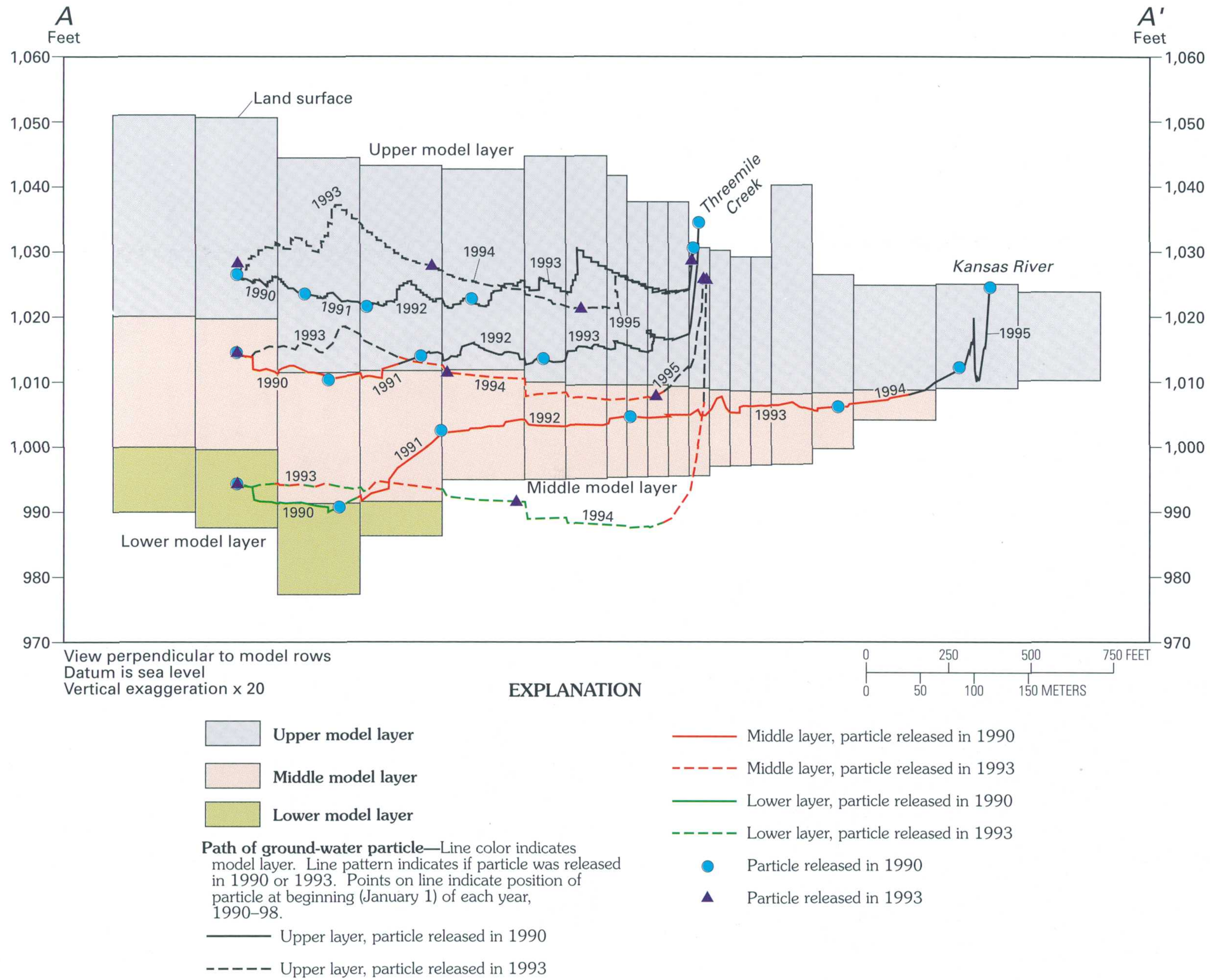


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

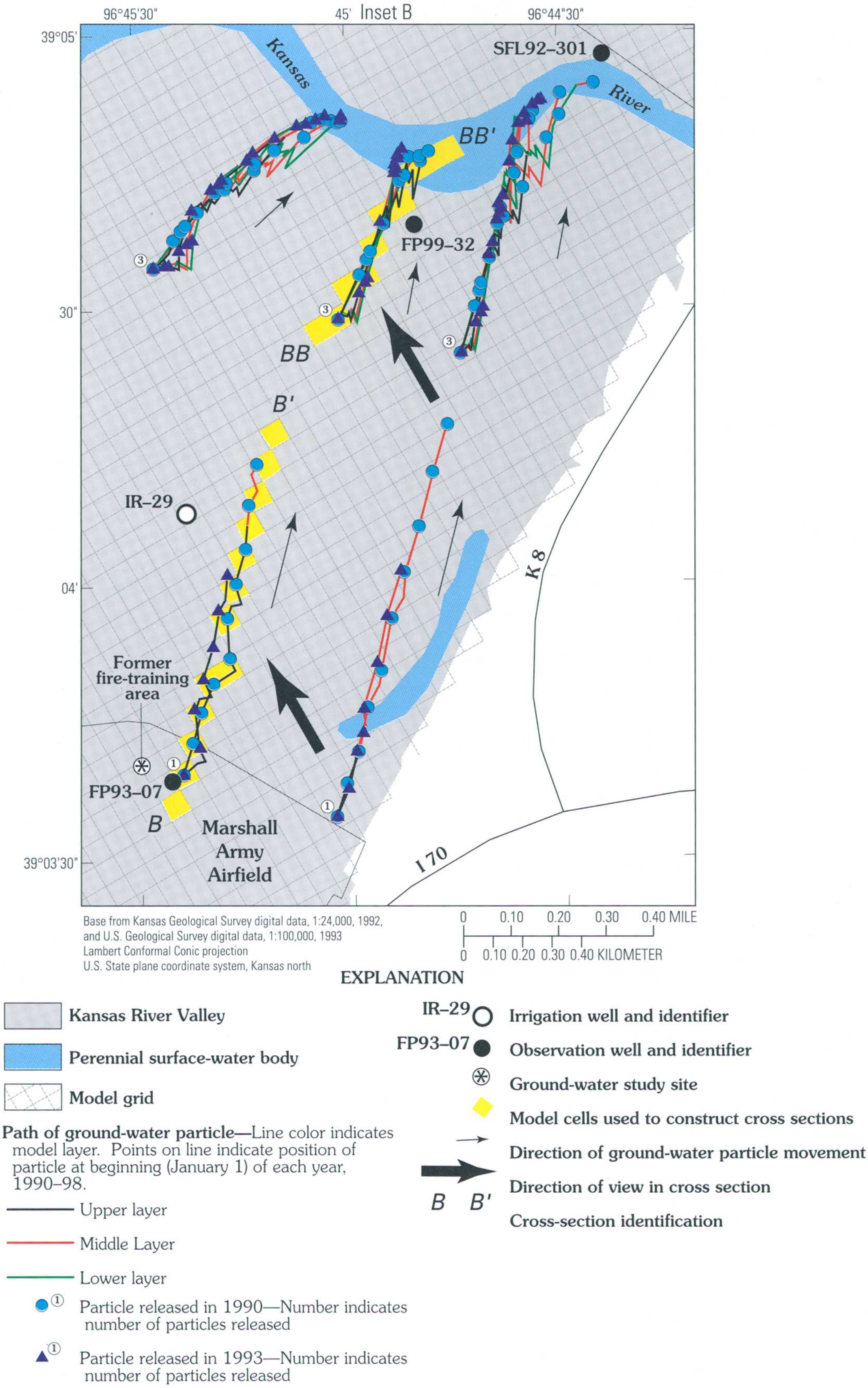


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

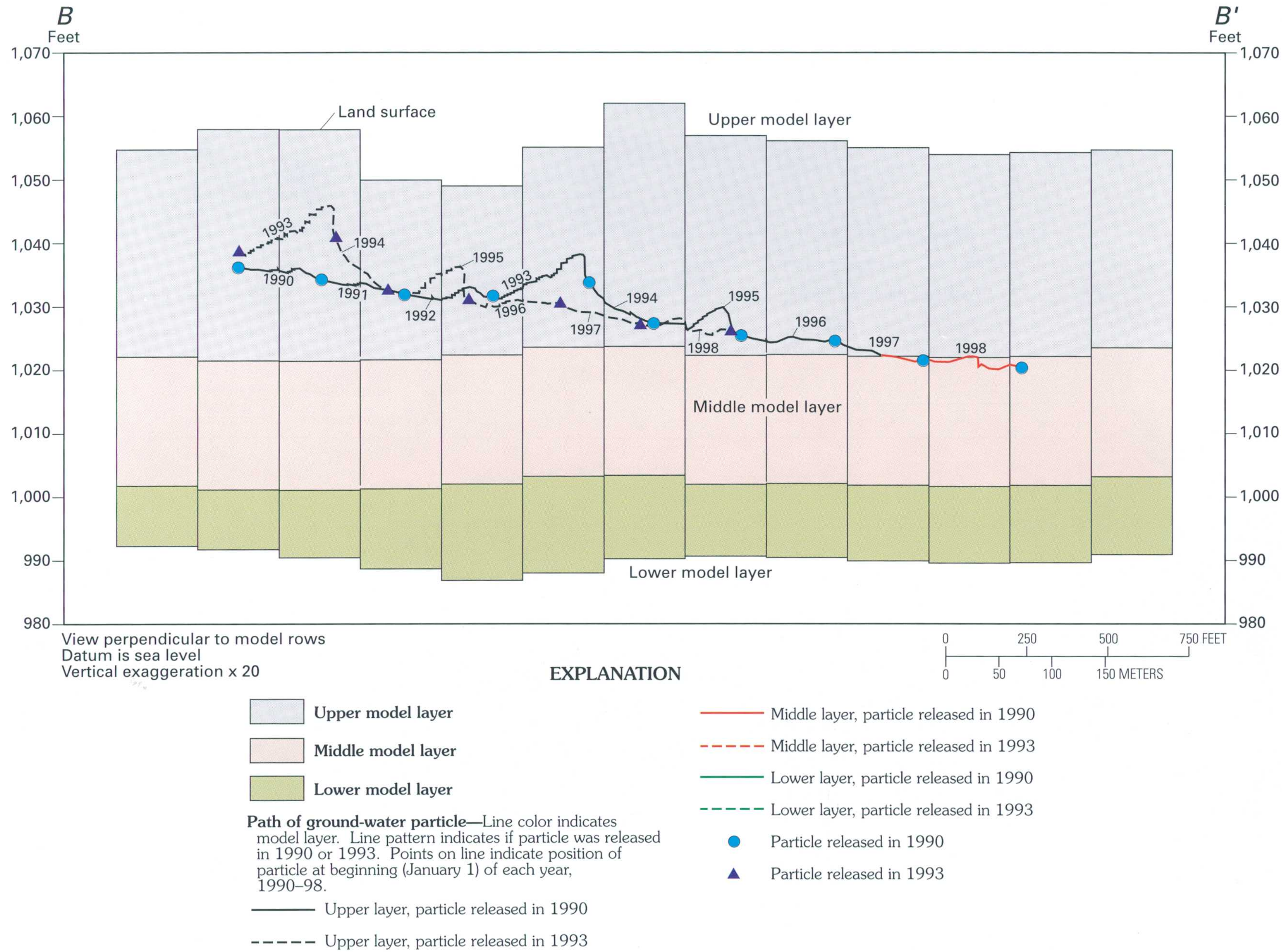


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

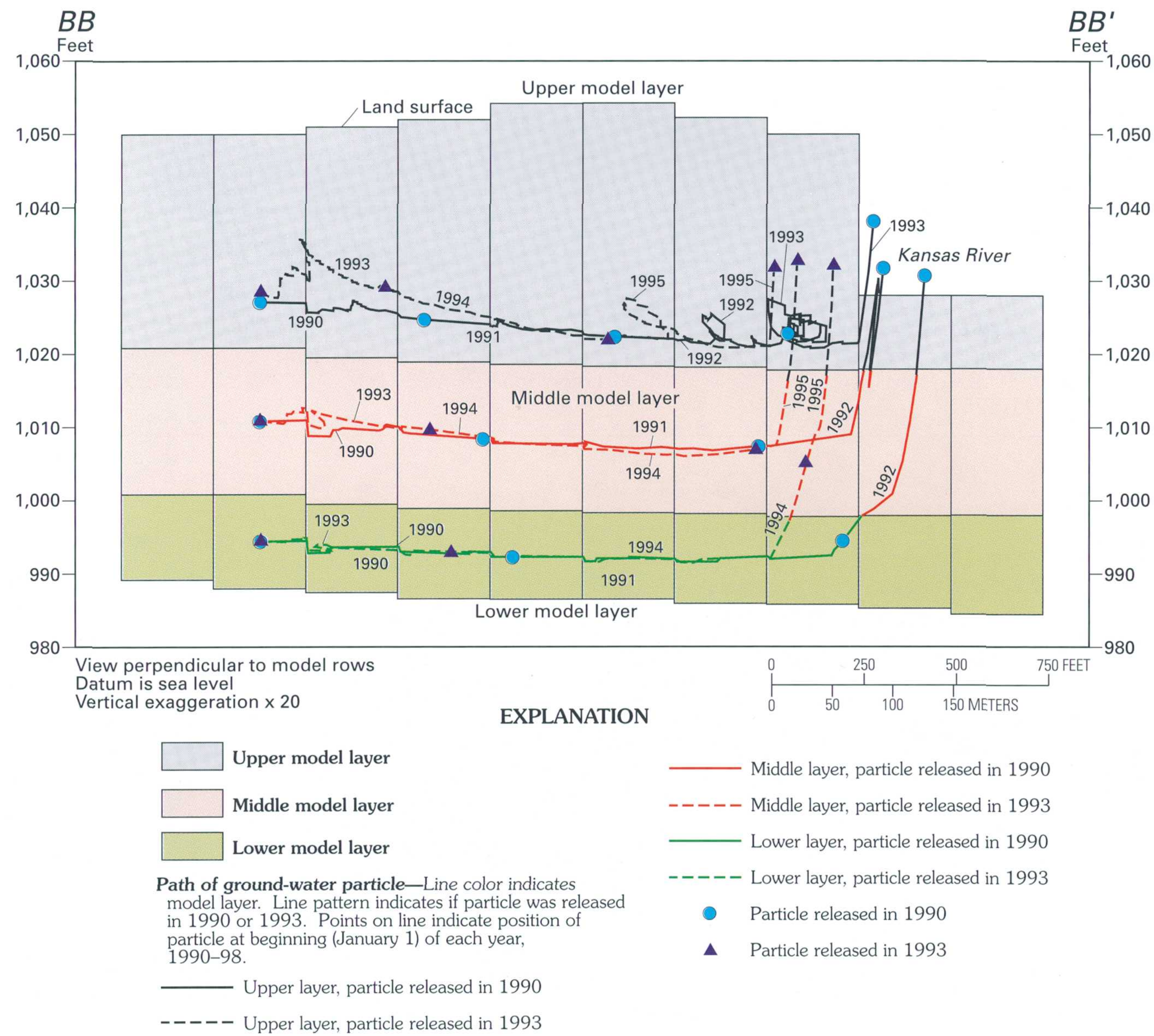


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

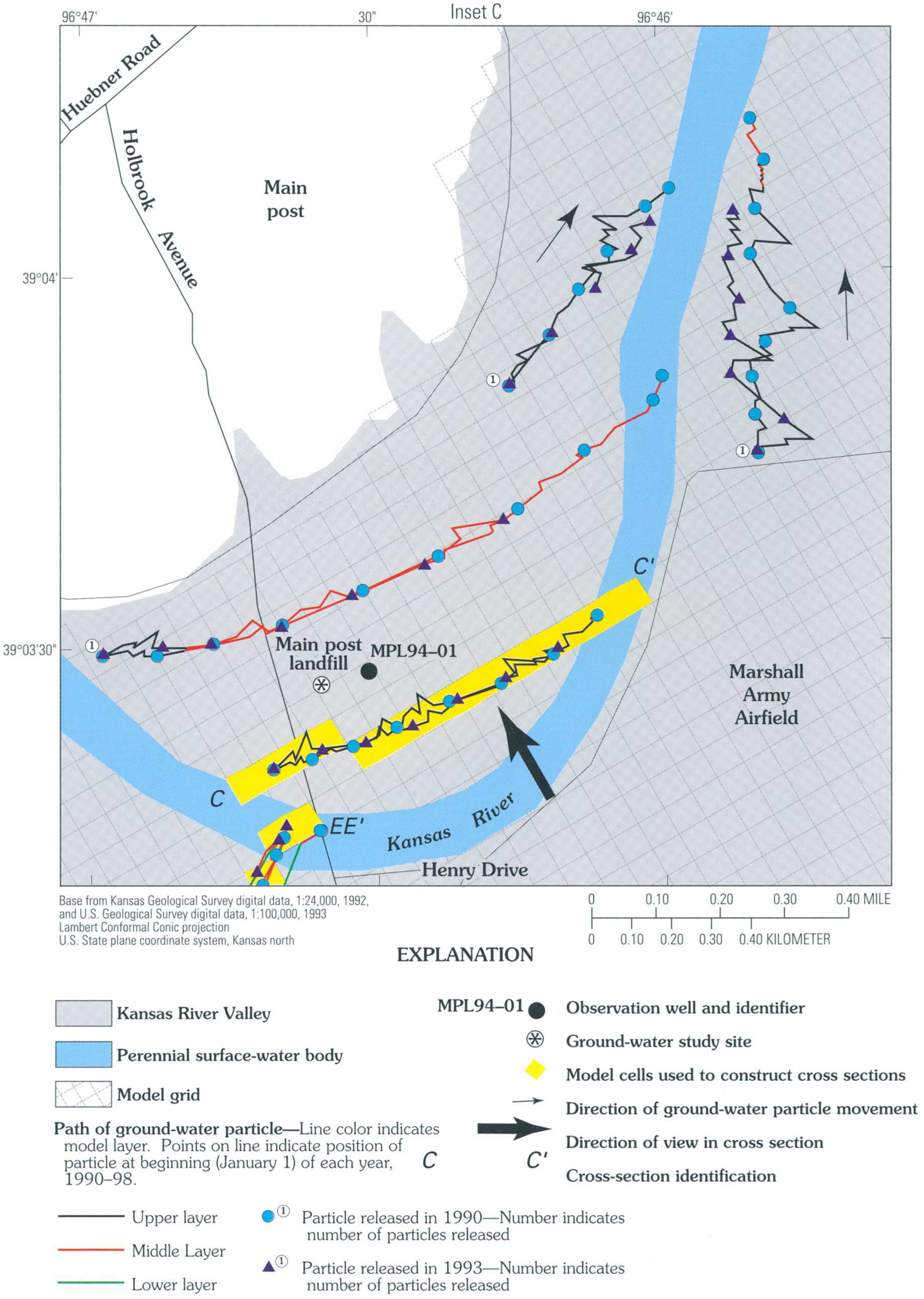


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

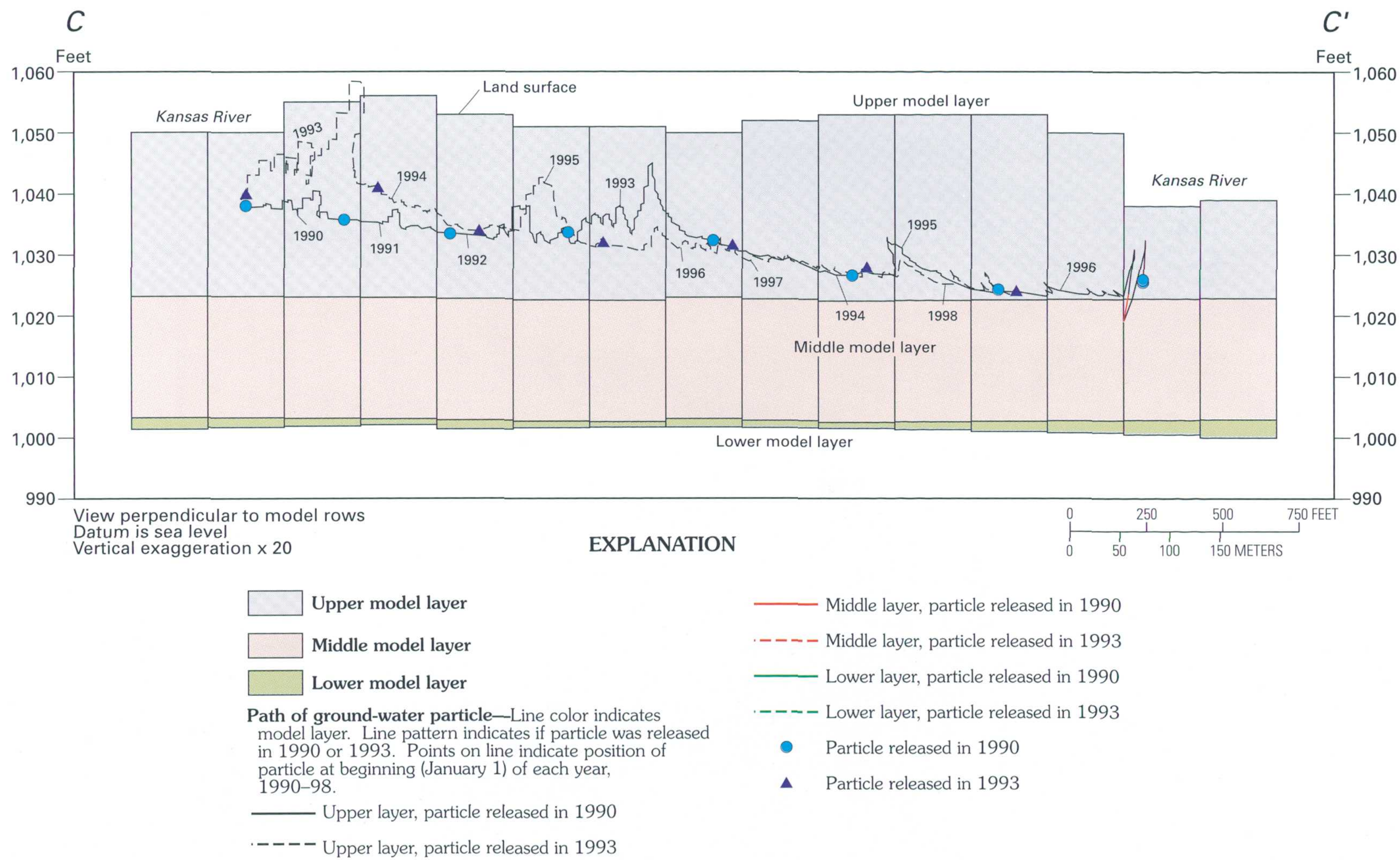


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

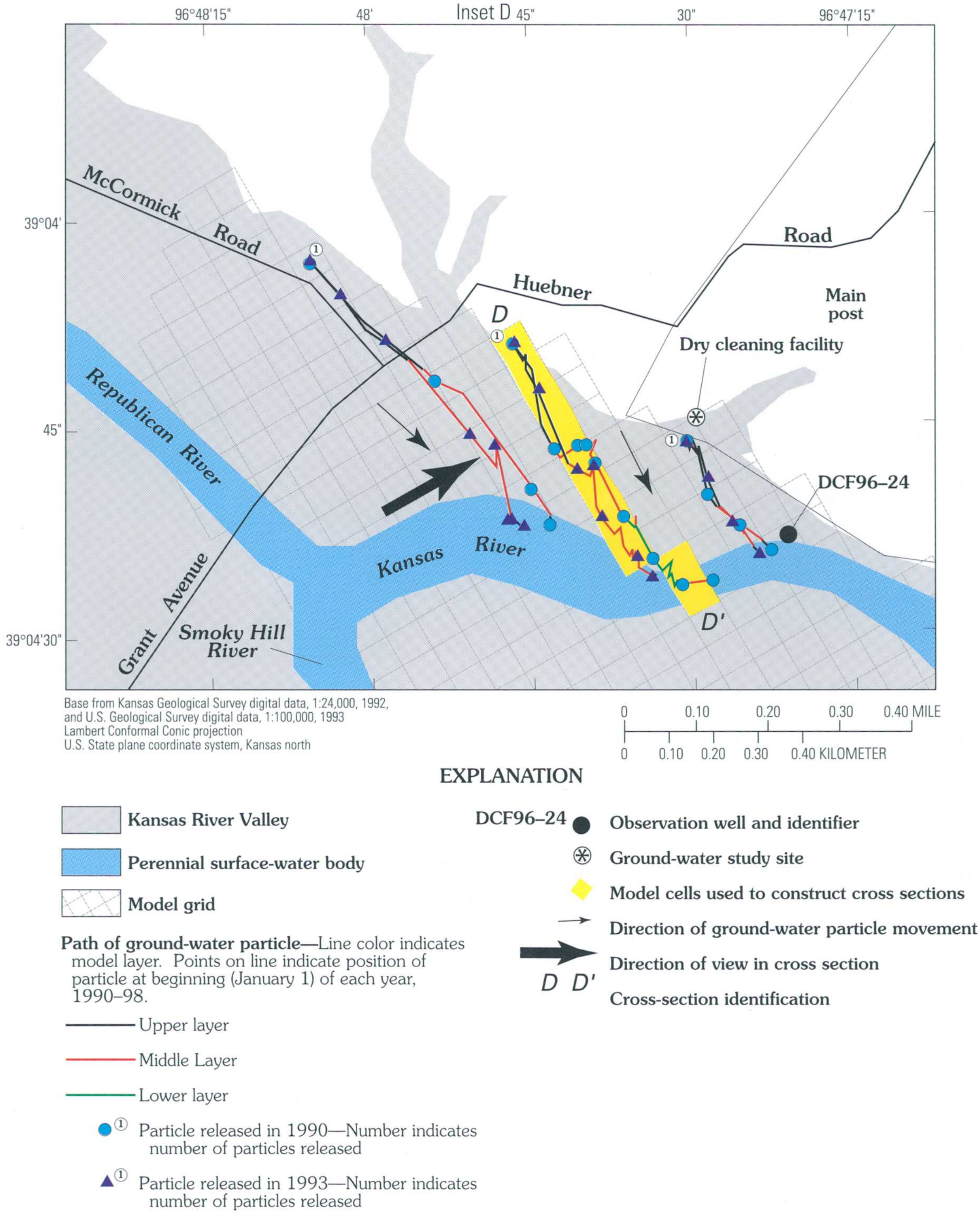


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

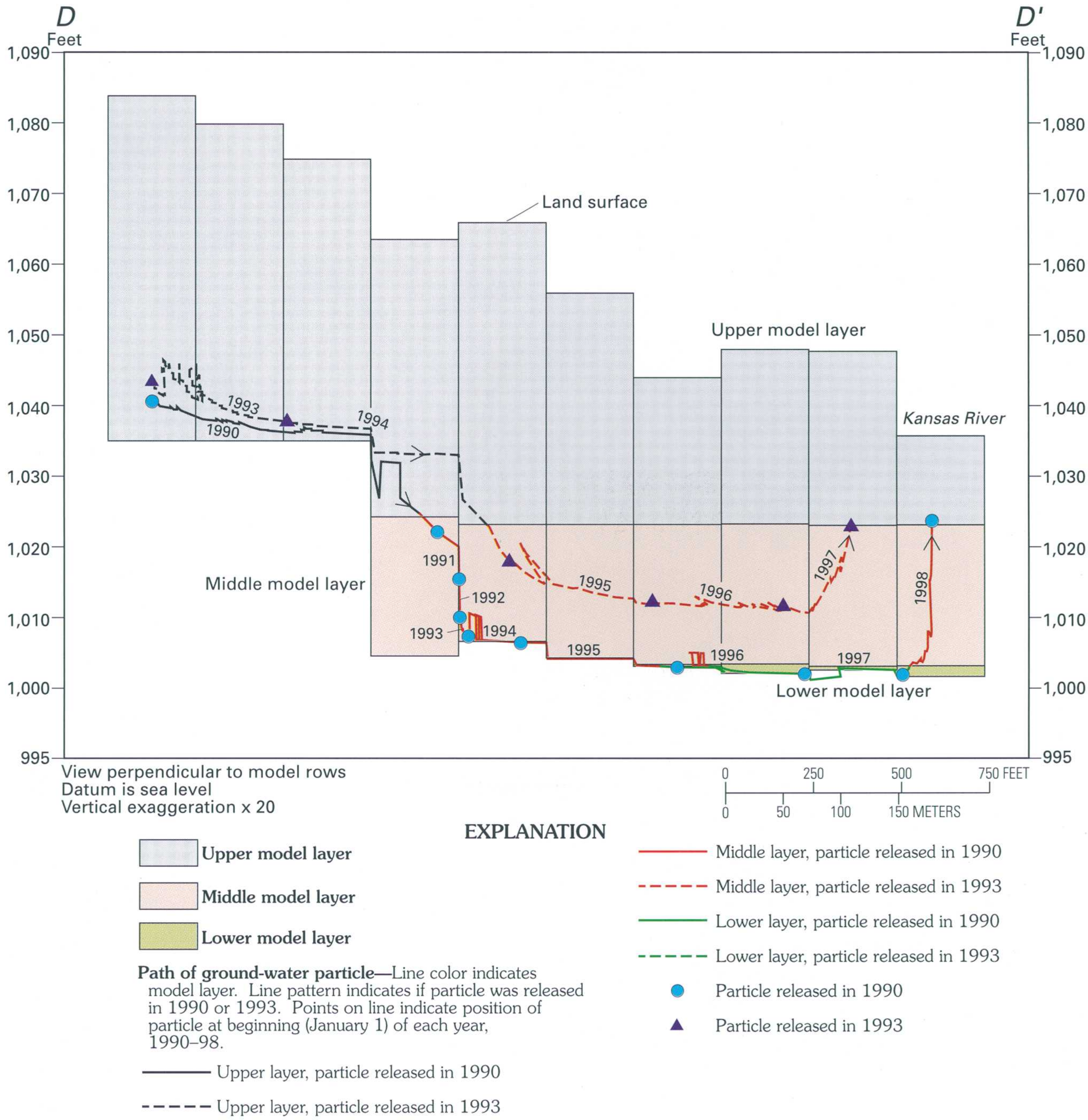
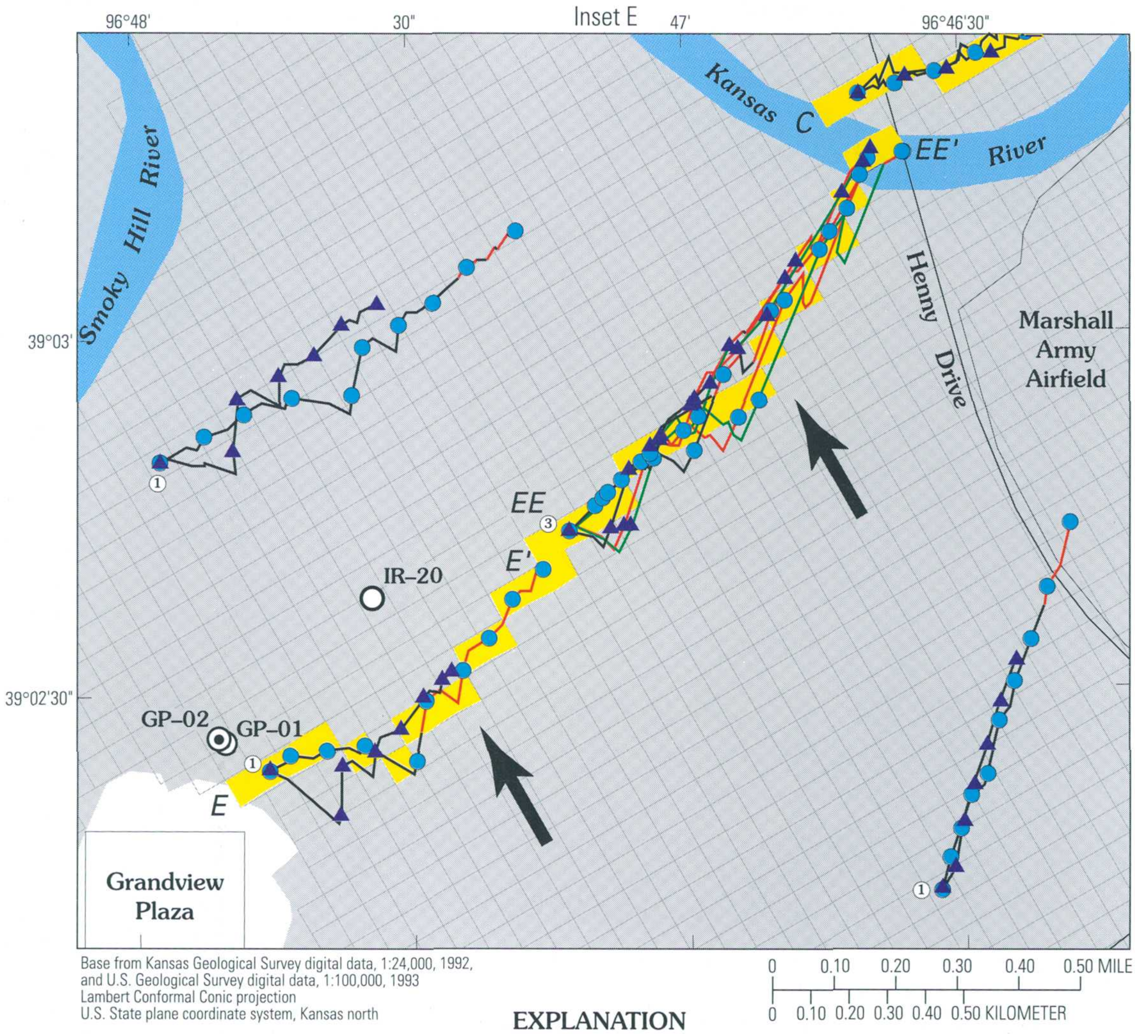


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.



EXPLANATION

- Kansas River Valley
- Perennial surface-water body
- Model grid

Path of ground-water particle—Line color indicates model layer. Points on line indicate position of particle at beginning (January 1) of each year, 1990–98.

- Upper layer
- Middle Layer
- Lower layer
- (1) Particle released in 1990—Number indicates number of particles released
- (1) Particle released in 1993—Number indicates number of particles released

- GP–02 Public-supply well and identifier
- IR–20 Irrigation well and identifier
- Model cells used to construct cross sections
- Direction of ground-water particle movement
- Direction of view in cross section
- *E E'* Cross-section identification

Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

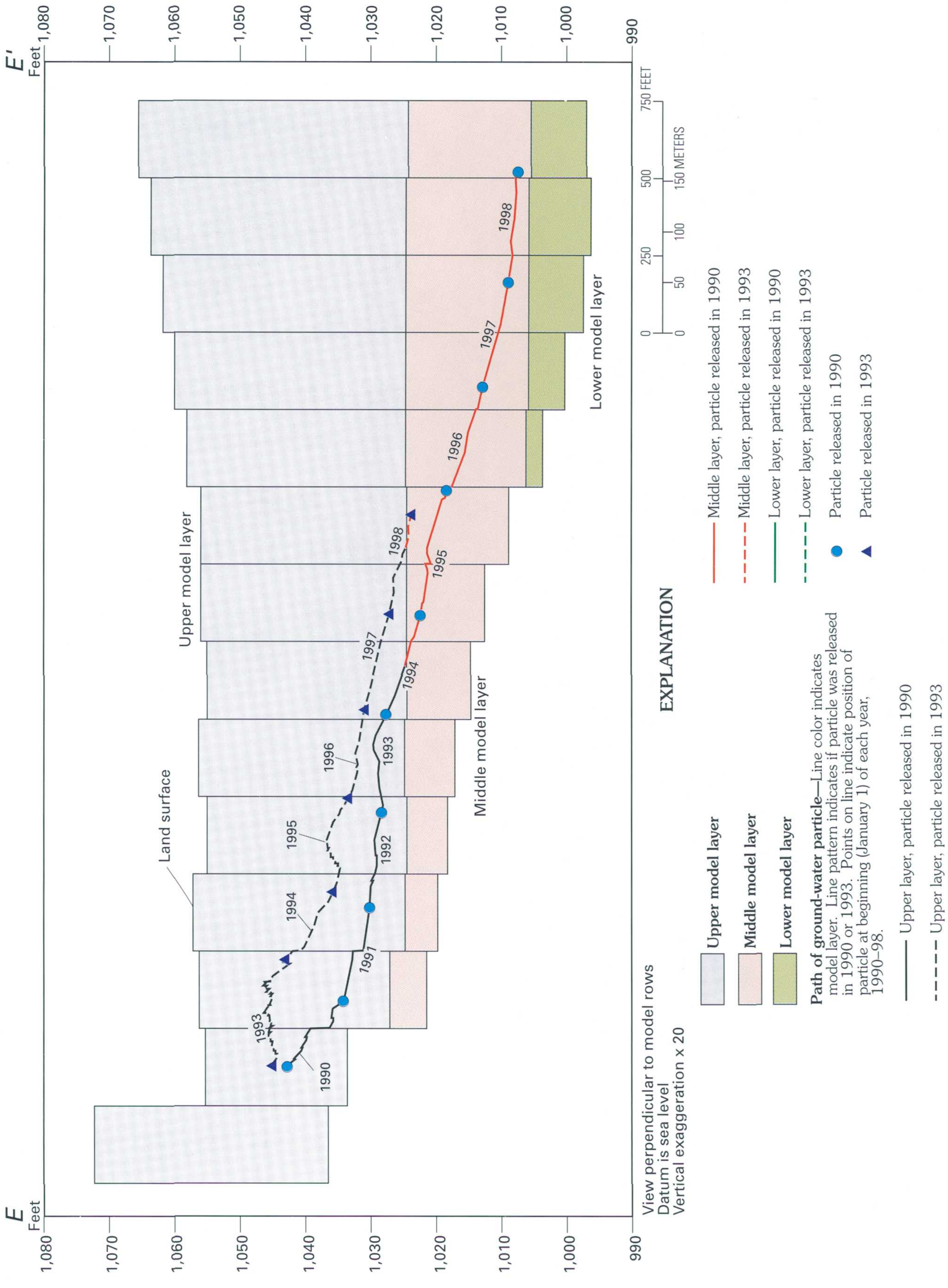


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

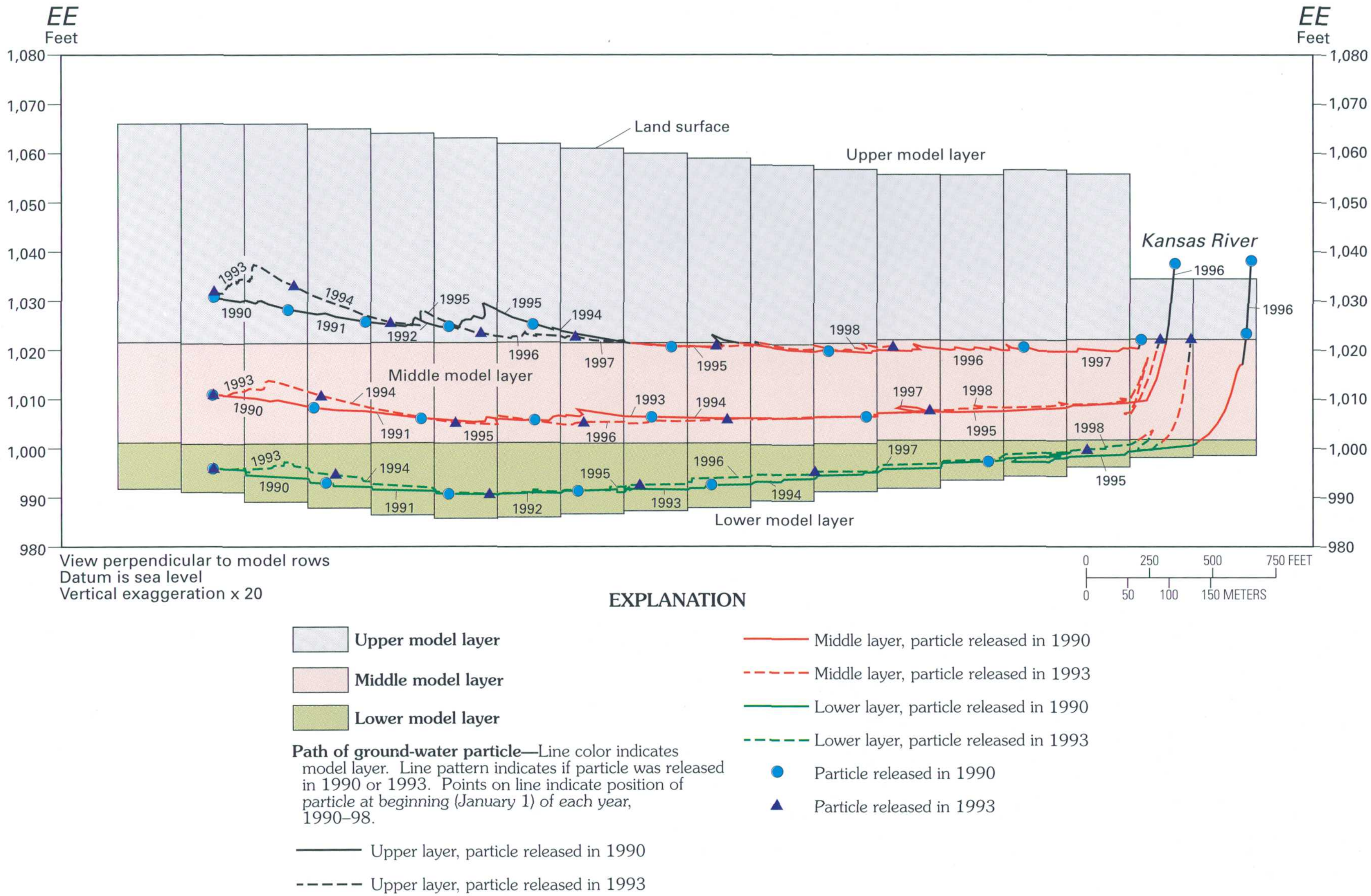


Figure 34. Simulated paths of ground-water particles released in 1990 and 1993 and tracked through 1998—Continued.

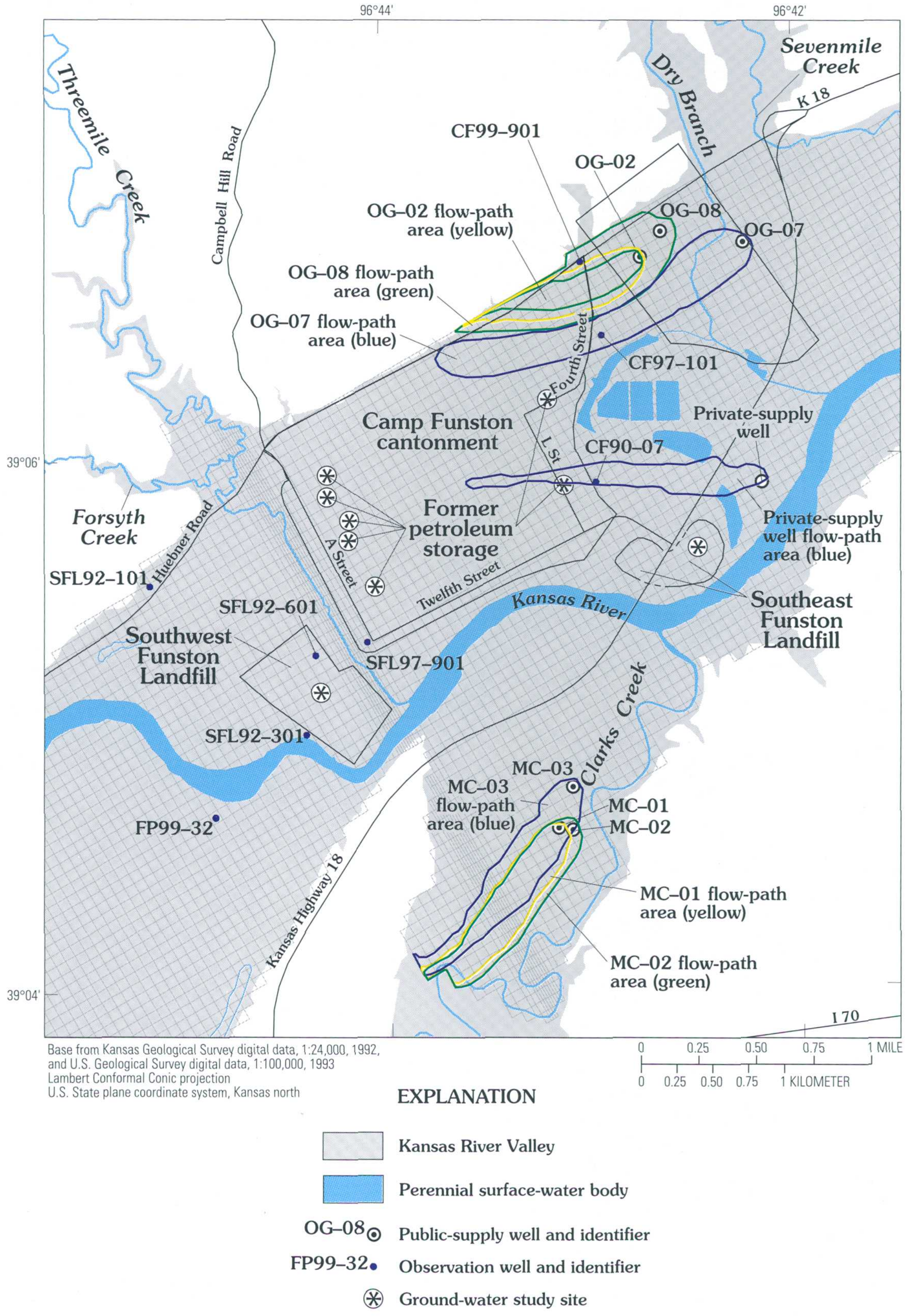


Figure 35. Flow-path areas defined by backward particle tracking from model cells corresponding to public-supply wells and a private-supply well, 1990–98.

duration of the simulation or until they reached their points of origin.

The flow-path areas shown in figure 35 indicate the areas through which simulated ground-water particles moved during 1990–98 on their way to their well cells. The flow-path areas are somewhat irregular in shape because variable hydrologic conditions (primarily changes in river stage and precipitation) caused changes in simulated ground-water flow-path areas during 1990–98. Changes in pumping and river-channel shifts also can affect the extent and location of flow-path areas. Flow-path areas do not necessarily indicate where simulated ground-water particles entered (recharged) the ground-water system. The areal and vertical extent of the flow-path areas are related to the amount of water passing through each well cell during 1990–98 and to the amount of simulated pumping by wells. More pumping would result in larger flow-path areas. All ground water passing into a well cell will be discharged from the model if the simulated well pumping equals or exceeds the amount of water that enters that well cell. If simulated well pumping is less than the amount of ground water entering a well cell, then only a part of that ground water will be discharged. Pumping was not simulated for the private-supply well (it is a small-capacity domestic well), so the flow-path area for its well cell is only an indication of the amount of simulated ground water that passed through that well cell during 1990–98.

The recharge areas shown in figure 36 indicate where simulated ground-water particles (that passed into well cells) entered the ground-water flow model during 1990–98. In this ground-water flow model, ground-water particles can enter the model at boundaries such as the water table, valley walls, streams, and upstream and downstream edges of the model. Some of the simulated recharge areas are smaller than their respective flow-path areas because the flow-path areas include particles that were not tracked backwards far enough in time to reach their points of origin (figs. 35 and 36). For this reason the simulated recharge areas for the public-supply well OG–07 and the private-supply well cells are smaller than their flow-path areas. The simulated recharge areas for well cells corresponding to Ogden wells OG–02 and OG–08, and Morris County Rural Water District wells MC–01, MC–02, and MC–03 are similar in size to their respective flow-path areas. The flow-path areas for the Ogden wells probably extend outside the model area, into the bedrock of the valley wall, with a corresponding recharge area. The flow-path areas for the Morris County Rural Water District wells originate, in part, along Clarks Creek (fig. 35) but also probably extend outside the model area southward into Clarks Creek Valley with a corresponding recharge area.

Suitable quality of water pumped from a well can be maintained by protecting the well's flow-path and recharge areas from unwanted contamination. The flow-path and recharge areas will vary in extent and location as hydrologic conditions change. Model simulations indicate that Ogden's wells obtain water from the alluvial aquifer along the northern valley wall and from bedrock in the uplands. Therefore, in addition to the flow-path and recharge areas defined in figures 35 and 36 in the Kansas River Valley, an appropriate protection area for Ogden's wells would include a part of the uplands adjacent to the Kansas River Valley. However, without simulating ground-water flow in the uplands, it is difficult to determine the area of the uplands that contributes water to Ogden's wells.

Hypothetical Simulations

The 1990–98 historical simulations were used as the basis for five hypothetical simulations. These simulations were done to simulate the flow-path areas that would have resulted from increased pumping of existing and hypothetical supply wells at and near Ogden. Although the 1990–98 simulations were used as the basis for these hypothetical simulations, the results of these simulations generally are applicable to future time periods with climatic conditions similar to 1990–98.

In the previous section of this report, it has been shown that Ogden's supply wells obtain their water from the Kansas River alluvium and from uplands along the northern Kansas River Valley wall. Shifts of flow-path areas for Ogden supply wells south into the Camp Funston Area could cause ground-water contaminants from ground-water study sites in the Camp Funston Area to flow towards the Ogden supply wells. The hypothetical pumping simulations help describe the effects of pumping increases from Ogden's wells and the addition of hypothetical supply wells on the flow-path areas for each well's corresponding model well cell.

For three of the five simulations, pumpage for the Ogden supply wells was increased by 2, 5, or 10 times 1997 pumpage rates [about 441 acre-ft/yr

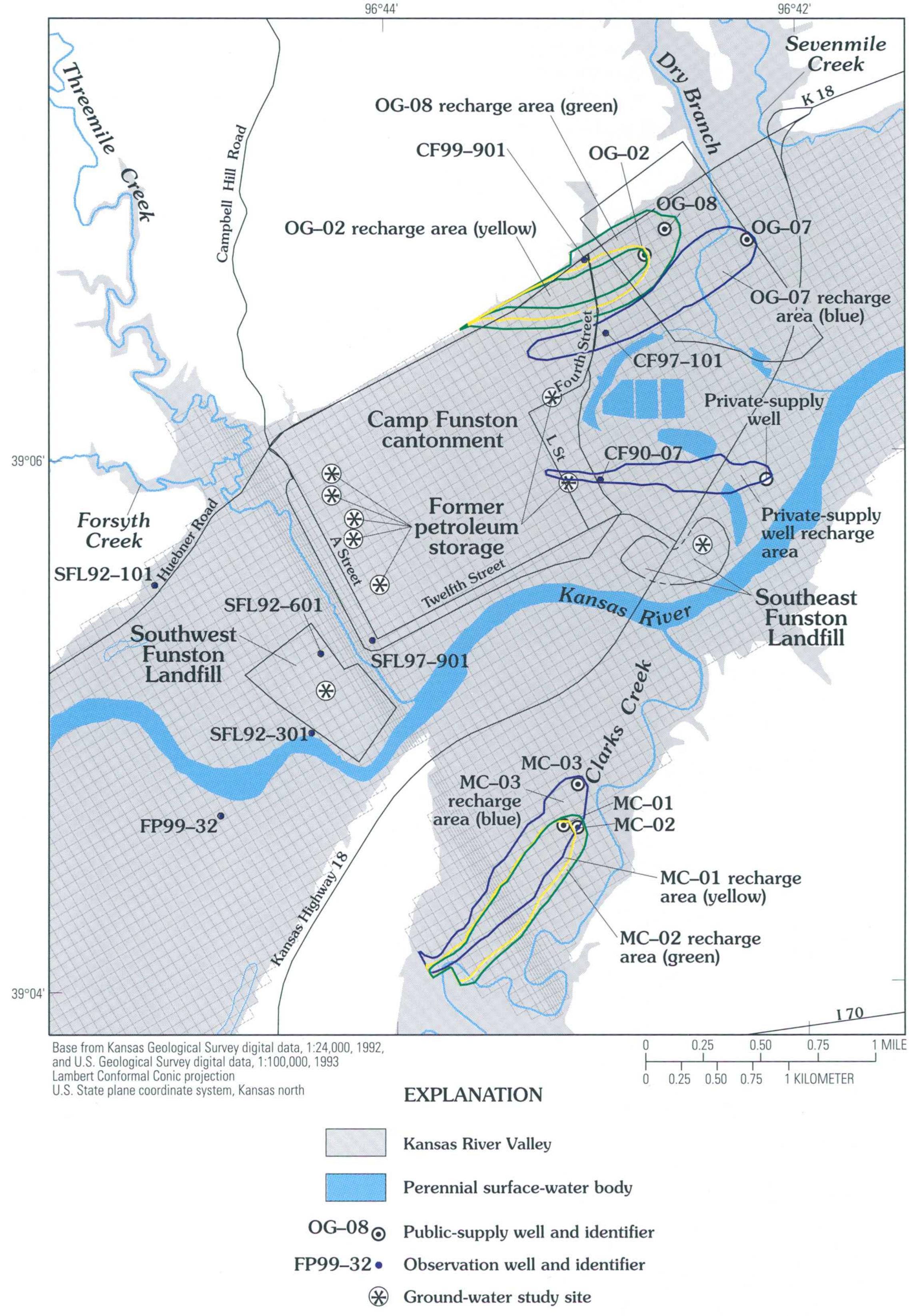


Figure 36. Recharge areas defined by backward particle tracking from model cells corresponding to public-supply wells and a private-supply well, 1990–98.

(273 gal/min) combined; table 5]. For the remaining two simulations, three hypothetical supply wells were added in the southeastern of Ogden and were each pumped at about 161 or 1,452 acre-ft/yr (about 100 or 900 gal/min). During these last two simulations, pumpage from Ogden's supply wells was set equal to 1997 pumpage rates.

The basis for these hypothetical pumping rates is a method used by DWR to compute allowable pumpage for a well (Division of Water Resources, 1994, p. 13). In this method the amount of precipitation that recharges an aquifer over a 2-mi-radius circle around the well of interest is the maximum amount of ground water allowed to be pumped from wells within that area. Allowable pumpage for existing wells in the area is subtracted from the amount allowed for a new well. A 2-mi-radius circle centered on Ogden supply well OG–08 encompasses the Kansas River Valley from south to north, part of Clarks Creek Valley, and parts of uplands adjacent to the Kansas River Valley. The area within this circle is about 8,042 acres. Multiplying by 0.62 ft of recharge per year (0.62 ft is 22 percent of the mean annual precipitation of 33.82 in. at Manhattan), the maximum amount of allowable pumpage in this circle is about 4,986 acre-ft/yr. DWR's calculation may differ from this because they may include other considerations such as minimum streamflow needs of rivers and creeks. Two existing irrigation wells that are within the 2-mi-radius circle around supply well OG–08 are authorized to pump as much as 375 acre-ft/yr, theoretically leaving 4,611 acre-ft/yr for other wells. Ogden's three supply wells currently (2000) are authorized to pump about 470 acre-ft/yr. On the basis of these computations, three hypothetical simulations were set up in which Ogden's wells were pumped at 2, 5, or 10 times 1997 pumpage, or 882, 2,204, or 4,409 acre-ft/yr. The 10-fold increase is equal to almost all of the theoretically allowable pumpage within the 2-mi-radius circle.

In the two simulations set up for hypothetical supply wells, Ogden's supply wells and the two existing irrigation wells were pumped at 1997 rates (about 441 and 181 acre-ft/yr, respectively). At these pumping rates, there theoretically is 4,364 acre-ft/yr of allowable pumpage. Pumping rates for each of the hypothetical supply wells were set to about 161 acre-ft/yr (100 gal/min) in one simulation and about 1,452 acre-ft/yr (900 gal/min) in the other. For all three hypothetical wells, the pumping rates totaled 483 acre-ft/yr in one simulation and 4,356 acre-ft/yr in the other. The lesser value is a minimal pumping rate, and the greater value is equal to almost all of the theoretically allowable pumage within the 2-mi-radius circle.

Backward particle tracking was used to delineate the simulated flow-path areas for model cells (well cells) corresponding to Ogden's existing and the hypothetical supply wells. For the first three simulations, particles were placed in model cells corresponding to Ogden supply-well locations. For the last two simulations, particles were placed in model cells corresponding to Ogden's supply-well locations and three hypothetical supply-well locations. Particles were released in the well cells at the end of each year and were tracked backward to the beginning of the simulation or until they reached their points of origin. Particles that did not reach their points of origin would have originated at points hydraulically upgradient of their backtracked positions and earlier in time than the earliest time of the simulation.

Figure 37 shows simulated flow-path areas for particles placed in Ogden's supply-well cells when the wells are pumped at two times 1997 rates. In general, the flow-path areas are larger and extend farther south into the Camp Funston Area than flow-path areas for 1997 pumping rates (fig. 35). The flow-path areas for well cells OG–02 and OG–08 do not intersect any ground-water study sites in the Camp Funston Area where ground-water contamination has been detected. The ground-water particles in these flow-path areas originate at the water table along the flow-path area and at the northern Kansas River Valley wall. The flow-path area for well cell OG–07, however, intersects a ground-water study site where petroleum fluids formerly were stored. Ground-water particles for this flow-path area originate at the water table within the flow-path area. Particle tracking was not carried back far enough in time to determine if particles for well cell OG–07 originated at the Kansas River Valley wall.

Figure 38 shows simulated flow-path areas for particles placed in Ogden's supply well cells when the wells are pumped at five times 1997 rates. The flow-path areas in this simulation are much larger and extend farther south than for previous simulations. The flow-path areas for all three well cells intersect ground-water study sites where petroleum fluids formerly were stored. Ground-water particles in the OG–02 and OG–08 flow-path areas originate at the water table along the flow-path area and along the Kansas River Valley wall. These flow-path areas

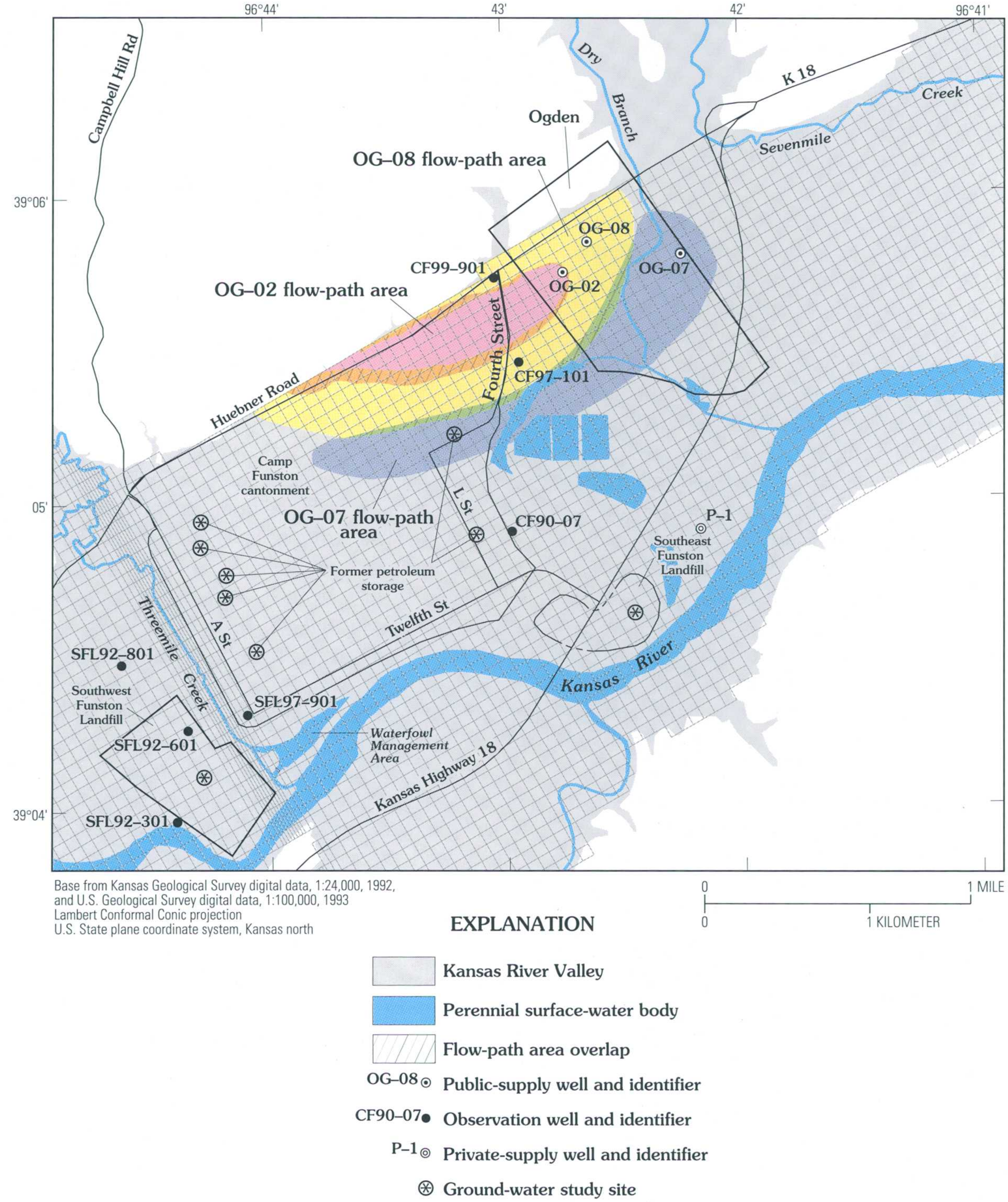


Figure 37. Outlines of simulated flow-path areas for particles backtracked from model cells corresponding to Ogden supply wells pumping at two times 1997 rates.

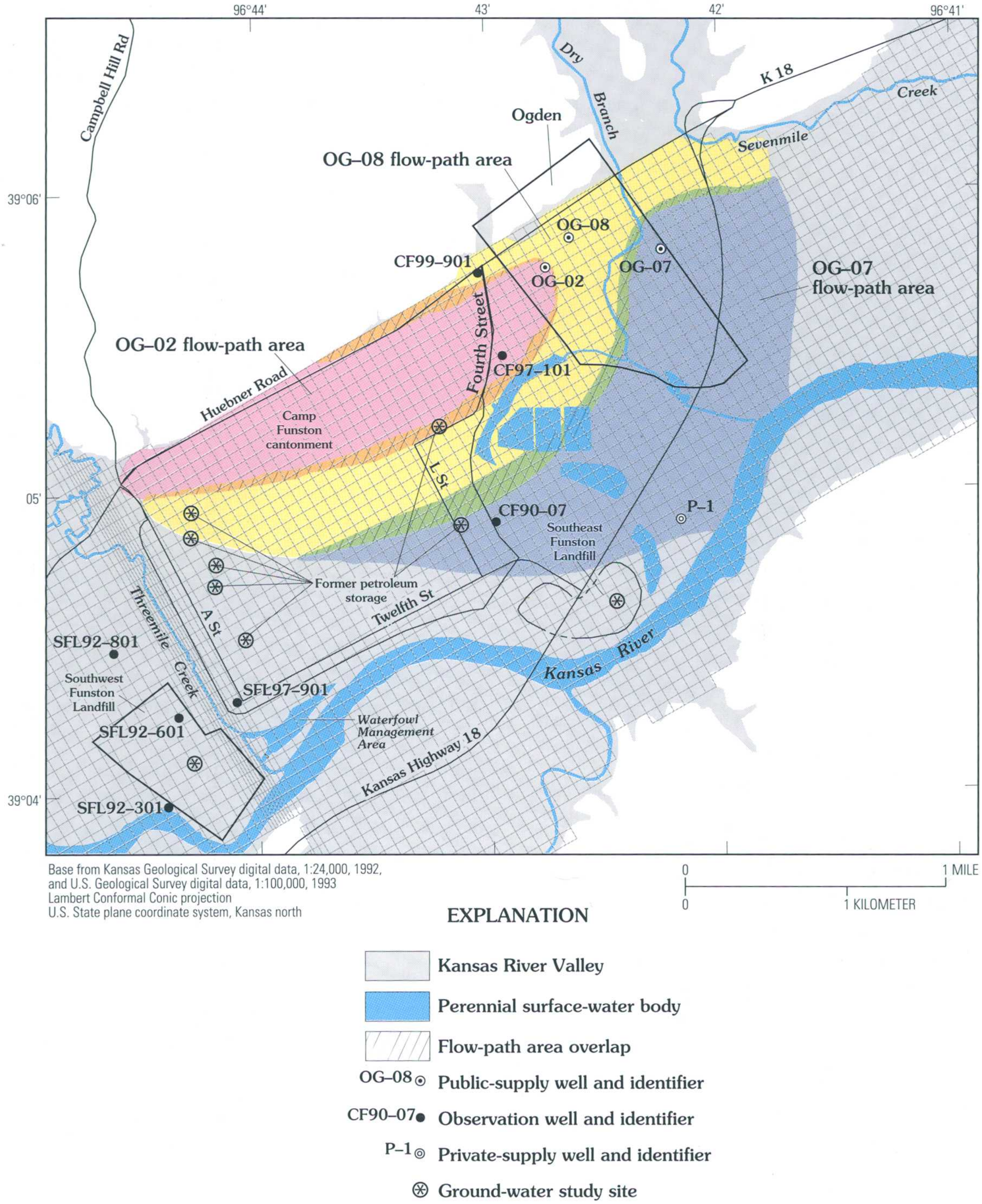


Figure 38. Outlines of simulated flow-path areas for particles backtracked from model cells corresponding to Ogden supply wells pumping at five times 1997 rates.

extend almost to Threemile Creek, which if particle tracking were extended farther back in time, probably would be the source of some of the particles. Ground water in the OG–07 flow-path area originates at the water table within the flow-path area and at the Kansas River. Although the OG-07 flow-path area intersects a ground-water study site in the Camp Funston cantonment where petroleum fluids formerly were stored, it does not intersect the Southeast Funston Landfill. Under these hypothetical pumping conditions, water pumped from well OG–07 would be expected to have a markedly different chemistry than water from wells OG–02 and OG–08.

Figure 39 shows simulated flow-path areas for particles placed in Ogden's supply well cells when the wells are pumped at 10 times 1997 rates, or about equal to the pumpage theoretically allowable inside a 2-mi-radius circle centered on well OG–08 (see discussion earlier in this section). The flow-path areas for this simulation are larger and extend farther south than for previous simulations, except that the OG–08 flow-path area is smaller because the upper layer model cell corresponding to well OG–08 went dry during the simulation (the water table declined below the bottom of the cell because of pumping), so the model only simulated pumping from the middle layer model cell of about three times the 1997 pumping rate. The flow-path areas for all three well cells intersect ground-water study sites where petroleum fluids formerly were stored. In addition, the OG–07 flow-path along intersects the Southeast Funston Landfill. None of the flow-path areas intersect the Southwest Funston Landfill. Ground-water particles in the OG–02 flow-path area originate at the water table within the flow-path area, along the Kansas River Valley wall, and at Threemile Creek. Ground-water particles in the OG–08 flow-path area originate at the water table within the flow-path area, along the Kansas River Valley wall, and along Sevenmile Creek. This flow-path area would be more extensive if the upper layer model cell had not gone dry. Ground-water particles in the OG–07 flow-path area originate at the water table within the flow-path area, along the Kansas River, and along Sevenmile Creek. In this hypothetical simulation, some ground-water particles were derived from south of the Kansas River, indicating that the well-pumping stresses in this simulation were strong enough to induce ground-water flow under the Kansas River.

Figure 40 shows simulated flow-path areas for particles placed in Ogden's supply well cells when the wells are pumped at 1997 rates and in three hypothetical supply well cells when the wells each are pumped at 100 gal/min. The flow-path areas generally are small and lie more or less parallel to each other. The Ogden flow-path areas extend into the northern Camp Funston Area but do not intersect any ground-water study sites. The H–1 flow-path area intersects a ground-water study site where petroleum fluids formerly were stored. The H–2 and H–3 flow-paths areas extend into the Camp Funston Area but do not intersect ground-water study sites. However, extending the model simulation farther back in time might cause them to intersect ground-water study sites where petroleum fluids formerly were stored on the west side of the Camp Funston cantonment. Ground-water particles in all of these flow-path areas originate at the water table within their respective flow-path areas, and for the OG–02, OG–07, and OG–08 well cells, along the Kansas River Valley wall.

Figure 41 shows simulated flow-path areas for particles placed in Ogden's supply well cells when the wells are pumped at 1997 rates and in three hypothetical supply well cells when the wells each are pumped at 900 gal/min. The flow-path areas are larger and have the greatest amount of overlap than in any of the flow-path areas for previous hypothetical simulations. Although the three Ogden supply wells were pumped at 1997 rates, the shapes of their flow-path areas changed as a result of the large amount of pumping from the hypothetical supply wells. The Ogden flow-path areas overlap and extend farther along the Kansas River Valley wall than in the previous simulation (fig. 40). Ground-water particles in the Ogden flow-path areas originate at the water table within the respective flow-path area and along the Kansas River Valley wall, but none of the flow-path areas intersect ground-water study sites in the Camp Funston Area. The flow-path area for well cell H–1 extends from Threemile Creek to about 1 mi downvalley from the well cell and from the northern part of the Camp Funston cantonment to and across the Kansas River. Ground-water particles in the H–1 flow-path area originate at the water table within the flow-path area, at Threemile Creek, Sevenmile Creek, and the Kansas River. This flow-path area intersects several ground-water study sites in the Camp Funston Area. The H–2 flow-path area extends across the Camp Funston cantonment, the Southeast Funston Landfill, the Kansas

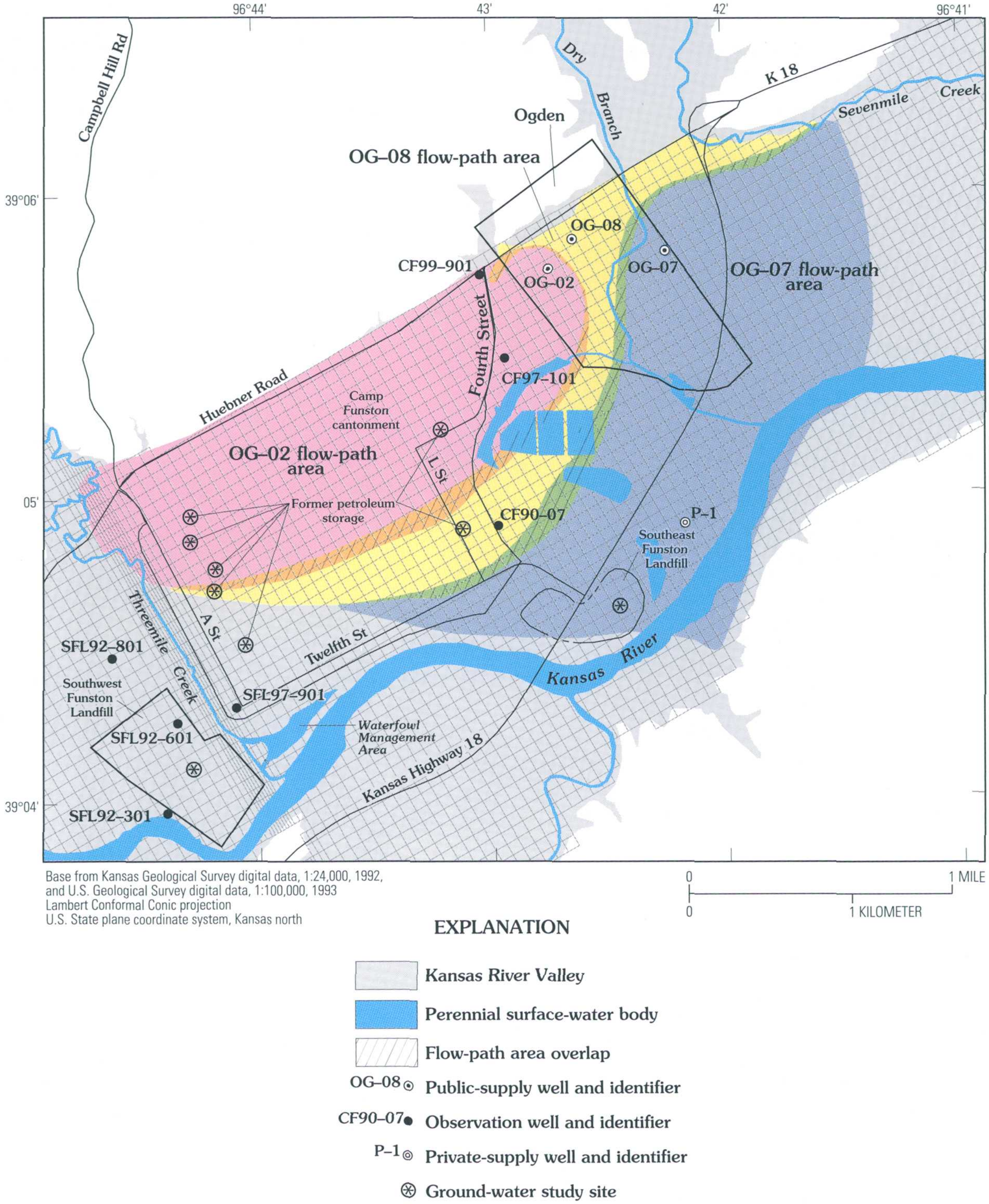


Figure 39. Outlines of simulated flow-path areas for particles backtracked from model cells corresponding to Ogden supply wells pumping at 10 times 1997 rates.

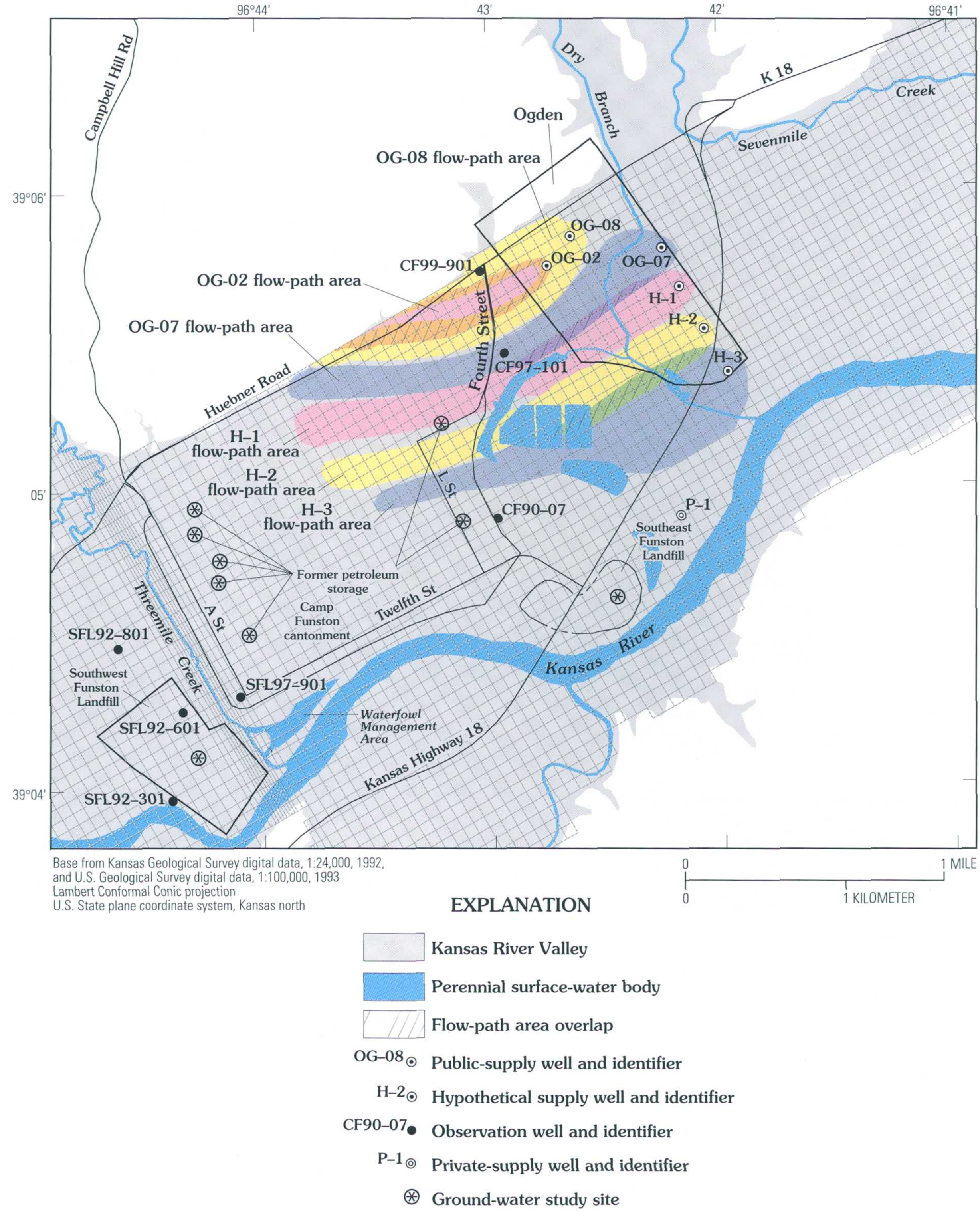
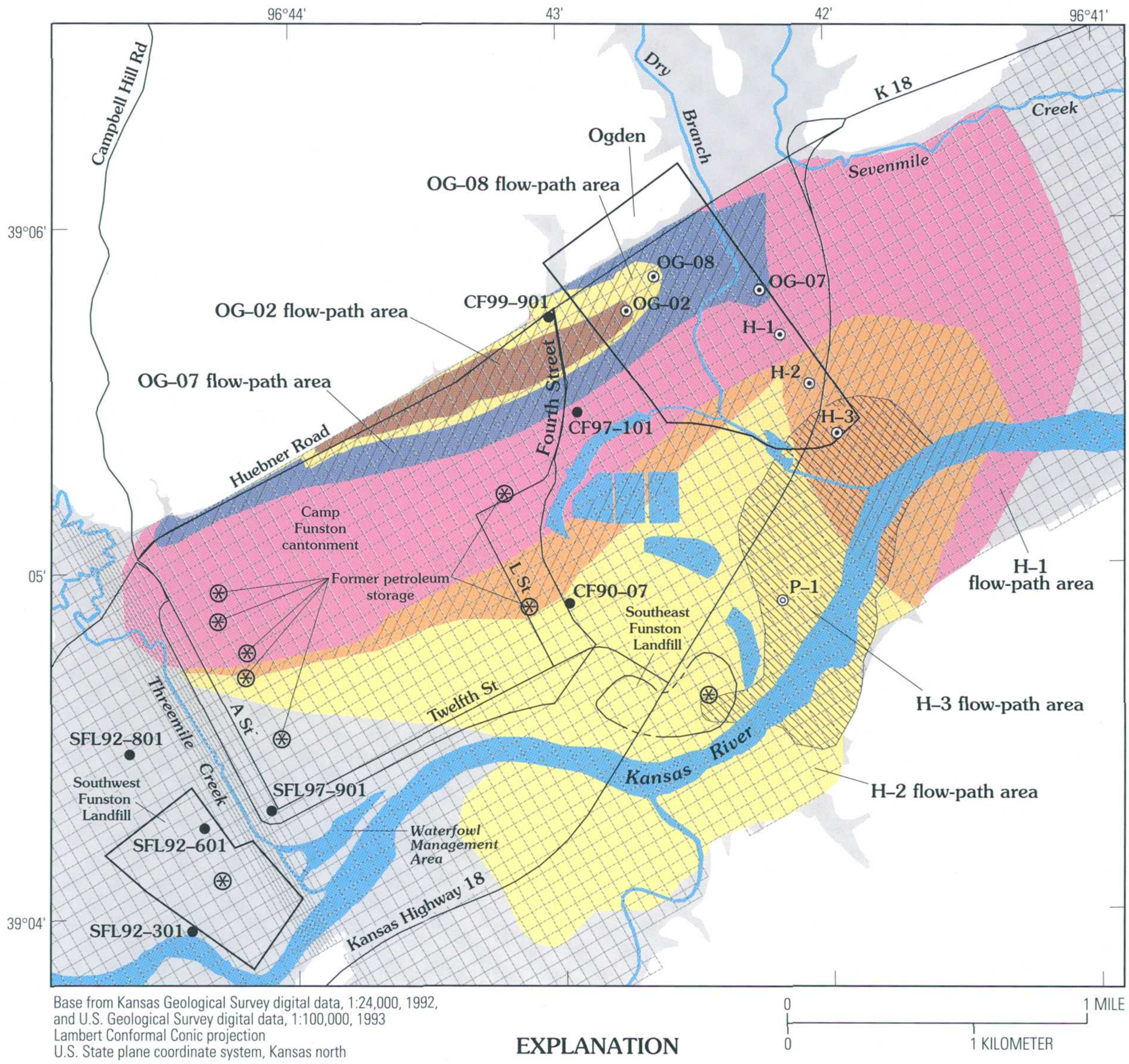


Figure 40. Outlines of simulated flow-path areas for particles backtracked from model cells corresponding to Ogden supply wells pumping at 1997 rates and hypothetical supply wells pumping at 100 gallons per minute.



Base from Kansas Geological Survey digital data, 1:24,000, 1992,
and U.S. Geological Survey digital data, 1:100,000, 1993
Lambert Conformal Conic projection
U.S. State plane coordinate system, Kansas north

EXPLANATION

- Kansas River Valley
- Perennial surface-water body
- Flow-path area overlap
- OG–08 ⊙ Public-supply well and identifier
- H–2 ⊙ Hypothetical supply well and identifier
- CF90–07 ● Observation well and identifier
- P–1 ◎ Private-supply well and identifier
- ⊛ Ground-water study site

Figure 41. Outlines of simulated flow-path areas for particles backtracked from model cells corresponding to Ogden supply wells pumping at 1997 rates and hypothetical supply wells pumping at 900 gallons per minute.

River to the southern valley wall, and extends into Clarks Creek Valley. Ground-water particles in the H–2 flow-path area originate at the water table along the flow-path area, at the Kansas River, and at Clarks Creek. This flow-path area intersects several ground-water study sites in the Camp Funston Area including the Southeast Funston Landfill. The H–3 flow-path area is the smallest of the hypothetical flow-path areas. It extends into the Camp Funston Area only at the Southeast Funston Landfill. Its small size probably is related to the well cell's close proximity to the Kansas River from which it obtains most of its water. Ground-water particles in the H–3 flow-path area originate at the water table within the flow-path area and at the Kansas River. In this simulation, some ground-water particles were derived from south of the Kansas River, indicating that the well-pumping stresses in this simulation were strong enough to induce ground-water flow under the Kansas River. However, none of the flow-path areas extend to the Southwest Funston Landfill.

These hypothetical simulations have shown how changes in pumpage rates and the introduction of hypothetical supply wells alter the shape and position of flow-path areas. Increasing the pumpage from Ogden's supply wells by as little as two times the 1997 pumping rates causes the OG–07 flow-path area to expand and intersect a ground-water study site where petroleum liquids formerly were stored (fig. 37). Increasing the pumpage from Ogden's supply wells by 5 and 10 times the 1997 pumping rates causes all three flow-path areas to intersect ground-water study sites. None of the hypothetical pumping simulations indicate that the flow-path areas intersect the Southwest Funston Landfill. Flow-path areas for hypothetical supply wells southeast of Ogden all extend into the Camp Funston Area. At the larger hypothetical well pumping rates (900 gal/min), the Ogden supply-well flow-path areas are compressed against the northern Kansas River Valley wall—away from ground-water study sites in the northern Camp Funston Area.

The hypothetical simulations indicate that further development of ground-water resources could degrade the quality of water pumped from Ogden's supply wells. Increasing the amount of ground water pumped from Ogden's wells over 1997 rates would cause flow-path areas for the wells to shift southward into the Camp Funston Area towards areas with contaminated ground water. Supply wells added south or southeast of Ogden would likely derive a major part of their water from the Camp Funston Area.

Although the hypothetical simulations indicate the general direction that ground-water contaminants would move under the simulated pumping and climatic conditions, the simulations do not indicate whether contaminants would actually reach pumping wells. The concentrations of many ground-water contaminants decrease over time as a result of naturally occurring processes such as chemical degradation, mechanical and chemical dispersion, and bacterial metabolic action. Thus, even if a flow-path area intersects an area of ground-water contamination, it does not necessarily indicate that the contaminant will reach the pumping well before naturally degrading to a concentration less than State or Federal water-quality standards. However, some contaminants are more persistent in the environment than others, and solute-transport studies of potential contaminants would help determine if a persistent ground-water contaminant has the potential to reach Ogden's wells before degradating to a concentration less than water-quality standards.

SUMMARY

Characterization of ground-water flow in the Kansas River Valley at the Fort Riley Military Reservation in northeast Kansas is important for understanding the movement of ground-water contaminants and the source of water pumped from wells. Geologic and hydrologic data characterization and a ground-water flow model were used to project ground-water flow paths in the Kansas River Valley at Fort Riley.

The study area is located in the Kansas River Valley between Junction City and Manhattan, Kansas, and includes the southernmost part of Fort Riley. The Kansas River Valley is characterized by landforms of low relief. Much of the river valley is used for crop production. The ground-water flow model area covers most of the study area. It extends from the Smoky Hill River down the valley to about 2.5 mi downstream from Ogden, Kansas.

Tasks identified to support ground-water flow characterization and simulation were to: (1) develop a GIS data base of map features, geology, hydrology, and ground-water quality; (2) use this information to characterize ground-water flow; and (3) develop a ground-water flow model.

Unconsolidated sedimentary deposits in the Kansas River Valley consist primarily of alluvium with some terrace deposits. The alluvium consists primarily of coarse-to-fine sand with layers of silt and clay. Alluvial sediment tends to be coarser near the bottom of the alluvium and finer near the top. Alluvium thickness ranges from less than 1 to about 75 ft. The alluvium is bounded by shale and limestone bedrock.

During 1961–90, mean annual precipitation at the Manhattan Municipal Airport was 33.82 in. and ranged from 15.52 to 51.48 in. During 1990–98, mean annual precipitation was 36.23 in. and ranged from 26.33 to 55.78 in. Streamflow in the Kansas River at Fort Riley (Henry Drive Bridge) reached an instantaneous peak of 87,600 ft^3/s on July 26, 1993, because of the large amount of precipitation that year. High stream stages in the Smoky Hill, Republican, and Kansas Rivers create backwater conditions in tributaries. Backwater conditions also can occur in the Smoky Hill and Republican Rivers.

The direction of ground-water flow generally is down the Kansas River Valley but can be quite variable near the Kansas River because of the effects of river stage on ground-water flow. Strontium-isotope data indicate a zone in the alluvial aquifer along the northern Kansas River Valley wall in the Camp Funston cantonment where ground water in the alluvium originates, in part, from isolated uplands north of the river valley. Hydrographs from wells in the Camp Funston cantonment also indicate that ground-water inflow from bedrock may be occurring.

Evaluation of Threemile Creek ground- and surface-water levels, seepage surveys along the creek, and ground-water-quality data indicate that the creek interacts with shallow ground water but probably does not prevent ground-water flow under the creek. The response of ground-water levels to changes in creek stage indicate that creek water can seep into the aquifer. Seepage surveys indicated that Threemile Creek both gained water from and lost water to the alluvial aquifer and that the creek was generally losing water to the aquifer between the Threemile Creek Upstream gaging station and the Waterfowl Management Area diversion and outlet structures. Ground-water-quality data show that volatile organic compounds consistently have been detected in most shallow and deep wells west of Threemile Creek but generally only in deep wells east of the creek. This is another indication that Threemile Creek water is interacting with ground water.

Pumping tests in and near the Kansas River Valley have indicated a median hydraulic conductivity of 730 ft/d and a median specific yield of 0.185. Vertical-to-horizontal hydraulic-conductivity ratio estimates were 0.12 to 0.48. Porosity was assumed to be equal to specific yield plus specific retention. Hydraulic boundaries in the Kansas River Valley are the Republican, Smoky Hill, and Kansas Rivers and the bedrock adjacent and subjacent to the alluvium.

Ground water in the study area is used primarily as a water supply for public, military, and irrigation purposes. Public and military water-supply use is year around, whereas irrigation use occurs during June through August. An estimated water budget for the alluvial aquifer shows that the major water-budget item is seepage to or from the rivers.

Ground-water flow was simulated using a modular, three-dimensional, finite-difference, ground-water flow model (MODFLOW). A transient model calibration simulation was conducted for September 7, 1997, through April 2, 1998. A steady-state simulation was used to prepare starting hydraulic-head values for the transient calibration simulation. The transient model was calibrated by comparisons of simulated results to observed water levels from wells, to observed mean daily water levels from wells equipped with continuous recorders, to measured seepage to and from Threemile Creek, to observed Kansas River and Threemile Creek stage, and to estimated ground-water flow budgets. Differences between observed and simulated hydraulic-head values generally were less than 1 ft. Observed and simulated Threemile Creek seepage values were reasonably similar. Differences between observed and simulated Kansas River and Threemile Creek stages were generally less than 0.5 ft. Simulated ground-water inflow and outflow budgets were similar. Sensitivity analyses indicated that the ground-water flow model is most sensitive to decreases in hydraulic conductivity and increases in precipitation recharge.

The calibrated model was used as the basis for nine 1-year transient simulations representing 1990–98. A steady-state model simulation representing January 1, 1990, conditions was used to provide starting hydraulic-head values for the transient historical simulation.

The MODPATH particle-tracking program was used to trace the paths of water particles forward and backward in time. In general, forward tracking showed that particles released near the Kansas River followed much more variable paths than particles near the valley wall. Increased path variability near the river indicates that, when near the river, ground-water contaminants could follow many possible paths, making consistent detection difficult in water from a single monitoring well. More distant from the river, contaminants likely would follow a narrower corridor. Particle paths in the Camp Funston Area indicated that during 1990–98 ground water from ground-water study sites in the Camp Funston Area likely would not have moved into the vicinity of the city of Ogden wells.

Backward particle tracking was used to estimate ground-water flow-path and recharge areas for wells. Backward tracking for 1990–98 indicated that the flow-path and recharge areas for the three Ogden supply wells lie near the northern valley wall, extend into the northern Camp Funston Area, and probably extend outside the model area into the bedrock of the valley wall.

The 1990–98 historical simulations were used as the basis for five hypothetical simulations. In three of the simulations, pumpage from Ogden's supply wells was increased by 2, 5, or 10 times the 1997 pumping rates. In the other two simulations, hypothetical supply wells were added southeast of Ogden and were pumped at 100 or 900 gal/min. These hypothetical simulations indicate that further development of ground-water resources could degrade the quality of water pumped from Ogden's supply wells. Although the hypothetical simulations indicate the general direction that ground-water contaminants would move under the simulated pumping and climatic conditions, the simulations do not indicate whether contaminants would actually reach pumping wells because the concentrations of many ground-water contaminants decrease over time as a result of naturally occurring processes such as chemical degradation, mechanical and chemical dispersion, and bacterial metabolic action.

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SUPPLEMENTAL INFORMATION

Table 12. Monitoring wells located at Fort Riley, Kansas

[NA, not applicable]

Well identifier (fig. 4)	Year drilled	Well cluster	Relative depth of well screen	Comments
		Camp Funston Area		
1044CF94–02	1994	NA	Shallow	Near former building 1044
1090CF92–04	1992	NA	Shallow	Near former building 1090
1190CF92–05	1992	NA	Shallow	Near former building 1190
1245CF92–02	1992	NA	Shallow	Near former building 1245
1245CF94–02	1994	NA	Shallow	Near former building 1245
1245CF94–06	1994	NA	Shallow	Near former building 1245
1539CF92–02	1992	NA	Shallow	Near former building 1539
1539CF95–05	1995	NA	Shallow	Near former building 1539
1637CF92–01	1992	NA	Shallow	Near former building 1637
1637CF94–03	1994	NA	Shallow	Near former building 1637
1637CF94–04	1994	NA	Shallow	Near former building 1637
1890CF92–03	1992	NA	Shallow	Near former building 1890
1890CF94–04	1994	NA	Shallow	Near former building 1890
1915CF92–03	1992	NA	Shallow	Near former building 1915
CF90–05	1990	CF90–05	Shallow	These three monitoring wells installed during Fort Riley-wide installation assessment of potential environmental concerns
CF90–06	1990	NA	Shallow	
CF90–07	1990	NA	Shallow	
CF97–101	1997	CF97–100	Shallow	
CF97–103	1997	CF97–100	Deep	
CF97–201	1997	NA	Shallow	
CF97–301	1997	NA	Shallow	
CF97–401	1997	NA	Shallow	
CF97–501	1997	NA	Shallow	
CF98–601	1998	NA	Shallow	
CF98–701	1998	NA	Shallow	
CF98–803	1998	CF90–05	Deep	This well is clustered with well CF90–05
WRCF93–01	1993	NA	Shallow	This well originally intended to supply water for vehicle wash facility but was never used for this purpose
		Main post		
MPL94–01	1994	NA	Shallow	
		Marshall Army Airfield		
FP93–07	1993	FP93–07	Shallow	

Table 12. Monitoring wells located at Fort Riley, Kansas—Continued

Well identifier (fig. 4)	Year drilled	Well cluster	Relative depth of well screen	Comments
		Marshall Army Airfield—Continued		
FP96–07C	1996	FP93–07	Deep	
FP96–20	1996	FP96–20	Shallow	
FP96–20C	1996	FP96–20	Deep	
FP96–21	1996	FP96–21	Shallow	
FP96–21B	1996	FP96–21	Intermediate	
FP96–21C	1996	FP96–21	Deep	
FP96–22	1996	NA	Shallow	
FP96–23	1996	FP96–23	Shallow	
FP96–23C	1996	FP96–23	Deep	
FP98–26	1998	NA	Shallow	
FP98–31	1998	FP98–31	Shallow	
FP98–31B	1998	FP98–31	Intermediate	
FP98–31C	1998	FP98–31	Deep	
		Southeast Funston Landfill		
SEFL94–01	1994	NA	Shallow	
SEFL94–02	1994	NA	Shallow	
SEFL94–03	1994	NA	Shallow	
		Southwest Funston Landfill		
SFL92–101	1992	SFL92–100	Shallow	
SFL92–102	1992	SFL92–100	Intermediate	
SFL92–103	1992	SFL92–100	Deep	
SFL92–201	1992	SFL92–200	Shallow	
SFL92–203	1992	SFL92–200	Deep	
SFL92–301	1992	SFL92–300	Shallow	
SFL92–302	1992	SFL92–300	Intermediate	
SFL92–303	1992	SFL92–300	Deep	
SFL92–401	1992	SFL92–400	Shallow	
SFL92–403	1992	SFL92–400	Deep	
SFL92–501	1992	SFL92–500	Shallow	
SFL92–502	1992	SFL92–500	Intermediate	
SFL92–503	1992	SFL92–500	Deep	
SFL92–601	1992	SFL92–600	Shallow	
SFL92–602	1992	SFL92–600	Intermediate	
SFL92–603	1992	SFL92–600	Deep	
SFL92–701	1992	SFL92–700	Shallow	
SFL92–703	1992	SFL92–700	Deep	
SFL92–801	1992	SFL92–800	Shallow	
SFL92–803	1992	SFL92–800	Deep	

Table 12. Monitoring wells located at Fort Riley, Kansas—Continued

Well identifier (fig. 4)	Year drilled	Well cluster	Relative depth of well screen	Comments
		Southwest Funston Landfill—Continued		
SFL94–01A	1994	SFL94–01	Shallow	
SFL94–01B	1994	SFL94–01	Deep	
SFL94–02A	1994	SFL94–02	Shallow	
SFL94–02B	1994	SFL94–02	Deep	
SFL94–03A	1994	SFL94–03	Shallow	
SFL94–03B	1994	SFL94–03	Deep	
SFL94–04A	1994	SFL94–04	Shallow	
SFL94–04B	1994	SFL94–04	Deep	
SFL94–05A	1994	SFL94–05	Shallow	
SFL94–05B	1994	SFL94–05	Deep	
SFL94–06A	1994	SFL94–06	Shallow	
SFL94–06B	1994	SFL94–06	Deep	
SFL97-901	1997	SFL97-900	Shallow	
SFL97-903	1997	SFL97-900	Deep	

Table 13. Ground-water-level observation wells and piezometers located at Fort Riley, Kansas

Well identifier (fig. 4)	Year drilled	Relative depth of well	Comments
		Camp Forsyth	
USGS–05	1992	Shallow	Observation wells installed by U.S. Geological Survey
USGS–06	1992	Shallow	
		Marshall Army Airfield	
FP96–13PZ	1996	Shallow	
FP96–15PZ	1996	Shallow	
		Southwest Funston Landfill	
MW–01	1983	Full thickness of aquifer	SFL closure well
MW–02	1983	Full thickness of aquifer	SFL closure well
MW–03	1983	Full thickness of aquifer	SFL closure well
MW–04	1983	Full thickness of aquifer	SFL closure well
MW–05	1983	Shallow	SFL closure well
MW–06	1983	Full thickness of aquifer	SFL closure well
OB97–13PZ–1	1997	Next to deepest	Nest of five piezometers at this location
PZ–01	1993	Shallow	
TMCD–PZ	1997	Shallow	
TMCM–PZ	1997	Shallow	
TMCU–PZ	1997	Shallow	
WMA–PZ	1997	Shallow	

Table 14. Ground-water-level observation wells not located at Fort Riley but in study area

Well identifier (fig. 4)	Water use	Comments
IR–06	Agriculture	
IR–07	Agriculture	
IR–10	Agriculture	
IR–16	Agriculture	
IR–17	Agriculture	
IR–19	Agriculture	
IR–20	Agriculture	
IR–29	Agriculture	
IR–51	Agriculture	
IR–52	Agriculture	
IR–53	Agriculture	
JCOBS–18	Not used	Observation well installed by Junction City
USGS–07	Not used	Observation well installed by U.S. Geological Survey

Table 15. Wells used to supply water for Fort Riley and public use in study area

Well identifier (fig. 4)	Comment
Fort Riley	
FR–01PLG	Well plugged in 1990
FR–02PLG	Well plugged in 1990
FR–03PLG	Well plugged in 1990
FR–04PLG	Well plugged in 1990
FR–3078	
FR–3198	
FR–3200	
FR–3201	
FR–3202	
FR–3203	
FR–3204	
FR–3205	
FR–801	Well serves as an emergency supply well for Marshall Army Airfield
Grandview Plaza	
GP–01	Use of wells discontinued after 1990
GP–02	
Morris County Rural Water District	
MC–01	Wells located in Clarks Creek Valley
MC–02	
MC–03	
Ogden	
OG–02	Wells used to supply water to Ogden and to a rural water district
OG–07	
OG–08	

Table 16. Surface-water data-collection sites in study area

Site name (fig. 2)	Comments
Kansas River at Fort Riley (Henry Drive Bridge)	Continuous-record stream-gaging station
Kansas River near Ogden (Highway 18 Bridge)	Wire-weight gage only
Republican River at Junction City well field	Continuous-record stream-gaging station
Republican River below Milford Dam	Continuous-record stream-gaging station
Smoky Hill River at Grandview Plaza	Wire-weight gage only
KSR–1 KSR–2 KSR–3	Kansas River sampling sites
RPR–1	Republican River sampling site
SW98–01 SW98–02 SW98–03A	Steel fence posts set at edge of oxbow lakes, Camp Funston Area
Threemile Creek diversion structure	Measuring point is chisel mark on sheet piling
Waterfowl Management Area outlet structure	Measuring point is chiseled square in concrete on top of structure
TMC–1 TMC–2 TMC–3	Threemile Creek sampling sites
TMCD TMCM TMCU	Continuous-record stream-gaging stations located along Threemile Creek, Camp Funston Area (stage only)

Table 17. Inclusive graphic standard deviation of alluvial-sediment grain size and sorting classification of sand-size and sand-silt-clay-size material for sediment samples from well borings at Southwest Funston Landfill and Marshall Army Airfield

[Sediment grain-size data from LAW Engineering and Environmental Services (1994) and Brian Manz (Burns & McDonnell, written commun., January 26, 2000)]

Well boring from which sample was obtained (fig. 4)	Sample depth (feet below land surface)	Inclusive graphic standard deviation[1] ($^2\Phi$; equivalent millimeter size in parentheses)	Sorting classification
		Sand-size material	
D83–502	20–24	1.02 (2.04)	Poorly sorted
	24–26	.84 (1.79)	Moderately sorted
	26–64	1.30 (2.48)	Poorly sorted
D83–116	22–28	.83 (1.78)	Moderately sorted
	28–30	1.04 (2.05)	Poorly sorted
	32–34	1.07 (2.10)	Poorly sorted
	36–38	1.60 (3.03)	Poorly sorted
	38–48	1.52 (2.91)	Poorly sorted
	50–54	1.48 (2.80)	Poorly sorted
	56–64	1.47 (2.68)	Poorly sorted
FP96–18	8–10	.80 (1.74)	Moderately sorted
	12–14	.92 (1.89)	Moderately sorted
	14–16	.69 (1.61)	Moderately well sorted
FP96–20C	20	1.20 (2.29)	Poorly sorted
	25	.88 (1.84)	Moderately sorted
	35	1.47 (2.77)	Poorly sorted
	45	1.65 (3.14)	Poorly sorted
	65	.77 (1.70)	Moderately sorted
FP96–21	16–18	1.09 (2.13)	Poorly sorted
	20–22	.93 (1.91)	Moderately sorted
	23–25	1.17 (2.25)	Poorly sorted
FP96–23	20	1.02 (2.03)	Poorly sorted
	25	.98 (1.97)	Moderately sorted
	30	1.54 (2.90)	Poorly sorted
	35	1.52 (2.87)	Poorly sorted
	45	2.02 (4.07)	Very poorly sorted
	65	1.80 (3.49)	Poorly sorted
FP96–26	20	.72 (1.64)	Moderately sorted
	25	1.15 (2.21)	Poorly sorted
	30	.72 (1.65)	Moderately sorted
	35	1.50 (2.82)	Poorly sorted
	45	.90 (1.86)	Moderately sorted
	65	1.40 (2.65)	Poorly sorted

Table 17. Inclusive graphic standard deviation of alluvial-sediment grain size and sorting classification of sand-size and sand-silt-clay-size material for sediment samples from well borings at Southwest Funston Landfill and Marshall Army Airfield—Continued

Well boring from which sample was obtained (fig. 4)	Sample depth (feet below land surface)	Inclusive graphic standard deviation[1] ([2]Φ; equivalent millimeter size in parentheses)	Sorting classification
		Sand-silt-clay-size material	
FP96–19	4–6	3.124 (8.72)	Very poorly sorted
FP96–20	30	2.186 (4.55)	Very poorly sorted
SFL92–103	36–38	1.832 (3.56)	Poorly sorted
	52–54	1.486 (2.80)	Poorly sorted
SFL92–203	14–16	2.421 (5.36)	Very poorly sorted
	58–60	2.404 (5.29)	Very poorly sorted
SFL92–303	20–22	.974 (1.96)	Moderately sorted
	50–54	2.956 (7.76)	Very poorly sorted
SFL92–403	10–12	1.277 (2.42)	Poorly sorted
	32–34	1.939 (3.83)	Poorly sorted
SFL92–503	22–24	1.568 (2.97)	Poorly sorted
	30–32	1.533 (2.89)	Poorly sorted
SFL92–603	16–18	1.742 (3.34)	Poorly sorted
	58–60	1.536 (2.90)	Poorly sorted
SFL92–703	14–22	1.502 (2.83)	Poorly sorted
	50–52	1.674 (3.19)	Poorly sorted
SFL92–803	depth unknown	1.698 (3.24)	Poorly sorted
	58–60	1.755 (3.37)	Poorly sorted

[1] Inclusive graphic standard deviation (IGSD) (Folk, 1974) is a measure of the uniformity of grain sizes (sorting) in a sample. Smaller IGSD values indicate a narrower range of grain sizes and better sorting in a sediment sample. IGSD is computed as

$$\frac{(\Phi 84 - \Phi 16)}{4} - \frac{(\Phi 95 - \Phi 5)}{6.6}$$

, where $\Phi 5$, $\Phi 16$, $\Phi 84$, and $\Phi 95$ are the Φ values for which 5, 16, 84, and 95 percent of the grains are smaller, respectively. Folk's (1974) sorting classification, expressed in Φ units, is: less than 0.35, very well sorted; 0.35–0.50, well sorted; 0.50–0.70, moderately well sorted; 0.70–1.0, moderately sorted; 1.0–2.0, poorly sorted; 2.0–4.0, very poorly sorted; greater than 4.0, extremely poorly sorted.

[2] Phi (Φ) units are computed as Φ=-$\log_2$(d), where $\log_2$() is the base-2 logarithm function and d is grain diameter, in millimeters.

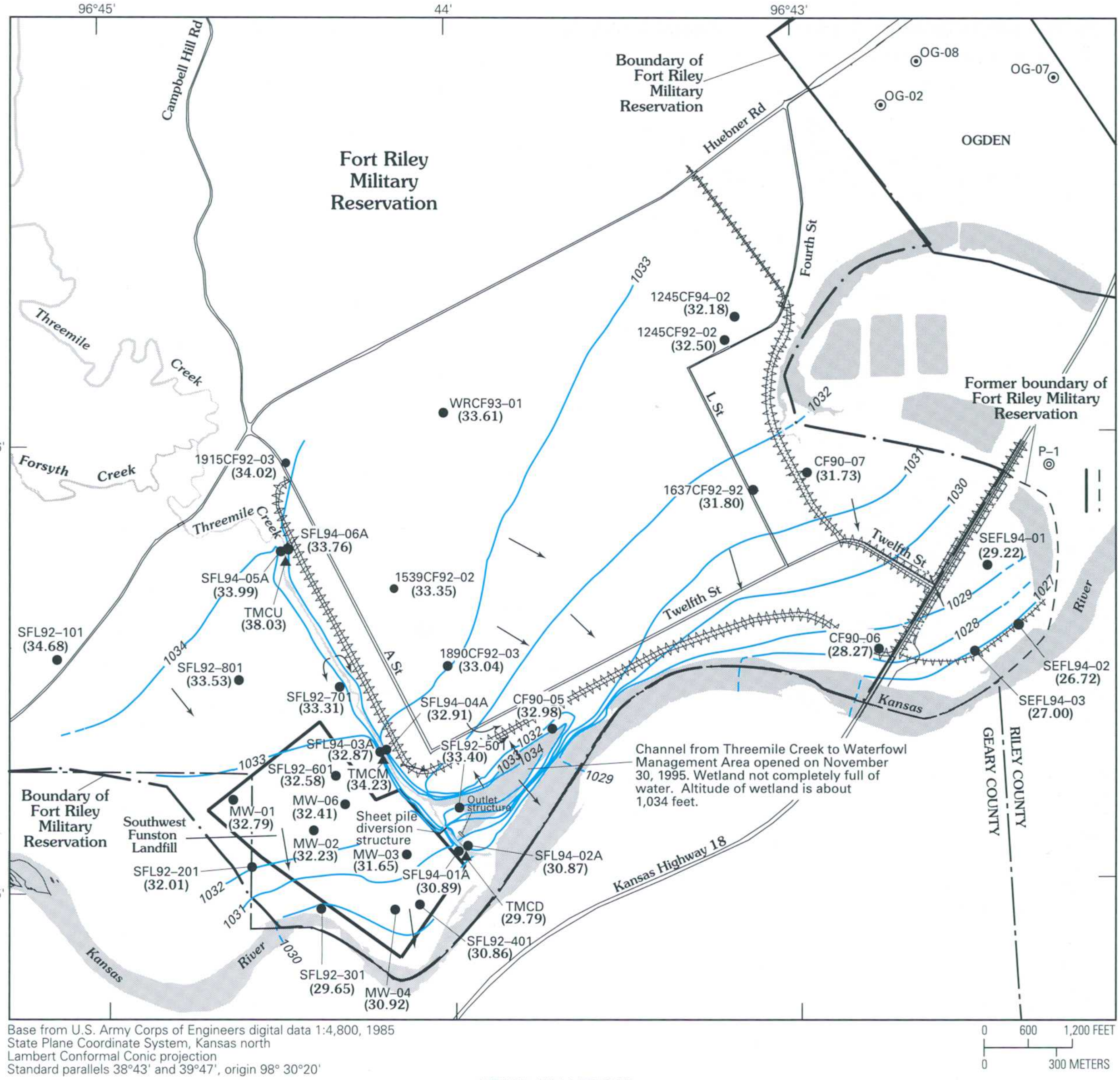
Table 18. Stream parameter values used in calibrated transient model historical simulations, 1990–98

Stream	Stream-segment number(s) for model (fig. 26)	Channel slope (foot per foot)	Streambed roughness (Manning's roughness coefficient)	Streambed width (feet)	Streambed vertical hydraulic conductivity (feet per day)
Republican River	1	0.0004302	0.035	variable: 190–258	60
Smoky Hill River	2	.0004302	.035	variable: 149–365	60
Kansas River	3, 4, 22, 23, 24	.0004302	.035	variable: 234–689	60
Forsyth Creek	10	.0026169	.035	20	.05
Threemile Creek (upstream from Forsyth Creek)	6	.0010220	.035	20	.05
Threemile Creek (Forsyth Creek to Waterfowl Management Area inlet channel)	11	[1].0011170 [2].0001580	[1].035 [2].035	[1]20 [2]20	[1]1.0 [2].05
Threemile Creek (Waterfowl Management Area inlet channel to diversion structure)	12	[1].0011170 [2].0011309	[1].035 [2].035	[1]20 [2]20	[1]1.0 [2].05
Threemile Creek diversion structure	14	[1].0011170 [2].1692569	[1].035 [2].035	[1]20 [2]20	[1]1.0 [2].05
Threemile Creek (diversion structure to Waterfowl management Area outlet channel)	16	[1].0011170 [2].0046070	[1].035 [2].035	[1]20 [2]20	[1]1.0 [2]1.0
Threemile Creek (Waterfowl Management Area outlet channel to Kansas River)	18	[1].0011170 [2].0005818	[1].035 [2].035	[1]20 [2]20	[1]1.0 [2]1.0
Waterfowl Management Area inlet channel and pond[3]	13	[2].0000234	[2].035	[2]20	[2].5
Waterfowl Management Area outlet channel[3]	17	[2].0279660	[2].035	[2]20	[2].5
Clarks Creek	8	.0004022	.035	20	.5
Unnamed tributary to Dry Branch	9	.0000361	.035	20	.05
Unnamed tributary to Dry Branch	15	.0003037	.035	20	.05
Unnamed tributary to Dry Branch	19	.0000864	.035	20	.05
Dry Branch	5	.0028847	.035	20	.05
Dry Branch	20	.0000916	.035	20	.05
Dry Branch	21	.0017876	.035	20	.05
Sevenmile Creek	7	.0011191	.035	20	.05

[1]Value used for 1990–95 simulations.

[2]Value used for 1996–98 simulations.

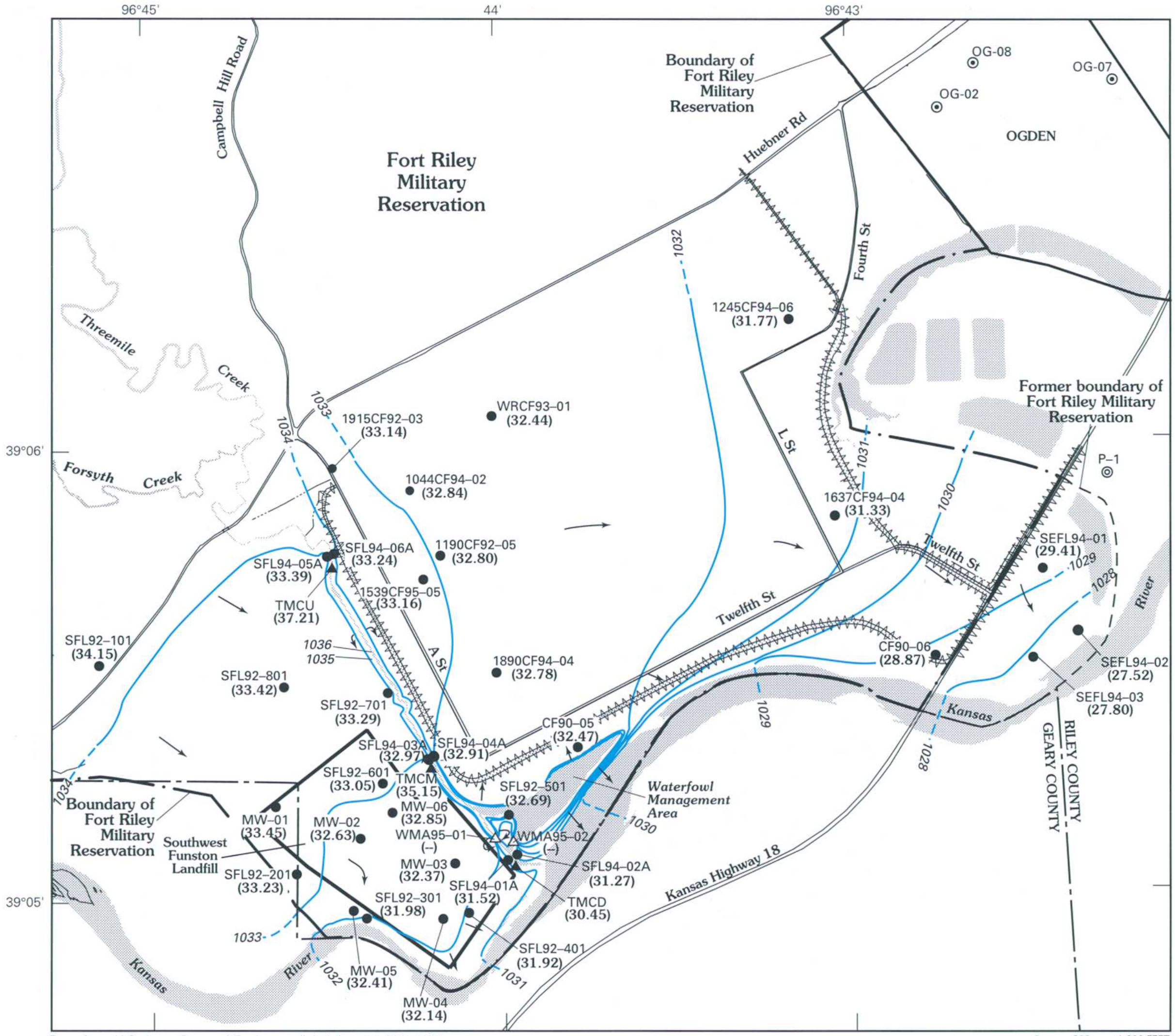
[3]Waterfowl Management Area inlet channel, pond, and outlet channel not simulated for 1990–95.



EXPLANATION

- Perennial surface-water body
- 1033 — Potentiometric contour—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- Levee
- Approximate direction of ground-water flow
- P-1 Private-supply well and identifier
- OG-07 Municipal supply well and identifier
- SFL94-02A (30.87) Observation well and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCU (38.03) Stream-gaging station and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level

Figure 42. Water-table surface in Camp Funston Area, Fort Riley, Kansas, December 10, 1995.

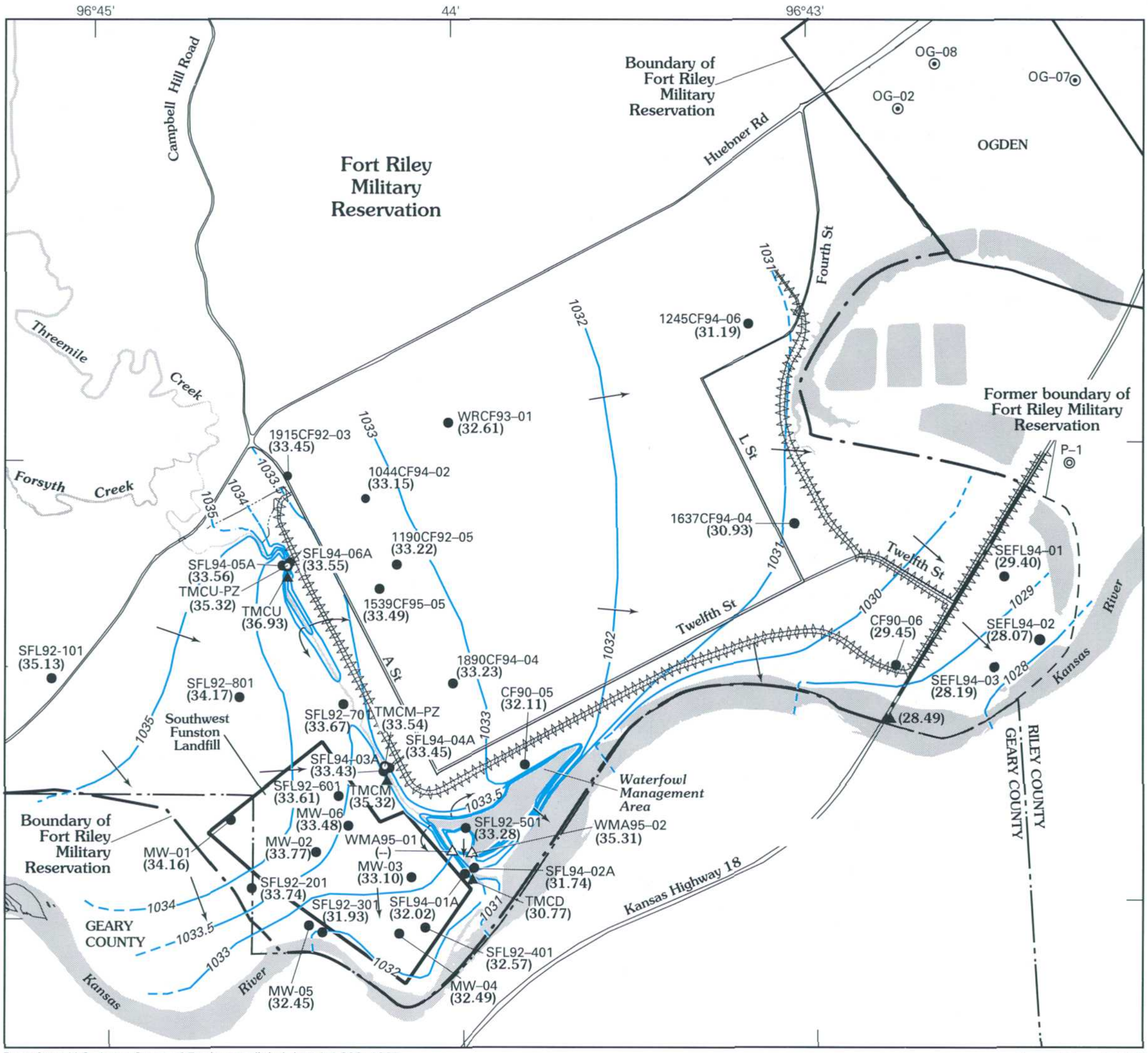


Base from U.S. Army Corps of Engineers digital data 1:4,800, 1985
State Plane Coordinate System, Kansas north
Lambert Conformal Conic projection
Standard parallels 38°43' and 39°47', origin 98° 30'20'

EXPLANATION

- Perennial surface-water body
- 1033 Potentiometric contour—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- Levee
- Approximate direction of ground-water flow
- P-1 Private-supply well and identifier
- OG-07 Municipal supply well and identifier
- SFL94-02A (31.27) Observation well and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCU (37.21) Stream-gaging station and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- WMA95-02 (–) Surface-water-measurement site—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- (–) No measurement

Figure 43. Water-table surface in Camp Funston Area, Fort Riley, Kansas, May 20, 1996.



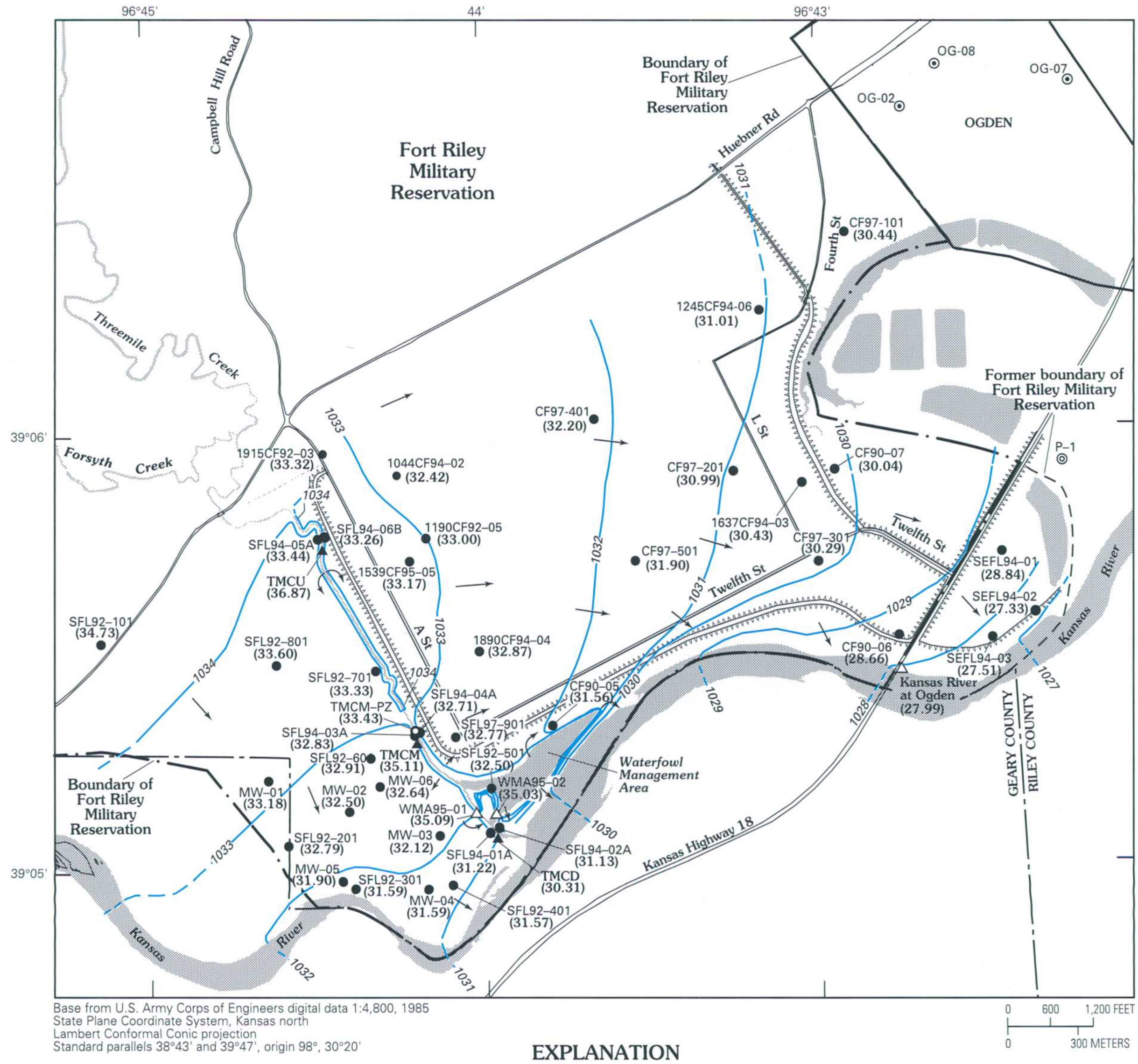
Base from U.S. Army Corps of Engineers digital data 1:4,800, 1985
State Plane Coordinate System, Kansas north
Lambert Conformal Conic projection
Standard parallels 38°43' and 39°47', origin 98° 30°20'

0 600 1,200 FEET
0 300 METERS

EXPLANATION

- Perennial surface-water body
- 1028 — Potentiometric contour—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- Levee
- Approximate direction of ground-water flow
- P–1 Private-supply well and identifier
- OG–07 Municipal supply well and identifier
- SFL94–01A (32.02) Observation well and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCU (30.77) Stream-gaging station and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- WMA95–02 (35.31) Surface-water-measurement site and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- (–) No measurement

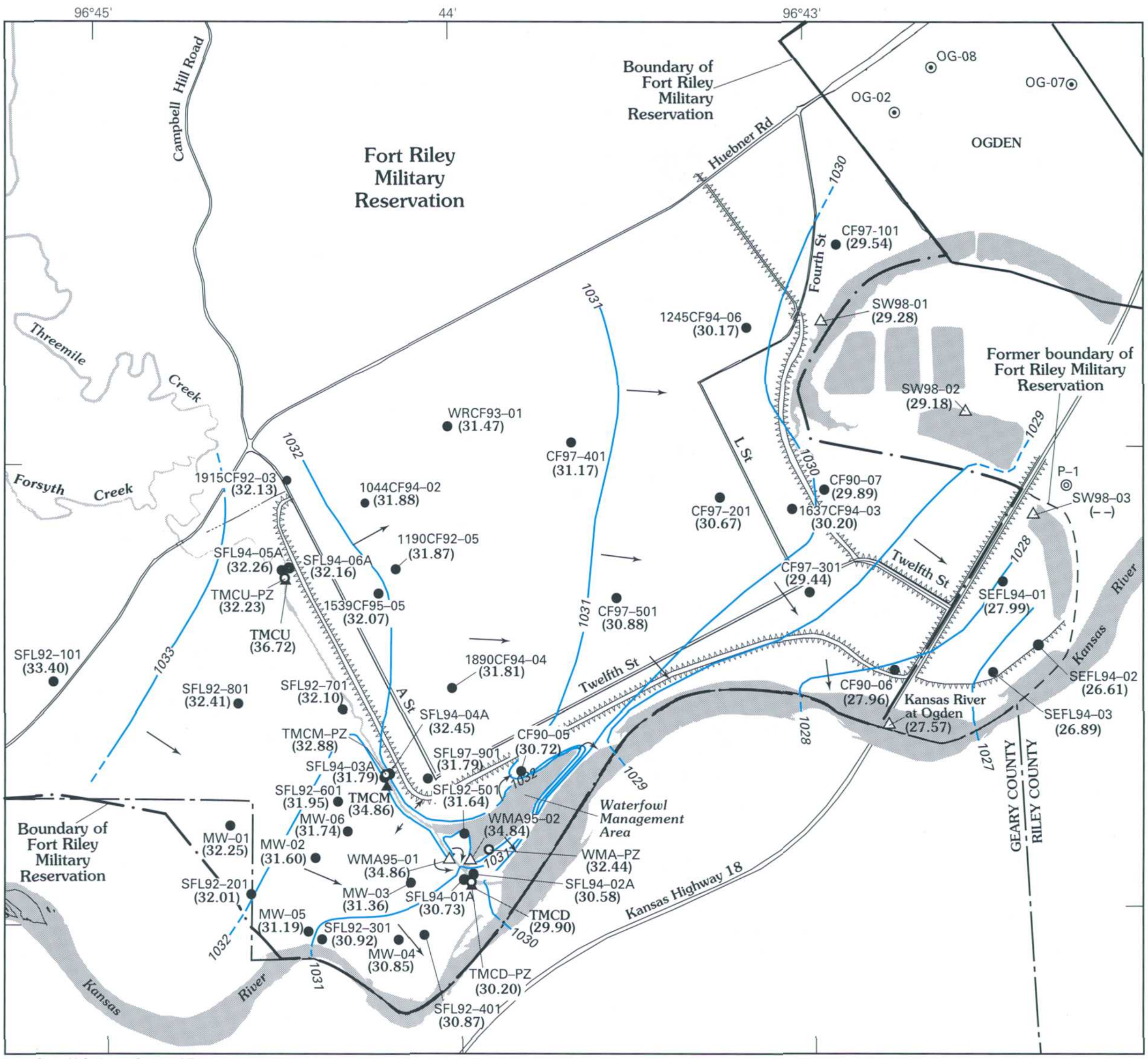
Figure 44. Water-table surface in Camp Funston Area, Fort Riley, Kansas, November 4, 1996.



EXPLANATION

- Perennial surface-water body
- **Potentiometric contour**—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- Levee
- Approximate direction of ground-water flow
- P–1 Private-supply well and identifier
- OG–07 Municipal supply well and identifier
- SFL92–101 (34.73) **Observation well and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCD (30.31) **Stream-gaging station and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- WMA95–01 (35.09) **Surface-water-measurement site and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCM-PZ (33.43) **Piezometer and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level

Figure 45. Water-table surface in Camp Funston Area, Fort Riley, Kansas, June 23–24, 1997.



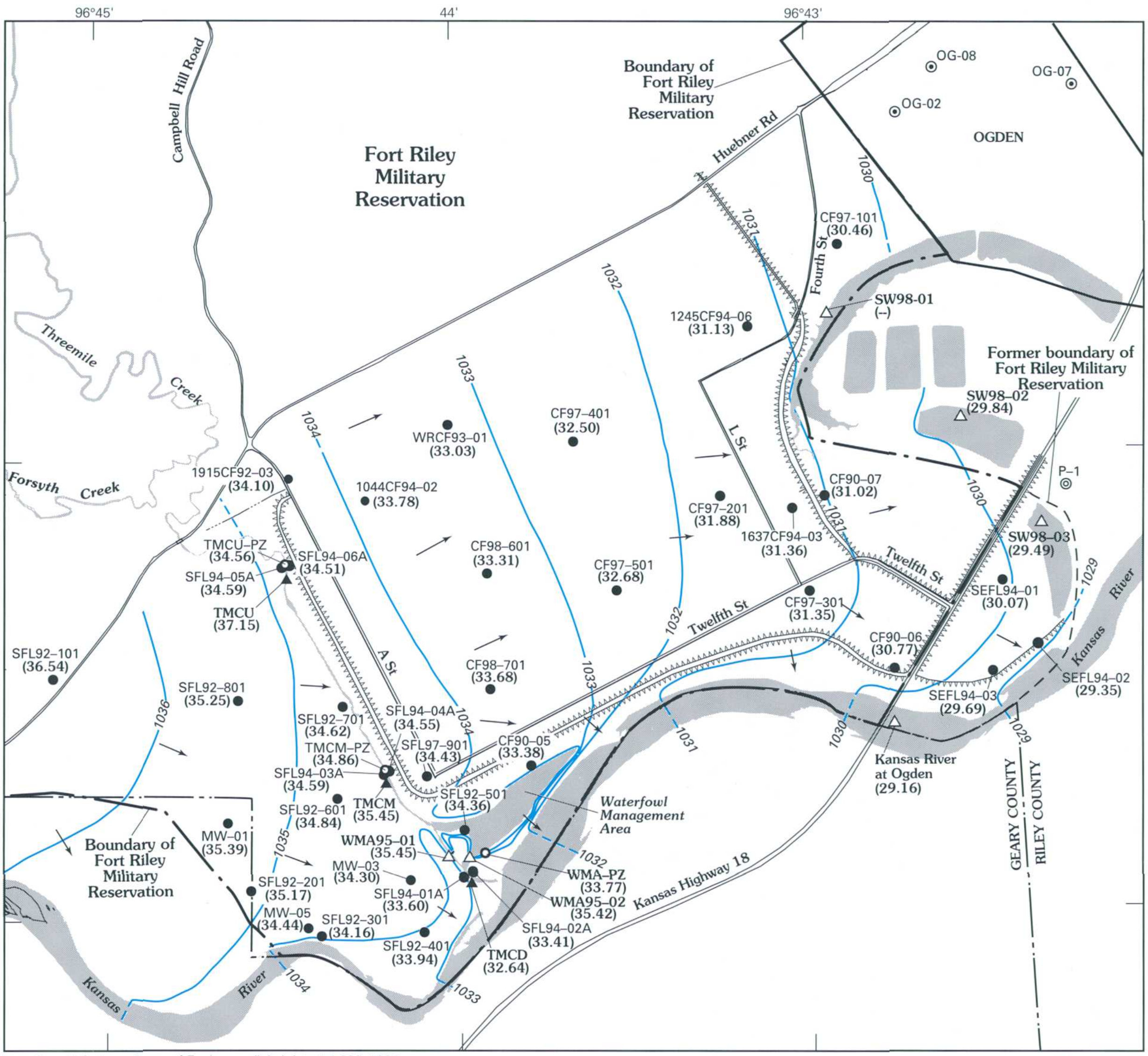
Base from U.S. Army Corps of Engineers digital data 1:4,800, 1985
State Plane Coordinate System, Kansas north
Lambert Conformal Conic projection
Standard parallels 38°43' and 39°47', origin 98°, 30°20'

0 600 1,200 FEET
0 300 METERS

EXPLANATION

- Perennial surface-water body
- 1033 — **Potentiometric contour**—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- **Levee**
- **Approximate direction of ground-water flow**
- P-1 **Private-supply well and identifier**
- OG-07 **Municipal supply well and identifier**
- SFL92-101 (33.40) **Observation well and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCD (29.90) **Stream-gaging station and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- SW98-02 (29.18) **Surface-water-measurement site and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- WMA-PZ (32.44) **Piezometer and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- (- -) **No measurement**

Figure 46. Water-table surface in Camp Funston Area, Fort Riley, Kansas, November 10, 1997.

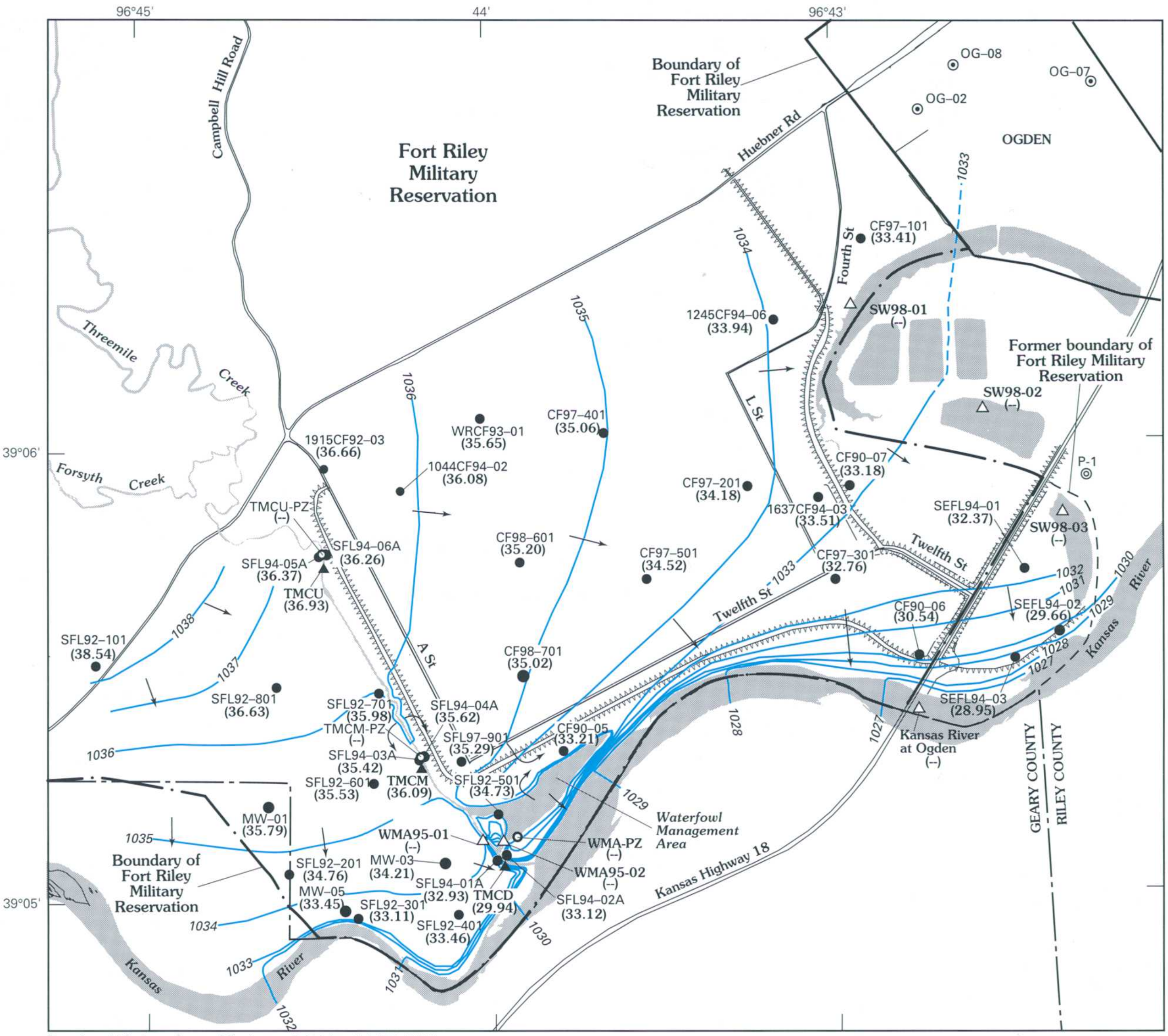


Base from U.S. Army Corps of Engineers digital data 1:4,800, 1985
State Plane Coordinate System, Kansas north
Lambert Conformal Conic projection
Standard parallels 38°43' and 39°47', origin 98°, 30°20'

EXPLANATION

- **Perennial surface-water body**
- 1033 — **Potentiometric contour**—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- **Levee**
- **Approximate direction of ground-water flow**
- P-1 **Private-supply well and identifier**
- OG-07 **Municipal supply well and identifier**
- SFL92-101 (36.54) **Observation well and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCM (35.45) **Stream-gaging station and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- SW98-02 (29.84) **Surface-water-measurement site and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCU-PZ (34.56) **Piezometer and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level

Figure 47. Water-table surface in Camp Funston Area, Fort Riley, Kansas, May 12, 1998.



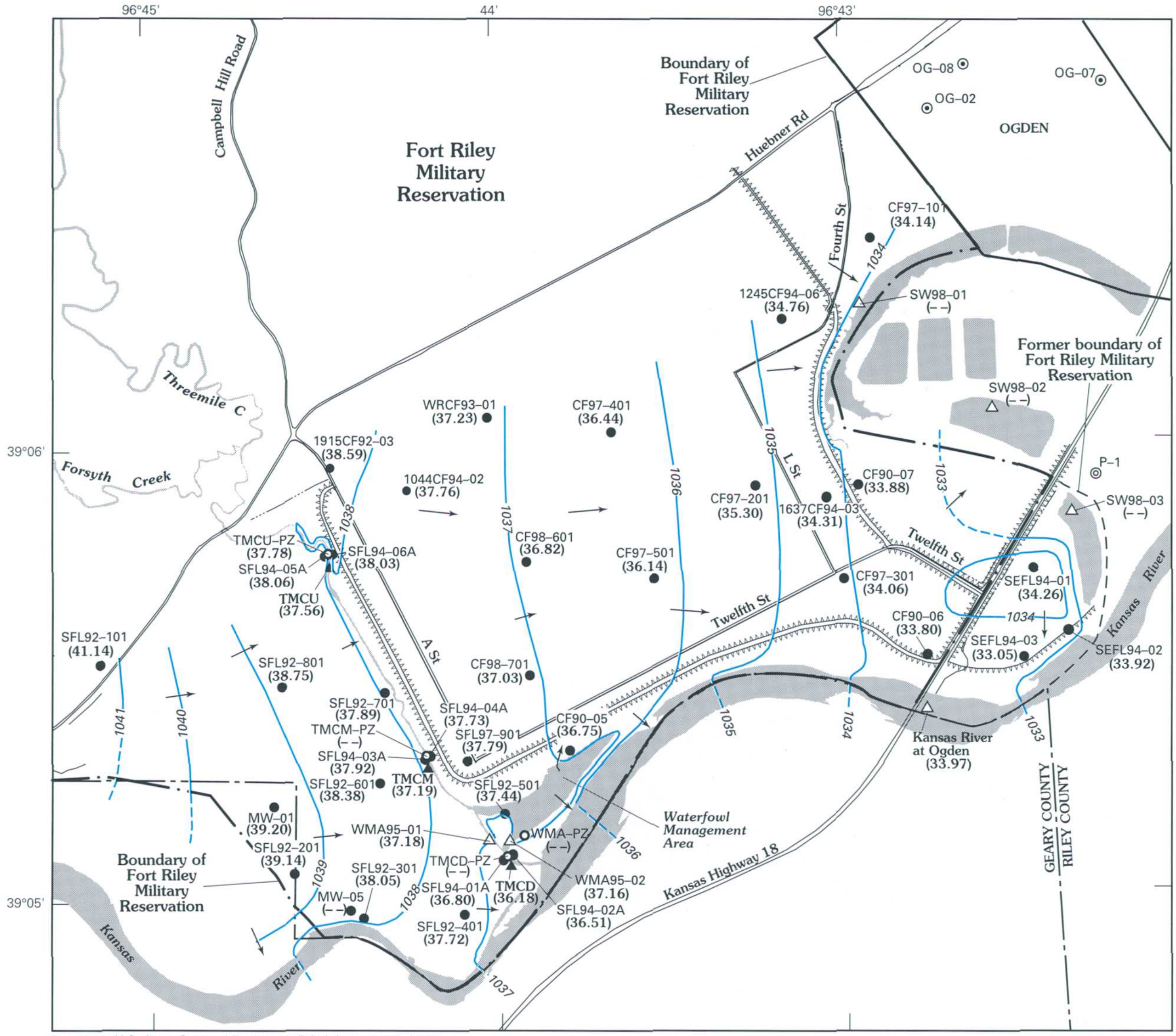
Base from U.S. Army Corps of Engineers digital data 1:4,800, 1985
State Plane Coordinate System, Kansas north
Lambert Conformal Conic projection
Standard parallels 38°43' and 39°47', origin 98°, 30°20'

0 600 1,200 FEET
0 300 METERS

EXPLANATION

- Perennial surface-water body
- 1033 — Potentiometric contour—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- Levee
- Approximate direction of ground-water flow
- P-1 ◎ **Private-supply well and identifier**
- OG-07 ◎ **Municipal supply well and identifier**
- SFL92-601 (35.53) ● **Observation well and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCM (36.09) ▲ **Stream-gaging station and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- SW98-02 (--) △ **Surface-water-measurement site and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCU-PZ (--) o **Piezometer and identifier**—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- (--) No measurement

Figure 48. Water-table surface in Camp Funston Area, Fort Riley, Kansas, December 1, 1998.



Base from U.S. Army Corps of Engineers digital data 1:4,800, 1985
State Plane Coordinate System, Kansas north
Lambert Conformal Conic projection
Standard parallels 38°43' and 39°47', origin 98°30'20"

EXPLANATION

- Perennial surface-water body
- 1033 — — Potentiometric contour—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level
- Levee
- Approximate direction of ground-water flow
- P-1 ◎ Private supply well and identifier
- OG-07 ◎ Municipal supply well and identifier
- SEFL94-02 (33.92) ● Observation well and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCM (37.19) ▲ Stream-gaging station and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- WMA95-02 (37.16) △ Surface-water-measurement site and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- TMCU-PZ (37.78) o Piezometer and identifier—Number in parentheses ( ) plus 1,000 is altitude of water surface, in feet. Datum is sea level
- (- -) No measurement

Figure 49. Water-table surface in Camp Funston Area, Fort Riley, Kansas, June 2, 1999.

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