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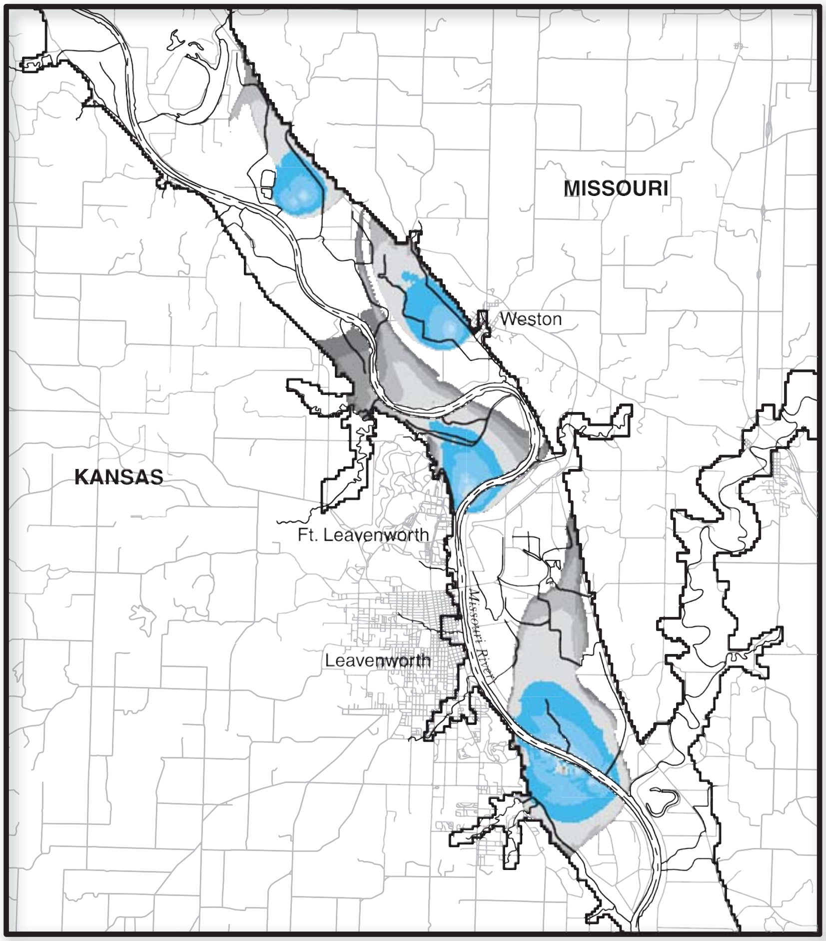

Scientific Investigations Report 2004–5215

U.S. Department of the Interior
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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
meter per day (m/d)	3.281	foot per day (ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
cubic meter per day per square kilometer [(m^3/d)/km^2]	684.28	gallon per day per square mile [(gal/d)/mi^2]
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
cubic meter per day per square kilometer [(m^3/d)/km^2]	0.0006844	million gallons per day per square mile [(Mga/d)/mi^2]
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Altitude, as used in this report, refers to distance above the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Simulation of Ground-Water Flow, Contributing Recharge Areas, and Ground-Water Travel Time in the Missouri River Alluvial Aquifer near Ft. Leavenworth, Kansas

By Brian P. Kelly

Abstract

The Missouri River alluvial aquifer near Ft. Leavenworth, Kansas, supplies all or part of the drinking water for Ft. Leavenworth; Leavenworth, Kansas; Weston, Missouri; and cooling water for the Kansas City Power and Light, Iatan Power Plant. Ground water at three sites within the alluvial aquifer near the Ft. Leavenworth well field is contaminated with trace metals and organic compounds and concerns have been raised about the potential contamination of drinking-water supplies. In 2001, the U.S. Geological Survey, U.S. Army Corps of Engineers, and the U.S. Army began a study of ground-water flow in the Missouri River alluvial aquifer near Ft. Leavenworth.

Hydrogeologic data from 173 locations in the study area was used to construct a ground-water flow model (MODFLOW-2000) and particle-tracking program (MODPATH) to determine the direction and travel time of ground-water flow and contributing recharge areas for water-supply well fields within the alluvial aquifer. The modeled area is 28.6 kilometers by 32.6 kilometers and contains the entire study area. The model uses a uniform grid size of 100 meters by 100 meters and contains 372,944 cells in 4 layers, 286 columns, and 326 rows. The model represents the alluvial aquifer using four layers of variable thickness with no intervening confining layers.

The model was calibrated to both quasi-steady-state and transient hydraulic head data collected during the study and ground-water flow was simulated for five well-pumping/river-stage scenarios. The model accuracy was calculated using the root mean square error between actual measurements of hydraulic head and model generated hydraulic head at the end of each model run. The accepted error for the model calibrations were below the maximum measurement errors. The error for the quasi-steady-state calibration was 0.82 meter; for the transient calibration it was 0.33 meter.

The shape, size, and ground-water travel time within the contributing recharge area for each well or well field is affected by changes in river stage and pumping rates and by the location of the well or well field with respect to the major rivers, alluvial valley walls, and other pumping wells. The shapes of the simulated contributing recharge areas for the well fields in the study area are elongated in the upstream direction for all well-pumping/river-stage scenarios. The capture of ground water by the pumping wells as it moved downgradient toward the Missouri River caused the long up-valley extent of the contributing recharge areas. Recharge to the Iatan and Weston well fields primarily is from precipitation and surface runoff from the surrounding uplands because the contributing recharge area does not intersect the Missouri River for any well-pumping/river-stage scenarios. Recharge to the Leavenworth and Ft. Leavenworth well fields is from precipitation, surface runoff from the surrounding uplands, and the Missouri River because the contributing recharge area intersects these boundaries for all well-pumping/river-stage scenarios.

Particle tracking analysis indicated ground water from the three contaminated sites was captured by the Ft. Leavenworth well field for all well-pumping/river-stage scenarios. Ground-water travel times to the Ft. Leavenworth well field for average well-pumping/river-stage scenario ranged from about 33 years for the closest contamination site to about 71 years for the farthest contamination site. Ground-water flow was induced below the Missouri River by the Ft. Leavenworth and Leavenworth well fields for all well-pumping/river-stage scenarios.

Introduction

The Missouri River alluvial aquifer in the Ft. Leavenworth, Kansas, area supplies all or part of the drinking water for Ft. Leavenworth, Kansas; Leavenworth, Kansas; and Weston, Missouri. Ft. Leavenworth is located in Leavenworth County, and occupies 5,634 acres on the west bank of the Missouri River (fig. 1). Currently (2003), Ft. Leavenworth has five operating water-supply wells in the Weston Bend meander loop of the Missouri River flood plain that pump 1.5 million gallons per day and are a reliable source of drinking water. Cooling water is supplied for the Kansas City Power and Light, Iatan Power Plant from the Iatan well field.

The United States Army Installation Restoration Program (IRP) under the Defense Environmental Restoration Program is for investigation and cleanup of hazardous waste at Department of Defense sites. Previous IRP investigations have discovered contaminated sites (Solid Waste Management Units) at Ft. Leavenworth (Ecology and Environment, Inc., 2000). Each Solid Waste Management Unit is referred to as a Ft. Leaven-

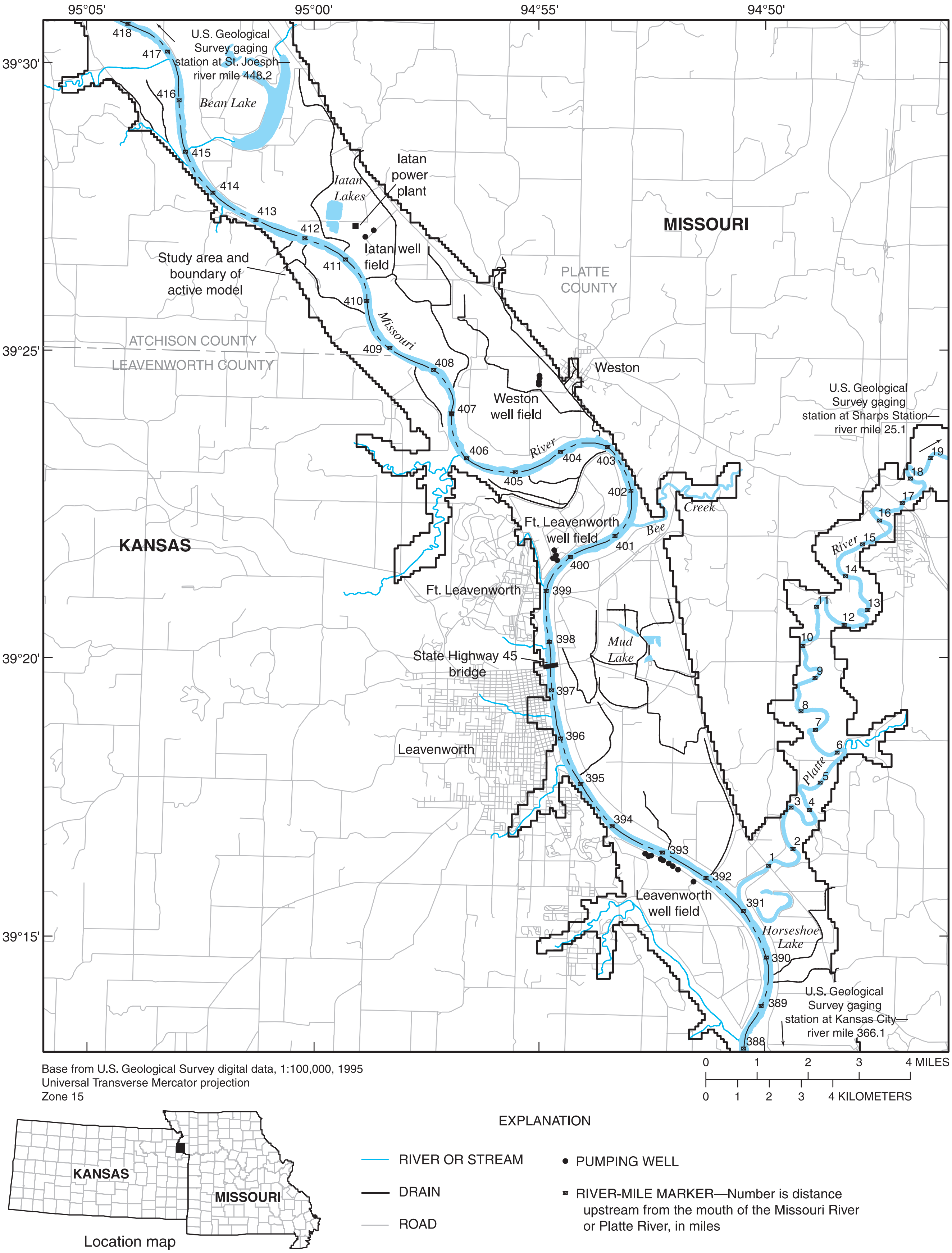


Figure 1. Location of well fields, rivers, streams, drains, and lakes in the study area.

worth site (FTL). The presence of ground-water contamination at three former fire training areas, (FTL-10, FTL-11, and FTL-69) within the river bend (fig. 2), and inundation of the existing supply wells by the Missouri River during the flood of 1993, have raised concerns about the future reliability of the existing drinking water supply at Ft. Leavenworth.

In 2001, three large public-water-supply well fields in the study area were supplied by the Missouri River alluvial aquifer, and to a lesser extent, the adjoining alluvial aquifer of the Platte River. These are the only aquifers in the study area that can supply large quantities of ground water for public and industrial use. Ground-water contamination at FTL-10 and FTL-11 and potential ground-water contamination by diesel fuel at FTL-69 pose a potential threat to the existing public-water-supply well field and other nearby public-water-supply well fields. Therefore, in 2001, the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers and the U.S. Army, began a study of ground-water flow in the Missouri River alluvial aquifer near Ft. Leavenworth.

The overall objective of this study was to characterize ground-water flow in the Missouri River alluvial aquifer in sup-

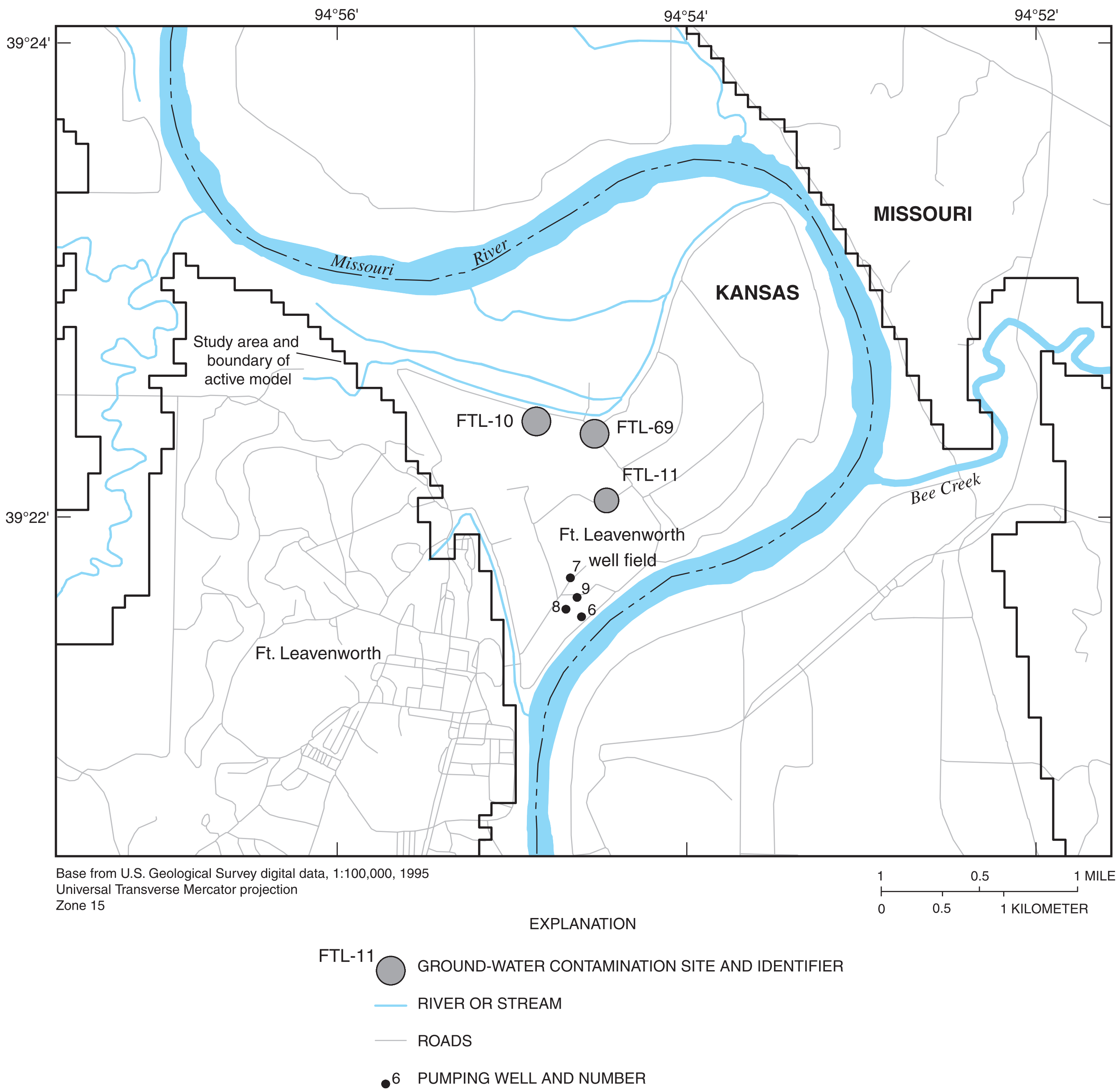


Figure 2. Location of ground-water contamination sites in the Missouri River flood plain at Ft. Leavenworth, Kansas.

port of the IRP at Ft. Leavenworth, Kansas. Specific objectives of the project were:

1. Determine simulated ground-water levels and the direction of ground-water flow in the Missouri River alluvial aquifer at Ft. Leavenworth under steady state and transient conditions.
2. Determine the travel time and the simulated zone of contribution to the existing public-water-supply well fields under several combinations of pumping and river-stage conditions.
3. Simulate ground-water flow direction and travel time from FTL-10, FTL-11, and FTL-69 to the Ft. Leavenworth well field for average yearly well pumping and average annual river stage and rainfall conditions.

Area FTL-10 operated from the 1950s to 1980, and area FTL-11 operated from 1980 to 1989. Both areas were used to store drummed flammable and hazardous waste materials before their use in fire training areas. During fire training exercises, the waste material was placed on the ground and burned. Soil samples from previous investigations between 1989 and 1999 at FTL-10 indicate the presence of arsenic, beryllium, and 1,1-dichloroethylene. Ground-water samples at FTL-10 detected benzene, toluene, ethyl benzene, trichloroethylene, dichloroethane, carbon tetrachloride, arsenic, and nickel. Soil samples from FTL-11 obtained in 1992 indicate the presence of Di-n-octylphthalate, a semi-volatile compound, barium, cadmium, and mercury. Analysis of ground-water samples indicated the presence of chromium, lead, iron, manganese, and sodium. Area FTL-69 was built in the 1950s and was used to house diesel generators for nearby radio transmitters. A 30,000-gallon diesel fuel storage tank was buried to the south of the building. The building was abandoned in the early 1970s and the tank was removed in July 1991. Diesel contamination was detected under the floor slab of the building at FTL-69 in February 1999 during demolition (Ecology and Environment, Inc., 2000).

Purpose and Scope

The purpose of this report is to describe the development, calibration, and results of a ground-water flow model of the Missouri River alluvial aquifer near Ft. Leavenworth, Kansas. The simulated results of five pumping-rate and river-stage scenarios are presented and include low pumping rates, average river stage; high pumping rates, average river stage; average pumping rates, average river stage; average pumping rates, low river stage; and average pumping rates, high river stage. The contributing recharge area (CRA) to each well field and related ground-water travel times at various distances from each public-water-supply well field are presented for each scenario as well as ground-water flow direction and travel time from FTL-10, FTL-11, and FTL-69 to the well fields for average yearly well pumping and average annual river stage and rainfall conditions. For this report, the Missouri River alluvial aquifer includes the alluvial aquifer adjacent to the Platte River in the study area.

The International System of Units is used in this report. However, locations along the Missouri River are identified by river miles to allow readers to easily identify Missouri River locations. Data collected for this study during 2001 and 2002 include hourly water levels from 13 monitoring wells installed in 2001, rates of ground-water pumpage from public-water-supply well fields located in the study area, daily rainfall amounts, and concurrent river stages for the Missouri and Platte Rivers.

Study Area Description

The approximately 202-km^2 (square kilometer) study area (fig. 1) extends from approximately 10.3 km (kilometers) north of the Leavenworth-Atchison County line in Kansas near Missouri River mile 418 to approximately 4.8 km south of the mouth of the Platte River in Missouri near Missouri River mile 388. The study area is bounded by the Missouri River alluvial valley walls on the east and west. Part of the alluvial valley of the Platte River is included. Parts of Atchison and Leavenworth Counties in Kansas and Platte County in Missouri lie within the study area. The boundary of the study area is the boundary of the ground-water flow model. The southern boundary overlaps the northern boundary of a ground-water model constructed for the Missouri River alluvial aquifer in the Kansas City metropolitan area (Kelly, 1996). Land use in the study area is row-crop agriculture or undeveloped land. Small parts of the flood plain at Ft. Leavenworth and the Iatan Power Plant are industrial.

Hydrogeologic Framework

Water-level data for the Missouri River alluvial aquifer were collected from 13 monitoring wells installed at the beginning of the study, wells with historical water-level data obtained from the U.S. Geological Survey National Water Information System (NWIS), and well installation forms from the Kansas Department of Health and Environment and Missouri Department of Natural Resources. Hydrogeologic data from numerous geologic and hydrologic investigations within the study area also were compiled. The description of the hydrogeologic framework of the study area is based on a literature review of the following reports: Fischel, 1948; Fischel and others, 1953; Emmett and Jeffery, 1969; Gann and others, 1973; Hasan and others, 1988; Kelly and Blevins, 1995; Kelly, 1996; and Ecology and Environment, Inc., 2000.

Physiography and Drainage

The Missouri River alluvial valley is flat within the study area. However, highway embankments, levees, and some construction activities have raised the surface of the alluvial valley in developed areas. Total relief within the study area is about 24 m (meters), with the highest elevations about 250 m above National Geodetic Vertical Datum (NGVD) of 1929 in the north and adjacent to the valley walls, and the lowest elevations about 226 m above NGVD of 1929 in the southeast and near the Missouri River. The major tributary to the Missouri River within the study area is the Platte River, but numerous smaller streams and constructed agricultural drains and ditches also drain into the Missouri River. Low-lying areas collect surface runoff during wet periods and standing water may remain for some time where soils are poorly drained.

The Missouri River is too small to have eroded the valley in which it flows (Grannemann and Sharp, 1979). Changes in discharge, sediment load, and base level during glacial and interglacial stages have caused the width, meander wavelength, and meander length of the Missouri River valley to be larger than that typically formed by a river the size of the present-day Missouri River. Consequently, the Missouri River is an underfit stream.

Climate

The humid continental climate of the study area is characterized by large variations and sudden changes in temperature and precipitation. The average high temperature in July, the hottest month of the year, is 26 °C (degrees Celsius), and the average high temperature in January, the coldest month, is 2.3 °C (Hasan and others, 1988). Average annual precipitation ranges from about 0.86 m in the north to about 0.89 m in the east of the study area. About 70 percent of precipitation falls during the growing season from April to October (Bevans and others, 1984).

Geology

The Missouri River and Platte River flood plains are underlain by alluvial deposits of Quaternary age consisting of clay, silt, sand, gravel, cobbles, and boulders (Emmett and Jeffery, 1969; Kelly and Blevins, 1995). These deposits form the alluvial aquifer discussed in the “Hydrology and Conceptual Ground-Water Flow Model” section. The nature and extent of the alluvial deposits have been greatly influenced by glacial processes that caused numerous changes in discharge, sediment load, and the course of these rivers with time. The present course of the Missouri River approximates the southern-most limit of continental glaciation. Previous investigations of the geology and geologic history of the study area include Fischel (1948); Fischel and others (1953); Hasan and others (1988).

Bedrock and Valley Walls

The Pennsylvanian age shale, limestone, sandstone, siltstone, conglomerate, coal, and clay define the bottom and walls of the alluvial aquifer. The altitude of the bedrock surface underlying the alluvial aquifer, as determined from existing borehole and well data, is bowl- or pan-shaped in cross section with steeply sloping sides and a flat bottom (fig. 3). Typical depth to bedrock is between 25 and 30 m.

Alluvial Deposits

The uppermost fine-grained clays, silty clays, and clayey silts are recent (Holocene) alluvial deposits and the lower coarse sands, gravels, cobbles, and boulders are Wisconsinian age alluvial deposits of glacial origin (Hasan and others, 1988). Although grain size typically increases with depth, this grain-size distribution in locally heterogeneous deposits can be reversed. Lithologic sections for five locations in the study area were developed from existing well-cutting descriptions and borehole log data to illustrate the shape of the alluvial aquifer and the extent and lithology of the alluvial deposits.

Lithologic sections A-A’, B-B’, C-C’, D-D’, and E-E’ (fig. 3) show the alluvial deposits of the Missouri River. The typical grain-size distribution includes several meters of clay and silt at the surface, a thick layer of sand and gravelly sand in the middle, and a thin layer of sandy-gravel, gravel, and boulders at the base of the aquifer.

Hydrology and Conceptual Ground-Water Flow Model

Ground-water flow in the Missouri River alluvial aquifer is affected largely by the hydraulic properties of the aquifer material, the areal extent and thickness of the aquifer, the stage of the Missouri River and its major tributaries, and water flow across the boundaries of the aquifer. These properties were used to construct a conceptual model of ground-water flow that describes the internal and external boundaries of the ground-water flow system, the inflow and outflow of water at each of these boundaries, and the effect each boundary has on ground-water flow in the aquifer. The conceptual model identifies the hydrologic processes that need to be simulated in a properly constructed numerical ground-water flow model.

Hydraulic Properties of the Aquifer

Ground water exists in the small openings between the particles of clay, silt, sand, and gravel that make up the alluvial deposits of the aquifer. The percent of the total volume of the aquifer occupied by these openings, or pores, is called the porosity. Typical porosity values for alluvial deposits are 40 to 70 percent for clays, 35 to 50 percent for silts, 25 to 50 percent for sands, and 25 to 40 percent for gravels (Freeze and Cherry, 1979).

The total maximum volume of ground water in the fully saturated Missouri River and Platte River alluvial aquifer in the study area can be estimated by multiplying the saturated volume of the aquifer by the porosity. Assuming the aquifer is saturated

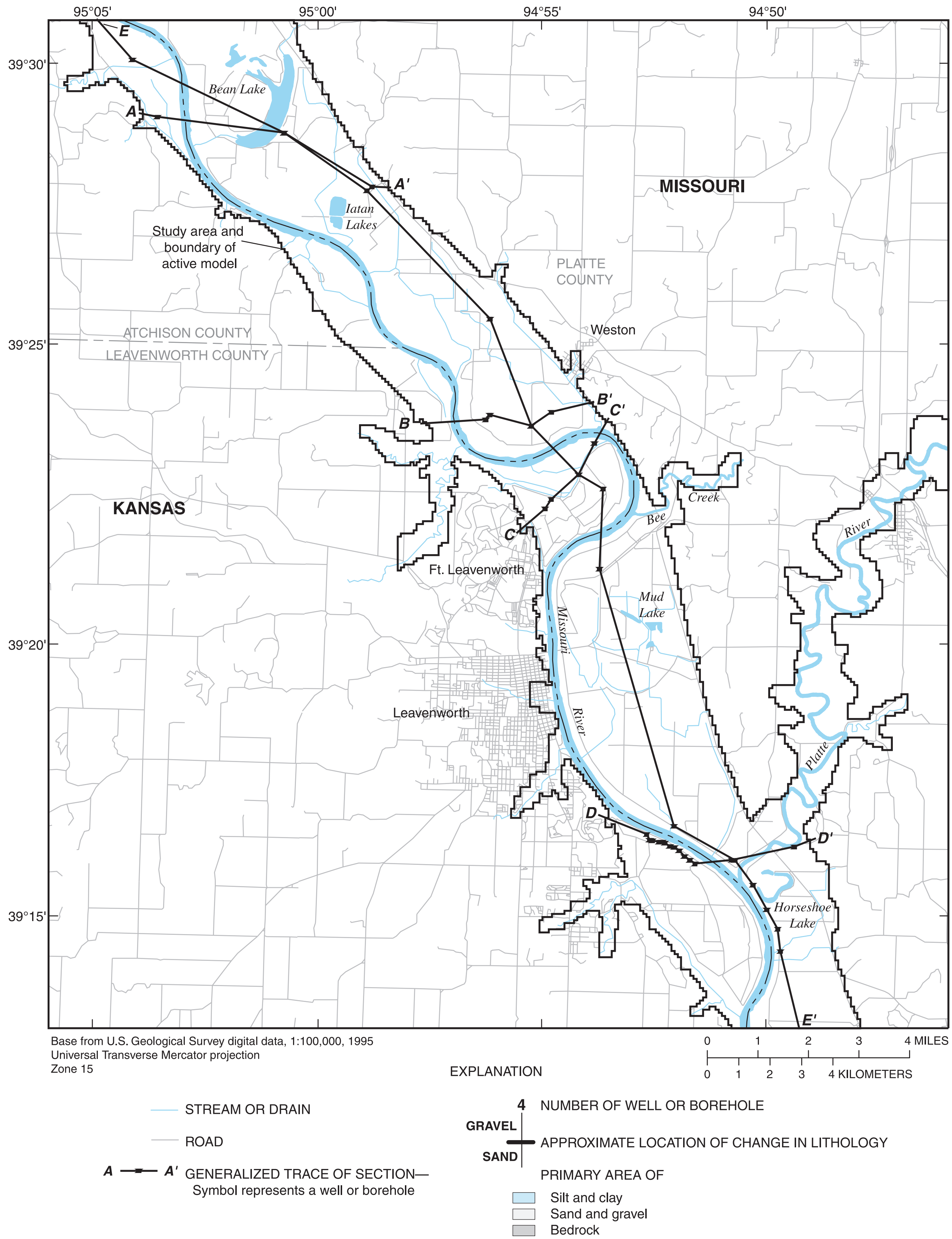


Figure 3. Lithologic sections of the Missouri River alluvial aquifer in the study area.

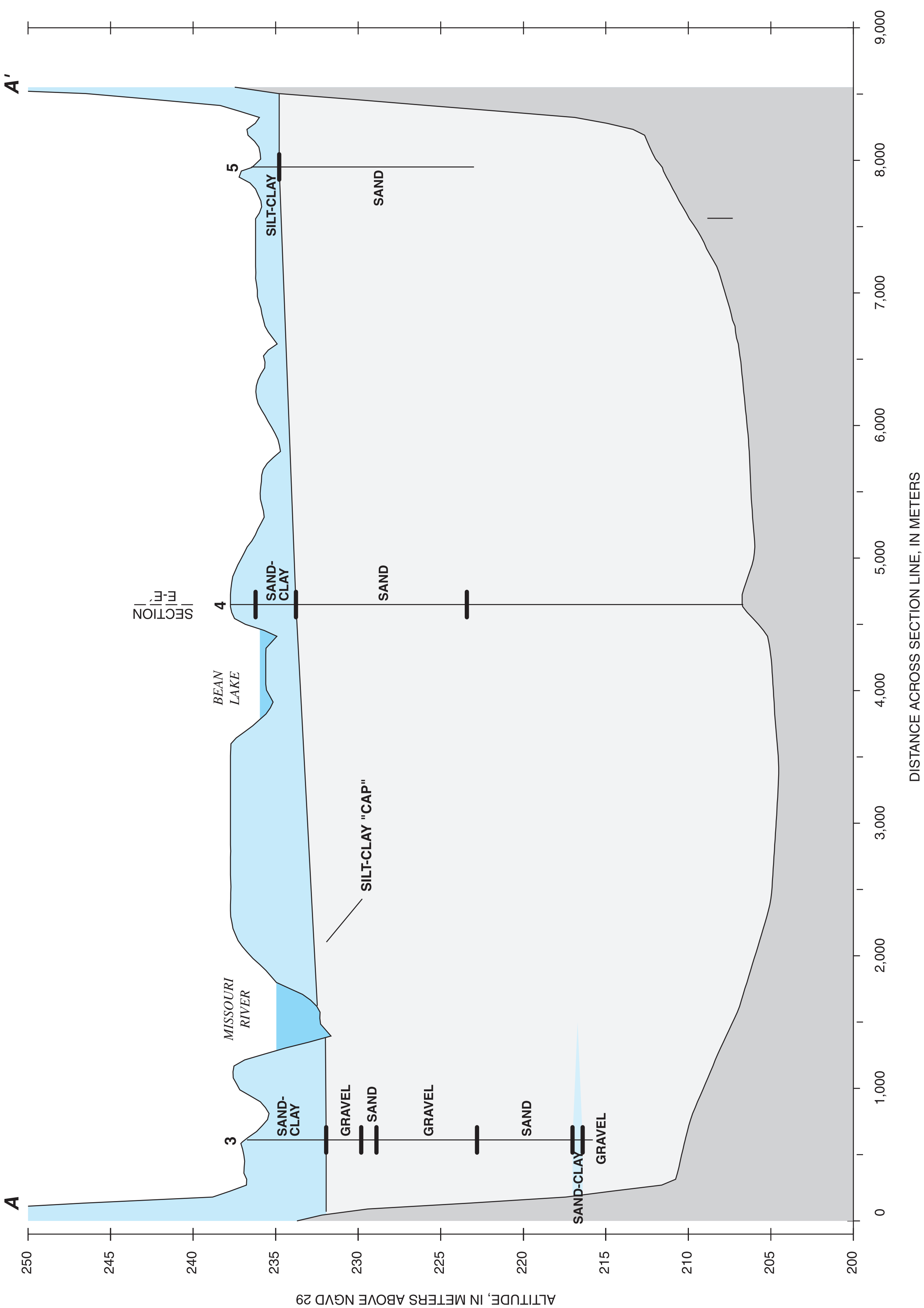


Figure 3. Lithologic sections of the Missouri River alluvial aquifer in the study area—Continued.

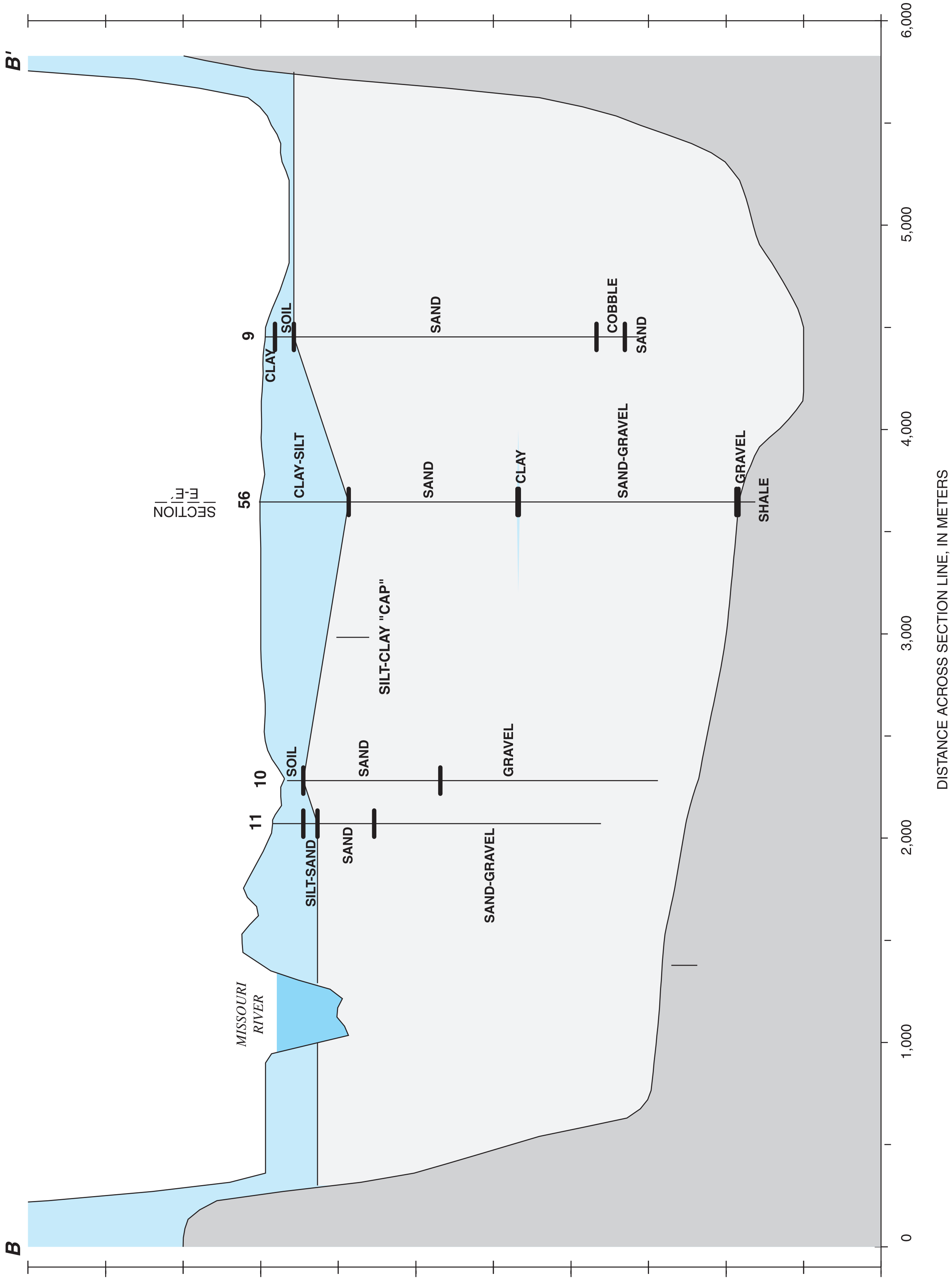


Figure 3. Lithologic sections of the Missouri River alluvial aquifer in the study area—Continued.

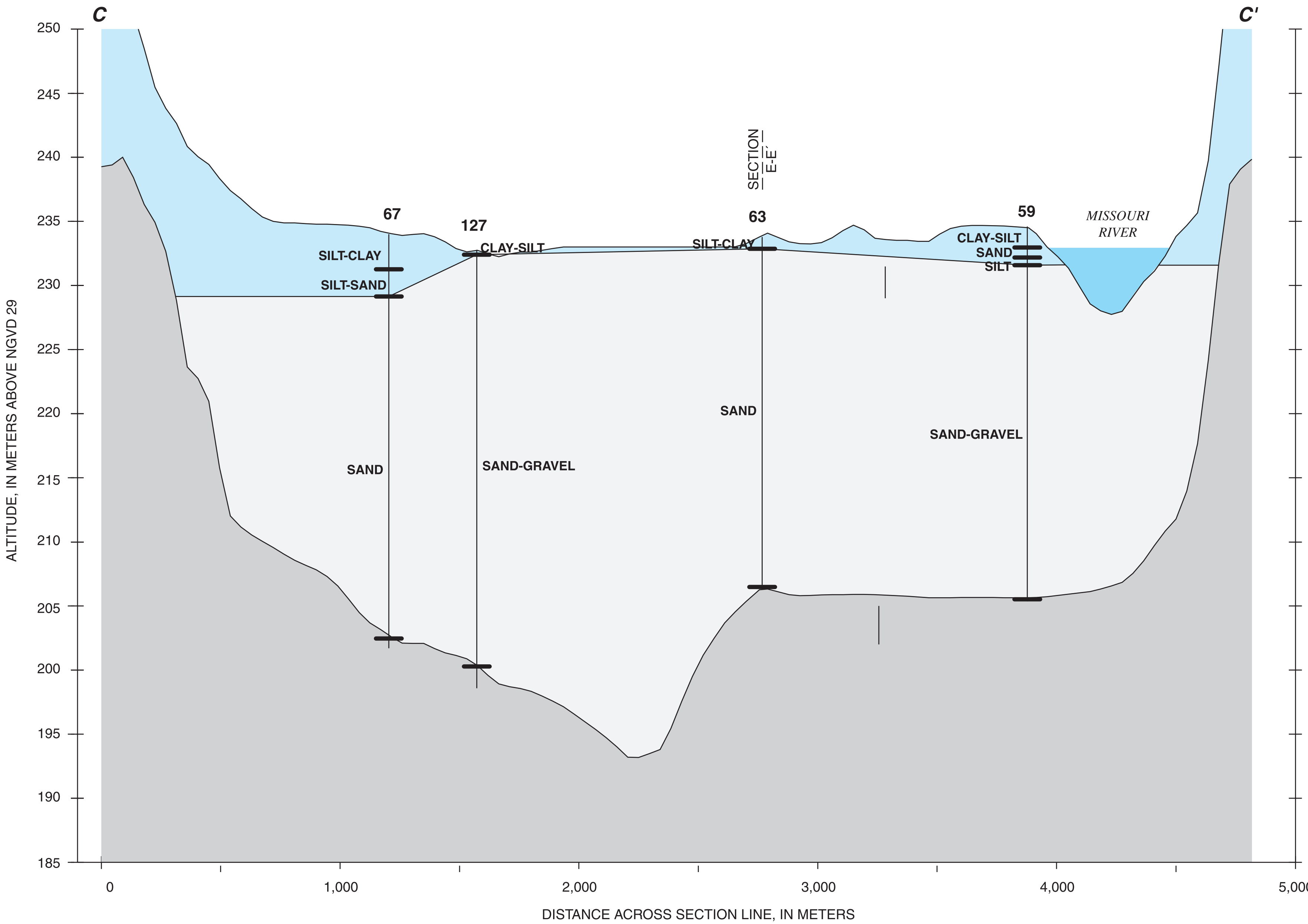


Figure 3. Lithologic sections of the Missouri River alluvial aquifer in the study area—Continued.

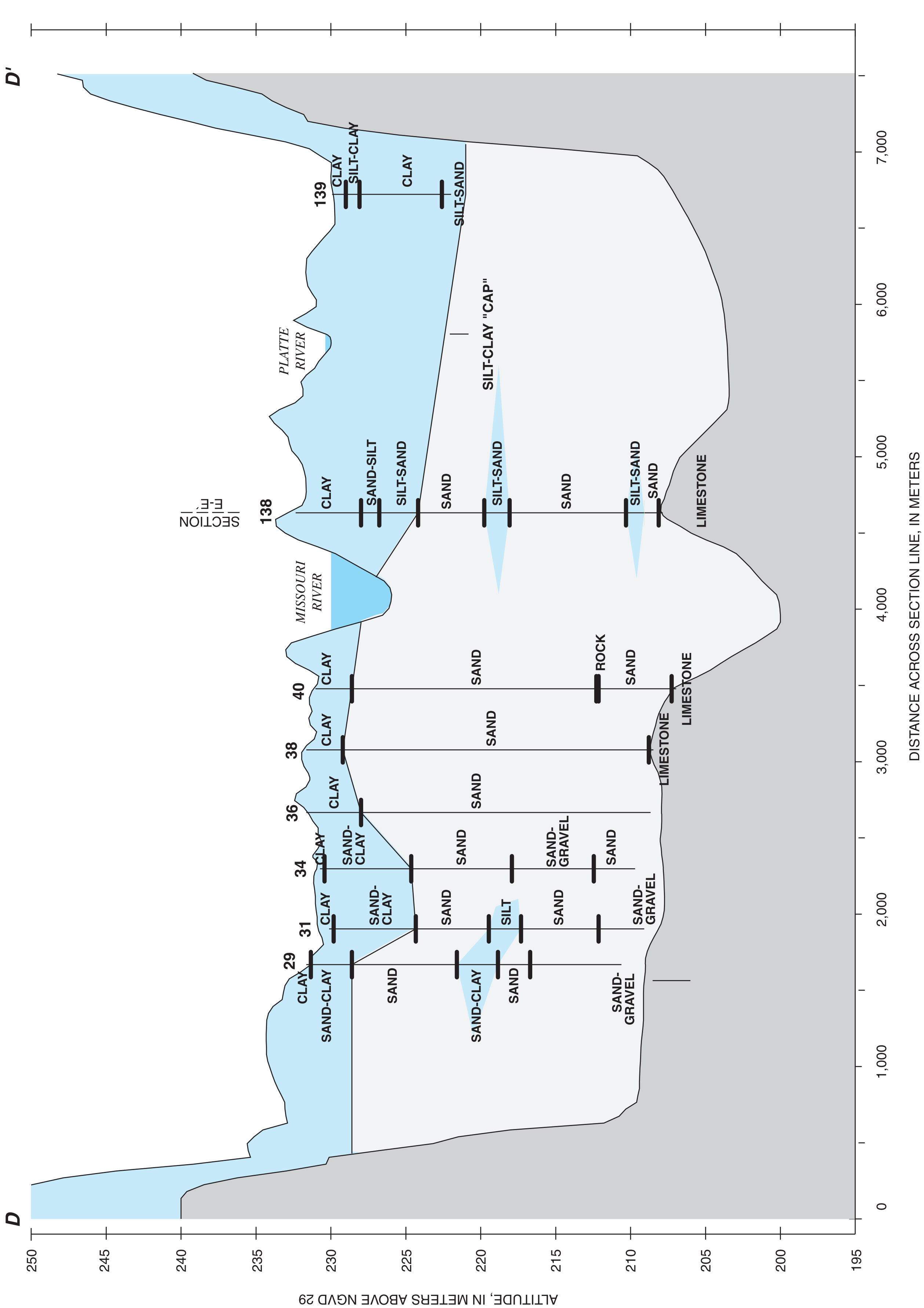


Figure 3. Lithologic sections of the Missouri River alluvial aquifer in the study area—Continued.

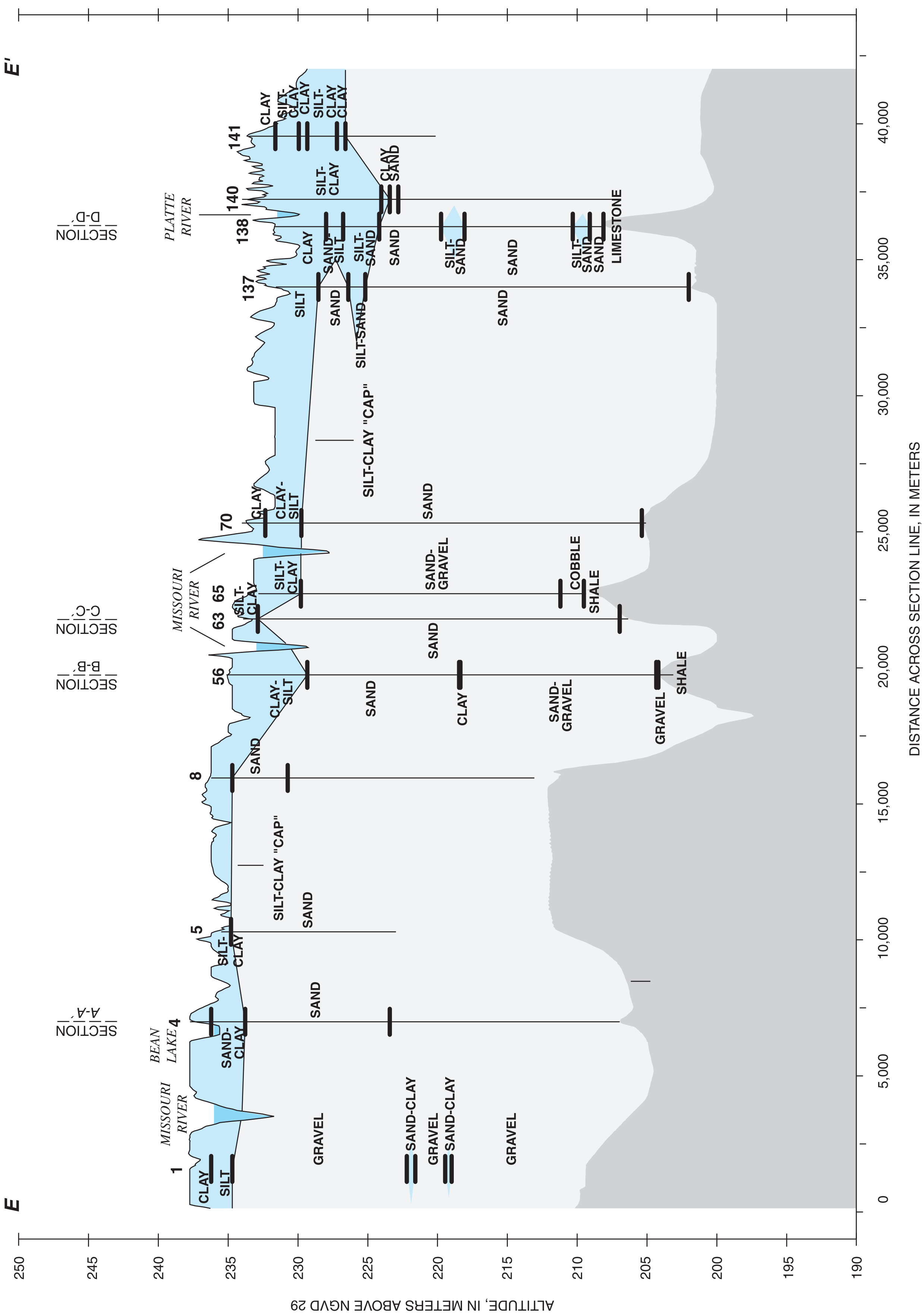


Figure 3. Lithologic sections of the Missouri River alluvial aquifer in the study area—Continued.

from land surface to bedrock and an average porosity of 30 percent in the saturated aquifer volume of 4.29 x 10^9 m^3 (cubic meters), the volume of water in the alluvial aquifer in the study area is approximately 1.29 x 10^9 m^3.

The porosity determines the total volume of water the aquifer can hold but does not determine how much water may be obtained from the aquifer for use. The specific yield, the storage coefficient in an unconfined aquifer, is a measure of the ratio of the volume of water that will drain because of gravity to the total volume of saturated aquifer. For this alluvial aquifer the specific yield usually is between 0.15 and 0.2 (Emmett and Jeffery, 1969). The maximum volume of water that can be obtained from an unconfined aquifer is estimated by the product of the saturated volume and specific yield of the aquifer. Using a fully saturated aquifer from land surface to bedrock and a specific yield of 0.2, the maximum volume of water available from the alluvial aquifer in the study area is approximately 8.58 x 10^8 m^3. The aquifer is confined by a clay layer in some areas. In these areas the volume of available water is determined by the storage coefficient. The storage coefficient is about 0.001 for this aquifer under confined conditions (Emmett and Jeffery, 1969).

The hydraulic conductivity is the capacity of the aquifer to transmit water and is measured as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area at a right angle to the direction of flow. Reported horizontal hydraulic conductivity values for the aquifer as measured by aquifer tests in the study area are between 1 m/d (meter per day) and 300 m/d (Ecology and Environment, Inc., 2000). Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient, and equals the hydraulic conductivity multiplied by the thickness of the aquifer. Reported transmissivity values are between 5 m^2/d (meter squared per day) and 7,400 m^2/d (Fischel, 1948; Emmett and Jeffery, 1969). The thickness and extent of the alluvial aquifer in the study area are shown in figure 4. The greatest aquifer thickness is about 40 m, but average thickness is about 25 m.

Aquifer Boundaries

The Missouri River alluvial aquifer is bounded at the top by the water table, laterally by the alluvial valley walls, and at the base by bedrock. The Missouri River alluvial aquifer extends for hundreds of kilometers upstream and downstream from the study area and arbitrary boundaries were established at the upstream and downstream edges of the study area. Water flows into or out of the aquifer through the river beds of the Missouri and Platte Rivers and at pumping wells. The potentiometric surface is defined by the level to which water will rise in tightly cased wells from a reference level. In an unconfined aquifer the potentiometric surface is the water table and is the boundary where recharge from precipitation enters the aquifer. No-flow boundaries include the potentiometric surface where recharge is zero and the alluvial valley walls and the bedrock base where the rock is of very low permeability compared to the permeability of the alluvial aquifer.

Rivers and Lakes

The fluctuation of river stage in the Missouri and Platte Rivers has a large effect on ground-water levels in the study area. Bean Lake, Horseshoe Lake, and other smaller lakes and ponds also affect ground-water levels. An increase in river stage with respect to the altitude of the potentiometric surface causes water to flow from the river into the aquifer and the altitude of the potentiometric surface to increase. A decrease in river stage with respect to the potentiometric surface causes water to flow from the aquifer into the river and the altitude of the potentiometric surface to decrease. The magnitude of the change in the potentiometric surface altitude in response to river stage fluctuations depends on the magnitude of the change in river stage, the length of time the river remains at the current river stage, the hydraulic properties of the aquifer material, and the distance from the river to the point of interest (Grannemann and Sharp, 1979). The potentiometric surface increases or decreases in altitude in response to increases or decreases in river stage more rapidly in areas closer to the river because of the time required for the change to propagate into and through the aquifer. Therefore, the area of the aquifer that is affected by an increase or decrease in river stage depends on the length of time that the river stage remains at the new altitude. Changes in the altitude of the potentiometric surface at distant locations from the river are the result of long term river-stage changes typically caused by seasonal high and low flows or long-term river-stage management.

The Missouri River has large streambed hydraulic conductivities. The bottom of the river channel is below the top of the potentiometric surface, and therefore river stage changes have a large effect on ground-water flow. The Missouri River streambed deposits typically are composed of sand and gravel and the channel bottom penetrates through the silt-clay cap and into the sand and gravel in the middle depths of the aquifer (fig. 3). Thus, the Missouri River is well connected hydraulically to the underlying alluvial aquifer.

The Platte River, and other smaller streams, have less affect on ground-water flow than the larger Missouri River. These rivers have smaller streambed hydraulic conductivities and locally, the bottoms of the river channels can be above the top of the potentiometric surface. Streambed deposits of the Platte River typically are composed of finer grained sand, clay, and silt compared to streambed deposits of the Missouri River, and the bottom of the channels intersects the finer grained alluvial deposits located at shallower depths. Thus, these rivers are poorly connected to the underlying alluvial aquifer, but can have some effect on ground-water flow.

Numerous smaller streams and drainage ditches are present in the study area. During most of the year the bottom of these streams are above the top of the potentiometric surface

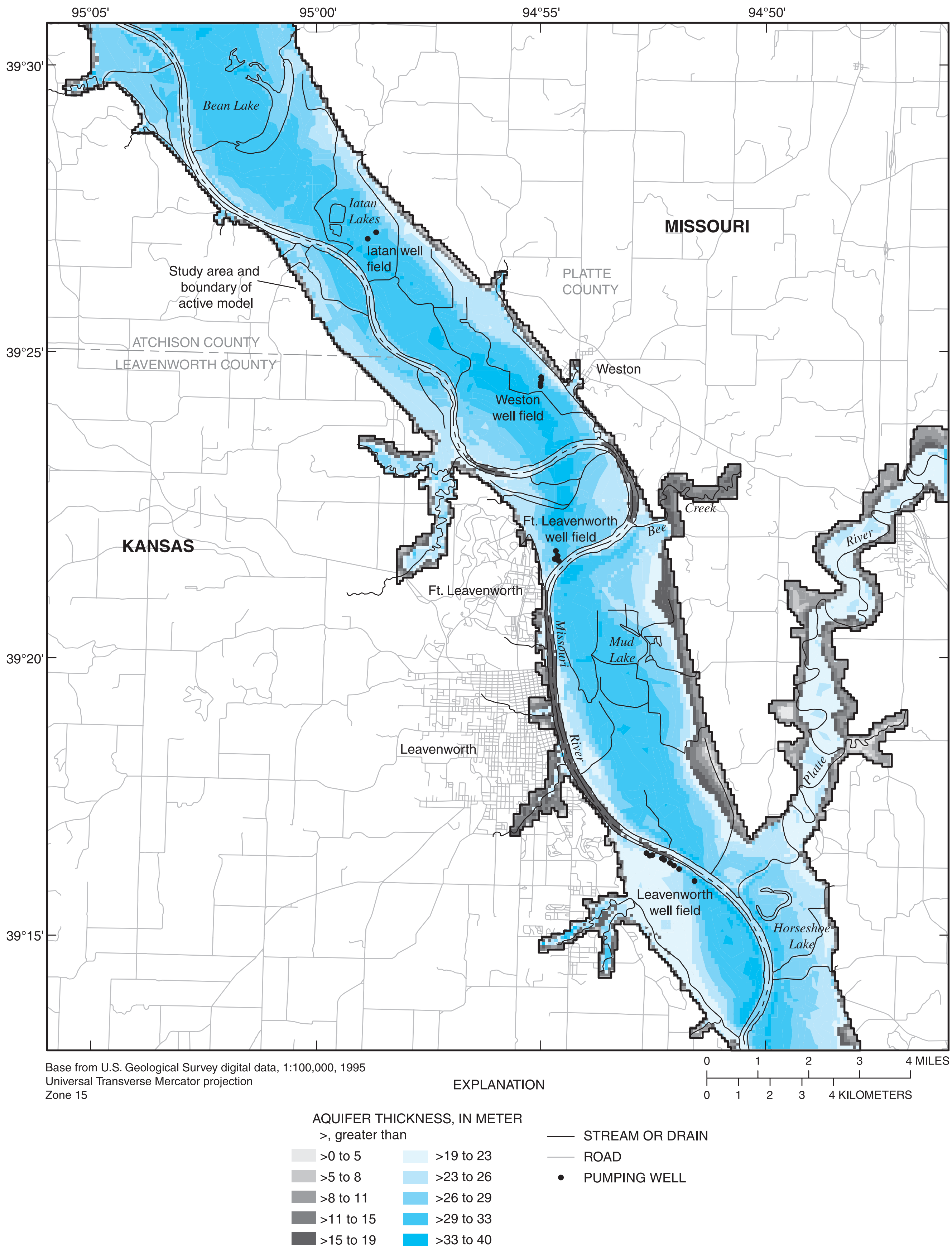


Figure 4. Thickness and extent of the Missouri River alluvial aquifer in the study area.

and have less affect on ground-water flow than larger streams. These smaller streams and ditches have low or intermittent discharges that supply small amounts of recharge to the aquifer during the year. However, these smaller streams may affect ground-water flow locally during floods when they supply recharge to the aquifer or during periods when the potentiometric surface rises above the stream stage and the aquifer drains into the streams.

Bean Lake and Horseshoe Lake are oxbow lakes. Lake bottom deposits of oxbow lakes typically are composed of clays and silts of low hydraulic conductivity. Lakes recharge the aquifer when the potentiometric surface is below the lake level, but drain the aquifer when the potentiometric surface is above the lake level. This recharge volume typically is small, however, because of the low hydraulic conductivity of the lake bottom deposits. Water levels in other small lakes are affected by increases or decreases in the potentiometric surface altitude that cause a corresponding increase or decrease in lake water levels. These lakes may be areas of increased recharge because they collect surface runoff.

Potentiometric Surface

The potentiometric surface is the boundary across which recharge from precipitation flows into the aquifer. Areally distributed recharge occurs when the rate of precipitation or snow melt exceeds the rate of evapotranspiration from the soil and water flows into the aquifer. During periods of high rates of recharge, the potentiometric surface altitude increases because the aquifer is gaining water. When recharge rates are low, the potentiometric surface altitude decreases as water drains out of the aquifer.

Total annual precipitation for the area ranges from 0.86 to 0.89 m and occurs mainly during the growing season between April and October (Hasan and others, 1988). Recharge has been estimated in two previous studies to be between 2 and 25 percent of precipitation (Fischel and others, 1953; Hedman and Jorgensen, 1990). Recharge to the alluvial aquifer in the study area from precipitation is about 4.045×10^7 m^3 per year, assuming about 0.2 m of recharge per year (22.5 percent of 0.89 m precipitation).

Topography generally has little affect on the areal distribution of recharge, although low-lying areas in the study area may have larger recharge rates caused by collected runoff. Rather, the vertical hydraulic conductivity of soils directly controls the rate of infiltration in most areas. Aquifer recharge is greater beneath ponded areas or soils with larger vertical hydraulic conductivities than beneath soils with a smaller vertical hydraulic conductivities. Therefore, soil variability affects the areal distribution of recharge to the aquifer.

Alluvial Valley Walls and Bedrock

The alluvial valley walls form the lateral boundary of the alluvial aquifer. Bedrock forms the lower boundary of the alluvial aquifer. Ground-water flow between the alluvial aquifer and bedrock has not been quantified. However, bedrock units have estimated hydraulic conductivities between 0.003 and 3 m/d and very slow rates of water flow (Gann and others, 1973). This range of hydraulic conductivity is between 10 and 10,000 times lower than the range for the alluvial aquifer. Consequently, flow between the aquifer and the valley walls and bedrock is considered to be low in comparison to the total flow of ground water in the aquifer.

Upstream and Downstream Aquifer Boundaries

The Missouri River alluvial aquifer extends the length of the Missouri River. The alluvial aquifer of the Platte River also extends beyond the study area. The upstream and downstream boundaries of the study area are not physical hydraulic boundaries, but were chosen based on the study objectives and area of interest. Ground water flows into the system through the upstream boundaries of the study area and flows out of the system through the downstream boundaries of the study area. The ground-water flow rate across the boundary depends on the direction of ground-water flow with respect to the boundary, the hydraulic conductivity of the material at the boundary, the gradient of the potentiometric surface at the boundary, and the thickness of the aquifer at the boundary. When the direction of ground-water flow is parallel to the boundary, no ground water crosses the boundary. The upstream and downstream boundaries were chosen to be located at some distance from the area of interest to minimize their effect on the study results.

Well Pumping

In 2003, three public-water-supply well fields (Weston, Ft. Leavenworth, and Leavenworth) and one industrial well field (Kansas City Power and Light, Iatan Power Plant) were in operation in the study area. Water pumped from the alluvial aquifer in the study area by public-water-supply well fields in 2003 totalled 21,439 m^3/d (cubic meters per day) (7,825,235 m^3 per year) (S. Wood, U.S. Army, written commun., 1997; D. Masoner, City of Weston, Missouri, written commun., 2000; D. Murphy, City of Leavenworth, written commun., 2000; H. Sweet, Kansas City Power and Light, Iatan Power Plant, written commun., 2000). Recharge from precipitation supplies about 4.045×10^7 m^3 of water per year to the aquifer; the volume of stored water available for use at any one time is about 8.58×10^8 m^3. Therefore, about 19 percent of annual recharge supplied to ground water from precipitation and a maximum of about 0.9 percent of the ground water stored in the aquifer was withdrawn in 2003 by public-water-supply well fields. However, the actual percent of ground water removed was less because wells located close to the Missouri River can obtain a large part of their water from recharge induced from the river.

Withdrawal of water from the aquifer by well pumping creates cones of depression on the potentiometric surface around each well or well field and causes ground water to flow toward the wells. A cone of depression generally has the shape of an inverted cone with the lowest part centered at the pumping well. Most water recharging the Missouri River alluvial aquifer comes from surface recharge from precipitation or recharge from the Missouri River.

Ground-Water Movement

In the absence of pumping, ground-water flow within the alluvial aquifer typically is away from the valley walls, toward the Missouri River, and down the river valley (Emmett and Jeffery, 1969; Kelly and Blevins, 1995). A sudden increase in river stage can temporarily reverse the direction of ground-water flow near the river. Flooding, irrigation, well pumping, and dewatering during construction also can alter ground-water flow directions. Historic water levels, average historic water levels when more than one measurement was available for a particular well, and average water levels of wells with multiple or continuous measurements obtained during this study were used to develop a potentiometric surface map to illustrate the general flow of ground water down the river valley and toward the Missouri River (fig. 5).

Simulation of Ground-Water Flow

Ground-water flow was simulated for the Missouri River alluvial aquifer using the three-dimensional finite-difference ground-water flow model MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW-2000 is a modified version of MODFLOW (McDonald and Harbaugh, 1988) that incorporates the use of parameters to define model input, the calculation of parameter sensitivities, and the modification of parameter values to match observed heads, flows, or advective transport using the observation, sensitivity, and parameter-estimation processes described by Hill and others (2000).

The equation used in the computer model to describe ground-water flow is:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(Kyy\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right) - W = Ss\frac{\partial h}{\partial t}$$

where

Kx, Ky, and Kz	are the values of hydraulic conductivity along the x, y, and z coordinate axes and are assumed to be parallel to the major axes of hydraulic conductivity, in meters per day;
h	is the potentiometric head, in meters;
W	is a volumetric flux per unit volume and represents sources or sinks, or both, of water, such as well discharge, leakage through confining units, streambed leakage, recharge, and water removed from the aquifer by drains, per day;
Ss	is the storage coefficient of the porous material, per meter; and
t	is time, in days.

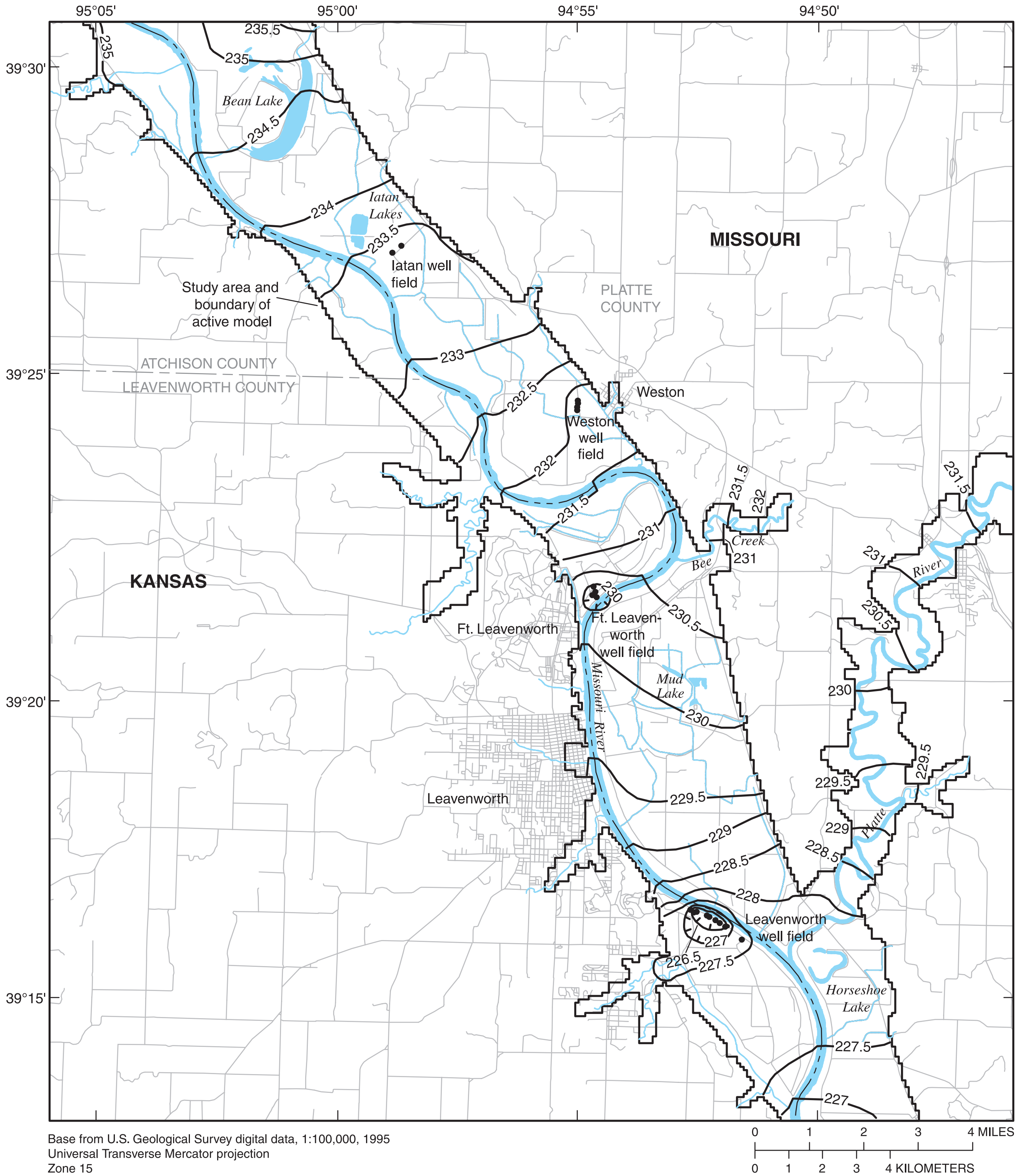
The flow equation was solved by the Link-AMG method (Mehl and Hill, 2001), a method for solving matrix equations using an algebraic multigrid solver.

Three-dimensional simulation of ground-water flow in the alluvial aquifer was necessary to accurately determine the hydraulic-head distribution beneath the larger rivers and around the multiple well fields in the study area. Discharge from the aquifer to rivers may vary according to river size or depth of the streambed. Ground-water flow may be divided into smaller flow subsystems because of the degree of interaction between ground water, the well fields, and the larger and smaller rivers in the study area. Three-dimensional simulation also is necessary in the analysis of ground-water travel times and the contributing recharge area around each pumping well field because of the vertical flow of ground water caused by well pumping. Also, pumping from the well fields located near the Missouri River can induce recharge from the river and cause ground-water flow beneath the river.

Model Description

The modeled area is 28.6 by 32.6 km and contains the entire study area shown in figure 1. The model uses a uniform grid size of 100 m by 100 m and contains 372,944 cells in 4 layers, 286 columns, and 326 rows. The irregular shape of the study area reduced the number of active cells in the model to 73,132, with 20,412 active cells in layer 1; 19,723 active cells in layer 2; 18,622 active cells in layer 3; and 14,375 active cells in layer 4. The regular grid spacing facilitated data input from a Geographic Information System (GIS) and analysis of model output by the GIS, and the grid size minimized errors in flow-path analysis that would be caused by a large grid size (Pollock, 1994; Zheng, 1994).

The model represents the alluvial aquifer using four layers, numbered 1 to 4, of variable thickness with no intervening confining layers. Layer thicknesses are shown in figure 6. Layer 1 corresponds to the upper part of the aquifer where clays, silts, and finer-grained sands are dominant. The thickness of layer 1 is adequate to account for the anticipated range of water-level variation within the aquifer during ground-water flow simulation and was modeled using both confined- and unconfined-aquifer hydraulic properties. Layers 2 and 3 correspond to the middle part of the aquifer where sand and gravelly sands predominate. These layers were not anticipated to dewater during the simulations and were modeled using confined aquifer



EXPLANATION

—227— POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased well. Hachures indicate depression. Contour interval 0.5 meter. Datum is NGVD 29

STREAM OR DRAIN

ROAD

• PUMPING WELL

Figure 5. Generalized potentiometric surface map of the Missouri River alluvial aquifer in the study area.

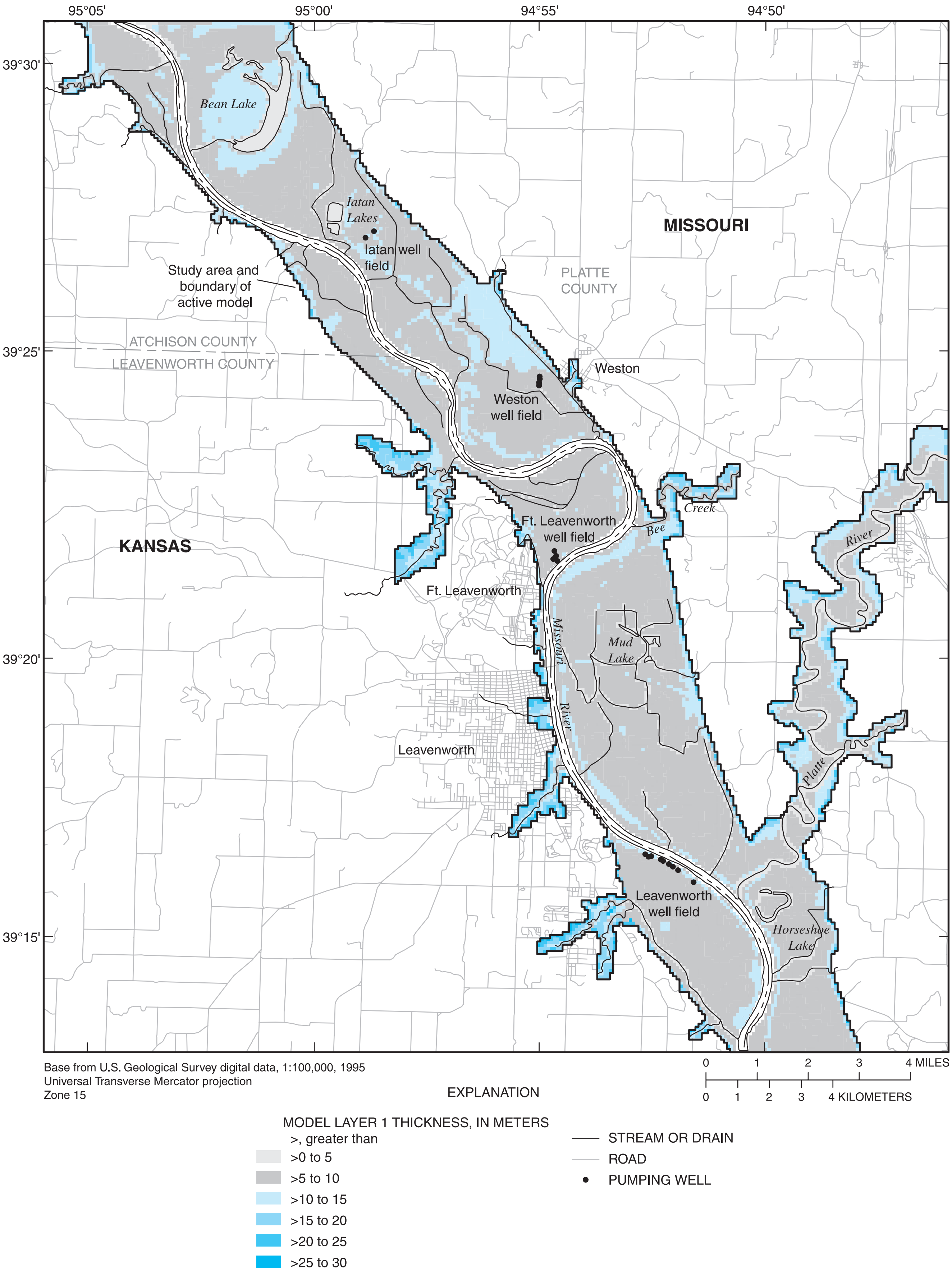


Figure 6. Thickness of model layers 1 through 4.

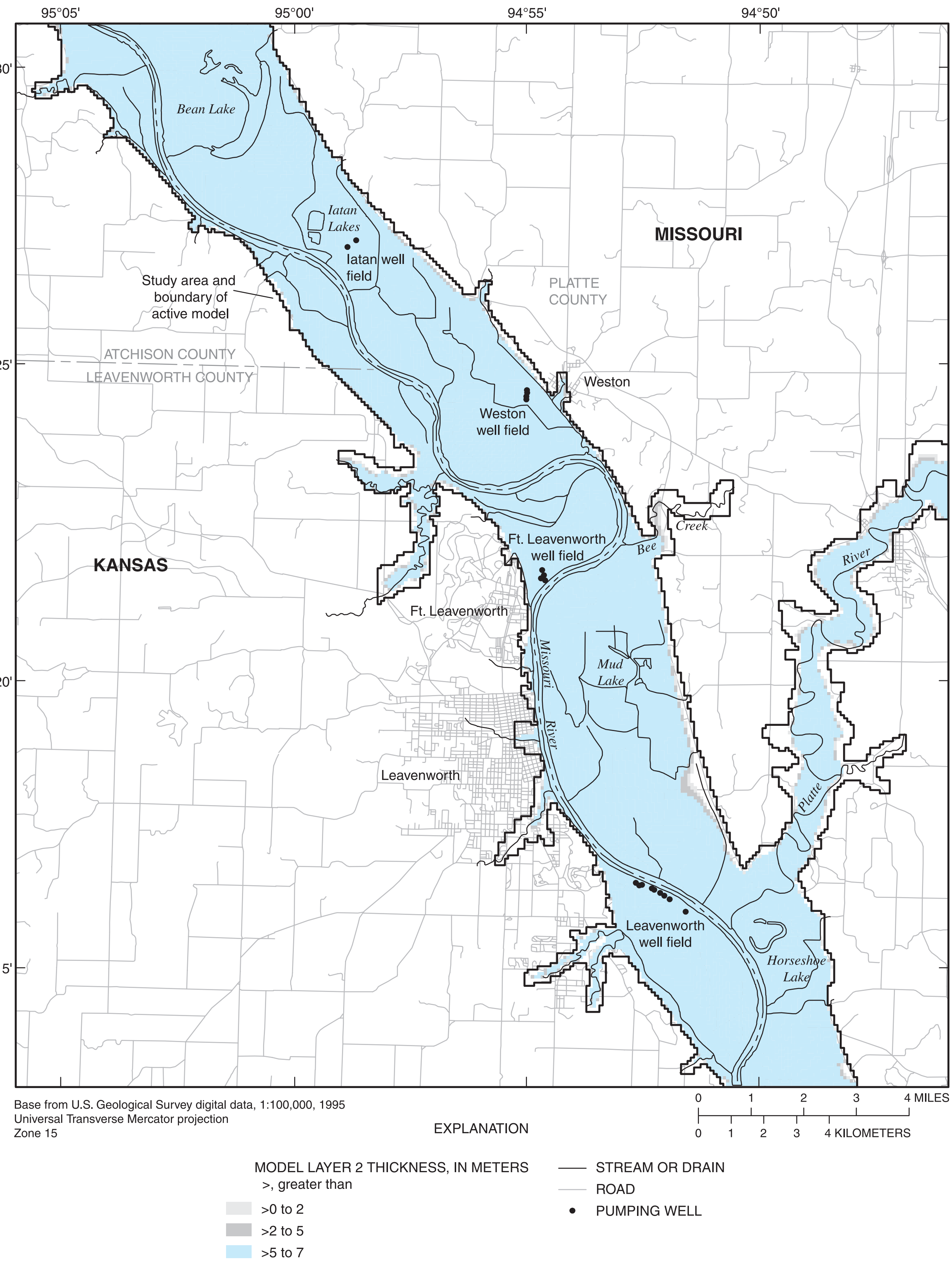


Figure 6. Thickness of model layers 1 through 4—Continued.

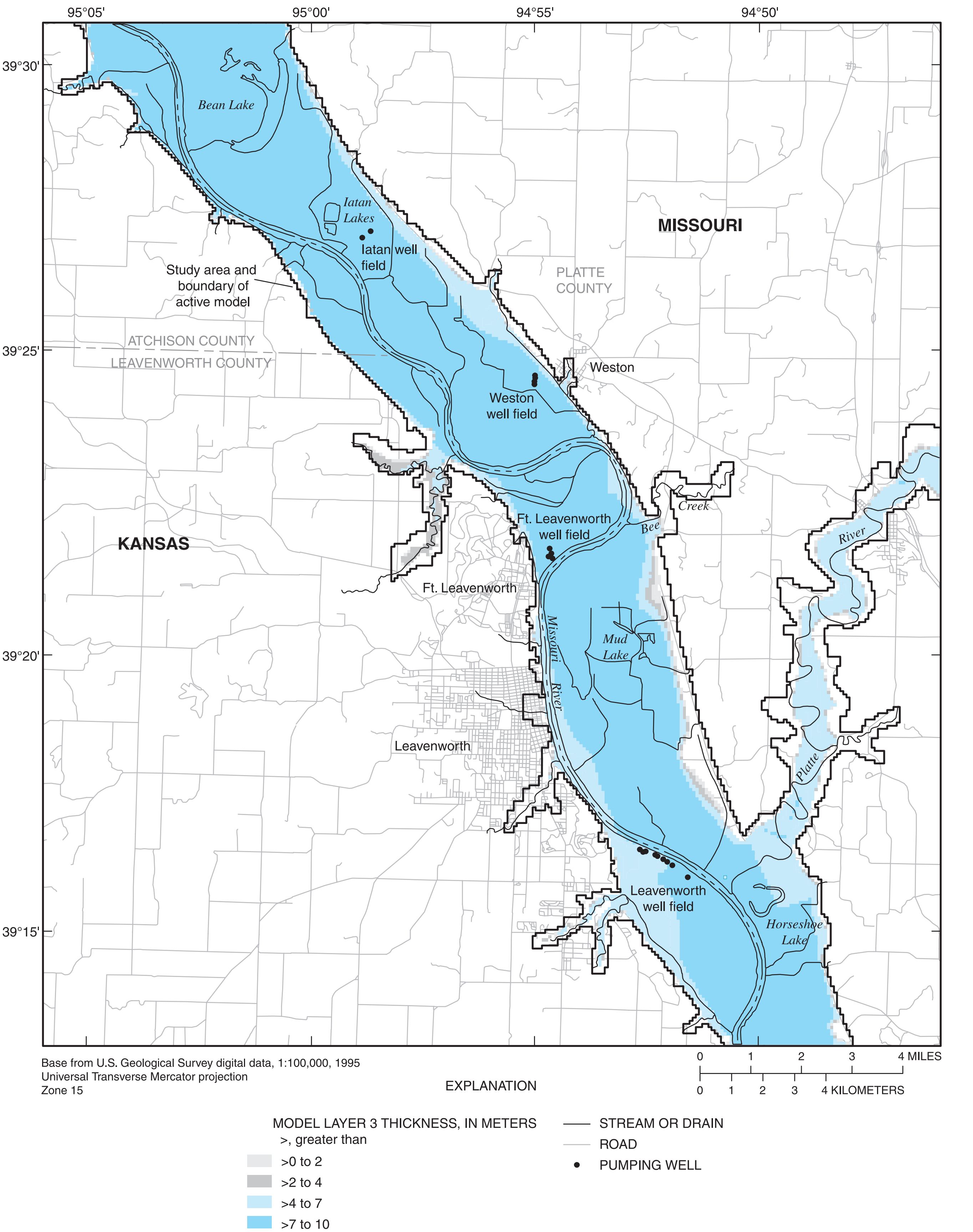


Figure 6. Thickness of model layers 1 through 4—Continued.

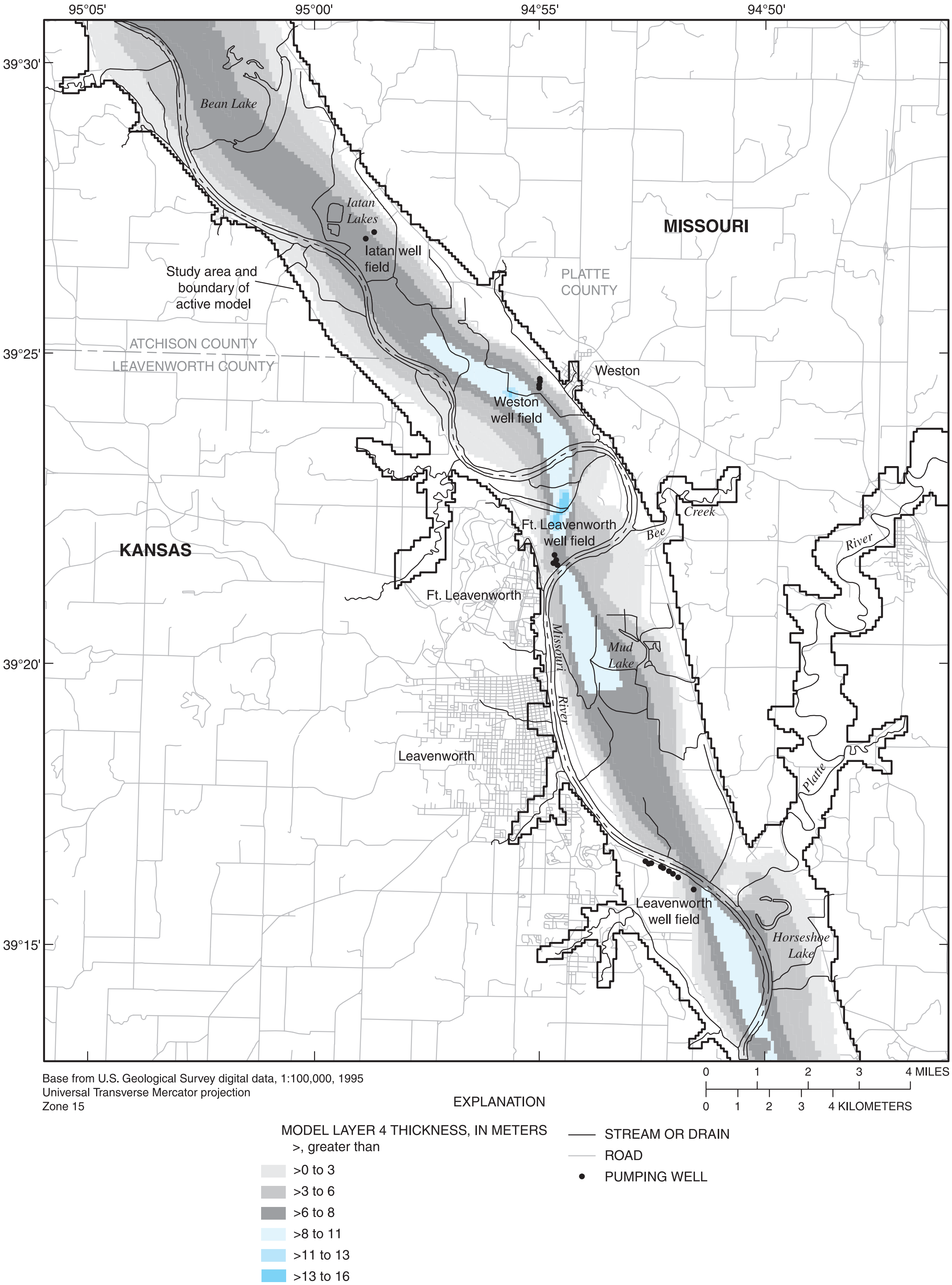


Figure 6. Thickness of model layers 1 through 4—Continued.

hydraulic properties. Layer 4 corresponds to the deep parts of the aquifer where gravels and sandy gravels are present and also was modeled using confined-aquifer hydraulic properties.

Boundary and Initial Conditions

Boundaries include rivers and lakes, the potentiometric surface, alluvial-valley walls and bedrock, edges of the study area, and pumping wells. The ground-water flow model simulates each of these boundaries as a specified head boundary, a specified flow boundary, a head-dependent flow (mixed boundary) condition, or a free-surface boundary (Franke and others, 1984). A specified-head boundary is used where the hydraulic head is maintained at a specified value as a function of time and position and ground-water flow across the boundary varies with respect to the difference in head between the boundary and the aquifer. A specified-flow boundary is used where the volume of water that flows across the boundary is a function of time and position and head varies as a function of flow. A head-dependent flow mixed boundary is used where the volume of flow across the boundary varies as a function of head at the boundary and varies as head varies. A free-surface boundary is used where the position of the boundary is not fixed but varies with time.

The Missouri and Platte Rivers, Bee Creek, and Bean, Iatan, Mud, and Horseshoe Lakes are represented in the model as head-dependent flow boundaries. For each cell in the model where a river or lake affects ground-water flow, the altitude of the river or lake stage must be assigned. Flow into or out of the aquifer at each of the cells where a river or lake is simulated is a function of the river or lake stage with respect to the altitude of the potentiometric surface, the hydraulic conductivity of the streambed or lakebed material, the cross-sectional area of flow between the river or lake bed and the aquifer, and the altitude of the potentiometric surface with respect to the altitude of the streambed or lakebed (McDonald and Harbaugh, 1988).

River stage in the Missouri and Platte Rivers was recorded hourly at nearby gaging stations at St. Joseph, Kansas City, and Sharps Station (fig. 1). The river stage used in each simulation was assigned by interpolation of the specified river stage between gaging stations along the midline of each river to each model cell that contained a river. River stage in the Platte River was interpolated along the midline of the river between the gaging station at Sharps Station and the Missouri River stage at the Platte River mouth. River stage in the ungaged Bee Creek was estimated using Missouri River stage at the mouth of Bee Creek and the slope of the land surface and interpolated along the midline of Bee Creek to the edge of the study area.

The shallower parts of the Missouri River channel located near the banks of the river correspond to the clay and silt found in layer 1 of the model. The channel bottom of the Missouri River intersects the sand and gravel found in the middle of the aquifer that corresponds to layer 2 of the model. Therefore, the bottom of the Missouri River was placed in layer 1 for model cells near the banks of the river and in layer 2 for model cells representing the deeper main channel of the river. The channel bottoms of the smaller Platte River and Bee Creek are within layer 1 of the model because they are shallower than the bottom of the Missouri River and intersect the shallower clay and silt in the upper parts of the aquifer. The effect on ground-water flow by lake stage in Bean, Iatan, Mud, and Horseshoe Lakes is similar to the effect of river stage on ground-water flow, and is simulated in the model with the same equation used for the rivers. The lake beds intersect the clay and silt of the upper parts of the aquifer and were placed in layer 1 of the model.

Numerous small ungaged streams and drainage ditches are in the study area. These streams can supply small amounts of recharge to the aquifer during runoff events and drain the aquifer when the potentiometric surface intersects the stream beds. Drainage ditches were constructed to drain agricultural land but can provide small amounts of focused recharge during periods of high rainfall. These ditches do not receive water from the uplands. Because recharge from these ungaged streams and ditches is considered to be small compared to drainage, they were simulated in the model as drains. Drains are head-dependent flow boundaries but, unlike the simulated rivers, cannot supply water to the aquifer. Water was removed from the aquifer by the drains at a rate proportional to the difference between the head in the aquifer and the altitude of the bottom of the drain and the hydraulic conductivity of the drain bottom material (McDonald and Harbaugh, 1988). Rivers, streams, drainage ditches and lakes are shown on figure 1.

The potentiometric surface, the upper boundary of the alluvial aquifer, was simulated in the model as a free-surface boundary and is the boundary across which areally distributed recharge enters the aquifer. Recharge to the model is applied to the top-most active cell in each vertical column and is varied temporally as a function of precipitation. Recharge is estimated to be between 2 and 25 percent of precipitation. Precipitation was recorded hourly with a rain gage located at Ft. Leavenworth between March 28, 2001, and September 26, 2002.

The alluvial valley walls and bedrock were simulated in the model as no-flow boundaries, a form of the specified flow boundary. The rate of water flow between the alluvial aquifer and the valley walls and bedrock has not been quantified. However, the hydraulic conductivities of the alluvial valley walls and bedrock are between 1 and 4 orders of magnitude less than hydraulic conductivities in the alluvial aquifer. Therefore, simulating the alluvial valley walls and bedrock as no-flow boundaries is reasonable because the amount of flow is a negligible percentage of the total flow.

Several boundaries of the model do not represent actual physical or ground-water flow boundaries of the alluvial aquifer, but are located where the alluvial aquifers of the Missouri and Platte Rivers intersect the model boundary. The locations of these boundaries were extended as far as practical from areas of well pumping to limit boundary effects on model results within the anticipated CRAs. Also, the orientation of each boundary was set parallel or sub-parallel to the estimated direction of ground-water flow at the boundary. This orientation further limits the effects of these boundaries on model results. These boundaries were simulated in the model as general head boundaries, a form of the head-dependent flow boundary that allows flow to enter or exit the model proportional to the difference between the water level in the model and the water level assigned to the boundary multiplied by a conductance term that limits the rate of flow (McDonald and Harbaugh, 1988). Water levels along the boundary were assigned to each general head boundary cell based on the river stage at the boundary plus the average gradient of the land surface from the river to the alluvial walls multiplied by the distance from the river.

Pumping wells are internal boundaries of the model where water was removed from the model at a specified rate equal to the discharge of each well. The total volume of water withdrawn annually from the aquifer by pumping of public-water-supply and industrial wells was obtained from each water supplier when available. The total annual volume of water removed from the aquifer by other wells in the study area was obtained from the Missouri Department of Natural Resources (2001). The depth of each pumping well in the model was based on the altitude of the screened interval, when known, or model layer 4 when the altitude of the screened interval was unknown.

Parameters and Model Zones

Parameters are used in the model to represent various hydraulic properties of the aquifer. Groups of cells in each layer in the model are assigned zones, and a parameter value is associated with each zone or group of zones. These properties include horizontal hydraulic conductivity, vertical hydraulic conductivity, porosity, specific storage, specific yield, and recharge rate. Lithologic descriptions recorded during the installation of wells and boreholes are the most numerous and have the greatest areal extent of all data types in the study area. The distribution of clay, silt, sand, and gravel within the aquifer was used to determine parameter zones among model cells for horizontal hydraulic conductivity, vertical hydraulic conductivity, porosity, specific yield, and specific storage. The distribution of clay, silt, sand, and gravel within the top layer of the model was used to determine zones for recharge rate as a percent of rainfall. Nomenclature for parameter zones are based on the type of parameter, the layer number, and the zone number (if more than one zone per layer). For example, the zone designation L3-Z1 denotes the 1st zone in layer 3. The layer number and zone number nomenclature is used for hydraulic conductivity parameter names. Parameter names, types, layer and zone numbers, and final values, units, and comments are listed in table 1. Recharge zones are shown in figure 7. Zones for each model layer are shown in figure 8.

Some parameters represent hydraulic properties that are not distributed using zones. These properties include streambed

Table 1. Parameter names, types, layer number, zone number, and final value.

[m/d, meter per day; --, not applicable; -, no data available]

Parameter name	Parameter type	Layer number	Zone number	Final parameter value	Unit	Comment
L1-Z1	Horizontal hydraulic conductivity	1	1	0.5	m/d	Porosity is 0.45.
L1-Z2	Horizontal hydraulic conductivity	1	2	5.0	m/d	Porosity is 0.4.
L1-Z3	Horizontal hydraulic conductivity	1	3	10.0	m/d	Porosity is 0.35.
L2-Z1	Horizontal hydraulic conductivity	2	1	.5	m/d	Porosity is 0.45.
L2-Z2	Horizontal hydraulic conductivity	2	2	5.0	m/d	Porosity is 0.4.
L2-Z3	Horizontal hydraulic conductivity	2	3	10.0	m/d	Porosity is 0.35.
L2-Z4	Horizontal hydraulic conductivity	2	4	50.0	m/d	Porosity is 0.35.
L2-Z5	Horizontal hydraulic conductivity	2	5	80.0	m/d	Porosity is 0.3.
L3-Z1	Horizontal hydraulic conductivity	3	1	10.0	m/d	Porosity is 0.45.
L3-Z2	Horizontal hydraulic conductivity	3	2	50.0	m/d	Porosity is 0.35.
L3-Z3	Horizontal hydraulic conductivity	3	3	120.0	m/d	Porosity is 0.35.
L4-Z1	Horizontal hydraulic conductivity	4	1	30.0	m/d	Porosity is 0.4.
L4-Z2	Horizontal hydraulic conductivity	4	2	120.0	m/d	Porosity is 0.35.

Table 1. Parameter names, types, layer number, zone number, and final value.—Continued

[m/d, meter per day; --, not applicable; -, no data available]

Parameter name	Parameter type	Layer number	Zone number	Final parameter value	Unit	Comment
VK1	Ratio of horizontal to vertical hydraulic conductivity	1	--	5	-	--
VK234	Ratio of horizontal to vertical hydraulic conductivity	2, 3, 4	--	1	-	--
SS1	Specific storage	1	--	.0014	-	Transient ground-water flow simulation only.
SY1	Specific yield	1	--	.01	-	Transient ground-water flow simulation only.
SS2	Specific storage	2	--	.0013	-	Transient ground-water flow simulation only.
SS3	Specific storage	3	--	.0012	-	Transient ground-water flow simulation only.
SS4	Specific storage	4	--	.0014	-	Transient ground-water flow simulation only.
MRV11	River conductance	1	1	.004	m/d	--
MRV12	River conductance	1	2	.004	m/d	--
MRV13	River conductance	1	3	.004	m/d	--
MRV21	River conductance	2	1	.0085	m/d	--
MRV22	River conductance	2	2	.0085	m/d	--
STREAMS	Drain conductance	1	--	.001	m/d	Small streams simulated using drain package.
DRAINS	Drain conductance	1	--	.000001	m/d	--
WELLS	Well pumping rate		--	5.3		Factor to convert gallons per minute to cubic meters per day.
RECH1	Recharge as a percent of precipitation	1	1	.05	--	--
RECH2	Recharge as a percent of precipitation	1	2	5	--	--
RECH3	Recharge as a percent of precipitation	1	3	8.5	--	--
RECH4	Recharge as a percent of precipitation	1	4	8.5	--	--
PLATTE	Streambed conductance	1	--	.001	m/d	--
BEE	Streambed conductance	1	--	.001	m/d	--
BEAN	Bean Lake lakebed conductance	1	--	.001	m/d	Bean Lake simulated using river package.

Table 1. Parameter names, types, layer number, zone number, and final value.—Continued

[m/d, meter per day; --, not applicable; -, no data available]

Parameter name	Parameter type	Layer number	Zone number	Final parameter value	Unit	Comment
IATAN	Iatan Lake lakebed conductance	1	--	0.001	m/d	Iatan Lake simulated using river package.
MUD	Mud Lake lakebed conductance	1	--	.001	m/d	Mud Lake simulated using river package.
HORSE	Horseshoe Lake lakebed conductance	1	--	.001	m/d	Horseshoe Lake simulated using river package.
GHB1	General head boundary	1	--	2.0	m/d	--
GHB2	General head boundary	2	--	50.0	m/d	--
GHB3	General head boundary	3	--	100.0	m/d	--
GHB4	General head boundary	4	--	100.0	m/d	--

conductances, drain conductances, well pumping rates, and rate of flow across general head boundaries. Each of these properties is distributed within the model using the row and column number of each cell.

Hydraulic Properties

Hydraulic conductivity or transmissivity data are available for 16 locations within or near the study area (table 2). However, locations for which lithologic data are known are more numerous and have the widest distribution within the study area. Aquifer tests conducted during previous investigations to determine hydraulic conductivity or transmissivity typically were performed in wells where the lithology and altitude of the screened interval were known.

Hydraulic data were used to associate an initial hydraulic conductivity value with a specific lithology for this report. Typical ranges of the hydraulic conductivities of clays, silts, sands, and gravels (Freeze and Cherry, 1979; Driscoll, 1986; table 3) were used for initial values where hydraulic conductivity data were unavailable for a specific lithology.

Streambed hydraulic conductivity was calculated in MODFLOW (McDonald and Harbaugh, 1988) by multiplying the hydraulic conductivity of the model cell within each river reach by the area of the river within the cell. This value was adjusted during model calibration for each river.

Drain conductances were calculated in the same manner as the streambed conductances. All drain bottoms are within layer 1 of the model. The altitude of the drain bottom within layer 1 was assigned using a constant altitude of 1 m less than the land surface altitude for agricultural ditches or 2 m less than the land surface altitude for streams.

The simulated flow of water between model cells in adjacent model layers is controlled by the vertical conductance term. Vertical conductance, or leakance, is calculated within MODFLOW from the thickness of each model layer between its node and common layer contact and the vertical hydraulic conductivity of each layer (McDonald and Harbaugh, 1988). The vertical conductance terms between cells of adjacent layers simulate the presence of vertical anisotropy in clay, silt, and fine sand deposits. The vertical anisotropy was assumed to decrease with depth because of the increase in particle grain size with depth. There also is a high probability that fine grained layered depositional features such as overbank and channel fill deposits have been reworked or removed by erosional and depositional processes of the Missouri River. Therefore, the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity between adjacent cells of layers 1 and 2 was 5 to 1. The ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity between layers 2, 3, and 4 was 1 to 1.

A specific yield of 0.01 was used for layer 1. A storage coefficient of 0.0014 was used for layer 1, 0.0013 was used for layer 2, 0.0012 was used for layer 3, and 0.0013 was used for layer 4 and represents conditions where water is released from storage because of expansion of the water or compaction of the aquifer material and not actual drainage of the aquifer.

Calibration

The ground-water flow model was calibrated by adjusting model input data and model geometry until model results matched field observations within an acceptable level of accuracy (Konikow, 1978). Parameters adjusted during the calibration process include horizontal hydraulic conductivity, vertical hydraulic conductivity between model layers, specific storage,

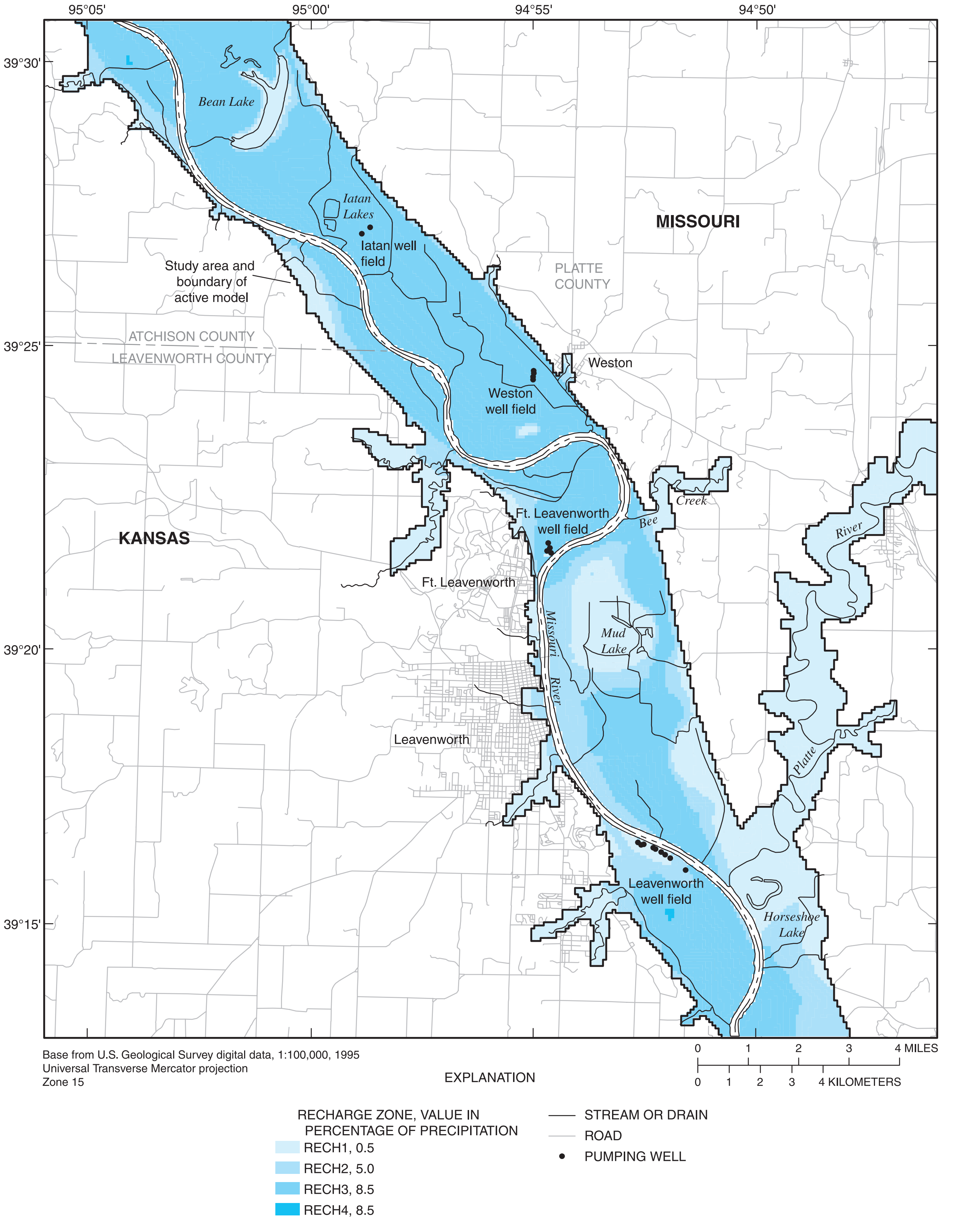


Figure 7. Parameter zones for recharge.

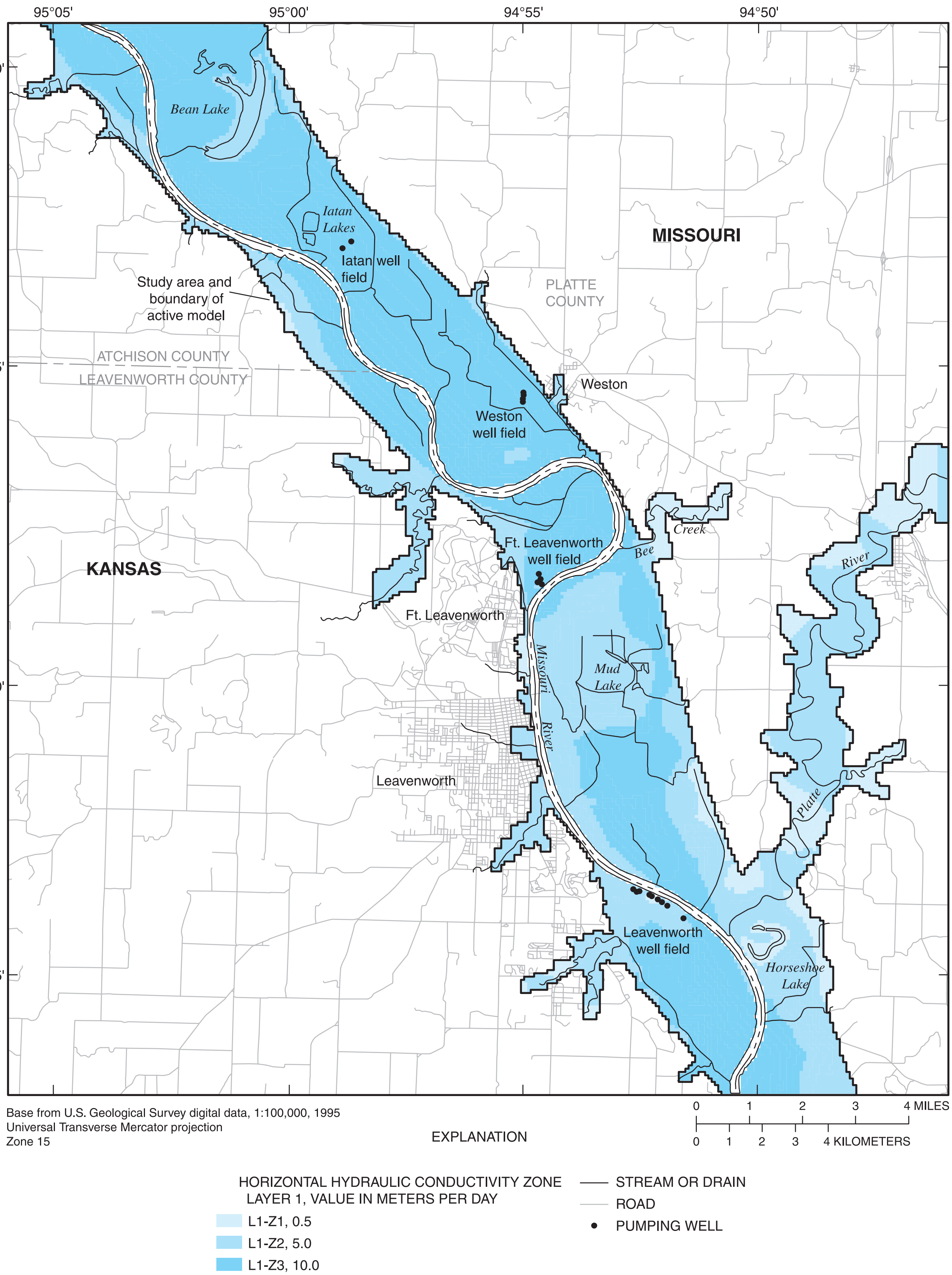


Figure 8. Parameter zones for model layers 1 through 4.

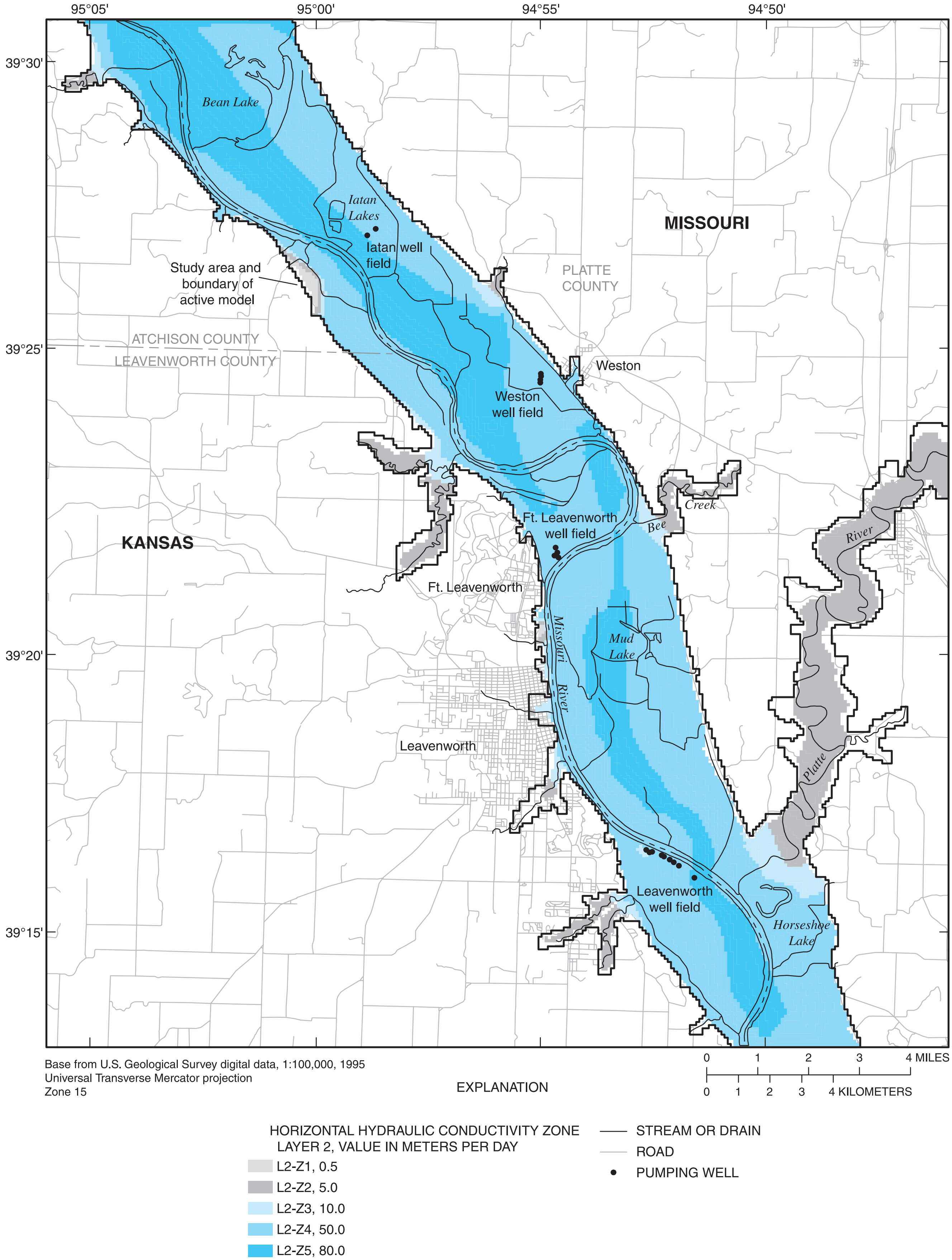


Figure 8. Parameter zones for model layers 1 through 4—Continued.

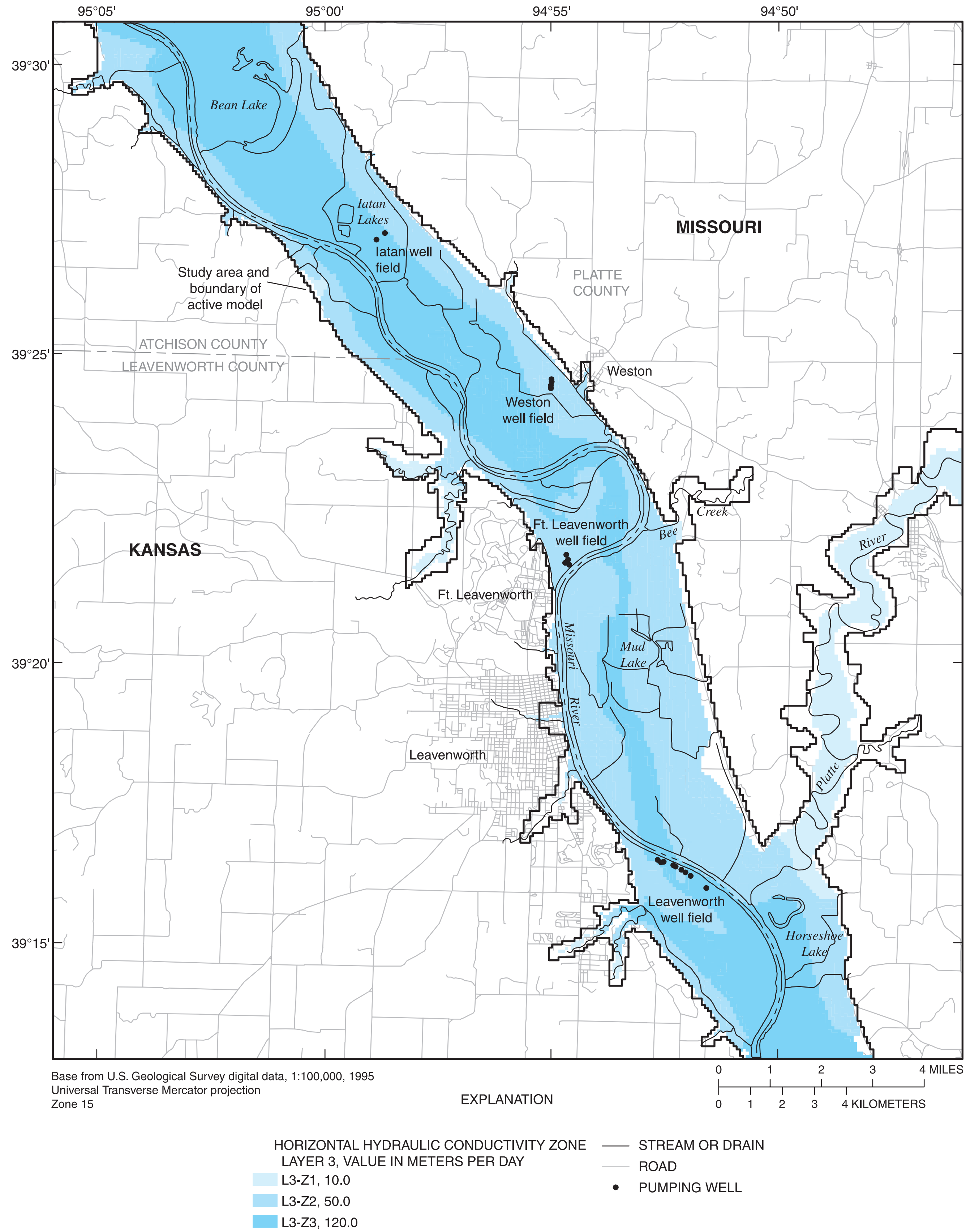
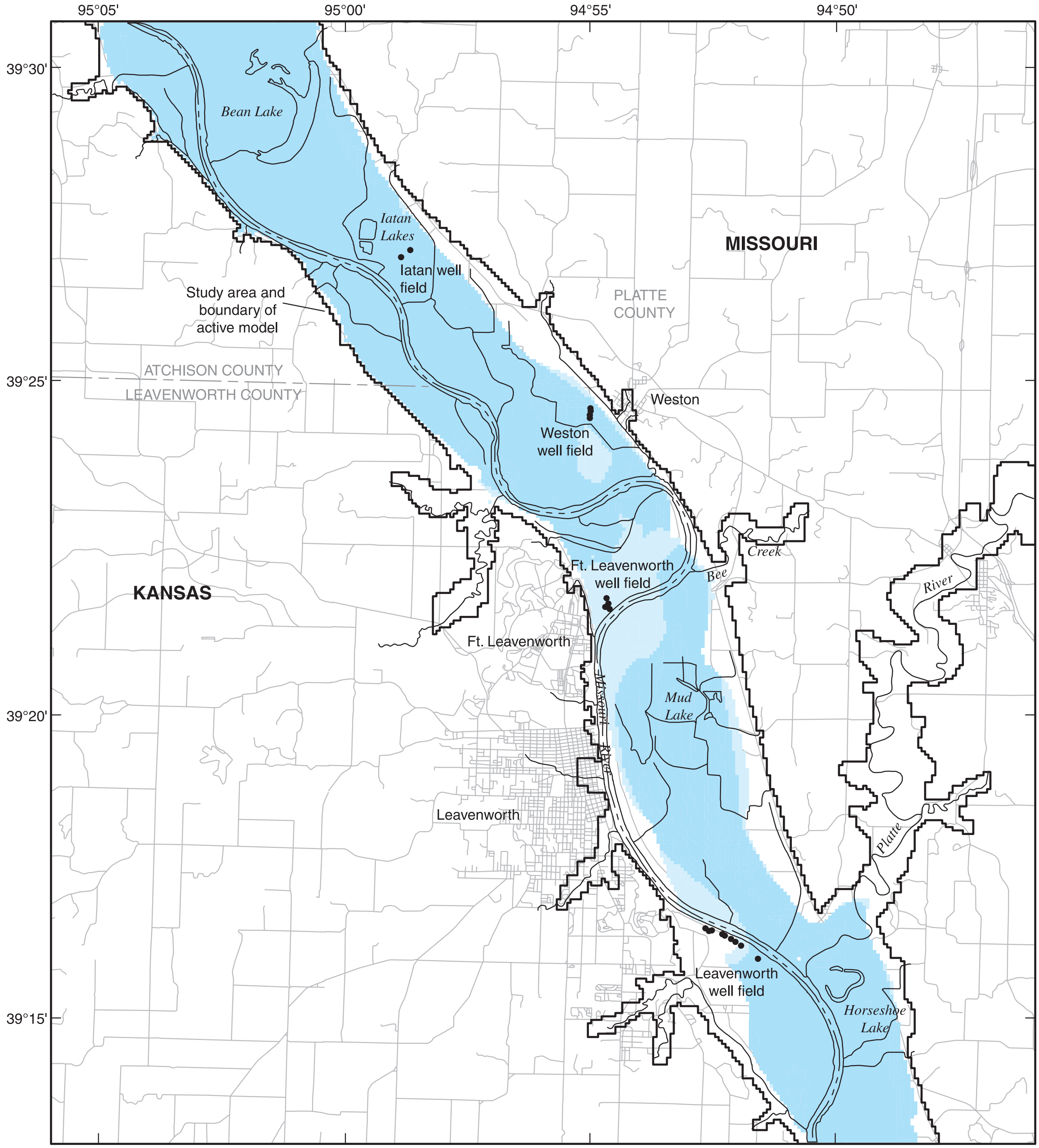


Figure 8. Parameter zones for model layers 1 through 4—Continued.



Base from U.S. Geological Survey digital data, 1:100,000, 1995
Universal Transverse Mercator projection
Zone 15

0 1 2 3 4 MILES
0 1 2 3 4 KILOMETERS

EXPLANATION

HORIZONTAL HYDRAULIC CONDUCTIVITY ZONE LAYER 4, VALUE IN METERS PER DAY
- L4-Z1, 30.0
- L4-Z2, 120.0

- STREAM OR DRAIN
- ROAD
- PUMPING WELL

Figure 8. Parameter zones for model layers 1 through 4—Continued.

Table 2. Horizontal hydraulic conductivity, transmissivity, and storage data.

[na, not applicable; m/d, meter per day; m^2/d, meter squared per day; --, no data]

Well number (fig. 1)	Well name	Aquifer test	Horizontal hydraulic conductivity (m/d)	Trans-missivity (m^2/d)	Storage coefficient	Source
63	USGS WELL 1	Slug	92	--	--	Ecology and Environment, Inc., 2000.
64	USGS WELL 2	Slug	13	--	--	Ecology and Environment, Inc., 2000.
67	USGS WELL 3	Slug	78	--	--	Ecology and Environment, Inc., 2000.
70	USGS WELL 4	Slug	95	--	--	Ecology and Environment, Inc., 2000.
61	USGS WELL 5	Slug	48	--	--	Ecology and Environment, Inc., 2000.
62	USGS WELL 6	Slug	16	--	--	Ecology and Environment, Inc., 2000.
71	USGS WELL 7	Slug	7	--	--	Ecology and Environment, Inc., 2000.
56	USGS WELL 8	Slug	109	--	--	Ecology and Environment, Inc., 2000.
57	USGS WELL 9	Slug	4	--	--	Ecology and Environment, Inc., 2000.
65	USGS WELL 10	Slug	37	--	--	Ecology and Environment, Inc., 2000.
66	USGS WELL 11	Slug	15	--	--	Ecology and Environment, Inc., 2000.
59	USGS WELL 12	Slug	82	--	--	Ecology and Environment, Inc., 2000.
60	USGS WELL 13	Slug	9	--	--	Ecology and Environment, Inc., 2000.
na	Lewis and Clark State Park	Drawdown	126	3,105	0.17	Emmett and Jeffery, 1969.
na	Ft. Leavenworth water supply well PW-9	Drawdown	196	5,341		Burns and McDonnell, 1998.
na	T-8 R-22E Sec. 13BAA	Drawdown	298	7,452	.001 - .004	Denne and others, 1998.

Table 3. Horizontal hydraulic conductivities for clay, silt, sand, and gravel.

[Freeze and Cherry, 1979; Driscoll, 1986; m/d, meter per day]

Lithology	Horizontal hydraulic conductivity range, in m/d
Clay	10^{-7} to 10^{-4}
Silt	10^{-4} to 1
Sand	10^{-2} to 10^{3}
Gravel	10^{2} to 10^{5}

specific yield, river conductance, drain conductance, and recharge rates.

After each change in one of these parameters, the simulation was run and simulated ground-water levels were compared to observed ground-water levels. The model accuracy was calculated using the root mean square (RMS) error between actual hydraulic head measurements and model-generated hydraulic head at the end of each model run. Model accuracy is increased by minimizing the RMS error. The RMS error measures the absolute value of the variation between measured and simulated hydraulic heads at control points. The equation to calculate the RMS error is:

$$RMSerror = \sqrt{\frac{e_1^2 + e_2^2 + e_3^2 + \ldots + e_n^2}{n}}$$

where

e is the difference between measured hydraulic heads and the simulated hydraulic heads; and

n is the number of control points.

The accuracy of water-level measurements was the basis for choosing the RMS error used to determine if the model simulation was acceptable. Most ground-water levels were measured with a steel tape or an electric water-level measuring tape to the nearest 0.003 m. Hourly ground-water level measurements were measured with vented pressure transducers to the nearest 0.003 m. Therefore, the largest error from measurement of hourly ground-water levels was 0.003 m. Water levels of public-water-supply wells were measured by personnel on site using air-line methods. Historical water levels for wells were measured or estimated using unknown techniques. For these water-level measurements, the accuracy is assumed to be within 0.3 m.

Another component of the accuracy of the water-level measurement is the accuracy of the measuring point altitude. The measuring point altitudes for most wells used in this study were obtained using standard surveying or global positioning system methods. The accuracy of these altitudes are between 0.01 and 0.15 m. The measuring point altitude of a few wells in the study area were estimated from 7.5-minute topographic maps. The vertical accuracy of land-surface altitudes from these maps is one-half of the contour interval. The contour interval on topographic maps of the alluvial valley is 5 or 10 feet (1.5 or 3 m) and the accuracy of measuring point altitudes from these wells is 0.75 or 1.5 m, respectively. Therefore, the largest possible error in water level altitudes is 1.5 m.

Missouri River stage was measured at USGS gaging stations at St. Joseph and Kansas City, and Platte River stage was measured at the USGS gaging station at Sharps Station. These gages measure river stage to the nearest 0.003 m. River stage was distributed among model cells using linear interpolation between gages along the midline of each river. Manual measurements of Missouri River stage were made from the Missouri State Highway 45 bridge in 2001 on June 11, August 1, September 19, and November 16, and in 2002 on January 9 and March 12. These measurements were compared to interpolated river stage for the same location to obtain an estimate of the accuracy of estimating Missouri River stage using linear interpolation between the St. Joseph and Kansas City gages. The largest absolute difference between measured and interpolated stage was 0.87 m, and the smallest was 0.11 m; the differences ranged from -0.87 to 0.68 m.

The maximum possible error for water-level measurements is the sum of the maximum errors caused by water-level measurement errors, measuring point altitude errors, and errors introduced by interpolation of river stage. The chance that the maximum error would occur at any well is small. More likely to occur is a combination of errors of varying value and sign. However, knowledge of these errors and their magnitude is necessary to determine the appropriate RMS error to assess model accuracy. The accepted RMS errors for all the model calibrations discussed in the following sections is below the largest maximum measurement errors listed in table 4.

Quasi-Steady-State and Transient Calibration

The strategy for calibration of the ground-water flow model was to use both quasi-steady-state hydraulic head data and transient hydraulic head data. Steady-state conditions occur when inflow to the system equals outflow from the system. The quasi-steady-state calibration was used to test the conceptual model of ground-water flow, test the appropriateness of simulated boundary conditions, and obtain approximate transmissivity and recharge arrays in preparation for more rigorous transient calibration. The transient calibration was used to fine tune the model hydraulic properties determined for the quasi-steady-state simulation.

The quasi-steady-state hydraulic head data were obtained from the November 16, 2001, ground-water level data measured in the 13 wells installed for this study and from historic ground-water level data from 51 wells in the study area. Well locations are shown in figure 9 and the well number and model simulated and average observed water level of each well used in the quasi-steady-state calibration is listed in table 5. The data

Table 4. Water-level measurement error sources and maximum error values.

[m, meter]

Measurement type	Measurement error (m)	Measuring point altitude error (m)	Total maximum error (m)
Hourly ground-water data	0.003	0.15	0.153
Manual ground-water data	.3	.15	.45
Historical ground-water data	.3	1.5	1.8
Interpolated river-stage data	.87	.15	1.02

represent an approximation of steady-state conditions where water levels, river stage, antecedent precipitation (used to calculate recharge rates), and well pumping data were readily available. The rationale for using a quasi-steady-state calibration was based on the complexity and size of the model and the availability of water-level data for the study area for November 2001, when hydrologic conditions were relatively stable and river stage was close to the annual average. The historical water-level data from 51 wells in the study area were used to calibrate the model for parts of the study area where current ground-water level data were unavailable.

The areal distribution of hydraulic conductivity was based on the lithologic distribution within each layer. Recharge rates were correlated to precipitation and spatially distributed according to the lithologic distribution of layer 1. Pumping rates for wells in the study area were determined using pumping records from water suppliers and industries or from the Missouri Department of Natural Resources (2001) when otherwise unavailable.

The assignment of hydraulic conductivity based on lithologic distribution, recharge rate based on the lithologic distribution of the top layer, inclusion of well pumping, and head-dependent flow boundaries to simulate the effects of small streams and ditches on ground-water flow reduced the RMS error to a value of 0.82 m. The level of accuracy of the simulation in representing the November 16, 2001, hydraulic head distribution was accepted because the hydraulic head distribution for that time was not completely at steady state. Further calibration of the quasi-steady-state model would have resulted in erroneously changing model input parameters to match a hydraulic head distribution that resulted partially from transient ground-water flow. The difference between flow into the model and flow out of the model across all model boundaries was 0 percent of total flow for the quasi-steady-state calibration. The flow budget for the quasi-steady-state calibration simulation is shown in table 6. Cumulative volumes for the quasi-steady-state calibration simulation were calculated based on a model assigned single stress period of 11.774 days. Slight discrepancies between the cumulative volumes and the rates reported in the simulation output are caused by rounding errors.

Transient calibration of the ground-water flow model was accomplished by varying model parameters and matching ground-water levels measured between March 26, 2001, and July 25, 2002, with the simulated hydraulic-head distribution. This was done by measuring the changes in various hydrologic stresses that affected the distribution of hydraulic head and simulating those stresses in the model. A stress on the ground-water flow system was any change in river stage, recharge, or well pumping that caused the distribution of hydraulic head to change. These changes occurred as gradual increases or decreases of river stage, intermittent and varying rates of recharge from precipitation, and intermittent or constant pumping of wells at varying rates. The ground-water flow model applied areal and temporal changes in stress to the ground-water flow system during a series of stress periods. Within each stress period, river stage, recharge, and pumping rates of wells were held constant. Each stress period in the transient calibration was 1 day and was divided into three time steps. In each stress period the first time step was 3.43 hours, the second time step was 6.86 hours, and the third time step was 13.71 hours.

River stage for each stress period was assigned to each river model cell using interpolation methods previously discussed in the “Boundary and Initial Conditions” section. Average daily river-stage altitudes for each gaging station in the study area are shown in figure 10. Recharge for each stress period was assigned to the top most active cell in each vertical column using daily precipitation. Precipitation amounts from March 26, 2001, to July 25, 2002, are shown in figure 11. The percentage of precipitation that was supplied to the model as recharge is shown in table 1 for each zone in layer 1. Average well pumping rates for each stress period were assigned to each model cell that contained a pumping well or wells in the transient calibration simulation.

The transient calibration of the ground-water flow model used hydraulic head data obtained from 13 wells located near Ft. Leavenworth. Hourly measurements were collected between April 5, 2001, and July 25, 2002, for wells 61, 62, 70, and 71; between April 6, 2001, and July 25, 2002, for wells 56, 57, 59, 60, 63, 64, 65, and 66; and between April 14, 2001, and July 25, 2002, for well 67. The model was allowed to run 548 simulated

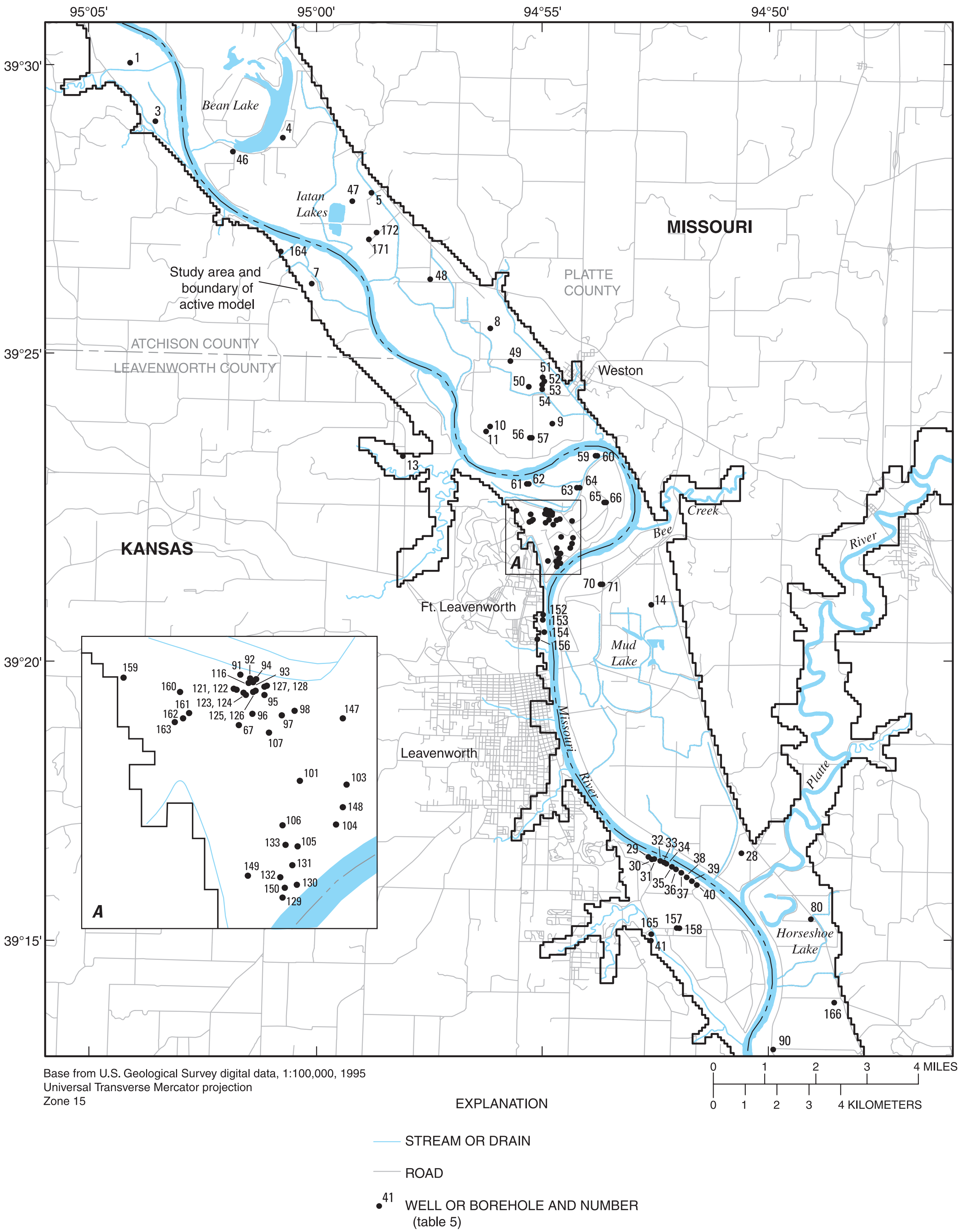


Figure 9. Location of wells in the study area.

Table 5. Well numbers and simulated and observed ground-water altitudes.

[--, not applicable]

Well number (fig. 9)	Ground-water altitude, in meters		Additional well description
	Simulated	Observed	
1	234.41	233.78	--
3	234.26	234.70	--
4	233.94	235.15	--
5	233.30	233.68	--
7	232.92	233.48	--
8	232.34	233.32	--
9	231.24	231.34	--
11	231.64	230.73	--
14	229.88	230.73	--
28	227.43	229.21	--
46	233.96	234.16	--
47	233.29	232.38	--
48	232.81	232.86	--
49	231.92	233.00	--
50	231.50	231.66	--
56	231.32	231.61	USGS WELL8
57	231.32	231.59	USGS WELL9
59	230.78	230.43	USGS WELL12
60	230.78	230.43	USGS WELL13
61	231.00	230.97	USGS WELL5
62	231.00	230.97	USGS WELL6
63	230.74	230.53	USGS WELL1
64	230.74	230.53	USGS WELL2
65	230.48	230.18	USGS WELL10
66	230.48	230.20	USGS WELL11
67	230.48	230.23	USGS WELL3
70	229.77	230.32	USGS WELL4
71	229.77	230.32	USGS WELL7
80	227.29	228.83	--
90	226.30	226.59	--
91	230.64	230.09	FTL10W-2
93	230.61	230.19	FTL10W-3

Table 5. Well numbers and simulated and observed ground-water altitudes.—Continued

[--, not applicable]

Well number (fig. 9)	Ground-water altitude, in meters		Additional well description
	Simulated	Observed	
94	230.61	230.14	FTL10W-4
95	230.56	228.97	PZ-1
96	230.51	229.18	PZ-2
98	230.49	229.23	PZ-4
101	230.07	229.76	PZ-6
103	230.07	228.63	PZ-7
104	229.81	229.08	PZ-9
105	229.43	229.81	PZ-10
106	229.68	228.88	PZ-8
107	230.41	228.75	PZ-5
116	230.61	230.94	FTL10W-1
121	230.60	229.84	FTL10W-6
122	230.60	229.91	FTL10W-7
123	230.58	229.85	FTL10W-8
124	230.58	229.80	FTL10W-9
125	230.57	230.21	FTL10W-10
126	230.57	230.25	FTL10W-11
127	230.58	230.03	FTL10W-12
128	230.58	230.08	FTL10W-13
131	229.22	227.69	WELL 7
133	229.32	227.08	WELL 9
148	229.93	229.21	--
149	229.49	228.30	--
154	229.35	228.91	FTL03W-2
157	227.21	227.63	WELL 5
159	230.82	230.74	FTL57W-1
160	230.66	230.34	FTL57W-2
161	230.57	230.57	FTL57W-3
162	230.57	230.68	FTL57W-4
163	230.56	230.58	FTL57W-5
165	227.17	228.74	--
166	227.01	226.15	--

Table 6. Volumetric budget for quasi-steady-state calibration simulation.

[m^3, cubic meter; m^3/d, cubic meter per day]

	Cumulative volumes (11.774 days) m^3		Rates m^3/d	
	In	Out	In	Out
Storage	0	0	0	0
Constant head	0	0	0	0
Wells	0	175,040.0000	0	14,867.0000
Drains	0	806.20	0	68.4720
River leakage	109,220.0000	81,237.0000	9,276.5000	6,899.6000
Head dependent boundaries	19,469.0000	37,574.0000	1,653.5000	3,191.2000
Recharge	165,960.0000	0	14,095.0000	0.0000
Total	294,650.0000	294,660.0000	25,025.0000	25,026.0000
Total in - out	-10.0		-1.0	
Percent discrepancy	.00		.00	

days divided into daily stress periods. Simulated and observed ground-water levels are shown for the 13 wells in figure 12.

The RMS error calculated using 548 daily water-level observations for 13 wells (6,172 observations) and the corresponding simulated water levels was 0.33 m for the accepted calibration simulation. This value is less than the maximum measurement errors (table 4) and indicates the acceptability of the calibrated model. Calibrated parameter values for the ground-water simulations are listed in table 1.

Sensitivity Analysis

A sensitivity analysis was performed to assess the response of the model simulation to changes in various input parameter values. The model is considered sensitive to a parameter when a change of the parameter value changes the distribution of simulated hydraulic head. When the model is sensitive to an input parameter, the value of that parameter within the model is more accurately determined during model calibration because small changes to the parameter value cause large changes in hydraulic head. If a change of parameter value does not change the simulated hydraulic head distribution, the model is considered insensitive to that parameter. When the model is insensitive to an input parameter, the value of that parameter within the model is more difficult to accurately determine from model calibration because large changes to the parameter do not cause large changes in hydraulic head.

Composite scaled sensitivities are calculated by MODFLOW-2000 using scaled sensitivities for all observations and indicate the total amount of information provided by the observations for the estimation of a parameter (Hill, 1998). Composite scaled sensitivities are shown for both the quasi-steady-state and transient calibration simulations for parameters with composite scaled sensitivities greater than 0.01 (fig. 13). The model is more sensitive to a parameter with a large composite sensitivity value than to a parameter with a small value. The quasi-steady-state simulation is most sensitive to the WELLS (well pumping), RECH4 (recharge in layer 1, zone 4), L3-Z2 (horizontal hydraulic conductivity in layer 3, zone 2), and RECH3 (recharge in layer 1, zone 3) parameters. The transient simulation is most sensitive to the RECH3, MRV21 (Missouri River conductance layer 2, zone 1), MRV22 (Missouri River conductance layer 2, zone 2), and L3-Z2 parameters. Composite scaled sensitivities for parameters differ between the quasi-steady-state and transient calibration simulations for several reasons. Ground-water level data used for the quasi-steady-state calibration are from locations throughout the study area, but ground-water level data used for the transient calibration were measured hourly from the 13 wells near Ft. Leavenworth. Observations may be highly sensitive to a parameter change if the observation is located where a parameter change has great effect. For example, the WELLS parameter has the largest composite sensitivity for the quasi-steady-state simulation because more observations are located close to or are based on observations within pumping wells. Observations used in the transient calibration were located farther from pumping wells, and the composite sensitivity for the WELLS parameter is smaller for the transient calibration. The RECH3 parameter has the largest composite sensitivity for the transient calibration because most of the observations used were located in the RECH3 zone. The transient calibration is more sensitive to the conductance of the

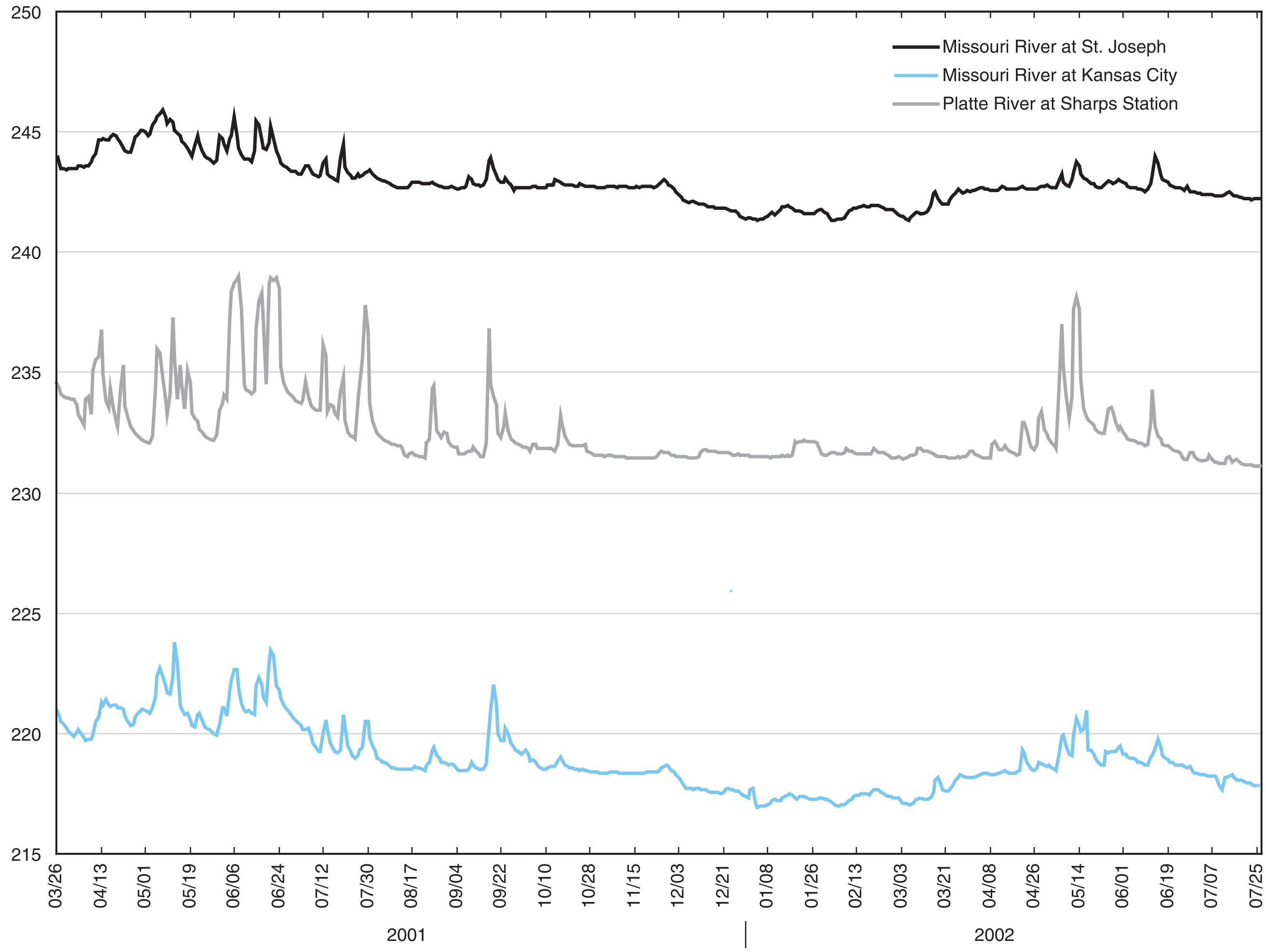


Figure 10. Average daily river-stage altitude at St. Joseph, Kansas City, and Sharps Station, Missouri, from March 26, 2001, to

Missouri River (MRV21, MRV22) than the quasi-steady-state calibration because river stage changed with each stress period in the transient calibration, and ground-water levels in all wells used for the transient calibration changed in response to changes in Missouri River stage.

One percent scaled sensitivities indicate how much a simulated value of head would change for an observation location based on a one-percent increase in the value of the parameter and show the relative importance of a parameter value between observation locations. One percent scaled sensitivities for ground-water level observations used for the quasi-steady-state calibration simulation are shown for selected parameters in figure 14. Positive sensitivities indicate an increase in head with an increase in parameter value; negative sensitivities indicate a decrease in head with an increase in parameter value. Different one-percent sensitivities for different water-level observations are caused by the location of the observed head value (location of the measured well) with respect to the value of the model parameter. A water-level observation from a well located close to the Missouri River will be more sensitive to the MRV21 (Missouri River conductance layer 2, zone 1) parameter than a well located far from the river. Wells 28, 105, and 131 are located close to the Missouri River (fig. 9) and water levels have larger one-percent sensitivities to MRV21 (fig. 14) than water levels in other wells. Similarly, water-level observations from a well screened at a depth and represented by the L3-Z2 (hydraulic conductivity layer 3, zone 2) parameter will have a larger one-percent sensitivity to that parameter than to a parameter representing hydraulic conductivity in layer 1. For example, wells 105 and 133 (a pumping well) have large positive one-percent sensitivities to the L3-Z2 parameter, but well 14 has a large negative one-percent sensitivity to the L3-Z2 parameter. Increasing the value of L3-Z2 causes an increase in simulated water level for well 105 because it is close to the Missouri River and the Ft. Leavenworth well field (fig. 9). More water can supply the nearby pumping well from the river when L3-Z2 is larger, drawdown is reduced near the well field, and simulated ground-water levels increase. Well 133 is a pumping well in the Ft. Leavenworth well field. Increasing the L3-Z2 parameter value increases the simulated ground-water level for well 133

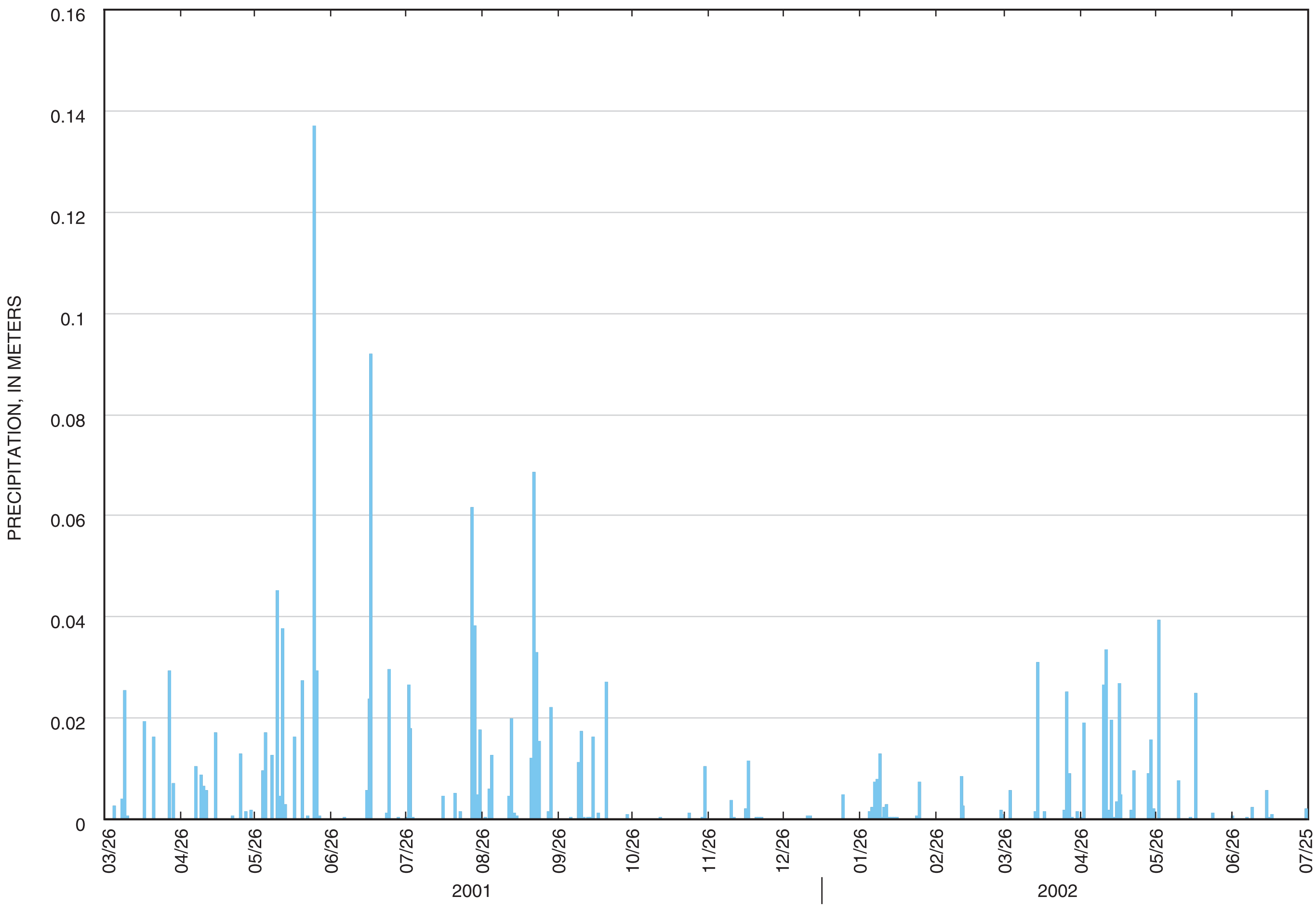


Figure 11. Precipitation between March 26, 2001, and July 25, 2002.

because drawdown is less in a pumping well when hydraulic conductivity is larger and more water can supply the well from the Missouri River. Well 14 is located farther from the Missouri River and is not located near well pumping (fig. 9). Increasing the L3-Z2 parameter value allows ground water to move more quickly to the Missouri River and simulated ground-water levels decrease.

Ground-water level data from June 13, 2001, to July 31, 2001, were used to calculate the one-percent scaled sensitivities for the transient ground-water flow simulation because of excessive execution times required to calculate sensitivities for the entire 548 days of data. The one-percent scaled sensitivities for selected parameters for each observed head value in the transient calibration simulation are shown for well 63 (USGS Well 1) in figure 15 to illustrate how one-percent sensitivities for ground-water level observations change with time as different stresses are applied to the model. The change in sensitivity to the RECH3 parameter is caused by changes in recharge with time. Rainfall events increase the sensitivity of the simulated ground-water level to the RECH3 parameter by a large amount on the day the event occurred, but the sensitivity decreases during subsequent stress periods where no rainfall occurs. Similarly, changes in the MRV21 parameter are caused by changes in stage of the Missouri River with time. The one-percent sensitivity to the SS2 (specific storage for layer 2) parameter changes as water enters and is released from storage. This occurs when recharge occurs and water enters storage (negative one-percent sensitivity), and when the Missouri River stage decreases and water is released from storage (positive one-percent sensitivity).

Model Limitations

A ground-water model is a simplified approximation of actual conditions. The accuracy of the ground-water model results depends on the accuracy of the input data. The ground-water flow model for this study was constructed with available historical and site specific hydrologic data to determine ground-water flow direction, contributing recharge areas to public-water-supply wells, and ground-water travel time in the

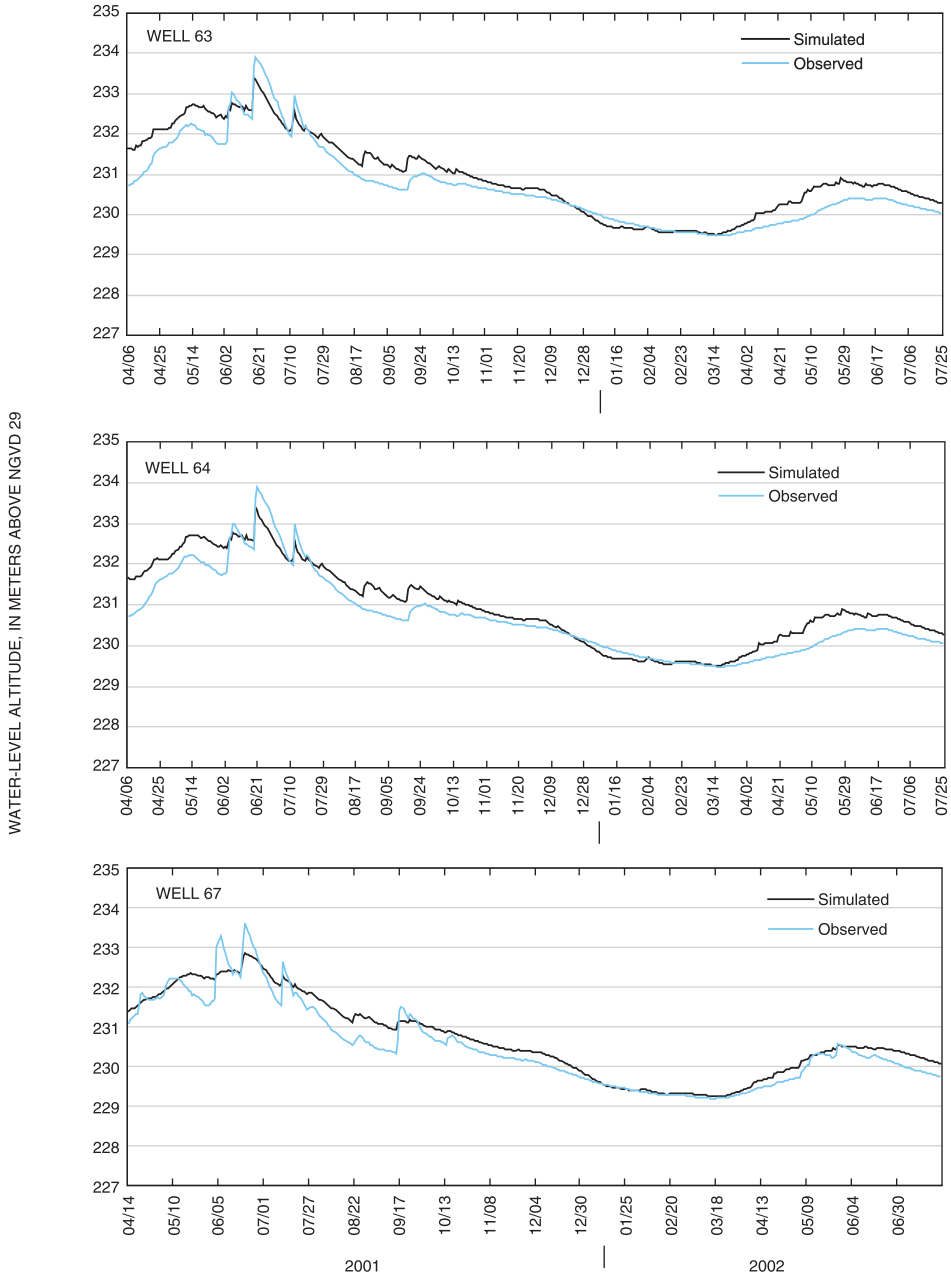


Figure 12. Simulated and observed ground-water levels from April 5, 2001, to July 25, 2002, for 13 wells in the study area.

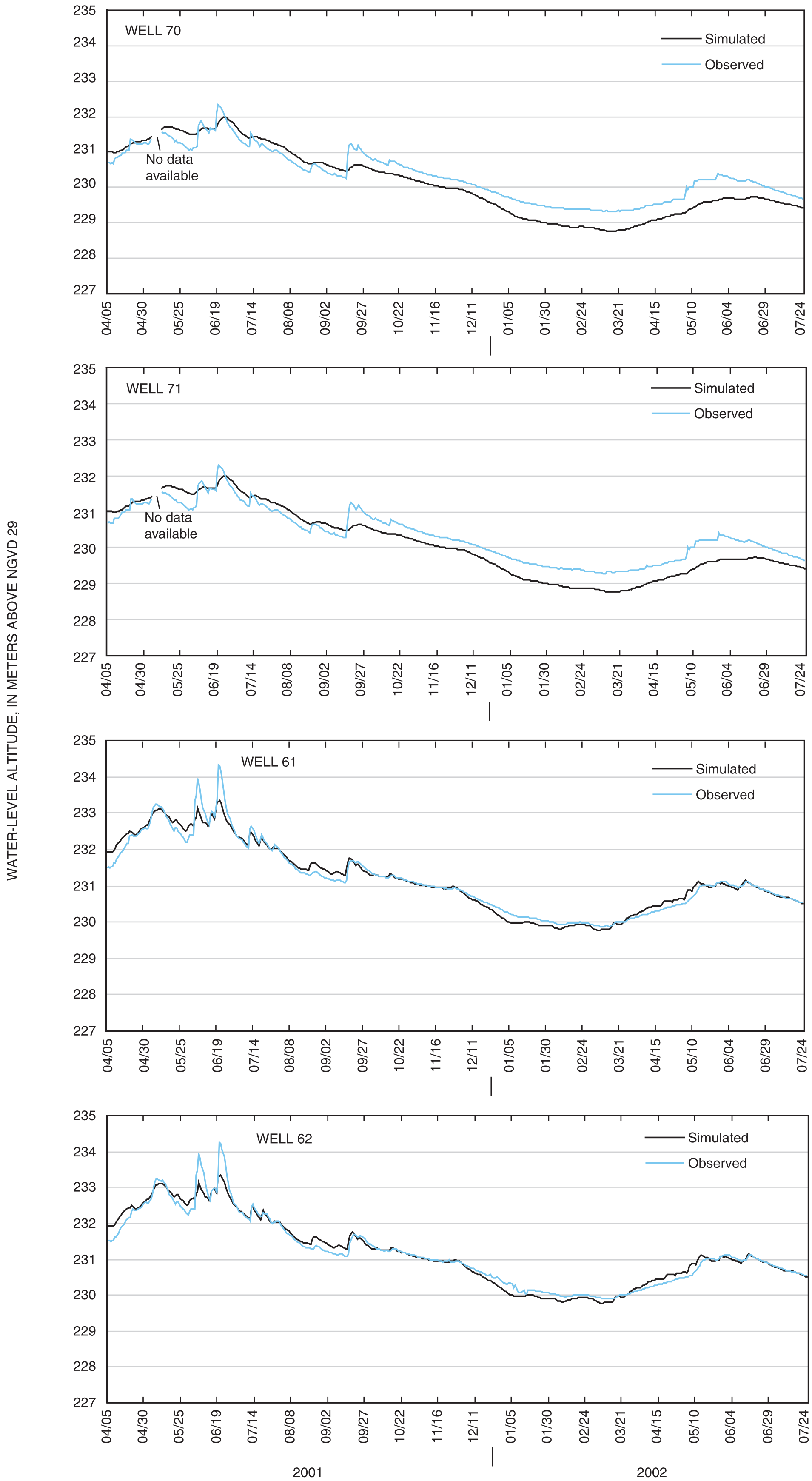


Figure 12. Simulated and observed ground-water levels from April 5, 2001, to July 25, 2002, for 13 wells in the study area—Continued.

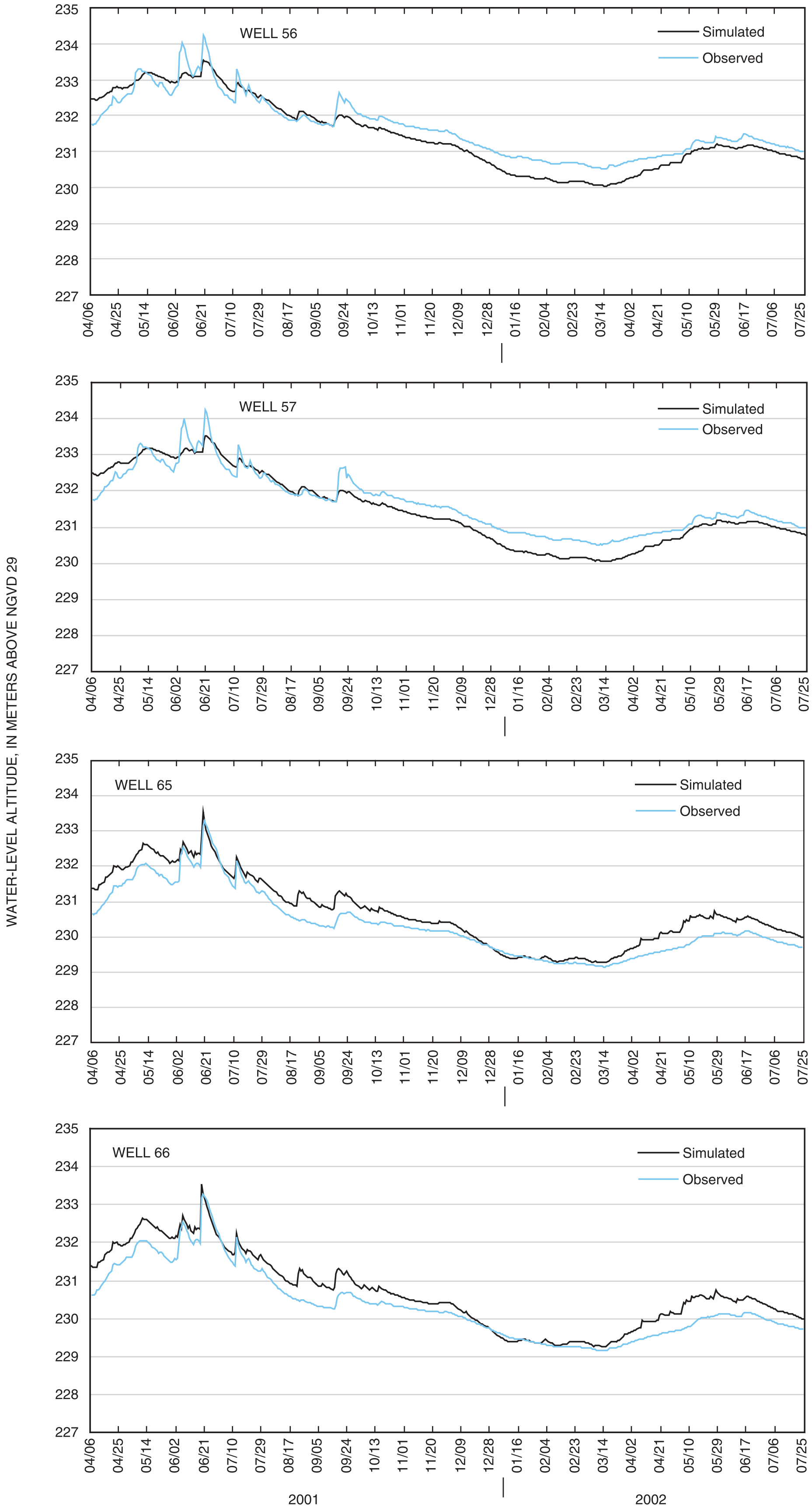


Figure 12. Simulated and observed ground-water levels from April 5, 2001, to July 25, 2002, for 13 wells in the study area—Continued.

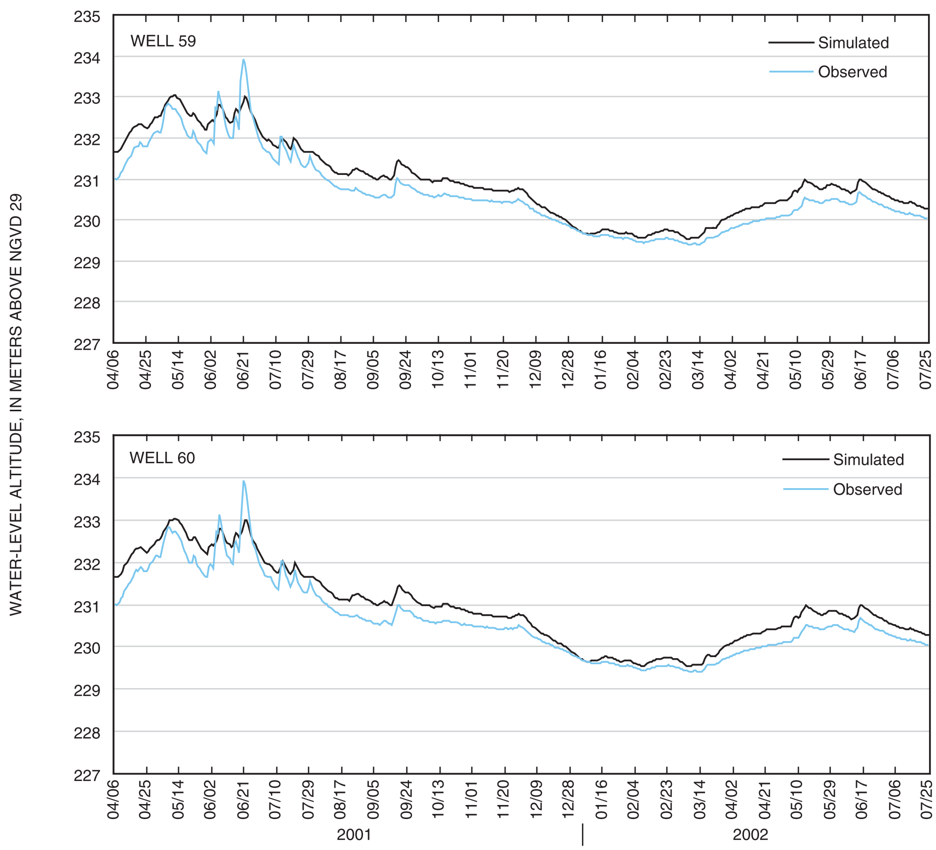


Figure 12. Simulated and observed ground-water levels from April 5, 2001, to July 25, 2002, for 13 wells in the study area—Continued.

Missouri River alluvial aquifer in the study area. To correctly interpret model results the following limitations of the model should be considered.

1. Model parameters such as hydraulic conductivity and recharge are applied uniformly to a model cell. The assumption of homogeneity can cause inaccuracies because geologic materials and climatic conditions are typically heterogeneous.

2. The ground-water flow model was discretized using a grid with cells measuring 100 m by 100 m. Model results were evaluated on a relatively large scale and cannot be used for detailed analyses such as simulating water-level drawdown near a single well. A grid with smaller cells would be needed for such detailed analysis.

3. Although the model was calibrated to both steady-state and transient conditions, analyses of ground-water flow, contributing recharge areas, and travel time were based on simulated steady-state conditions. In alluvial aquifers like the Missouri River alluvial aquifer, steady-state conditions rarely, if ever, occur because of constantly changing river stage, rainfall, and well pumping. Analyses based on steady-state conditions should be considered approximations of actual or historical conditions.

4. Well pumping rates used in the ground-water flow model were average annual rates for public-water-supply wells or well fields. Average pumping rates may introduce some error in contributing recharge areas if most pumping is from a small subset of wells in a well field but pumping is distributed evenly between all wells of the well field.

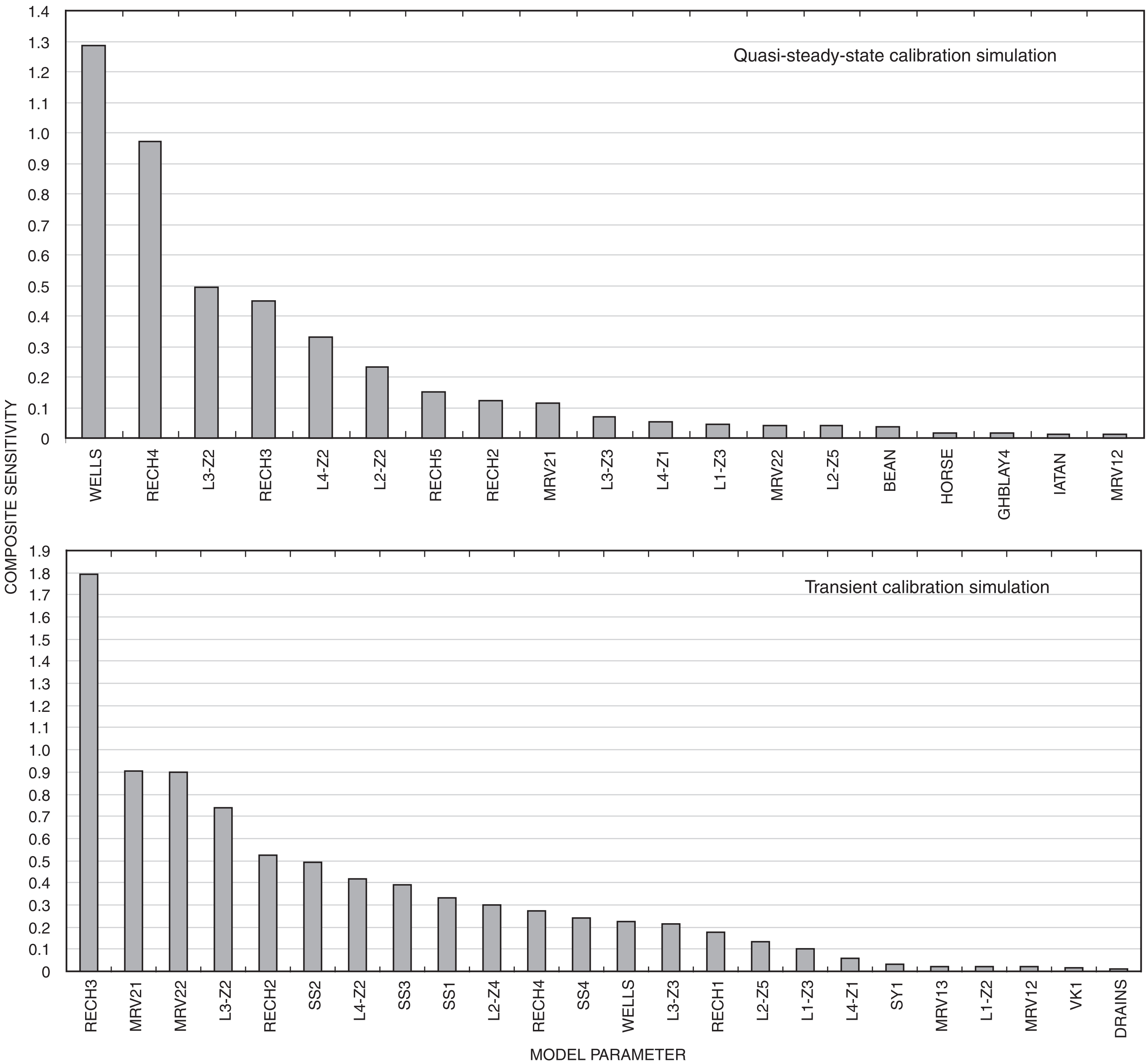


Figure 13. Composite scaled sensitivities for the quasi-steady-state and transient calibration simulations (parameter descriptions listed in table 1).

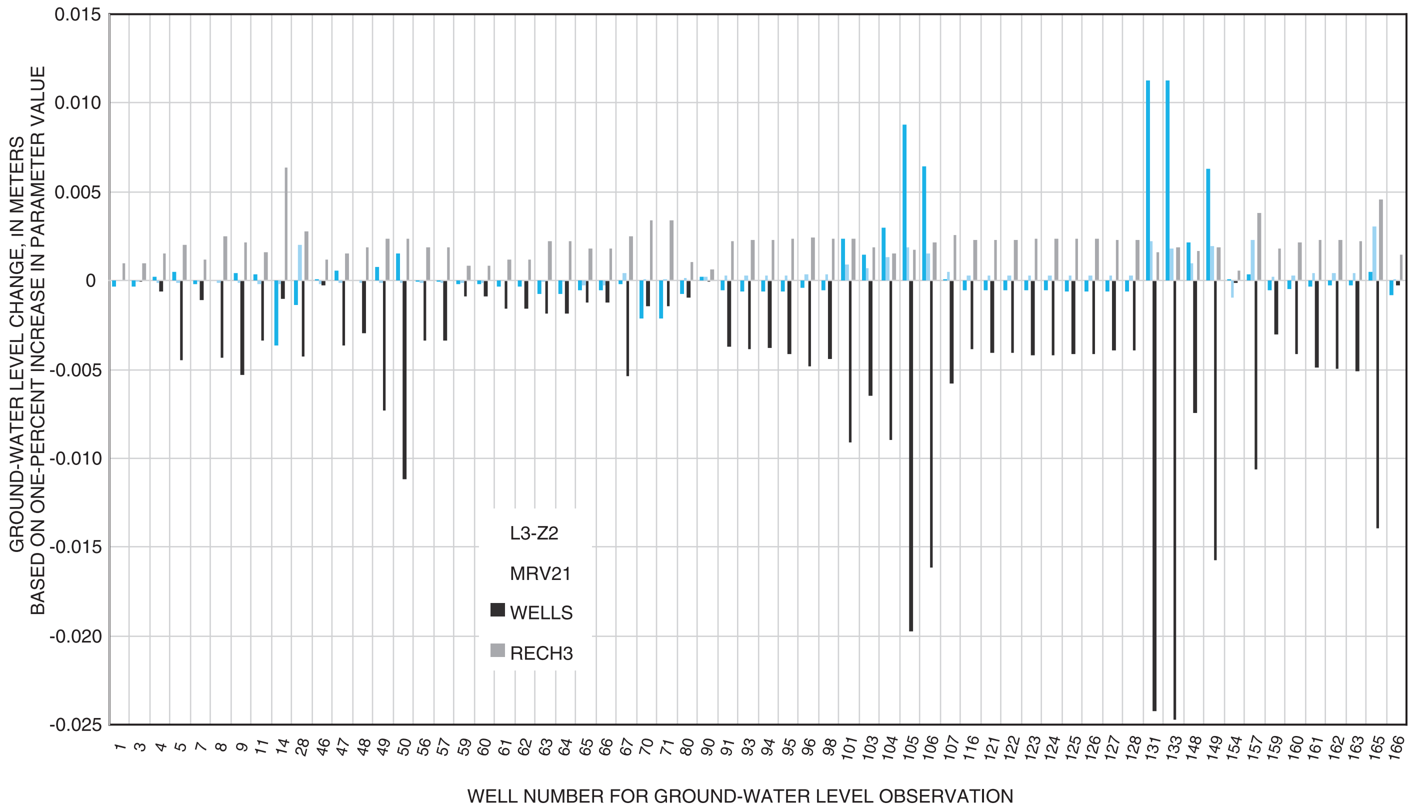


Figure 14. One-percent scaled sensitivities for selected parameters for the quasi-steady-state calibration simulation (parameter descriptions listed in table 1).

Contributing Recharge Areas and Ground-Water Travel Time

Particle tracking analysis, using the USGS particle-tracking program MODPATH (Pollock, 1994), was used to determine the CRA and ground-water travel times for each known pumping well or well field in the study area. MODPATH uses the hydraulic heads and flow distribution output from MODFLOW to calculate the paths and travel times of imaginary particles of water moving through the simulated ground-water flow system. The accuracy of particle-tracking analysis must be known for correct interpretation of MODPATH results. Limitations of particle-tracking analysis are discussed at length by Pollock (1994), but several important factors that affect particle tracking results follow. Ground-water particle movement and ground-water travel times computed by MODPATH are based solely on ground-water flow. Because hydraulic conductivities are large in the Missouri River alluvial aquifer, ground-water flow probably is the largest component of contaminant movement. While the rate of movement of a particular contaminant is not fully described by MODPATH results alone, a conservative estimate is computed that can be used for planning purposes. The spatial discretization of the ground-water flow model also may limit the accuracy of particle tracking results because cells containing sinks that do not discharge at a rate large enough to consume all the water entering the cell introduce uncertainty into the computed path of the imaginary water particle. However, the most significant factor affecting the accuracy of particle-tracking analysis is the accuracy of the hydraulic head and flow distribution computed by the ground-water flow model. Therefore, all of the limitations associated with the ground-water flow model also apply to the particle-tracking analysis.

The porosity of the alluvial aquifer has a large affect on ground-water velocities computed by MODPATH. The same ground-water discharge through a unit cross-sectional area of porous material with a high porosity will have a lower average ground-water flow velocity than a material with a low porosity. This occurs because the higher porosity material has more openings per unit area of porous material than does a lower porosity material, thereby allowing the same amount of discharge at a lower average ground-water velocity than in a lower porosity material. Typical values of porosity (Freeze and Cherry, 1979; Driscoll, 1986) were based on lithology and were distributed among model cells by assigning porosity values to hydraulic conductivity zones listed in table 1.

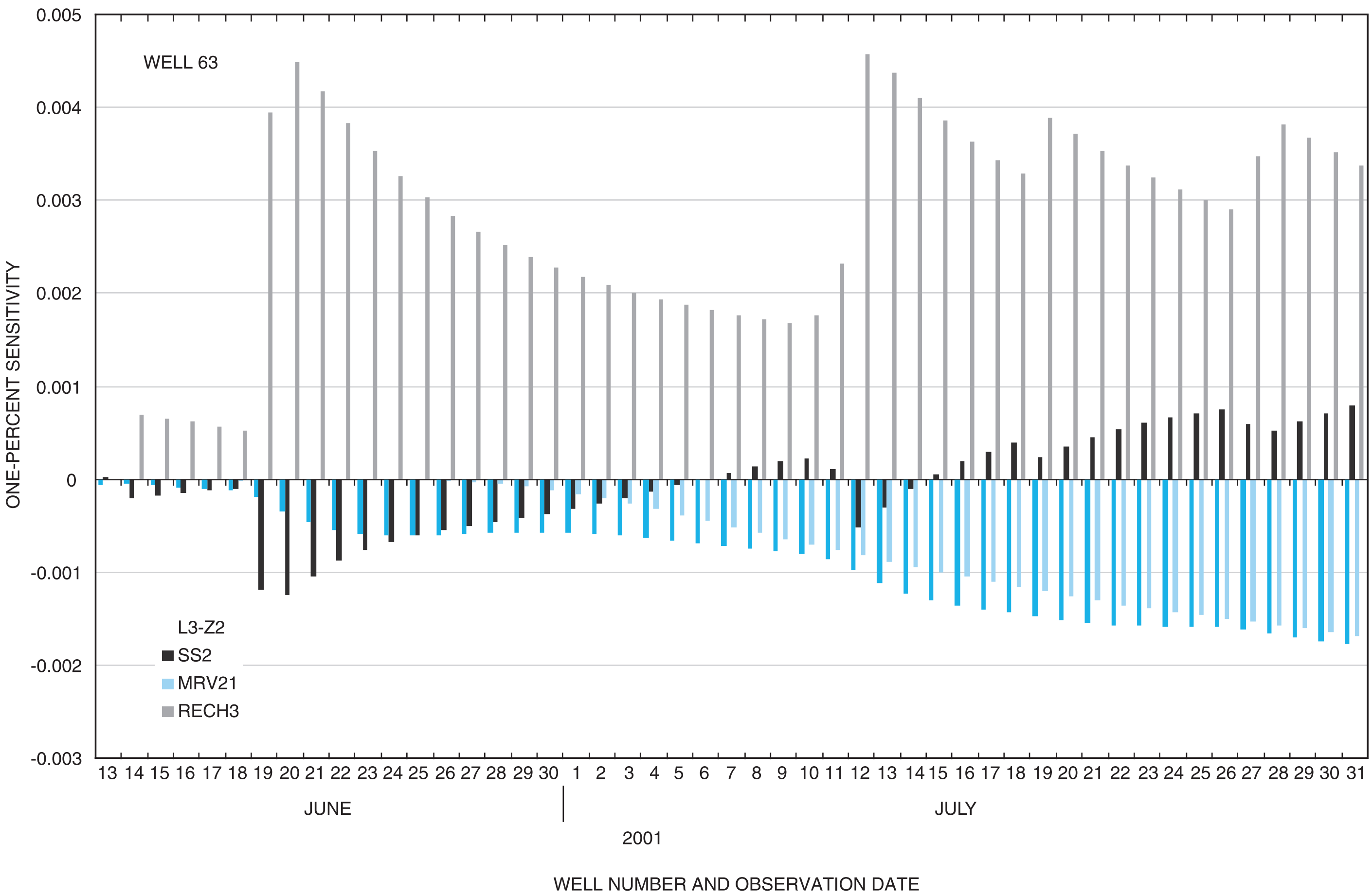


Figure 15. One-percent scaled sensitivities for selected parameters for the transient calibration simulation (parameter descriptions listed in table 1).

Pumping- and River-Stage Scenarios

Steady-state ground-water flow was simulated for five different combinations of well pumping and river stage to determine the hydraulic head distribution in the study area during low, average, and high well pumping rates and low, average, and high river stage. Particle tracking analysis was used to determine the CRA for pumping wells in each of the five scenarios. The well pumping, river stage scenarios are: low pumping rate, average river stage (LPAR); high pumping rate, average river stage (HPAR); average pumping rate, average river stage (APAR); average pumping rate, low river stage (APLR); and average pumping rate, high river stage (APHR).

Well pumping rates used in the quasi-steady-state calibration and average well-pumping simulations are average annual pumping rates. Average annual pumping rates for each well field are listed in table 7. High well pumping rates were set at 1.25 times average annual pumping rates; low pumping rates were set at 0.75 times average annual pumping rates.

The river-surface altitude was defined for each cell in the model that contained a river for the quasi-steady-state calibration and for each stress period of the transient calibration. Low, average, and high river stage data sets were chosen from the transient stress period data based on a comparison of the river stage at the USGS gaging station located in St. Joseph, Missouri, with the average annual high, average, and low stages. For the USGS gaging station in St. Joseph, Missouri, between 1958 and 2001 a discharge of 2,084 m^3/s (cubic meters per second) [73,600 ft^3/s (cubic feet per second)] was exceeded 10 percent of the time, the annual mean discharge was 1,333 m^3/s (47,070 ft^3/s) and a discharge of 626 m^3/s (22,100 ft^3/s) was exceeded 90 percent of the time (Hauck and Nagel, 2001). High river stage conditions were represented by the May 8, 2001, river

Table 7. Well field, well number, well name, well layer, row, column, and pumping rates used for the steady state and transient simulation ground-water flow.

[na, not applicable; gal/min, gallon per minute; m^3/d, cubic meter per day]

Well field (fig. 1)	Well number (fig. 9)	Well name	Layer	Row	Column	Pump rate (gal/min)	Pump rate (m^3/d)
Iatan	172	Well E	4	67	105	175	954
	171	Well D	4	69	102	100	545
Weston	51	Well 4	4	113	157	106	578
	52	Well 3	4	114	157	106	578
	53	Well 2	4	115	157	59	322
	54	Well 1	4	116	157	59	322
Ft. Leavenworth	133	Well 9	4	168	162	100	545
	131	Well 7	4	170	163	100	545
	132	Well 8	4	171	162	100	545
	130	Well 6	4	171	163	100	545
Leavenworth	29	Well 3	3	264	191	200	1,090
	30	Well 3A	3	265	192	200	1,090
	31	Well 4	3	265	193	200	1,090
	33	Well 5A	3	266	196	200	1,090
	34	Well 6	3	266	196	200	1,090
	35	Well 7	3	267	198	200	1,090
	36	Well 8	3	268	199	200	1,090
	37	Well 9	4	269	201	200	1,090
	40	Well 12	4	273	206	200	1,090

stage data when the stage at the St. Joseph, Missouri, gage was 245.92 m (2,917 m^3/s discharge). Average river stage conditions were represented by the July 11, 2001, river stage data when the stage at the St. Joseph, Missouri, gage was 243.21 m (1,133 m^3/s discharge). Low river stage conditions were represented by the December 27, 2001, river stage data when the stage at the St. Joseph, Missouri, gage was 241.59 m (637 m^3/s discharge).

For each scenario, one imaginary particle of water was placed on the water table in each quadrant of the top-most active model cell and tracked to its eventual discharge point. Particles were placed in this manner for two reasons: most water entering the alluvial aquifer comes from direct infiltration by precipitation or from the major rivers, and the primary source of potential contamination to the alluvial aquifer is from leaks or spills that occur on the land surface. Consequently, the CRAs computed by MODPATH include the source area of water to each well or well field and advective ground-water travel times from the land surface and the major rivers to each well or well field. The starting locations and travel times of the particles that eventually discharged to a well or well field were identified for each scenario, which estimated the entire CRAs for each well field. Next particles with travel times from 0 to 6 months, 6 months to 1 year, 1 to 2 years, 2 to 3 years, 3 to 4 years, 4 to 5 years, 5 to 10 years, 10 to 25 years, 25 to 50 years, 50 to 100 years, 100 to 200 years, 200 to 300 years, 300 to 400 years, and 400 to 500 years were grouped to create CRAs for each scenario.

The shape, size, and ground-water travel time within the CRA for each well or well field is affected by changes in river stage and pumping rates and by the location of the well or well field with respect to the major rivers, alluvial valley walls, and other pumping wells. Similarities in the shapes of CRAs between different wells and well fields can be attributed to similarities in the pumping rate, and the position of the wells or well fields in relation to the major rivers, the alluvial valley walls, or other well fields. A typical CRA shape for a well located within an aquifer with uniform hydraulic conductivity such that effects from any hydrologic boundary are negligible will be circular. The simulated potentiometric surface and entire CRA for each well-pumping/river-stage scenario are shown for the Iatan, Weston, Ft. Leavenworth (wells 6, 7, 8, and 9; table 7), and Leavenworth well fields in figure 16. The size of the CRA for each well-pumping/river-stage scenario for each well field is listed in table 8.

Ground-water velocity is affected by the ground-water gradient, hydraulic conductivity of the aquifer, and porosity. Ground-water velocity is greater with increased ground-water gradient, larger hydraulic conductivity, or smaller porosity. The greatest ground-water gradients within the Missouri River alluvial aquifer in the study area are located near pumping wells and rivers. Pumping wells create a cone of depression on the potentiometric surface such that the ground-water gradient and ground-water velocity are greatest near a pumping well. Rivers can produce large changes in ground-water gradient and direction as stage rises and falls. Hydraulic conductivity is smallest in clays and silts, larger in sands, and largest in gravels. Within the Missouri River alluvial aquifer in the study area, clay and silt overlie sand and gravel (fig. 3). Assuming a constant ground-water gradient, ground-water velocity increases with depth. Ground-water velocity is smaller in clay and silt, larger in sand, and largest in gravel and because of the lithologic distribution within the alluvial aquifer; this relation causes ground-water velocity to increase with depth. A typical map of ground-water travel time for a well located within an aquifer such that effects from any hydrologic boundary are negligible would have a bull's-eye pattern with shorter travel times in the center and longer travel times at the edges. The simulated ground-water travel time within the 500-year CRA for each well-pumping/river-stage scenario is shown for the Iatan, Weston, Ft. Leavenworth (wells 6, 7, 8, and 9; table 7), and Leavenworth well fields in figure 17. The 500-year CRAs for the well-pumping/river-stage scenarios are substantially smaller than the CRAs shown in figure 16, because 500-year CRAs depict simulated ground-water travel time to the well fields of 500 years or less.

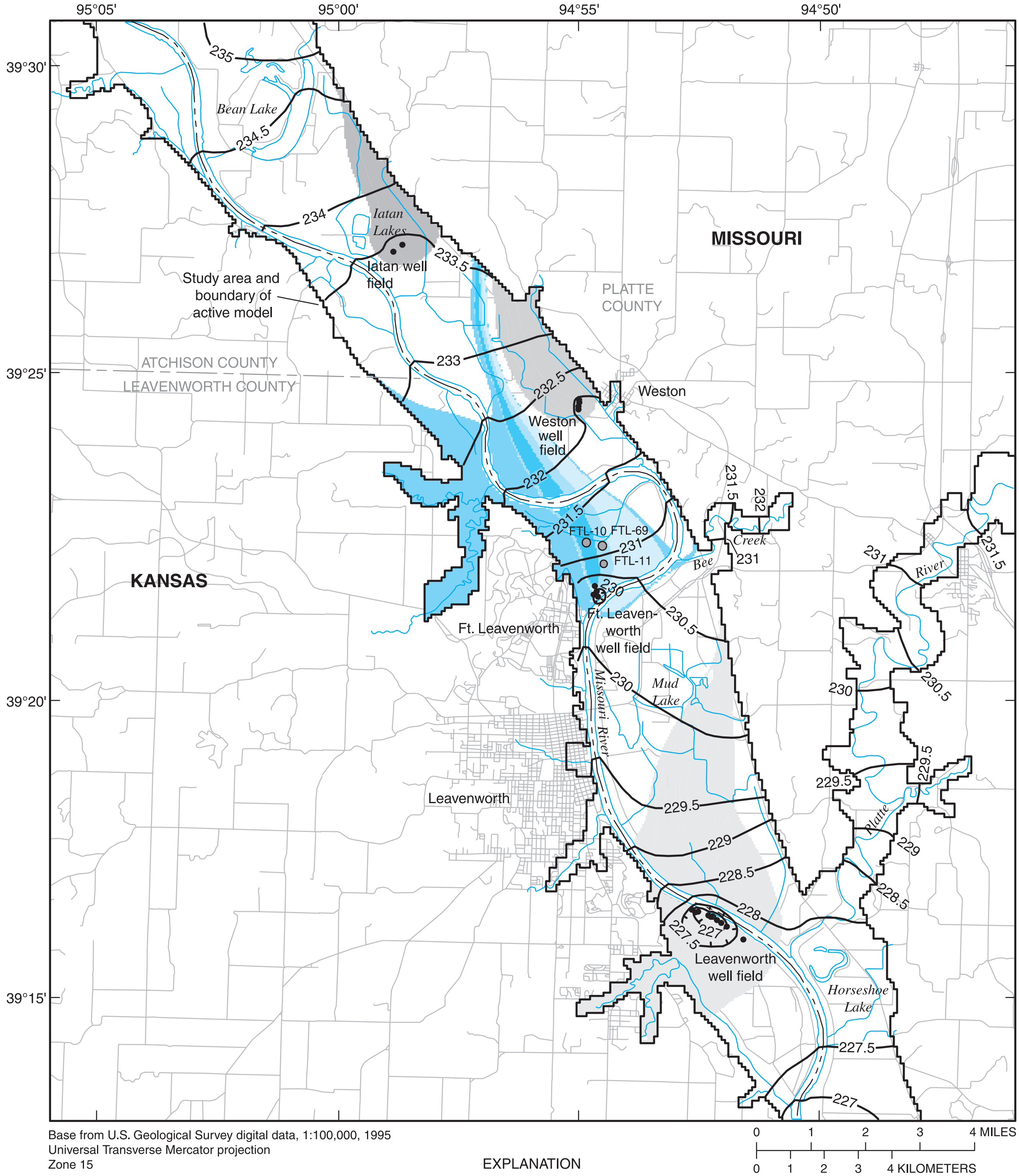
Iatan Power Plant Well Field

The shape of the simulated CRA for the Iatan Power Plant well field is elongated in the upstream direction for all well-pumping/river-stage scenarios (fig. 16). The capture of ground water by the pumping wells as it moved downgradient toward the Missouri River caused the long up-valley extent of the CRA. The CRAs listed from smallest to largest are LPAR (5.59 km^2), APLR (7.47 km^2), APAR (7.55 km^2), APHR (8.18 km^2), and HPAR (9.34 km^2). The alluvial valley walls form the northeast boundary of the CRA, which is 5.5 km long for the LPAR scenario and 7.6 km long for the HPAR scenario (fig. 16). The width of the CRAs range from approximately 1.8 km for the LPAR scenario to approximately 2.3 km for the HPAR scenario. The southwest boundary of the CRA is the computed ground-water divide between flow to the Missouri River, flow to the small lakes on the Iatan Power Plant property, and flow to the well field. Recharge to the well field primarily is from precipitation and surface runoff from the surrounding uplands. Little, if any, recharge to the well field comes from the Missouri River because the CRA does not intersect the Missouri River for any well-pumping/river-stage scenarios. Ground-water discharges to the two small lakes on the Iatan Power Plant property when the potentiometric surface is higher than lake stages. This is most obvious for the HPAR scenario, where the CRA for the Iatan well field encloses the CRA for the two small lakes. Lake stage and potentiometric surface altitude are nearly the same for the APHR and APLR scenarios, and the Iatan CRAs are not substantially affected by ground-water discharge to these lakes.

Minimum ground-water travel time to the Iatan well field ranges from 5.15 years for the HPAR scenario to 7.55 years for the LPAR scenario. Maximum ground-water travel time ranges from 288 years for the APLR scenario to about 5,000 years for the APHR scenario. Simulated ground-water travel times from the top of the potentiometric surface to the well field are shown for the Iatan Power Plant well field in figure 17.

Weston Well Field

The shape of the simulated CRA for the Weston well field is elongated in the upstream direction for all pumping/river-stage scenarios (fig. 16). The capture of ground water by the pumping wells as it moved downgradient toward the Missouri River caused the long up-valley extent of the CRA. The CRAs listed from smallest to largest are LPAR (6.66 km^2), APAR (8.77 km^2), APLR (8.79 km^2), APHR (9.14 km^2), and HPAR (11.11 km^2). The alluvial valley walls form the northeast boundary of the CRA, which is 4.6 km long for the LPAR scenario and 6.0 km long for the HPAR scenario (fig. 16). The width of the CRA ranges from approximately 1.7 km for the LPAR scenario to approximately 2.3 km for the HPAR scenario. The southwest boundary of the CRA is the computed ground-water divide between flow to the Missouri River and flow to the well field. This divide changes position with changes in pumping and river stage. High pumping rates (HPAR) move the divide away from the Weston well field as the CRA increases in size; the opposite occurs for low pumping rates (LPAR). High river stage moves the computed divide away from the Weston well field; the opposite again occurs for low river stage, but to a much lesser degree than with changes in pumping rate. Recharge to the well field primarily is from precipitation and surface runoff from the surrounding uplands. Little, if any, recharge to the well field comes from the Missouri River because the CRA does not intersect the Missouri River for any well-pumping/river-stage scenarios.



EXPLANATION

CONTRIBUTING RECHARGE AREA FOR WELLS—
Low pumping/average river stage

- Iatan well field
- Weston well field
- City of Leavenworth well field
- Ft. Leavenworth well 6
- Ft. Leavenworth well 7
- Ft. Leavenworth well 8
- Ft. Leavenworth well 9

—227— POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased well. Hachures indicate depression. Contour interval 0.5 meter. Datum is NGVD 29

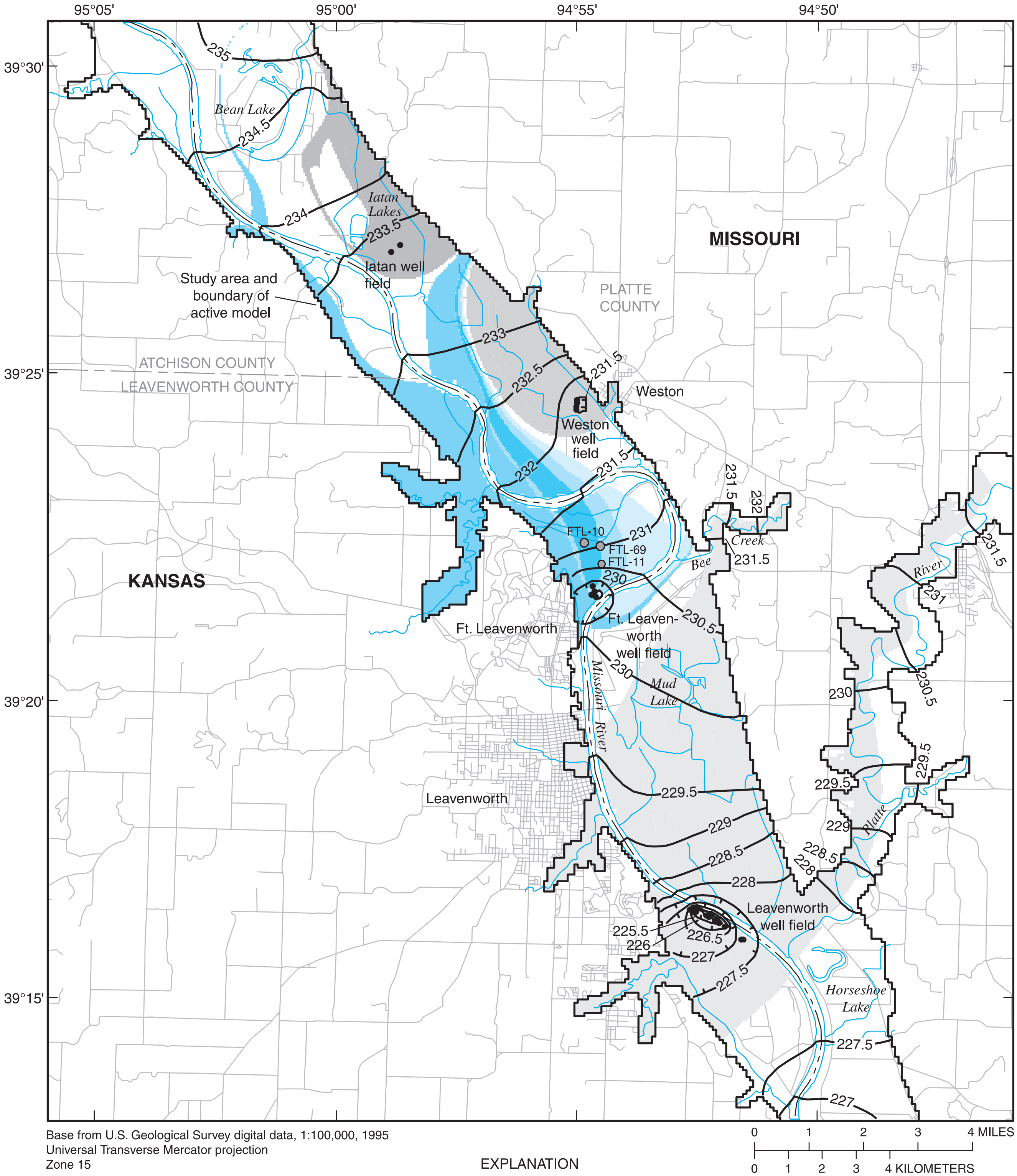
STREAM OR DRAIN

ROAD

PUMPING WELL

FTL-11 GROUND-WATER CONTAMINATION SITE AND IDENTIFIER

Figure 16. Simulated contributing recharge areas for each well-pumping/river-stage scenario.



EXPLANATION

CONTRIBUTING RECHARGE AREA FOR WELLS—
High pumping/average river stage

- Iatan well field
- Weston well field
- City of Leavenworth well field
- Ft. Leavenworth well 6
- Ft. Leavenworth well 7
- Ft. Leavenworth well 8
- Ft. Leavenworth well 9

—227— POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased well. Hachures indicate depression. Contour interval 0.5 meter. Datum is NGVD 29

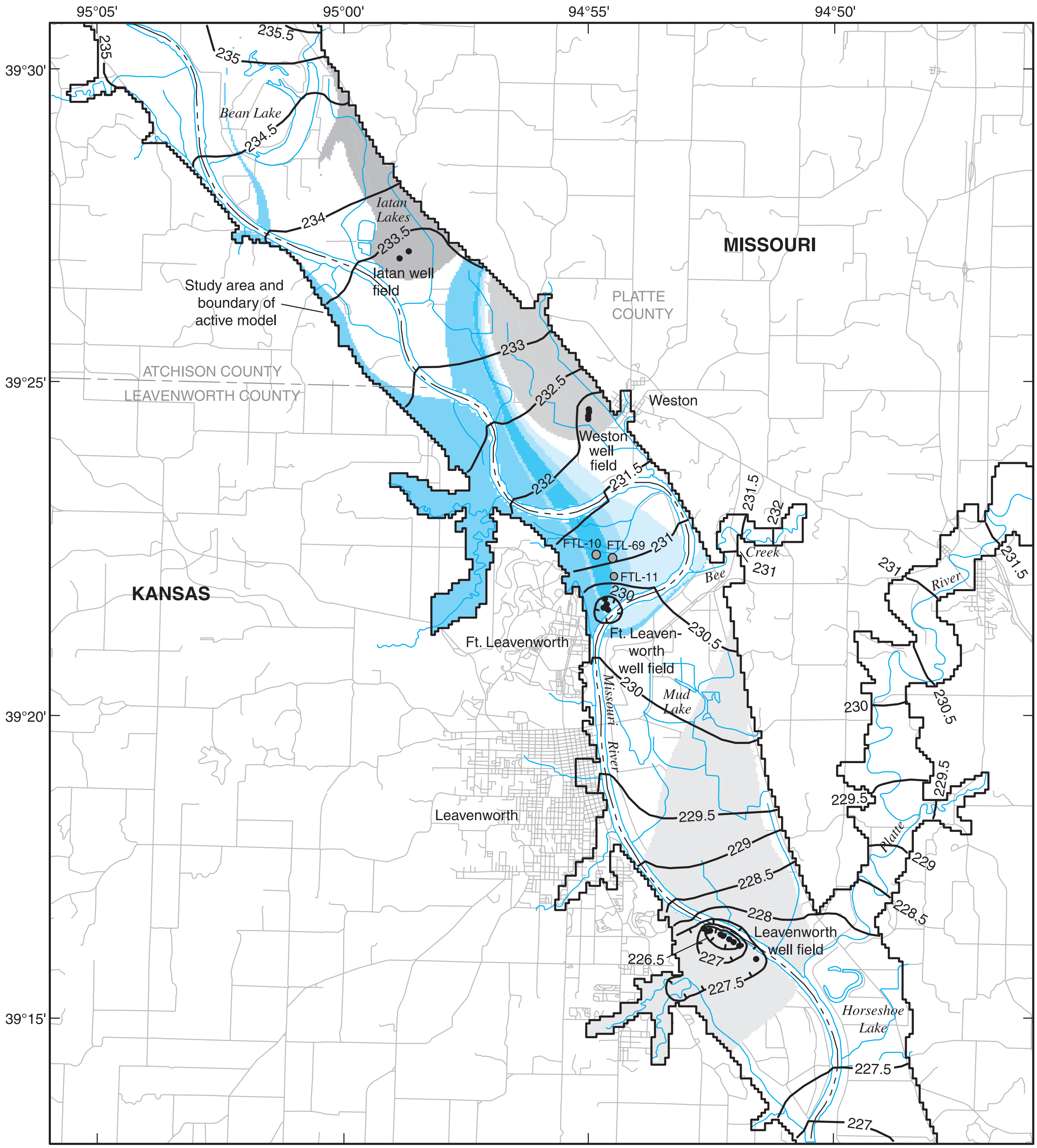
STREAM OR DRAIN

ROAD

PUMPING WELL

FTL-11 GROUND-WATER CONTAMINATION SITE AND IDENTIFIER

Figure 16. Simulated contributing recharge areas for each well-pumping/river-stage scenario—Continued.



Base from U.S. Geological Survey digital data, 1:100,000, 1995
Universal Transverse Mercator projection
Zone 15

0 1 2 3 4 MILES
0 1 2 3 4 KILOMETERS

EXPLANATION

CONTRIBUTING RECHARGE AREA FOR WELLS—Average pumping/average river stage

- Iatan well field
- Weston well field
- City of Leavenworth well field
- Ft. Leavenworth well 6
- Ft. Leavenworth well 7
- Ft. Leavenworth well 8
- Ft. Leavenworth well 9

227 POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased well. Hachures indicate depression. Contour interval 0.5 meter. Datum is NGVD 29

STREAM OR DRAIN

ROAD

PUMPING WELL

FTL-11 GROUND-WATER CONTAMINATION SITE AND IDENTIFIER

Figure 16. Simulated contributing recharge areas for each well-pumping/river-stage scenario—Continued.

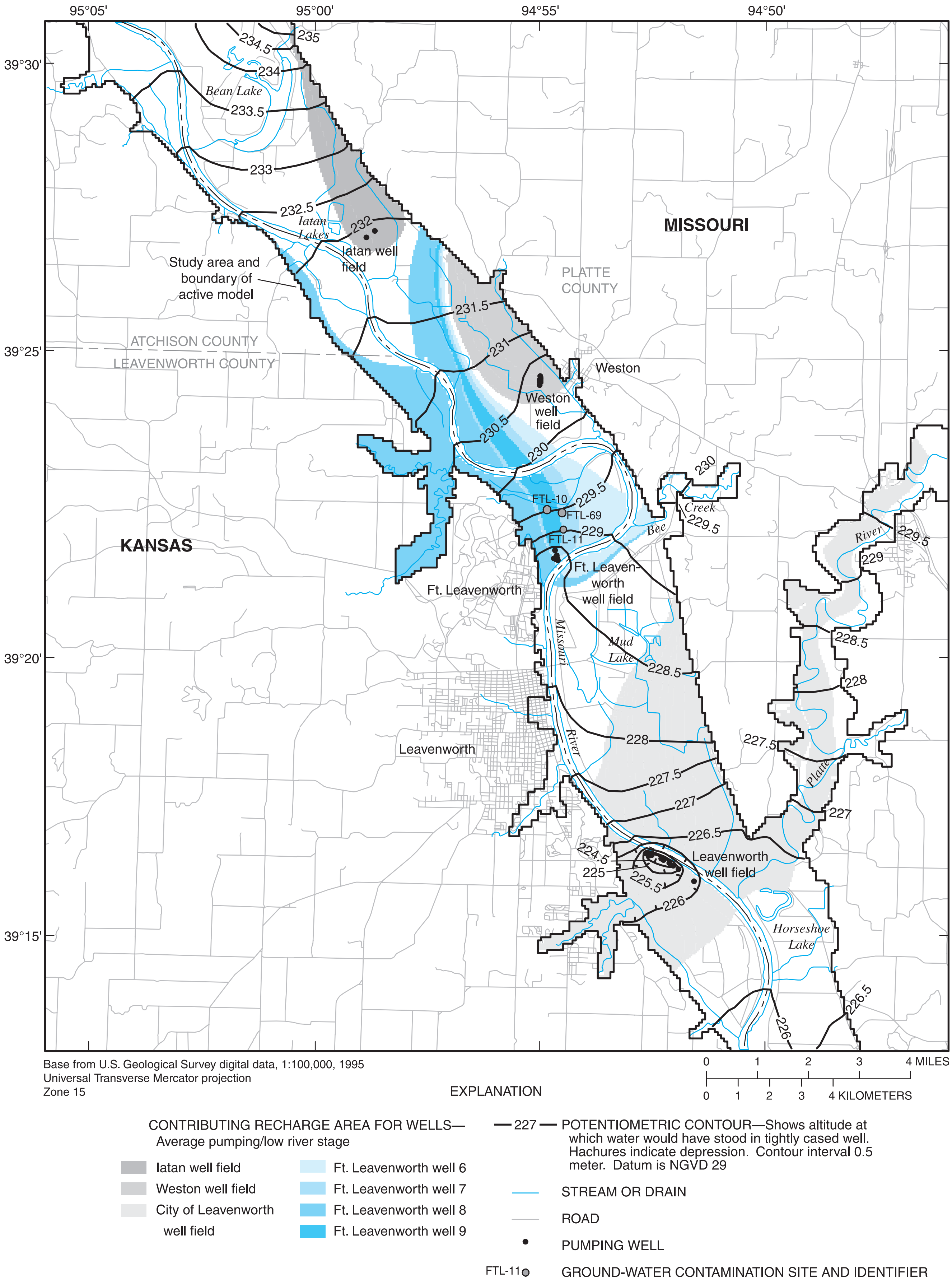


Figure 16. Simulated contributing recharge areas for each well-pumping/river-stage scenario—Continued.

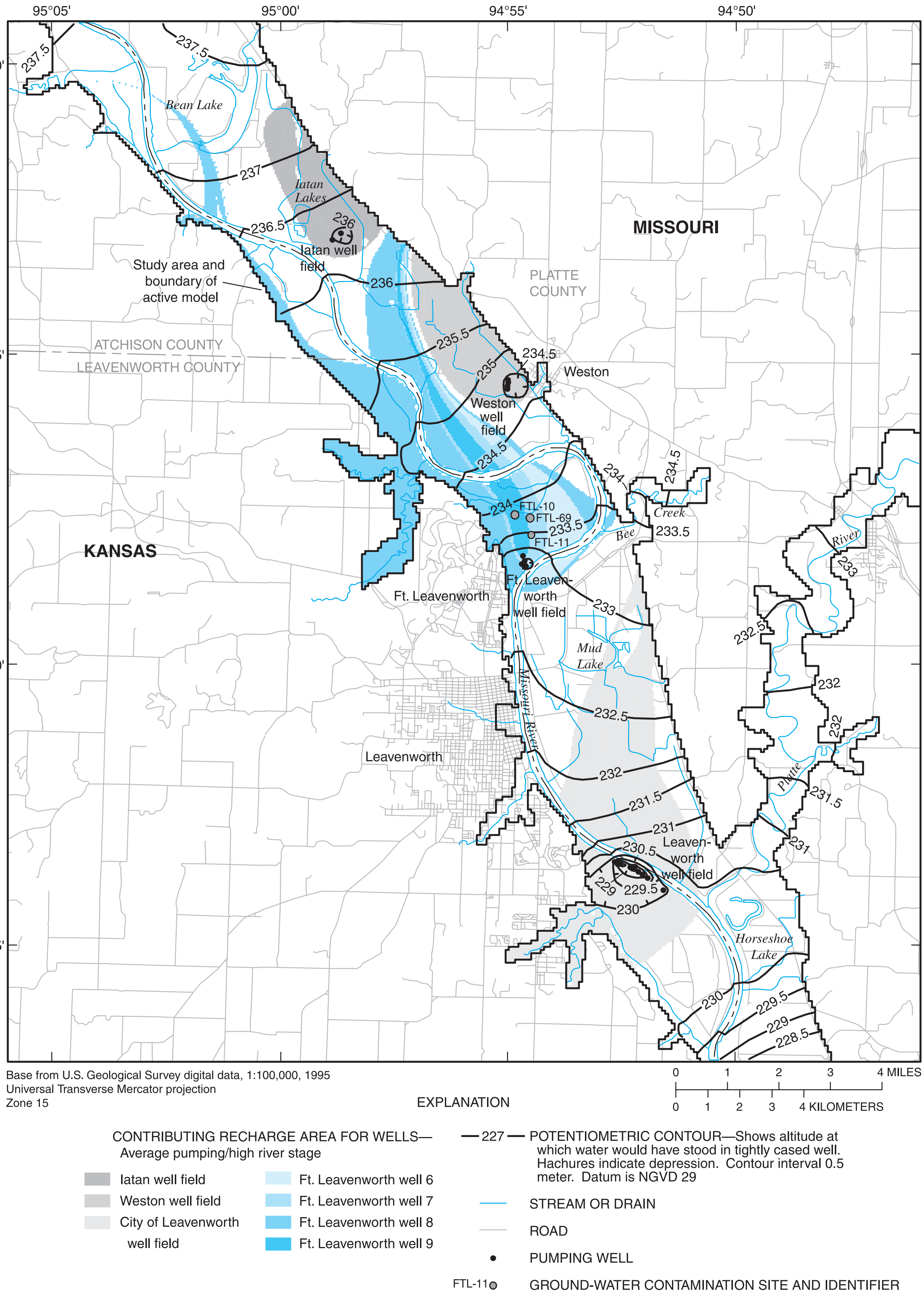


Figure 16. Simulated contributing recharge areas for each well-pumping/river-stage scenario—Continued.

Table 8. Contributing recharge areas for all well fields and all well-pumping/river-stage scenarios.

[km^2, square kilometer]

Well-pumping/river-stage scenario	Well field			
	Iatan (km^2)	Weston (km^2)	Leavenworth (km^2)	Ft. Leavenworth (km^2)
LPAR (Low pumping, average river stage)	5.59	6.66	28.20	25.06
HPAR (High pumping, average river stage)	9.34	11.11	64.27	33.47
APAR (Average pumping, average river stage)	7.55	8.77	36.73	32.88
APLR (Average pumping, low river stage)	7.47	8.79	51.11	32.89
APHR (Average pumping, high river stage)	8.18	9.14	29.67	34.61

Minimum ground-water travel time to the Weston well field ranges from 6.7 years for the HPAR scenario to 9.5 years for the LPAR scenario. Maximum ground-water travel time ranges from about 13,000 years for the APHR scenario to about 17,600 years for the APAR scenario. Simulated ground-water travel times from the top of the potentiometric surface to the well field are shown for the Weston well field in figure 17.

Leavenworth Well Field

The shape of the simulated CRA for the Leavenworth well field is elongated in the upstream direction for all well-pumping/river-stage scenarios (fig. 16). The capture of ground water by the pumping wells as it moved downgradient toward the Missouri River and downgradient along the Platte River flood plain towards the Missouri River caused the long up-valley extent of the CRA. The CRAs listed from smallest to largest are LPAR (28.20 km^2), APHR (29.67 km^2), APAR (36.73 km^2), APLR (51.11 km^2), and HPAR (64.27 km^2). The alluvial valley walls form the southwest boundary of the CRA, which is 4.4 km long for the LPAR scenario and 9.6 km long for the HPAR scenario (fig. 16). The eastern and western boundaries of the CRA define the computed ground-water divides between flow to the Missouri River and flow to the well field for the LPAR, APAR, and APHR scenarios. The northwestern boundaries of the CRA define the computed ground-water divides between flow to the Missouri River and flow to the well field for the HPAR and APLR scenarios. The eastern boundaries of the HPAR and APLR CRAs are formed by the valley walls within the Missouri River flood plain, and the valley walls and the computed ground-water flow divide between flow to the Missouri and Platte rivers and flow to the well field within the Platte River flood plain. The length of the CRA ranges from 11.7 km for the LPAR scenario to 13.8 km within the Missouri River flood plain, and 18.5 km within the Platte River flood plain for the HPAR scenario. The width of the CRA within the Missouri River flood plain ranges from approximately 3.5 km for the LPAR scenario to approximately 4.5 km (the width of the flood plain) for the HPAR scenario. Ground-water discharge to Mud Lake for the LPAR and APHR scenarios is indicated by the area near the lake that does not contribute to the Leavenworth well field. Recharge to the well field is from precipitation, surface runoff from the surrounding uplands, and the Missouri River because the CRA intersects these boundaries for all well-pumping/river-stage scenarios.

The CRAs of the LPAR, APAR, and APHR scenarios are small relative to the HPAR and APLR scenarios. Low pumping and high river stage result in a smaller CRA because less water is required from the alluvial aquifer for low pumping, and more water is available to the well field from the Missouri River at high river stage. The CRAs of the APLR and HPAR scenarios extend for some distance up the Platte River flood plain because at low river stage, less water is available to the well field from the Missouri River and more water must come from the alluvial aquifer. Similarly, at a high well-pumping rate, more water must come from the alluvial aquifer to supply enough water to the well field. For both situations the result is an increase in the size of the CRA.

Minimum ground-water travel time to the Leavenworth well field ranges from 4.29 years for the HPAR scenario to 7.07 years for the LPAR scenario. Maximum ground-water travel time ranges from about 35,200 years for the APAR scenario to about 51,000 years for the APHR scenario. Simulated ground-water travel times from the top of the potentiometric surface to

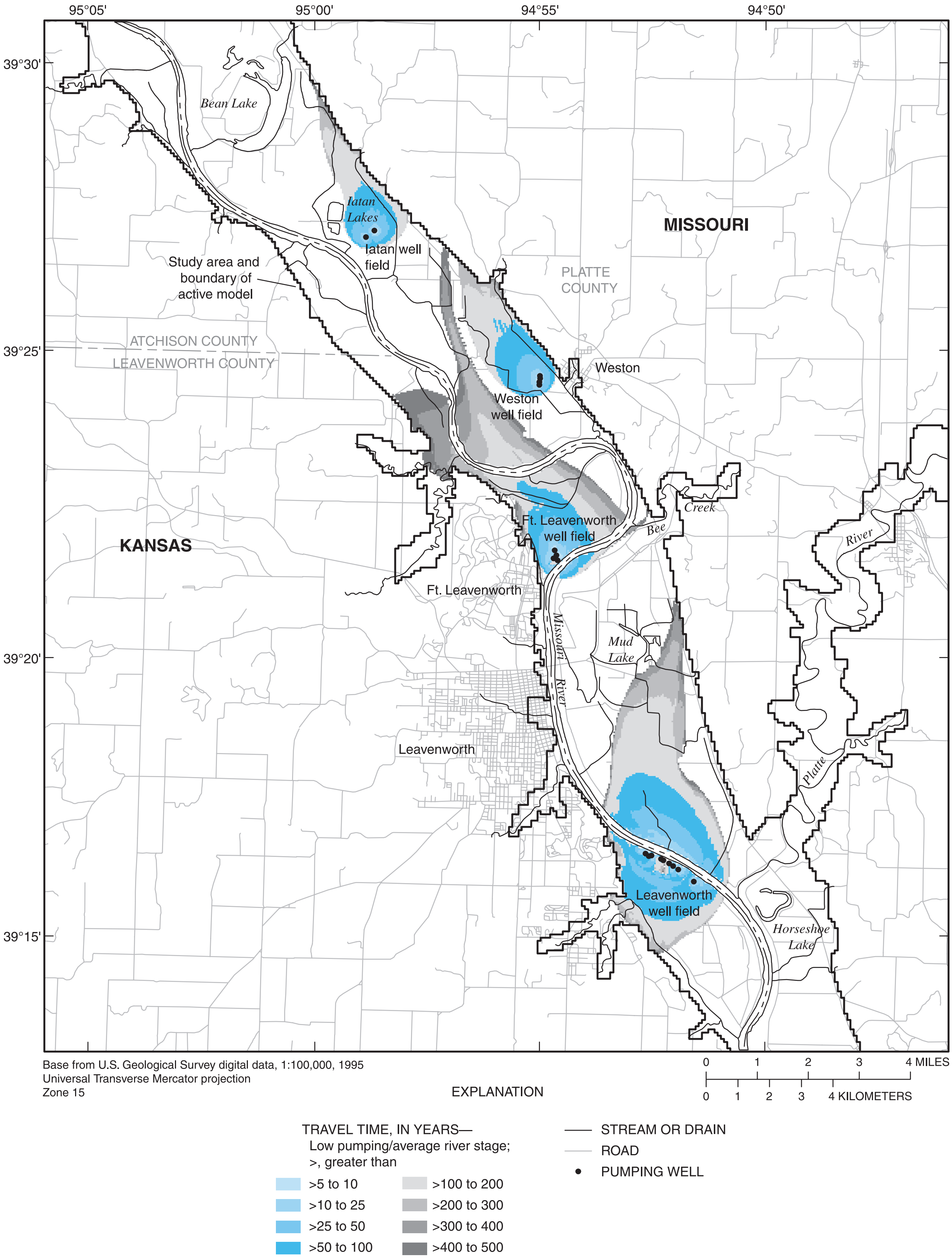
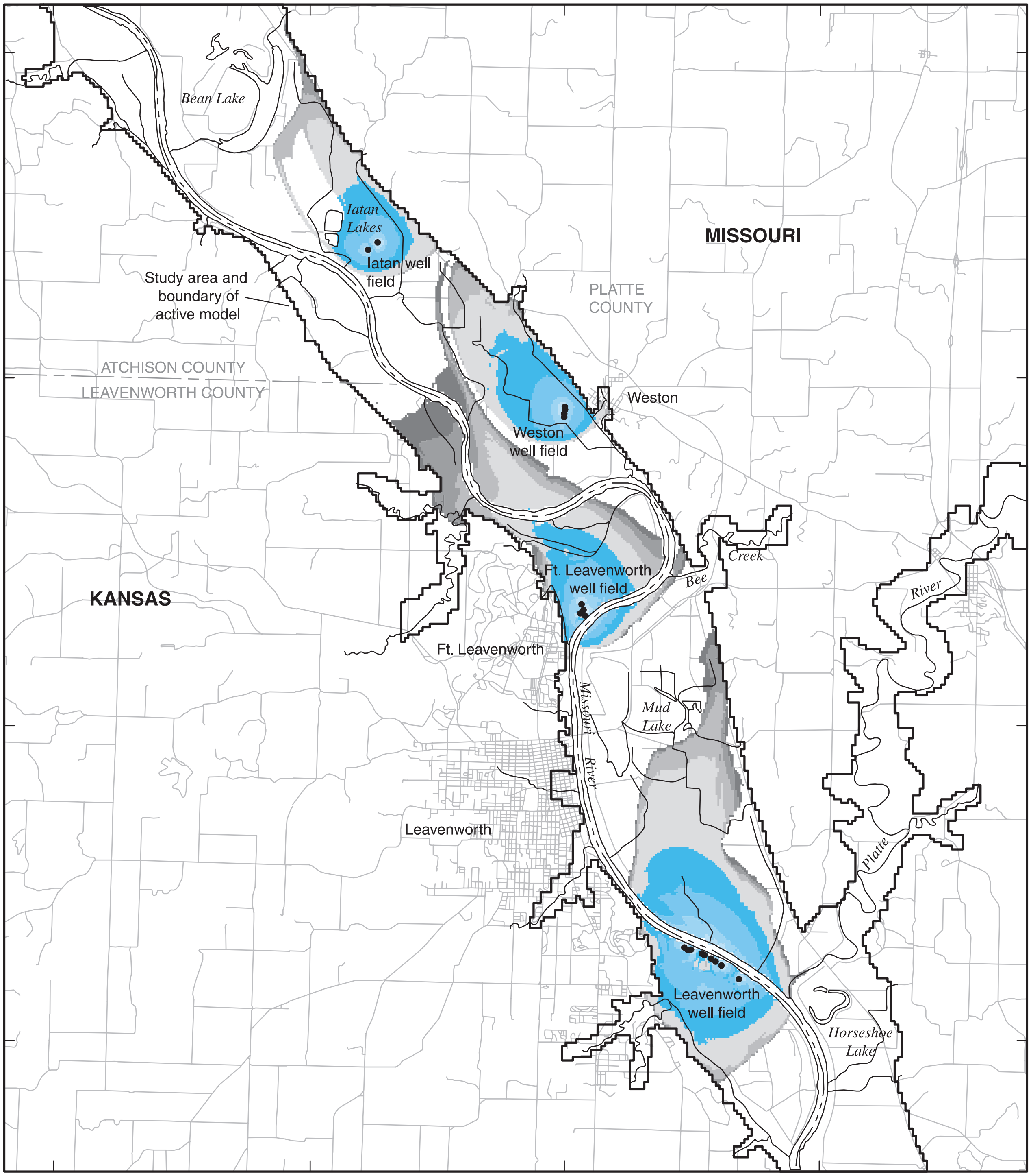


Figure 17. Simulated ground-water travel time for each well-pumping/river-stage scenario.



Base from U.S. Geological Survey digital data, 1:100,000, 1995
Universal Transverse Mercator projection
Zone 15

EXPLANATION

TRAVEL TIME, IN YEARS—
High pumping/average river stage;
>, greater than

>4 to 5	>100 to 200
>5 to 10	>200 to 300
>10 to 25	>300 to 400
>25 to 50	>400 to 500
>50 to 100	

STREAM OR DRAIN
ROAD
• PUMPING WELL

Figure 17. Simulated ground-water travel time for each well-pumping/river-stage scenario—Continued.

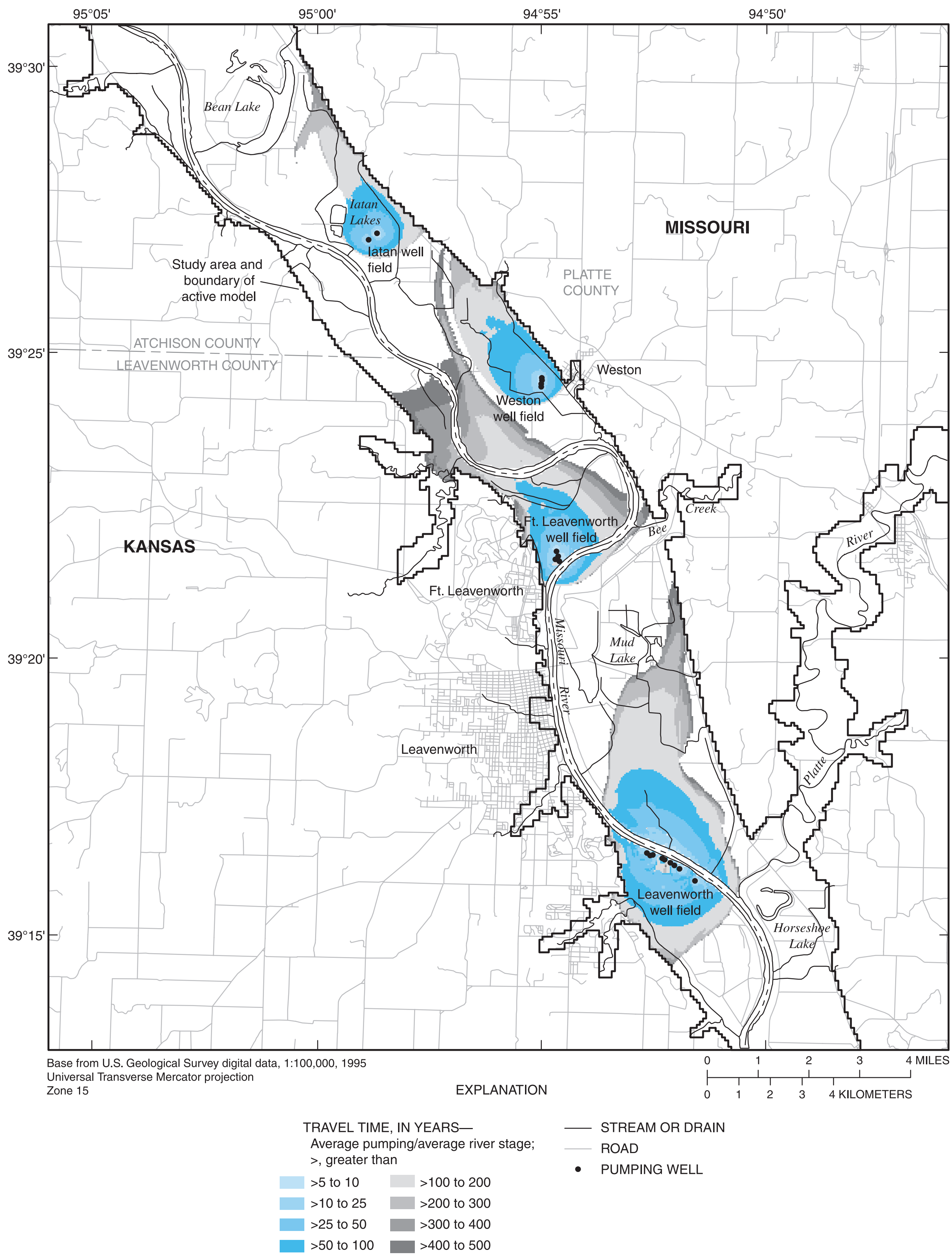


Figure 17. Simulated ground-water travel time for each well-pumping/river-stage scenario—Continued.

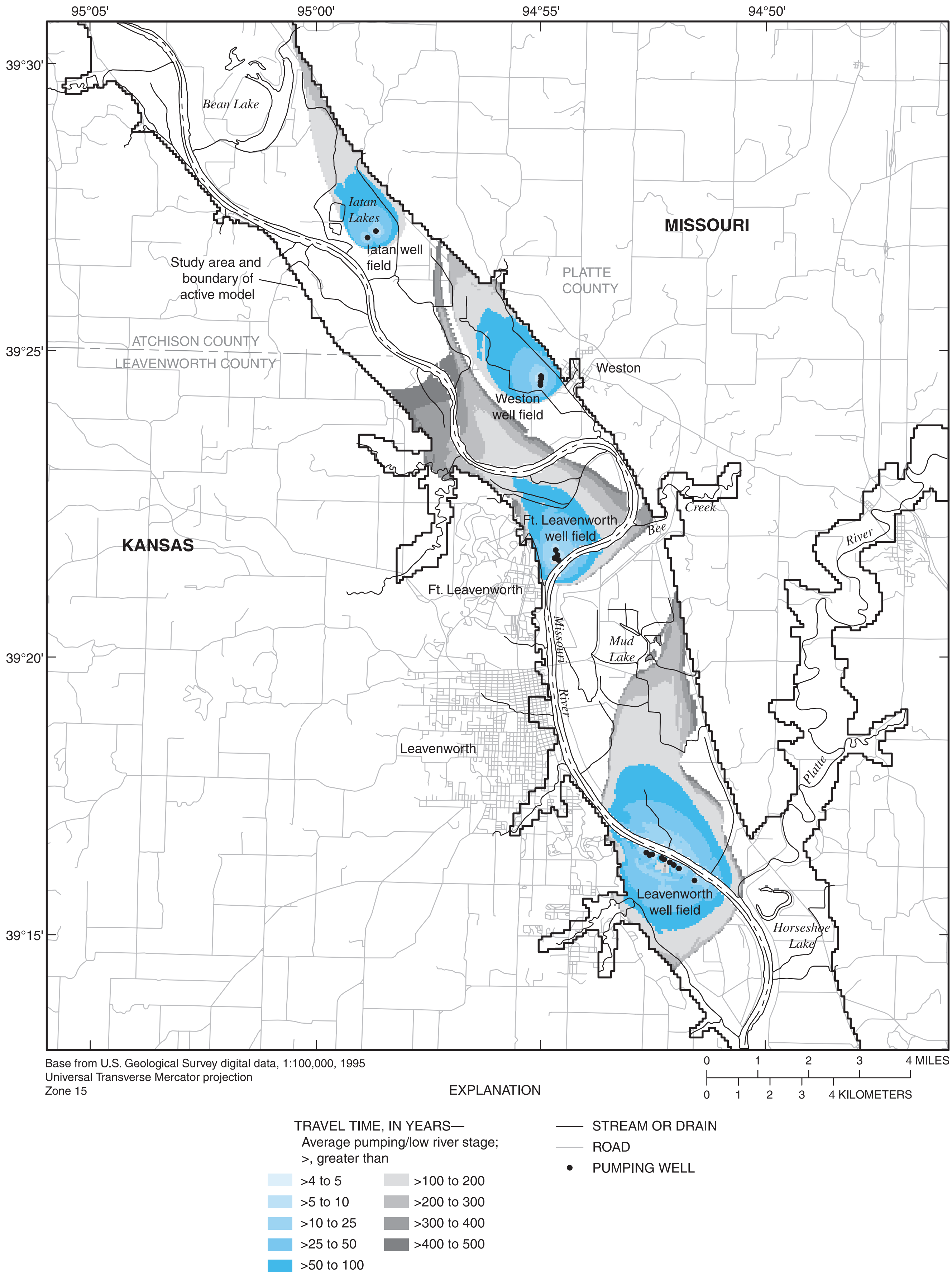


Figure 17. Simulated ground-water travel time for each well-pumping/river-stage scenario—Continued.

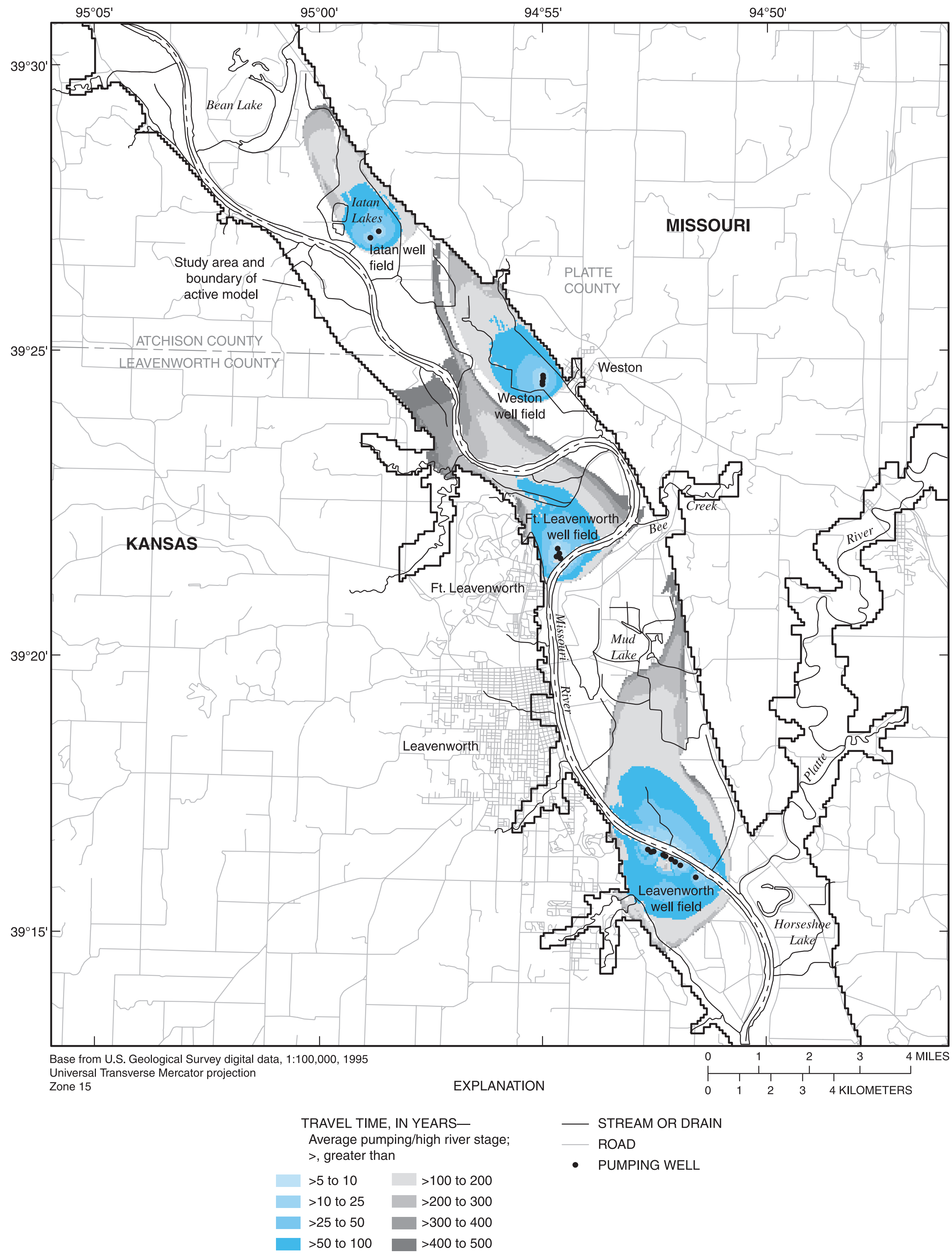


Figure 17. Simulated ground-water travel time for each well-pumping/river-stage scenario—Continued.

the well field are shown for the Leavenworth well field in figure 17.

Ft. Leavenworth Well Field

The shape of the simulated CRA for the Ft. Leavenworth well field is elongated in the upstream direction for all well-pumping/river-stage scenarios and is split into two arms up-valley from the well field (fig. 16). The capture of ground water by the pumping wells as it moved downgradient toward the Missouri River caused the long up-valley extent of the CRA. The CRAs listed from smallest to largest are LPAR (25.06 km^2), APAR (32.88 km^2), APLR (32.89 km^2), HPAR (33.47 km^2), and APHR (34.61 km^2). The alluvial valley walls form the southwest boundary of the CRA for the LPAR scenario, which is 9.4 km long and 15.6 km long for the APHR scenario (fig. 16). The boundaries of the two arms of the CRA are the computed ground-water divides between flow to the Missouri River and flow to the well field. The length of the CRA for the LPAR scenario ranges from 11.2 km to 20.3 km within the Missouri River flood plain along the longest arm for the HPAR scenario. The width of the CRA within the Missouri River flood plain ranges from approximately 3.0 km for the LPAR scenario, to approximately 3.9 km for the HPAR scenario. Recharge to the well field is from precipitation, surface runoff from the surrounding uplands, and the Missouri River because the CRA intersects these boundaries for all well-pumping/river-stage scenarios.

The CRA of the LPAR scenario is substantially smaller than the other CRAs for the Ft. Leavenworth well field. Low pumping results in a smaller CRA because less water is required from the alluvial aquifer by the well field. The HPAR scenario is larger than the LPAR scenario because more water must come from the alluvial aquifer to supply enough water to the well field. Low river stage decreases the amount of water available to the well field, and increases the size of the CRA for the APLR scenario in the down-valley direction compared to the high river stage of the APHR scenario. High river stage increases the amount of water available to the well field from the Missouri River and reduces the slope of the potentiometric surface. The CRA for the APHR scenario is smaller than for the APLR scenario in the down-valley direction (close to the Missouri River) but extends substantially farther in the up-valley direction because the slope of the potentiometric surface is less, and more water is captured by the well field from this direction as it moves down-valley.

Minimum ground-water travel time to the Ft. Leavenworth well field ranges from 4.46 years for the HPAR scenario to 6.31 years for the LPAR scenario. Maximum ground-water travel time ranges from about 50,100 years for the APLR scenario to about 63,700 years for the HPAR scenario. Simulated ground-water travel times from the top of the potentiometric surface to the well field are shown for the Ft. Leavenworth well field in figure 17.

Individual Wells of the Ft. Leavenworth Well Field

Four wells of the Ft. Leavenworth well field (wells, 6, 7, 8, and 9) are actively pumped. These wells are numbered 130, 131, 132, and 133 in table 7 and on figure 9. The CRAs for each well-pumping/river-stage scenario are shown for each well of the Ft. Leavenworth well field in figure 16. The size of the CRA for each well and each well-pumping/river-stage scenario are listed in table 9. The CRAs, listed from smallest to largest, for all well-pumping scenarios are well 7, well 6, well 9, and well 8.

Table 9. Contributing recharge areas for individual Ft. Leavenworth wells for each well-pumping/river-stage scenario.

[km^2, square kilometer]

Well-pumping/river-stage scenario	Well			
	Well 6 (km^2)	Well 7 (km^2)	Well 8 (km^2)	Well 9 (km^2)
LPAR (Low pumping, average river stage)	2.90	2.68	13.97	5.51
HPAR (High pumping, average river stage)	3.90	3.79	20.28	5.51
APAR (Average pumping, average river stage)	3.47	3.24	19.85	6.32
APLR (Average pumping, low river stage)	3.48	3.28	19.44	6.70
APHR (Average pumping, high river stage)	3.56	3.31	23.30	4.43

The well 8 CRA forms the outer most boundary of the Ft. Leavenworth well field CRA for the LPAR and APHR scenarios, and forms the southwest and south boundaries for the HPAR, APAR, and APLR scenarios. The well 6 CRA forms the eastern boundary for the HPAR, APAR, and APLR scenarios. The well 7 CRA is long and narrow, and is bounded by the well 8 CRA on the west and the well 6 CRA on the east for all well-pumping/river-stage scenarios. The well 9 CRA is long and narrow, and is bounded by the well 7 CRA for all well-pumping/river-stage scenarios.

Minimum ground-water travel time to the Ft. Leavenworth wells ranges from 4.46 years for well 9 (HPAR scenario) to 12.00 years for well 8 (LPAR scenario). Maximum ground-water travel time ranges from 490 years for well 6 (APLR scenario) to about 63,700 years for well 8 (HPAR scenario). Simulated ground-water travel times from the top of the potentiometric surface to the Ft. Leavenworth well field are shown in figure 17.

Three sites with known ground-water contamination (FTL-10, FTL-11, and FTL-69) are upgradient from the Ft. Leavenworth well field (fig. 2). These sites are within the Ft. Leavenworth well field CRA, and ground water flows only to the Ft. Leavenworth well field for all simulated well-pumping/river-stage scenarios. The FTL-10 site is within the well 9 CRA for all simulated well-pumping/river-stage scenarios. FTL-11 and FTL-69 are within the well 7 CRA for the LPAR, APAR, APLR, and APHR scenarios, and are within the well 9 and well 7 CRAs for the HPAR scenario (fig. 16).

Simulated ground-water travel times between FTL-10, FTL-11, and FTL-69 and the Ft. Leavenworth well field in are shown in figure 18. Minimum ground-water travel time to the Ft. Leavenworth well field from FTL-10 is 43.8 years for the HPAR scenario, from FTL-11 is 28.8 years for the APLR scenario, and from FTL-69 is 43.8 years for the HPAR scenario. Maximum ground-water travel time to the Ft. Leavenworth well field is 75.4 years from FTL-10 for the LPAR scenario, is 42.1 years from FTL-11 for the LPAR scenario, and is 59.6 years from FTL-69 for the LPAR scenario. Ground-water travel times from the three contaminated sites to the Ft. Leavenworth well field for the APAR scenario are most representative of long-term ground-water flow conditions that occurred in the study area. For the APAR scenario, minimum ground-water travel time from FTL-10 to the Ft. Leavenworth well field is 44.2 years, maximum is 70.8 years and mean is 55 years. Minimum ground-water travel time from FTL-11 to the Ft. Leavenworth well field is 33.5 years, maximum is 38.9 years, and mean is 36.1 years. Minimum ground-water travel time from FTL-69 to the Ft. Leavenworth well field is 48 years, maximum is 53.3 years, and mean is 49.8 years.

FTL-10 operated from the 1950s to 1980. If ground-water contamination began in 1950, the results from the APAR scenario indicate ground water from FTL-10 will arrive at the Ft. Leavenworth well field sometime between 1994 and 2020. FTL-11 operated from 1980 to 1989. If ground-water contamination began in 1980, the results from the APAR scenario indicate ground water from FTL-11 will arrive at the Ft. Leavenworth well field sometime between 2014 and 2019. The buildings at FTL-69 were built in the 1950s; the site was abandoned in the early 1970s, and a 30,000-gallon diesel underground fuel tank was removed in July 1991. If ground-water contamination began in 1950, the results from the APAR scenario indicate ground water from FTL-69 will arrive at the Ft. Leavenworth well field sometime between 1998 and 2003. Although these model results estimate the arrival of ground water from the contaminated sites at the Ft. Leavenworth well field, the movement of the contaminants within ground water are subject to dispersion that may increase or decrease the rate of contaminant movement relative to the rate of ground-water movement and chemical or biological processes that may decrease the rate of contaminant movement relative to the rate of ground-water movement. Therefore, the arrival of contaminants at the Ft. Leavenworth well field from these sites will likely take longer than the arrival of ground water.

Hydrologic Controls On Contributing Recharge Areas

The effect of well pumping and river stage on the size of the total CRA of well fields in the study area is complex because each well field has a unique orientation with respect to the geometry of the aquifer, the alluvial valley walls, the rivers, and the other pumping wells in the study area; the hydraulic properties of the aquifer in the vicinity of each well field are different in both magnitude and spatial orientation; and although each well field pumps at a different rate, an increase of well pumping always increased the CRA. The largest effect of a change in river stage is the change in the potentiometric surface. Typically, an increase of river stage lowers the regional ground-water gradient between the alluvial valley and the rivers in the study area. The effect on the CRA of each well field from a change in the ground-water gradient is different for each well field. The CRAs for the Iatan, Weston, and Ft. Leavenworth well fields increased with increased river stage. The CRA for the Leavenworth well field decreased with an increase in river stage.

Well fields without close hydrologic boundaries upgradient from the regional flow direction, such as the Missouri River or the alluvial valley walls, have long elliptically shaped CRAs because ground water in the simulation travelled a long distance along the flow gradient before it was affected by and discharged by the pumping wells. Wells located closer to the alluvial walls, like the Iatan and Weston well fields, have wide CRAs that extend away from the alluvial valley walls because little water is available from this boundary.

Proximity to a major river reduces the size of the CRA when compared to the CRAs of other wells or well fields with similar pumping rates but located farther from a major river,

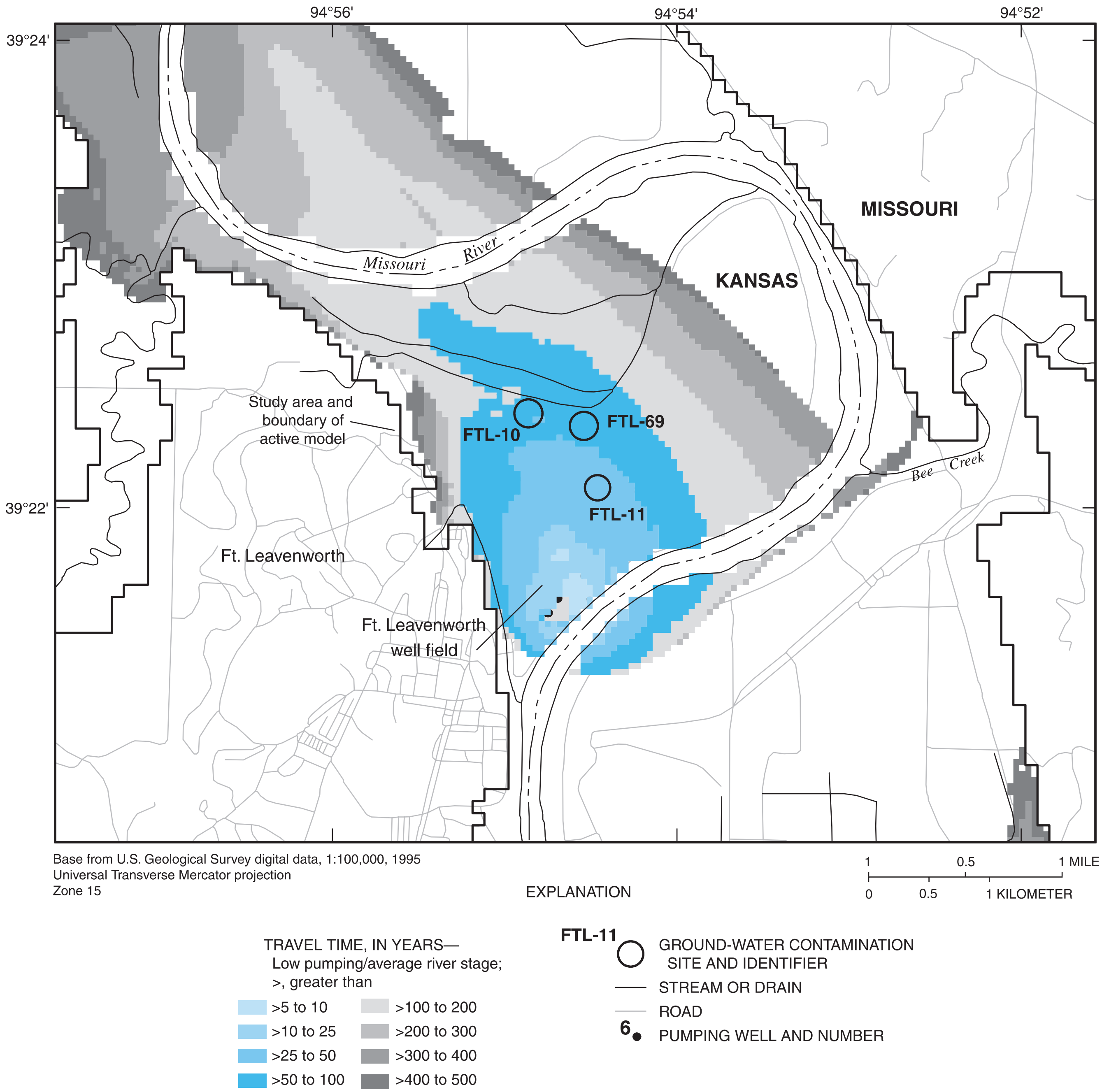


Figure 18. Simulated ground-water travel times between FTL-10, FTL-11, and FTL-69 and the Ft. Leavenworth well field.

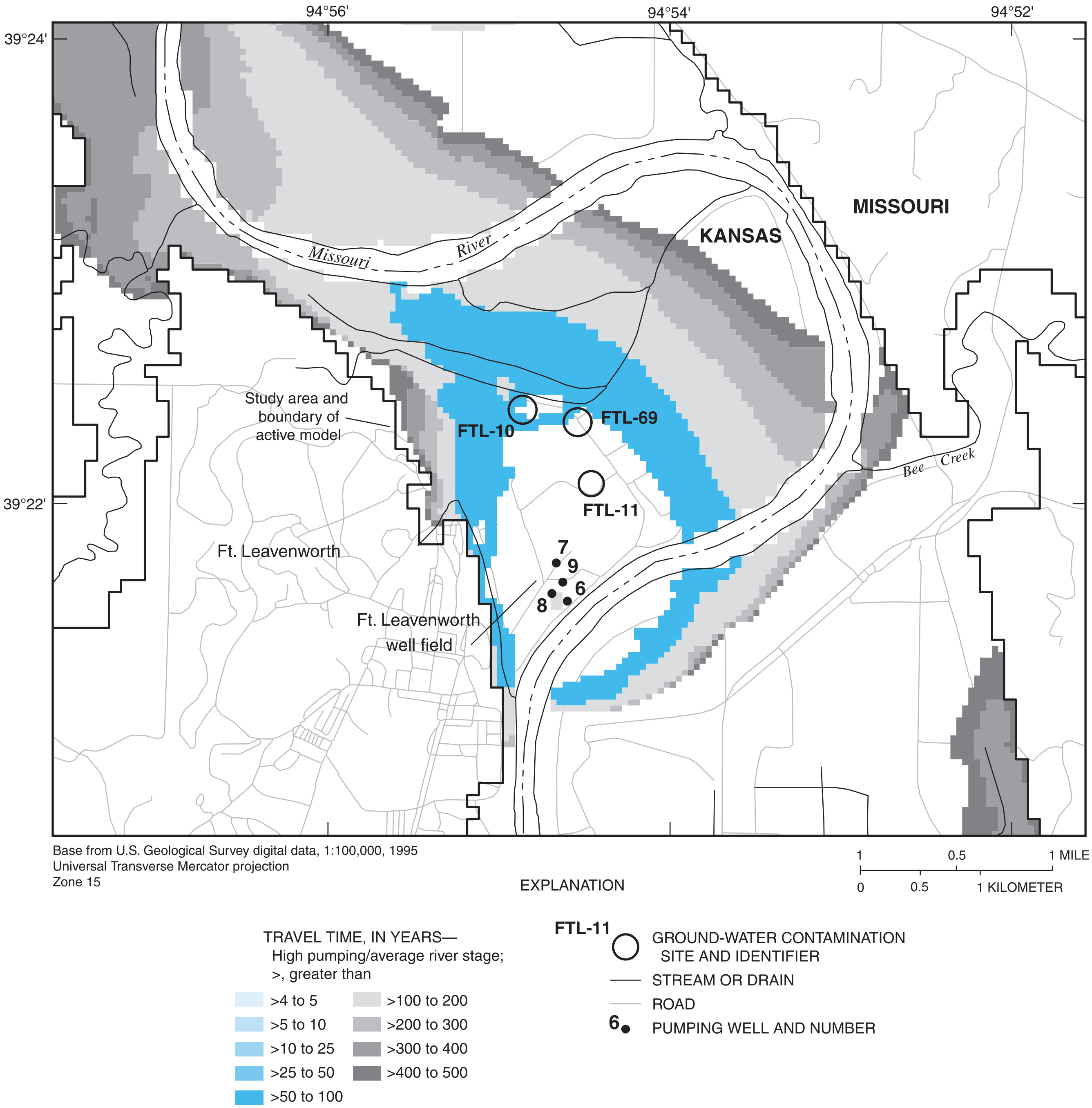


Figure 18. Simulated ground-water travel times between FTL-10, FTL-11, and FTL-69 and the Ft. Leavenworth well field—Continued.

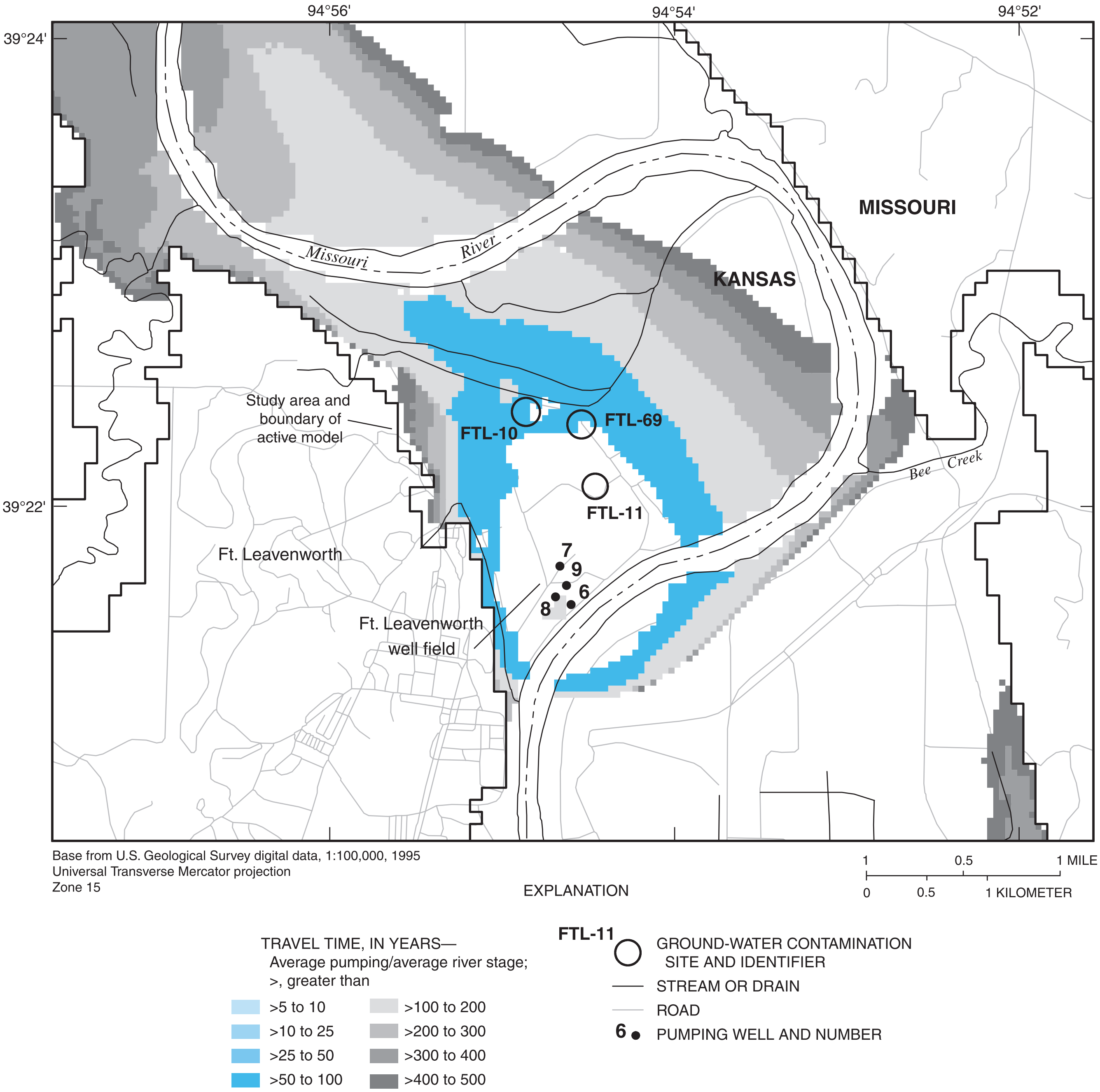


Figure 18. Simulated ground-water travel times between FTL-10, FTL-11, and FTL-69 and the Ft. Leavenworth well field—Continued.

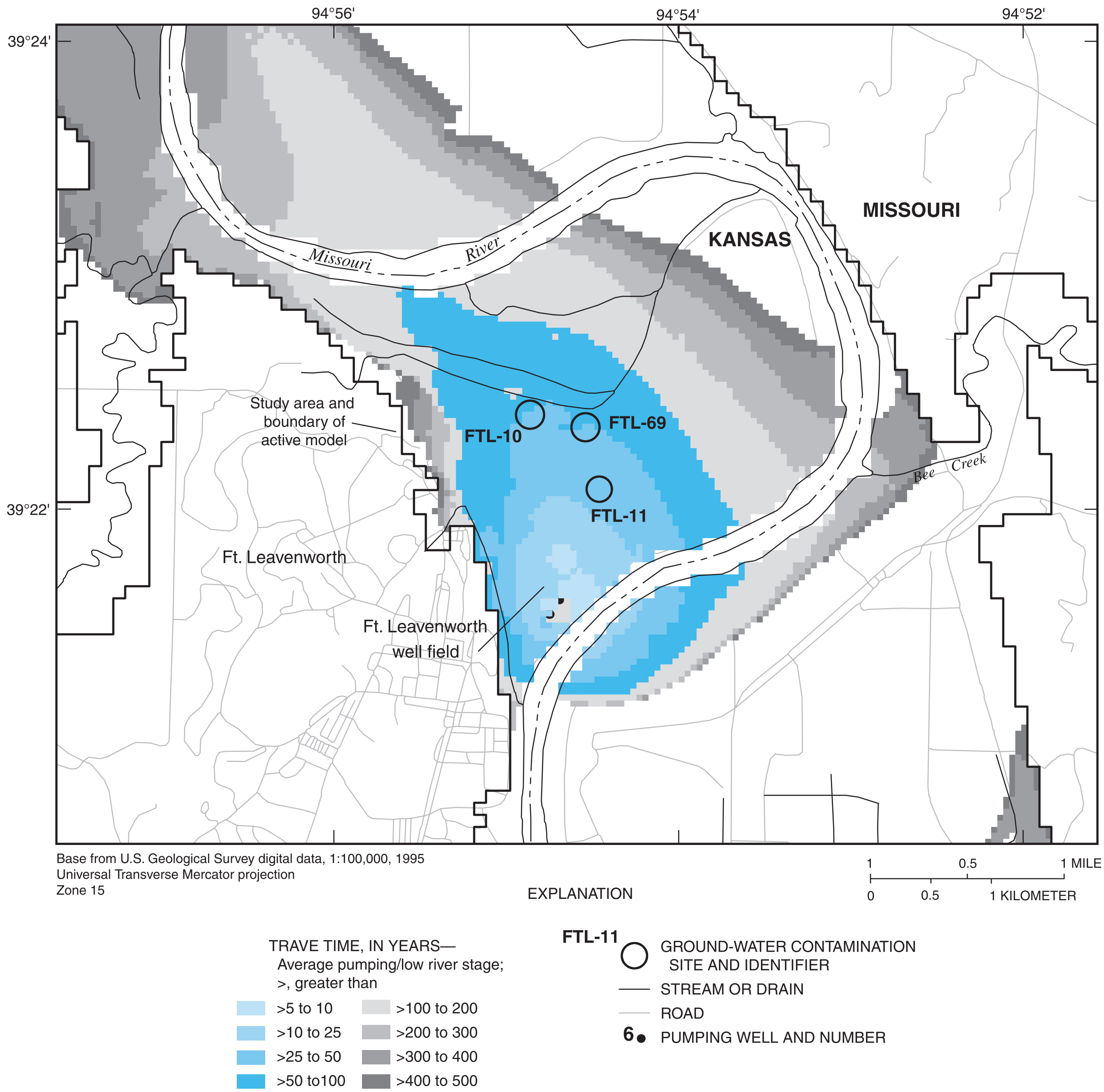


Figure 18. Simulated ground-water travel times between FTL-10, FTL-11, and FTL-69 and the Ft. Leavenworth well field—Continued.

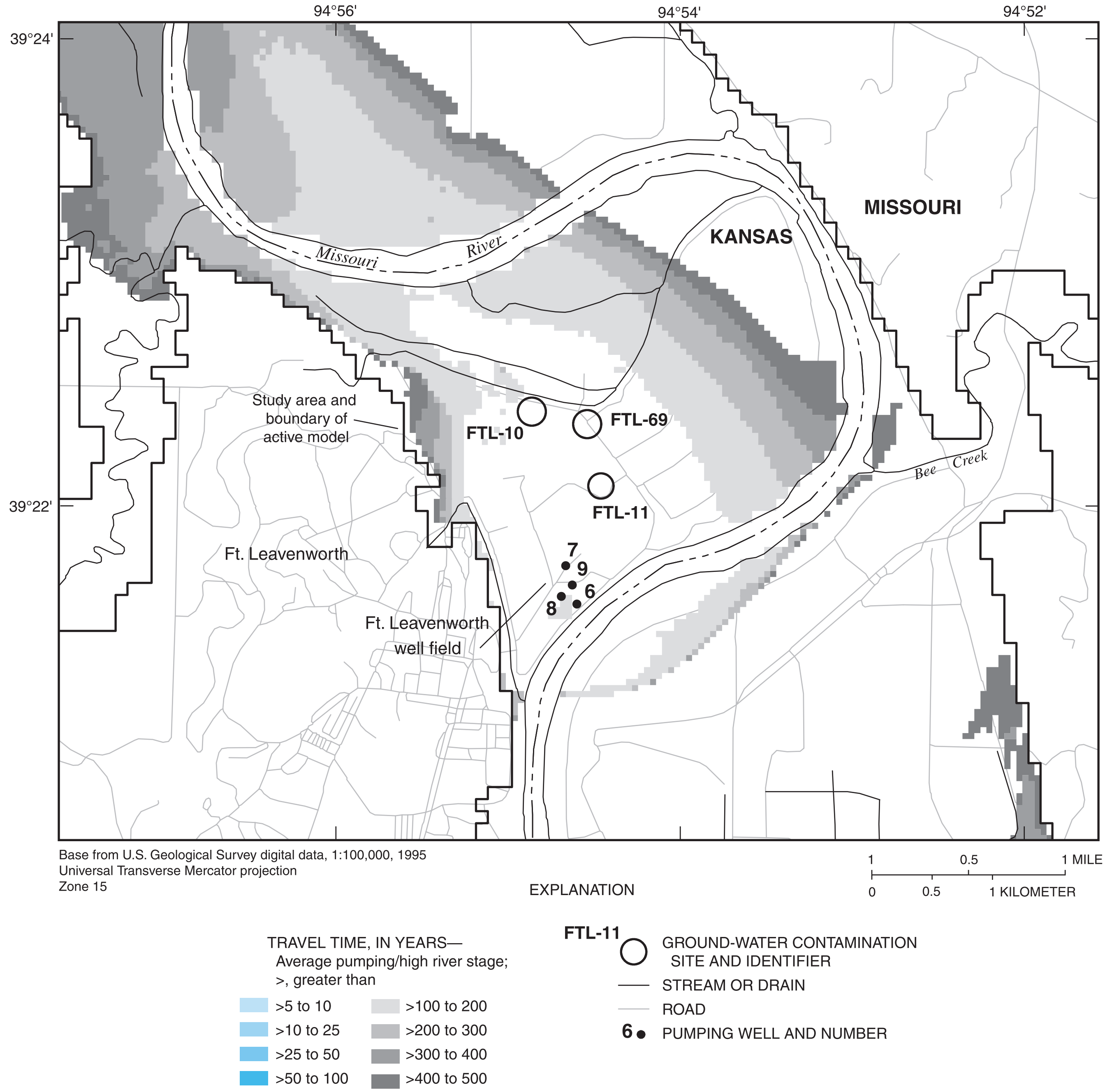


Figure 18. Simulated ground-water travel times between FTL-10, FTL-11, and FTL-69 and the Ft. Leavenworth well field—Continued.

because the well or well field obtains a large part of its water from recharge induced from the river. A comparison of the pumping rates and CRAs for Weston well field, which is not supplied water by the Missouri River, and the Leavenworth well field, which induces recharge from the Missouri River, illustrates the effect of river induced recharge. The simulated average pumping rate for the Weston well field is 1,800 m^3/d, which corresponds to a total CRA of 8.77 km^2 for the APAR scenario. The simulated average pumping rate for the Leavenworth well field is 9,810 m^3/d, which corresponds to a total CRA of 36.73 km^2 for the APAR scenario. The ratio of pumping rate to CRA is a rough estimate of water supplied to the well field per unit CRA. The ratio for the Weston well field is 205.25 $m^3/d/km^2$ (cubic meters per day per square kilometer); the ratio for the Leavenworth well field is 267.08 $m^3/d/km^2$. The higher number for the Leavenworth well field indicates more water is supplied to the well field per unit CRA, although the aquifer properties are similar. The extra water supplied to the Leavenworth well field is from induced recharge from the Missouri River. Dividing the pumping rate of the Leavenworth well field by the ratio for the Weston well field yields a CRA of 47.79 km^2, a rough estimate of how large the CRA for the Leavenworth well field would be without induced recharge from the Missouri River.

The vertical conductance term limits water flow between layers of the model to simulate the vertical anisotropy of hydraulic conductivity within the alluvial aquifer. This anisotropy is greatest in the heterogeneously distributed clay, silty clay, and silt present at shallow depths and represented in the model by layer 1. The distribution of vertical conductance between layers 1 and 2 affect the distribution of ground-water travel times within the total CRA of each well or well field. The most obvious example of this is within the Ft. Leavenworth CRA. The typical distribution of ground-water travel time has shorter travel times near pumping wells and longer travel times farther away. The typical distribution of ground-water travel times does not occur near the FTL-10 site for all well-pumping/river-stage scenarios. For example, in the APAR scenario a small area of 100- to 200-year ground-water travel time and another area of 25- to 50-year ground-water travel time exists within the larger 50- to 100-year travel time area that is more common near FTL-10. This occurred because in layer 1 aquifer material with lower hydraulic conductivity is located near the area of longer ground-water travel time. A low rate of vertical water movement caused by the presence of clay or silt near the land surface increased the travel time of water from the water table to deeper parts of the aquifer. In layer 2, aquifer material with higher hydraulic conductivity is located near the area of shorter ground-water travel time. A higher rate of vertical water movement caused by sand or coarse sand in layer 2 decreased the travel time of water from the water table to deeper parts of the aquifer. Because the hydraulic conductivity values in the deeper parts of the aquifer are higher and more uniformly distributed, the rate of water movement there is faster and more uniform than in shallower parts of the aquifer. Therefore, the rate of water flow vertically from the shallower to the deeper parts of the aquifer has a large effect on the travel time of water from the water table to the screened interval of a pumping well and on the distribution of the CRA of a well or well field.

Interference between pumping well fields also affects the size and shape of CRAs of well fields. Well interference between the Iatan, Weston, and Ft. Leavenworth well fields is evident for all well-pumping/river-stage scenarios, but is most evident for the HPAR and APHR scenarios where CRAs of the Ft. Leavenworth well field separates the CRAs of the Iatan and Weston well fields and the boundaries of the CRAs are close to one another. Reduction or elimination of pumping from the Weston well field would cause the CRA of the Ft. Leavenworth well field to shift toward the Weston well field and may cause the Iatan well field CRA to slightly shift down valley. The most notable effect of interference between pumping wells is within the Ft. Leavenworth well field. The individual CRAs of wells 6, 7, 8, and 9 are adjacent to each other and any change or elimination of pumping in one well will dramatically change the shape of the other CRAs. Wells or well fields located in the upgradient direction from the regional flow field will intercept ground water before it reaches wells or well fields located in the downgradient direction. This effectively cuts off the ground-water supply to the well fields located downgradient and causes the CRA of the downgradient well fields to expand to either side of the CRA of the upgradient well. This is shown for wells 6, 7, and 8 with respect to the CRA for well 9 in the Ft. Leavenworth well field for all well-pumping/river-stage scenarios (fig. 16 and fig. 17).

FTL-10, FTL-11, and FTL-69 are within the Ft. Leavenworth well field CRA for all well-pumping/river-stage scenarios. Both the Iatan and Weston well fields are located upgradient from the contaminated sites with respect to the regional flow field and it is unlikely that ground water will flow from the contaminated sites to these well fields. The Leavenworth well field is located downgradient from the three contaminated sites and the Ft. Leavenworth well field. Ground-water flow from the three contaminated sites to the Leavenworth well field likely will not occur as long as pumping continues from the Ft. Leavenworth well field. If pumping is discontinued from the Ft. Leavenworth well field, and pumping is not substantially increased from the Leavenworth well field, it is unlikely that ground-water flow from the three contaminated sites to the Leavenworth well field will occur because ground water from the sites will likely discharge to the Missouri River and the CRA for the Leavenworth well field does not extend north to the CRA of the Ft. Leavenworth well field.

Summary

The Missouri River alluvial aquifer in the Ft. Leavenworth, Kansas, area supplies all or part of the drinking water for Ft. Leavenworth, Kansas; Leavenworth, Kansas; and Weston, Missouri. Ft. Leavenworth has four operating water-supply wells on the west bank of the Missouri River that pump 1.5 million gallons per day and are a reliable source of drinking water.

The presence of ground-water contamination and inundation of the existing supply wells by the Missouri River during the flood of 1993 have raised concerns about the future reliability of the existing drinking water supply at Ft. Leavenworth. The Missouri River alluvial aquifer, and to a lesser extent, the adjoining alluvial aquifer of the Platte River, are the only aquifers in the study area that can supply large quantities of ground water for public and industrial use. Ground-water contamination poses a potential threat to the existing public-water-supply well field and other nearby public-water-supply well fields.

In 2003, three public-water-supply well fields (Weston, Ft. Leavenworth, and Leavenworth) and one industrial well field (Kansas City Power and Light, Iatan Power Plant) were in operation in the study area. Most water recharging the Missouri River alluvial aquifer comes from surface recharge from precipitation or recharge from the Missouri River. The source area for water that discharges from a pumping well is the contributing recharge area for that well. In the absence of pumping, ground-water flow within the alluvial aquifer typically is away from the valley walls, toward the Missouri River, and down the river valley. A sudden increase in river stage temporarily can reverse the direction of ground-water flow.

Ground-water flow was simulated for the Missouri River alluvial aquifer using the three-dimensional finite-difference ground-water flow model MODFLOW-2000. MODFLOW-2000 is a modified version of MODFLOW that incorporates the use of parameters to define model input, the calculation of parameter sensitivities, and the modification of parameter values to match observed heads, flows, or advective transport using the observation, sensitivity and parameter-estimation processes.

The modeled area is 28.6 kilometers by 32.6 kilometers and contains the entire study area. The model uses a uniform grid size of 100 meters by 100 meters, and contains 372,944 cells in 4 layers, 286 columns, and 326 rows. The model represents the alluvial aquifer using layers numbered 1 to 4 of variable thickness with no intervening confining layers.

The ground-water flow model was calibrated by adjusting model input data and model geometry to modify model output so that model results matched field observations within an acceptable level of accuracy. Parameters changed during the calibration process include horizontal hydraulic conductivity, vertical hydraulic conductivity between model layers, specific storage, specific yield, river conductance, drain conductance, and recharge rates. The strategy for calibration of the ground-water flow model was to use both quasi-steady-state hydraulic head data and transient hydraulic head data. The quasi-steady-state calibration was used to assess model geometry, confirm the conceptual model of ground-water flow, test the appropriateness of simulated boundary conditions, and obtain approximate transmissivity and recharge arrays in preparation for more rigorous transient calibration. The transient calibration was used to fine-tune the model hydraulic properties.

The model accuracy was calculated using the root mean square (RMS) error between actual measurements of hydraulic head and model generated hydraulic head at the end of each model run. The accepted RMS errors for the model calibrations were below the maximum measurement errors. The RMS error for the quasi-steady-state calibration was 0.82 meter and 0.33 meter for the transient calibration.

A sensitivity analysis was performed to assess the response of the model simulation to changes in various input parameter values. Composite scaled sensitivities indicate the quasi-steady-state simulation is most sensitive to the parameters for well pumping rate, recharge in zone 4, hydraulic conductivity in layer 3, zone 2, and recharge in zone 3, and the transient simulation is most sensitive to the parameters for recharge in zone 3, river conductance in layer 2, zone 1, river conductance in layer 2, zone 2, and hydraulic conductivity in layer 3, zone 2. One percent scaled sensitivities indicate how much a simulated value of head would change based on a one-percent increase in the value of the parameter. Different one-percent sensitivities for different water-level observations are caused by the location of the observed head value with respect to the value of the parameter in the model. The one-percent scaled sensitivities for parameters for each observed head value in the transient calibration simulation change with time as different stresses are applied to the model.

Particle tracking analysis using the U.S. Geological Survey (USGS) particle-tracking program MODPATH determined the contributing recharge area and ground-water travel times for each known pumping well or well field in the study area. Steady-state ground-water flow was simulated for five different combinations of well pumping and river stage to determine the hydraulic head distribution in the study area. Particle tracking analysis then determined the contributing recharge area (CRA) for pumping wells in each of the five scenarios. The well-pumping/river-stage scenarios are low pumping rate, average river stage (LPAR); high pumping rate, average river stage (HPAR); average pumping rate, average river stage (APAR); average pumping rate, low river stage (APLR); and average pumping rate, high river stage (APHR). Well pumping rates used in the quasi-steady-state calibration and average well pumping simulations are average annual pumping rates.

For each scenario, one imaginary particle of water was placed on the water table in each quadrant of the top-most active model cell and tracked to its eventual discharge point. Particles were placed in this manner for two reasons: most water entering the alluvial aquifer comes from direct infiltration by precipitation or from the major rivers, and the primary source of potential contamination to the alluvial aquifer is from leaks or spills that occur on the land surface. Consequently, the CRAs computed by MODPATH include the source area of water to each well or well field and advective ground-water travel times from the land surface and the major rivers to each well or well field.

The shape, size, and ground-water travel time within the CRA for each well or well field is affected by changes in river stage and pumping rates and by the location of the well or well field with respect to the major rivers, alluvial valley walls, and other pumping wells. Similarities in the shapes of CRAs between different wells and well fields can be attributed to similarities in the pumping rate and the position of the wells or well fields in relation to the major rivers, the alluvial valley walls, or other well fields.

The shapes of the simulated CRAs for the well fields in the study area are elongated in the upstream direction for all well-pumping/river-stage scenarios because of the capture of ground water by the pumping wells as it moved downgradient toward the Missouri River.

The CRAs for the Iatan well field listed from smallest to largest are LPAR [5.59 km^2 (square kilometers)], APLR (7.47 km^2), APAR (7.55 km^2), APHR (8.18 km^2), and HPAR (9.34 km^2). Recharge to the well field primarily is from precipitation and surface runoff from the surrounding uplands. Little if any recharge to the well field comes from the Missouri River because the CRA does not intersect the Missouri River for any well-pumping/river-stage scenarios. The CRAs for the Weston well field listed from smallest to largest are LPAR (6.66 km^2), APAR (8.77 km^2), APLR (8.79 km^2), APHR (9.14 km^2), and HPAR (11.11 km^2). Recharge to the well field primarily is from precipitation and surface runoff from the surrounding uplands. Little, if any, recharge to the well field comes from the Missouri River because the CRA does not intersect the Missouri River for any well-pumping/river-stage scenarios. The CRAs for the Leavenworth well field listed from smallest to largest are LPAR (28.2 km^2), APHR (29.67 km^2), APAR (36.73 km^2), APLR (51.11 km^2), and HPAR (64.27 km^2). Recharge to the well field is from precipitation, surface runoff from the surrounding uplands, and the Missouri River because the CRA intersects these boundaries for all well-pumping/river-stage scenarios.

The CRAs for the Ft. Leavenworth well field listed from smallest to largest are LPAR (25.06 km^2), APAR (32.88 km^2), APLR (32.89 km^2), HPAR (33.47 km^2), and APHR (34.61 km^2). Recharge to the well field is from precipitation, surface runoff from the surrounding uplands, and the Missouri River because the CRA intersects these boundaries for all well-pumping/river-stage scenarios. Four wells of the Ft. Leavenworth well field (wells, 6, 7, 8, and 9) are actively pumped. The CRAs listed from smallest to largest for all well-pumping/river-stage scenarios are well 7, well 6, well 9, and well 8. Well 7 has the smallest CRA (2.68 km^2) for the LPAR scenario. Well 8 has the largest CRA (23.3 km^2) for the APHR scenario.

Three sites with known ground-water contamination (FTL-10, FTL-11, and FTL-69) exist upgradient from the Ft. Leavenworth well field. These sites are within the Ft. Leavenworth well field CRA for all simulated well-pumping/river-stage scenarios. The FTL-10 site is within the well 9 CRA for all simulated well-pumping/river-stage scenarios. FTL-11 and FTL-69 are within the well 7 CRA for the LPAR, APAR, APLR, and APHR scenarios, and are within the well 9 and well 7 CRAs for the HPAR scenario.

Minimum ground-water travel time to the Ft. Leavenworth well field from FTL-10 is 43.8 years for the HPAR scenario, from FTL-11 is 28.8 years for the APLR scenario, and from FTL-69 is 43.8 years for the HPAR scenario. Maximum ground-water travel time to the Ft. Leavenworth well field from FTL-10 is 75.4 years for the LPAR scenario, from FTL-11 is 42.1 years for the LPAR scenario, and from FTL-69 is 59.6 years for the LPAR scenario. Ground-water travel times from the three contaminated sites to the Ft. Leavenworth well field for the APAR scenario are most representative of long-term ground-water flow conditions that occurred in the study area. For the APAR scenario, minimum ground-water travel time from FTL-10 to the Ft. Leavenworth well field is 44.2 years, maximum is 70.8 years, and the mean is 55 years. Minimum ground-water travel time from FTL-11 to the Ft. Leavenworth well field is 33.5 years, maximum is 38.9 years, and the mean is 36.1 years. Minimum ground-water travel time from FTL-69 to the Ft. Leavenworth well field is 48 years, maximum is 53.3 years, and the mean is 49.8 years.

The effect of well pumping and river stage on the total CRA of well fields in the study area is complex because each well field has a unique orientation with respect to the geometry of the aquifer, the alluvial valley walls, the rivers, and the other pumping wells in the study area; the hydraulic properties of the aquifer in the vicinity of each well field are different in both magnitude and spatial orientation; and although each well field pumps at a different rate, an increase in well pumping always increased the CRA. The CRAs for the Weston, Iatan, and Ft. Leavenworth well fields increased with increased river stage. The CRA for the Leavenworth well field decreased with an increase in river stage.

Proximity to a major river reduces the size of the CRA, when compared to the CRAs of other wells or well fields with similar pumping rates, but located farther from a major river, because the well or well field obtains a large part of its water from recharge induced from the river. The ratio of pumping rate to CRA is a rough estimate of water supplied to the well field per unit CRA. The ratio for the Weston well field is 205.25; the ratio for the Leavenworth well field is 267.08. The higher number for the Leavenworth well field indicates more water is supplied to the well field per unit CRA although the properties of the alluvial aquifer are similar. The extra water supplied to the City of Leavenworth well field is from induced recharge from the Missouri River.

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