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

In cooperation with the
Carroll County Water-Supply Board

Hydrogeology and Simulation of Ground-Water Flow in the Ohio River Alluvial Aquifer Near Carrollton, Kentucky

Water-Resources Investigations Report 98-4215

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By **Michael D. Unthank**

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Louisville, Kentucky
1999

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	0.003785	cubic meter
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	2.54	centimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

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

Altitude, as used in this report, refers to distance above or below sea level.

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.

Hydrogeology and Simulation of Ground-Water Flow in the Ohio River Alluvial Aquifer Near Carrollton, Kentucky

By Michael D. Unthank

Abstract

The alluvial aquifer near Carrollton, Kentucky, lies in a valley eroded by glacial meltwater that was later part filled with outwash sand and gravel deposits. The aquifer is unconfined, and ground water flows from the adjacent bedrock-valley wall toward the Ohio River and ground-water withdrawal wells. Ground-water-level and Ohio River stage data indicate the alluvial aquifer was at or near steady-state condition in November 1995.

A two-dimensional, steady-state ground-water-flow model was developed to estimate the hydraulic properties, the rate of recharge, and the contributing areas to discharge boundaries for the Ohio River alluvial aquifer at Carrollton and the surrounding area. Results from previous investigations, available hydrogeologic data, and observations of water levels from area ground-water wells were compiled to conceptualize the ground-water-flow system and construct the numerical model. Ground water enters the modeled area by induced infiltration from the Ohio River and smaller streams, flow from the bedrock-valley wall, and infiltration of precipitation. Ground water exits the modeled area primarily through withdrawal wells and flow to the Ohio River. A sensitivity analysis of the model indicates that it is most sensitive to changes in the stage of the Ohio River and conductance values for the riverbed material. A particle-tracking simulation was used to delineate recharge and discharge boundaries of the flow system and contributing areas for withdrawal wells, and to estimate time of travel through the flow system.

INTRODUCTION

The Ohio River alluvial aquifer beneath Carrollton, Ky., is an important water resource for the cities of Carrollton and Ghent, as well as for several industries in the area. Regional water managers and environmental coordinators seek the data and tools needed to understand and plan for current and future effects on this resource to ensure proper water use and environmental planning by all ground-water users in the Carrollton area. This is especially important in the Carrollton area because the aquifer is of limited areal extent (the width is less than 1.0 mi in some areas), and several ground-water users are located near one another along this narrow band. The interaction between the users on a regional scale becomes a limiting factor in the development of ground-water supplies in the area (Whitesides and Ryder, 1969).

In 1994, the U.S. Geological Survey (USGS), in cooperation with the Carroll County Water-Supply Board, began an investigation to characterize the hydrogeology of the Ohio River alluvial aquifer beneath Carrollton and the surrounding area. This investigation will provide water managers and other decisionmakers the types of information and tools necessary for the rational management of the area's ground-water resources.

Purpose and Scope

This report describes the results of an investigation conducted from 1994 to 1997 to refine the understanding of the hydrogeology of the alluvial aquifer in the Carroll and Gallatin County areas of northern Kentucky and to characterize the ground-water-flow system. The hydrologic significance of geologic units in the study area are briefly discussed on the basis of results of previous investigations, existing and newly gathered hydrologic and lithologic data, and observations of water levels. A conceptualization of the ground-water-flow system is represented in a two-dimensional, steady-state, finite-difference ground-water-flow model. Numerical simulation of the ground-water-flow system is a quick and thorough way to develop a regionally consistent tool that can be used as the basis for water-use and environmental-planning decisions. The study area was limited to the alluvial aquifer adjacent to the Ohio River in Carroll and Gallatin Counties, Ky.

Approach

The evaluation of the hydrogeology and ground-water flow in the Ohio River alluvial aquifer at Carrollton, Ky., consisted of four parts: (1) collection of hydrogeologic parameters and data, both in the field and from published literature; (2) conceptualization of the ground-water-flow system; (3) development and calibration of a numerical model of flow in the sand and gravel deposits of the alluvial aquifer; and (4) application of the numerical model through a particle-tracking simulation. Literature and data-file searches yielded information concerning well locations, yields and pumping rates, ground-water levels, Ohio River stage data, and geologic and water-bearing characteristics of area deposits. These data were used to develop a conceptual model of the ground-water-flow system to identify areas of recharge and discharge, boundary conditions, and regional flow patterns. Four semi-annual synoptic water-level measurements, beginning in November 1994, were used to determine seasonal highs and lows in water levels. Eight ground-water observation wells were equipped with continuous water-level recorders to determine trends in the water levels through the year and the aquifer's response to floodwaves from the Ohio River. A series of boreholes were drilled to determine the depth to bedrock and lithology of the unconsolidated deposits in the study area where pre-existing data were sparse. A steady-state, numerical model of flow in the alluvial aquifer was calibrated to ground-water levels in November 1995. Results from the calibrated ground-water-flow model were applied to an advective-flow particle-tracking program to delineate ground-water flowpaths, contributing areas to withdrawal wells, and time-of-travel estimates.

Previous Studies

The hydrology and geology of Carrollton and the surrounding area have been described in numerous reports and hydrologic investigations atlases. A general discussion of the Ohio River Valley and its alluvial deposits is presented by Walker (1957); the hydrology of the alluvial deposits in the Ohio River Valley, including the availability, quality, and development of ground-water supplies, is present by Gallaher and Price (1966). Details of the study area are included in two hydrologic investigations atlases. Hall and Palmquist (1960) describe the availability of ground water in a multi-county study, which includes Carroll County and the Carrollton area. The atlas presents a generalized geologic columnar section and a listing of the water-bearing characteristics of the area deposits. The geology and hydrology of the alluvial deposits along the Ohio River near Carrollton, including sections and fence diagrams, is the subject of an atlas by Price (1964). Whitesides and Ryder (1969) present the effects of pumping from the alluvial aquifer between Carrollton and Ghent, Ky. The report includes ground-water pumpage values, water levels, and transmissivity values are documented for several area well fields. The potential for induced infiltration from the Ohio River and total amount of ground water available for withdrawal also are discussed. Aquifer diffusivity (the ratio of transmissivity to the storage coefficient) was calculated by Grubb and Zehner (1973) using the floodwave-response method for a site midway between Carrollton and Ghent, Ky.

Description of the Study Area

The study area is in Carroll and Gallatin Counties in north central Kentucky (fig. 1) and consists of approximately 20 mi^2 in the Ohio River Valley from the Kentucky River at Carrollton northeast to Markland Locks and Dam. It is about 15 mi long and ranges in width from about 1.5 mi near Ghent to about 3 mi at Carrollton. The study area is bound on the northwest by the Ohio River and on the southeast by steep bedrock valley walls; soils in the area are mostly silt and clay. Land-surface altitudes in the study area range from 420 to 490 ft in the valley to slightly more than 800 ft atop the valley

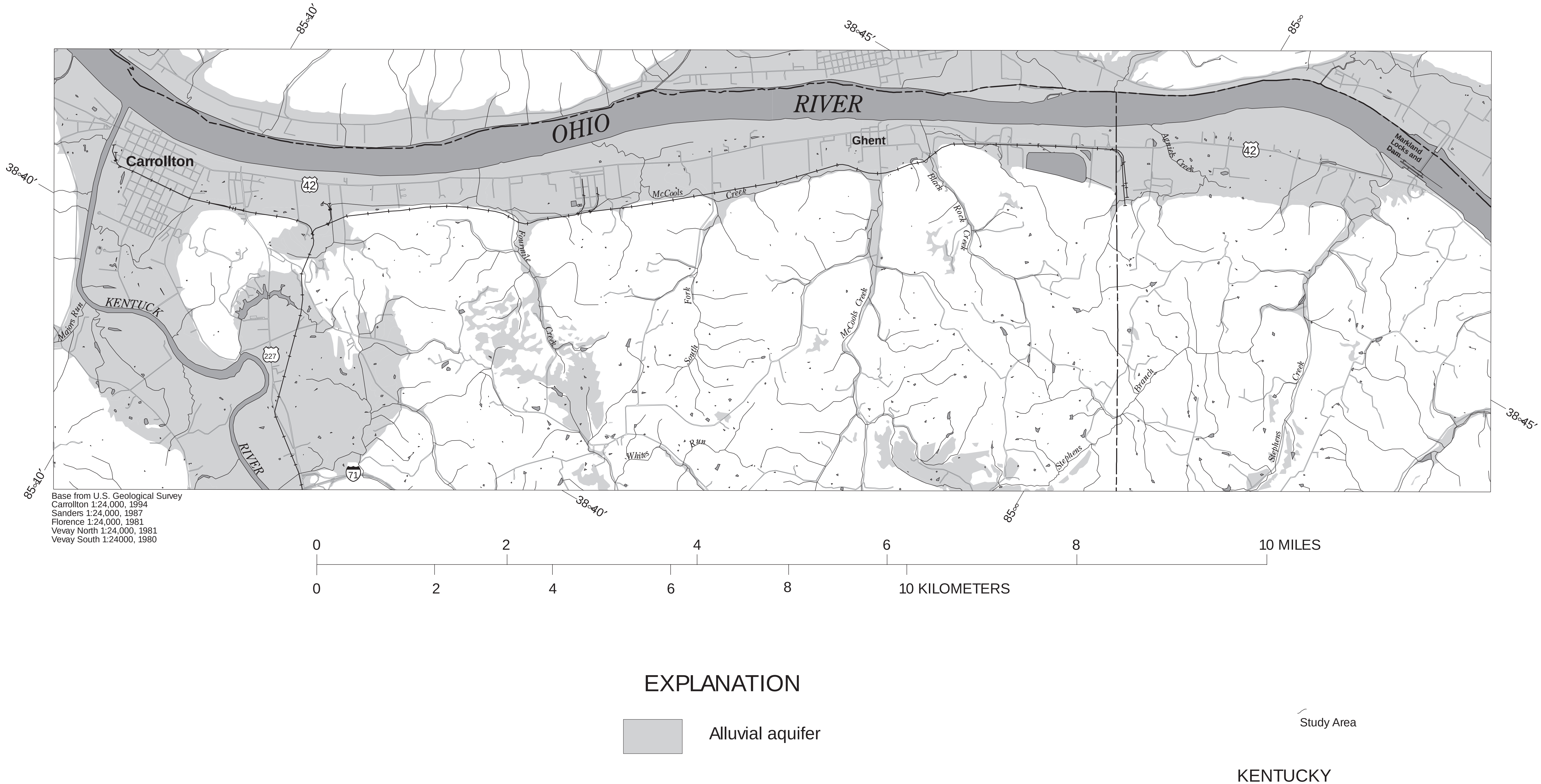

Figure 1. Location of study area and extent of the Ohio River alluvial aquifer.

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walls. Normal pool stage of the Ohio River and the Kentucky River in the study area is 421 ft above sea level. Most of the area has been cleared for industrial use, but areas of agriculture are interspersed with institutional, recreational, and residential areas.

The population of Carrollton was 3,715 in 1990; Carroll County had a population of 9,292 (U.S. Department of Commerce, Bureau of the Census). The climate is temperate, and the average annual precipitation from 1947 to 1994 was 44.39 in. (Kentucky Cabinet for Economic Development, 1996, p. 20). The average annual discharge of the Ohio River at Markland Dam from 1970 to 1996 was 115,600 ft^3/s (McClain and others, 1997).

HYDROGEOLOGY OF THE ALLUVIAL AQUIFER

The study area lies within the Ohio River alluvium physiographic region of Kentucky. The exposed consolidated rocks of the area are of sedimentary origin and the Ordovician age. The Ordovician rocks were eroded by glacial meltwater of the Pleistocene Epoch. Deep valleys were excavated prior to the deposition of a thick body of sand and gravel. Ground water in the study area typically flows from the valley wall toward the Ohio River. Ground-water discharges to the Ohio River, the Kentucky River, and to water-supply wells.

Geology

The rocks underlying the alluvial aquifer in the Carrollton area are primarily shales and limestones of Ordovician Age. The pertinent formation, the Kope Formation, is characterized by interbedded shale and limestone (table 1). The shale comprises about 80 percent of the deposits; limestone is present as single beds separated by a few inches to several feet of shale (Swadley, 1976).

During the Pleistocene or glacial epoch, ice sheets repeatedly advanced south from Canada. As the ice thawed, meltwaters eroded a deep valley through the Carrollton area. Down-cutting of the bedrock surface and deposition of alluvial materials occurred during the Wisconsin age. The depth to the valley floor or bedrock surface from the present land surface ranges from 100 ft at Carrollton and Ghent to as much as 150 ft in some places of the study area. The Pleistocene valley averages about 2.0 mi wide in the study area. The valley broadens at Carrollton near the confluence of the Kentucky River and the Ohio River. The down-cutting of the bedrock and the subsequent filling of the valley has left the upper part of the Kope Formation exposed along the valley walls. The Kope Formation is overlain by additional shales and limestones of the Upper Ordovician Series, namely the Calloway Creek Limestone and Fairview Formation, the Grant Lake Limestone, and the Bull Fork Formation. These Upper Ordovician formations do not figure prominently in the hydrogeology of the alluvial aquifer and are mentioned here only for thoroughness. Figure 2 shows the surficial geology of the study area. The geologic history of the area is described in detail by Walker (1957).

As the ice sheets of the Wisconsin Age advanced and melted, heavier, coarse-grained alluvium was deposited as the sediment-transport capacity of the floodwaters decreased. This portion of the alluvium is characterized by medium- to coarse-grained sand with lenses of gravel in the lower part; gravels as much as 3 in. in diameter are present in the study area. The coarse-grained alluvium was topped by a thick sheet of fine-grained alluvium during the final glacial melting of the Wisconsin Age, and this upper part of the alluvium consists of fine-grained sand and silt.

The alluvium is capped throughout the study area with a layer of silt and clay. These are non-glacial sediments brought to the area by the Ohio River and its tributaries.

Continued down-cutting by the Ohio River and the removal of Wisconsin Age alluvial fill are the principal features of post-glacial history. The Ohio River continues to meander from side to side, eroding the alluvium in its bed and along its banks. Floodwaters deposit a thin layer of sand, silt, and clay on the land surface, but a net gain is not necessarily realized as there is a considerable amount of scour accompanying the early stages of flooding (Walker, 1957).

Table 1. Stratigraphic column of the geologic units in the Carrollton area, Kentucky

[gal/min, gallons per minute; gal/d, gallons per day]

System	Series	Formation	Thickness (in feet)	Lithology and remarks
Quaternary	Pleistocene and Holocene	Alluvium	0-80+	Clay, silt, sand, and gravel. Yields as much as 500 gal/min to wells in the Ohio River Valley.
	Pleistocene	Terrace deposits	0-79+	Mixtures of clay, silt, sand, and gravel. Outwash represents the primary aquifer in the Carrollton area.
		Glacial outwash	0-80+	
		Glacial drift	0-90+	
Ordovician	Upper Ordovician	Bull Fork Formation	195-210	Interbedded limestone and shale.
		Grant Lake Limestone	60-85	Thin-bedded limestone, very irregular and discontinuous.
		Fairview Formation and Calloway Creek Limestone	85-105	Alternating rubbly limestone and lumpy calcareous shale. Wells yield 100 to 500 gal/d from thick limestone beds.
		Kope Formation	145+	Interbedded shale (80 percent) and limestone. Yields 100 to 500 gal/d from wells in broad valley bottoms.

Information compiled from Hall and Palmquist (1960), Price (1964), and Swadley (1976).

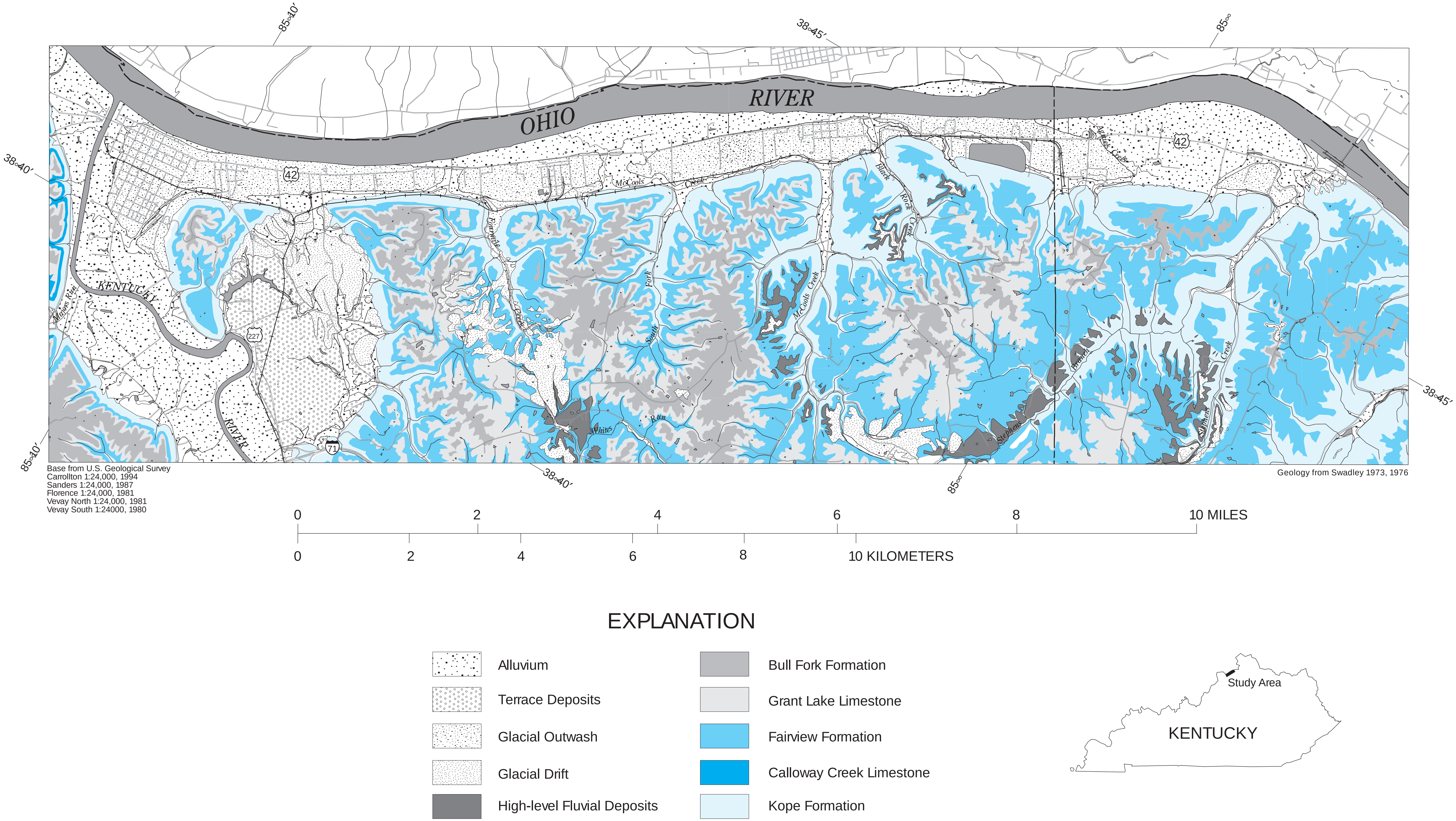

Figure 2. Surficial geology of the Carrollton area, Kentucky.

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Hydrologic Data

The alluvial aquifer beneath Carrollton typically has been studied as part of larger investigations that focused on the geology, hydrology, and alluvial deposits of the Ohio River Valley. The geology of the Carrollton area has been described by Swadley (1973, 1976). Price (1964) compiled available lithologic data, including fence diagrams, that described the geology and hydrology of the alluvial deposits for Carrollton and adjacent areas along the Ohio River. More general descriptions of the hydrology and physical characteristics of the alluvial deposits were presented by Gallaher and Price (1966) and Walker (1957). A variety of new hydrologic and geologic data were collected as part of this investigation. A ground-water-level observation network of 94 wells was monitored during the period November 1994–May 1996. Included in this network were eight wells equipped with continuous-recording devices that measured changes in the ground-water level and temperature. Geologic and lithologic data were collected during a drilling program. Twenty-seven boreholes were drilled to determine the thickness and lithology of the unconsolidated deposits at selected sites throughout the study area.

Ground-Water-Level Observation Network

A total of 94 ground-water-level observation wells were inventoried as part of this investigation. The network included abandoned domestic, commercial, and industrial wells, active domestic-supply wells, observation and test wells near public water-supply wells, monitoring wells from active and dormant remediation activities, and piezometers. Continuous recorders were installed on eight of the wells to document trends in water levels and the aquifer's response to stresses such as pumpage, precipitation, and flooding. Of the 94 wells, water-level measurements from 49 wells are used for presentation of the data and model calibration; the only criterion for choosing these 49 wells was location. Many of the original 94 wells are in clusters at industrial sites in the study area, and presentation of data at the scale used for this investigation makes the data cumbersome and hard to read. Therefore, a subset of 49 wells, evenly distributed throughout the study area, is used for presentation and calibration. Figure 3 shows the location of all the inventoried wells (94 wells).

Synoptic ground-water-level measurements were made four times during the course of this investigation: November 1994, May 1995, November 1995, and May 1996. The May and November time periods represent typical high and low points in ground-water levels, respectively. Hydrographs of water levels from wells 2 and 3 show seasonal trends in the ground-water levels and are indicative of trends in all of the recorder wells (fig. 4). Water-level measurements for the subset of 49 wells were available for each of the four synoptics.

Precipitation

A record of daily precipitation is kept at the U.S. Army Corps of Engineers office at the Markland Locks and Dam, on the Ohio River at the upstream end of the study area (fig. 1). The total precipitation recorded at this site for the period July 1994–June 1995 was 42.05 in. The normal annual precipitation for the study area is 44.39 in.

Ground-Water Pumpage

Ground water is used for public and domestic drinking-water supplies in the study area and for processing at many of the area industries. Table 2 summarizes the ground-water users inventoried for use in the model simulation. Pumpage volume and number of operational wells presented here are for November 1995 as reported by each ground-water user. Figure 5 shows the location of the inventoried ground-water withdrawals.

Ground-Water Flow in the Alluvial Aquifer

Under natural conditions, regional ground-water flow in the alluvial aquifer is predominantly horizontal, from the alluvium/bedrock boundary at the valley wall toward the Ohio River. This flow pattern is interrupted in areas of large ground-water withdrawals, where cones of depression in the potentiometric surface have formed (fig. 6). Water-level measurements and lithologic data indicate the alluvial aquifer to be unconfined.

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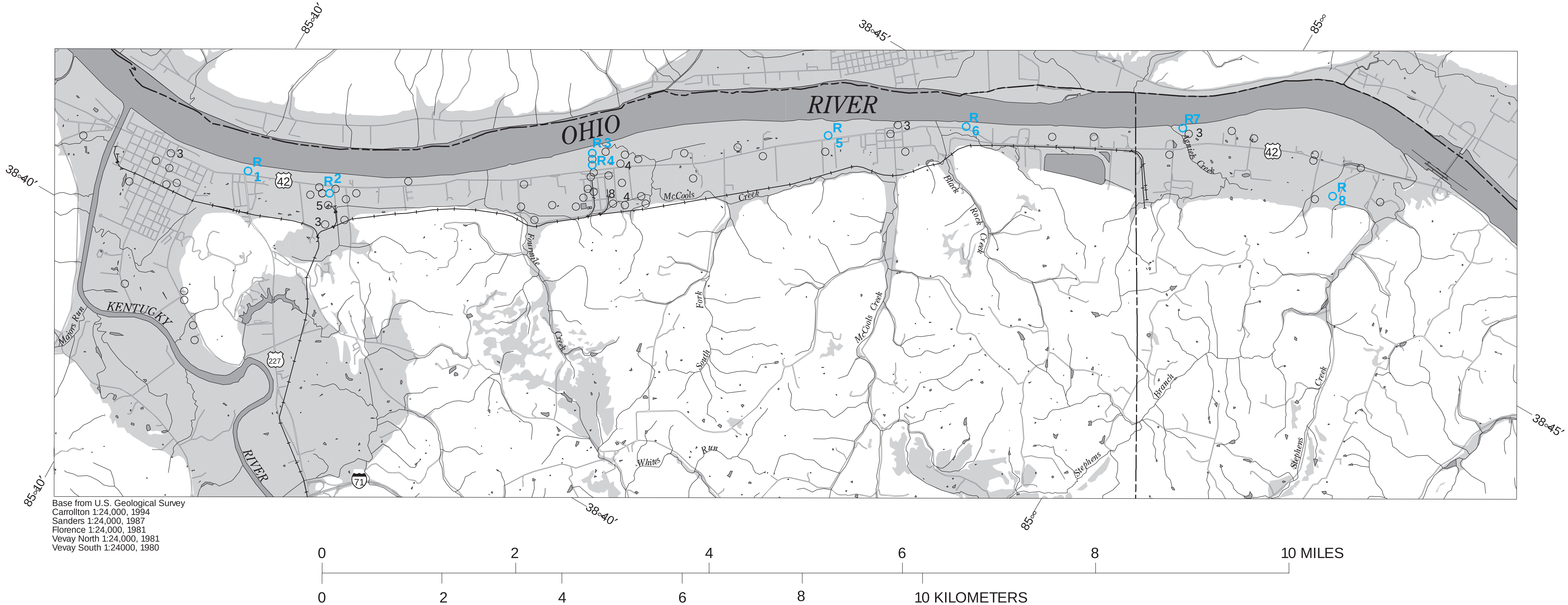

EXPLANATION

Alluvial aquifer

Observation well with continuous recorder

Observation well

Multiple observation wells

Study Area

KENTUCKY

Figure 3. Observation well network.

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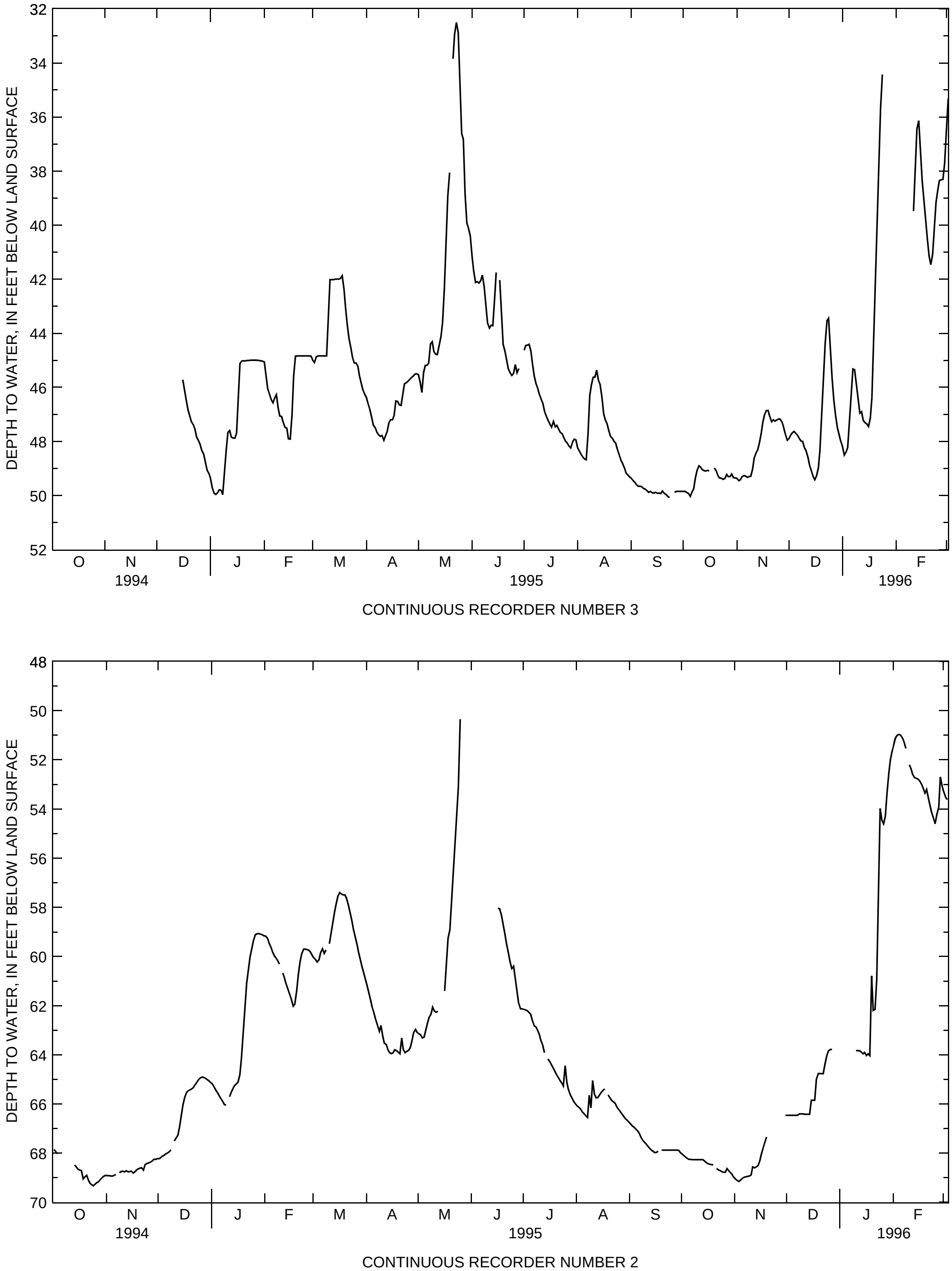

Figure 4. Typical water-level hydrographs for wells completed in the alluvial aquifer.

Table 2. Ground-water pumpage for public water-supply and industrial-supply wells, Carrollton, Kentucky, November 1995

[Mgal/d, million gallons per day]

Map number	Ground-water user	Number of wells	Volume pumped (Mgal/d)
1	Carrollton Utilities	3	0.7
2	Elf Atochem	4	2.8
3	Dow Corning	9	12.4
4	Dayton-Walther	1	<.1
5	Carroll County Water District	2	.5
6	Kentucky Utilities	5	.4

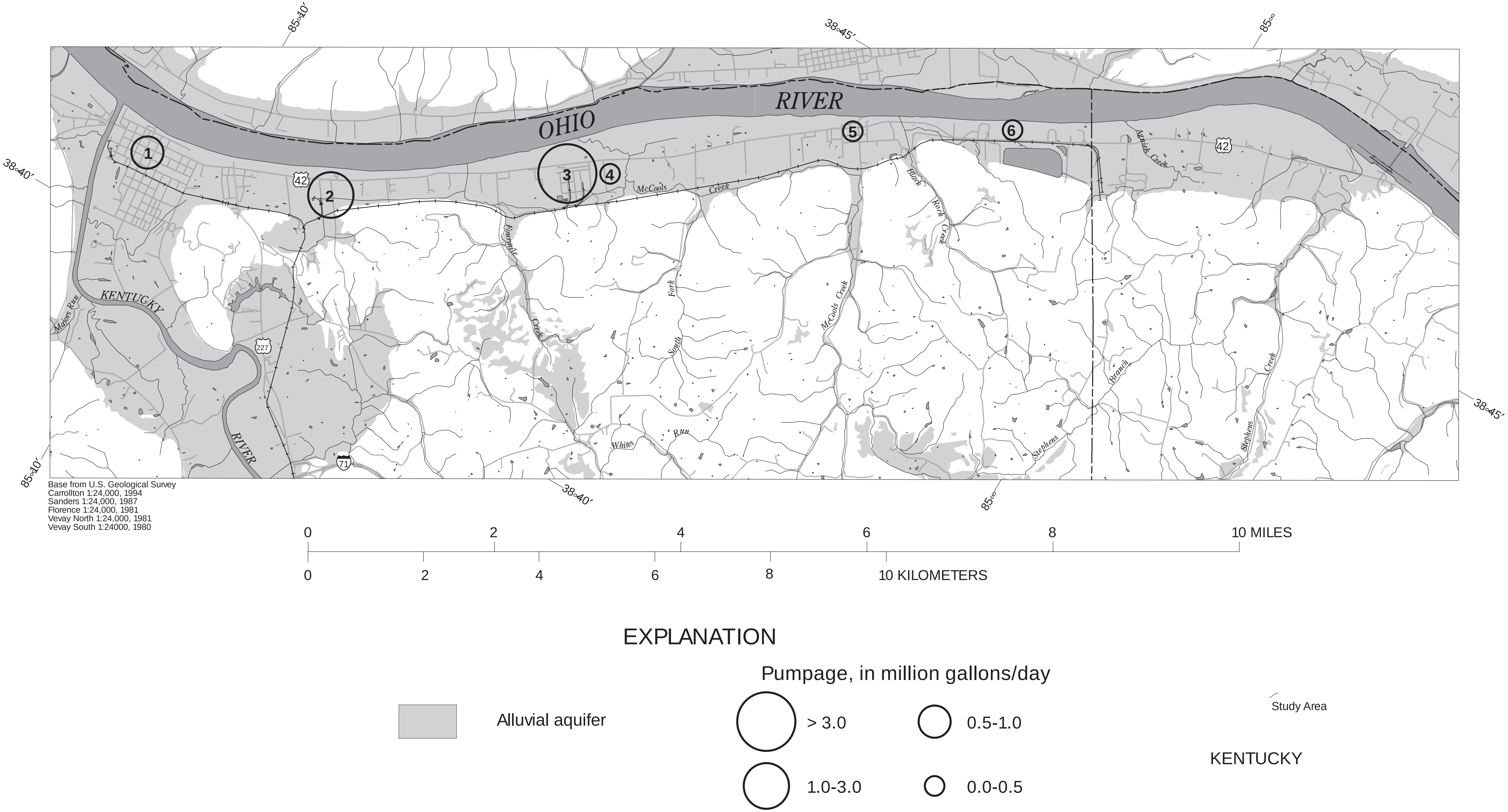

Figure 5. Location and amounts of ground-water pumpage.

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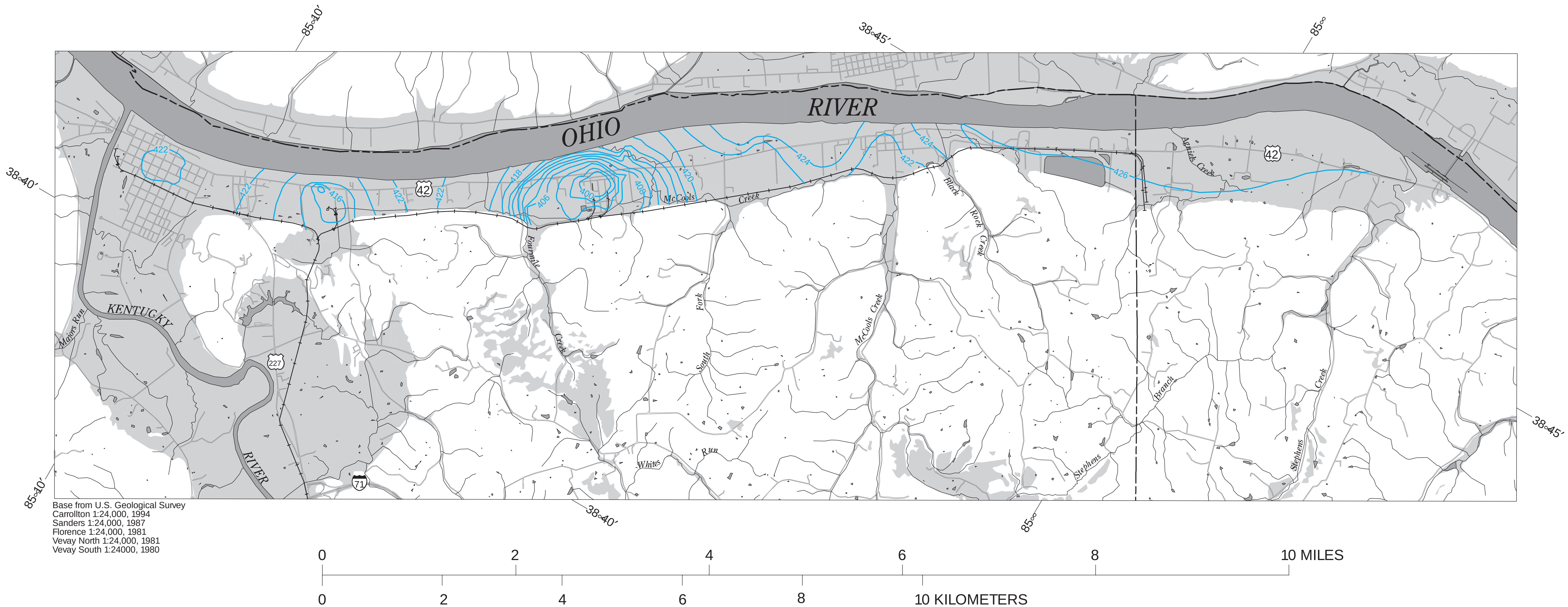

EXPLANATION

Alluvial aquifer

422 WATER-LEVEL CONTOURS - Showing altitude of water level. Contour interval 2 feet; datum is sea level

Study Area

KENTUCKY

Figure 6. Altitude of potentiometric surface of the alluvial aquifer near Carrollton, Kentucky, November 1995.

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Recharge to the alluvial aquifer is from vertical infiltration of precipitation, flow from the valley wall, and infiltration from the Ohio River, both natural and induced. The bedrock beneath the alluvium is considered to be a no-flow boundary, thus not contributing water to or extracting water from the alluvium. Natural infiltration of water from the Ohio River to the alluvial aquifer may occur during high-river stages. Flood pulses originating from the Ohio River reverse the ground-water gradients and recharge water back into the aquifer. Ground-water levels near the river rise during periods of flooding as water from the Ohio River recharges the aquifer and causes a mounding of ground water (fig. 7). Additional recharge to the alluvial aquifer occurs when pumping at wells along the river lowers the water table below the stage of the river, thus inducing infiltration of river water (fig. 8).

Discharge from the alluvial aquifer is by flow to the Ohio River and to pumped wells.

Bedrock Beneath the Alluvial Aquifer

Bedrock beneath the glacial outwash in the Carrollton area is composed primarily of shales and limestones of Ordovician Age. Altitudes at the top of the bedrock surface beneath the alluvial aquifer were compiled from data contained in previous studies, project files of the USGS, files from industries and utilities in the study area, and a drilling program conducted during this investigation. Altitudes of the bedrock surface are shown in figure 9. Knowledge of the type of rock, its water-bearing characteristics, and the altitudes of the surface are important because this surface forms the lower boundary for the alluvial aquifer.

Conceptually, the bedrock beneath the alluvial aquifer and along the valley walls serves as a “container” for the glacial-outwash deposits. Wells completed in the bedrock are expected to produce only 100 to 500 gal/d (Hall and Palmquist, 1960), whereas wells completed in the alluvial deposits produce up to 500 gal/min.

Stream-Aquifer Interaction

Surface water is an important factor in the hydrologic framework of the Carrollton area. The Ohio River is a dominant feature and an important source of recharge for the alluvial aquifer. The Ohio River is hydraulically connected to the alluvial aquifer throughout its course in the study area. The Kentucky River, to a lesser extent, is a source of recharge for the ground-water-flow system, during periods of high water and flooding. Several small streams contribute much of their flow to the ground-water-flow system; therefore, they are considered an important source of recharge.

Small Streams

Five small streams (Fourmile Creek, McCools Creek, Black Rock Creek, Agniels Creek, and Stephens Creek) provide most of the surface-water drainage in the study area. These streams do not have adequate flow for dependable supplies, however, and may cease to flow for a few days or weeks during extended drought periods. During this investigation, the only water observed in the reaches of Fourmile Creek and McCools Creek (within the study area) was backwater from the Ohio River. It was assumed for this investigation that the amounts of discharge calculated from the respective drainage areas of those streams and daily rainfall would be used for recharge to the ground-water-flow model. Additional studies, such as discharge measurements under various conditions would need to be conducted to ascertain a more accurate representation of these streams in the model. Altitudes for the water surface in Black Rock Creek and Agniels Creek were approximated, and the creeks were assumed to be discharge points for the ground-water-flow system. Stephens Creek flows near the upstream boundary of the study area and was not considered an integral part of the hydrologic system. Like Fourmile and McCools Creeks, additional studies are needed on all of the area small streams to account for their potential effect and possible contribution to the ground-water-flow system.

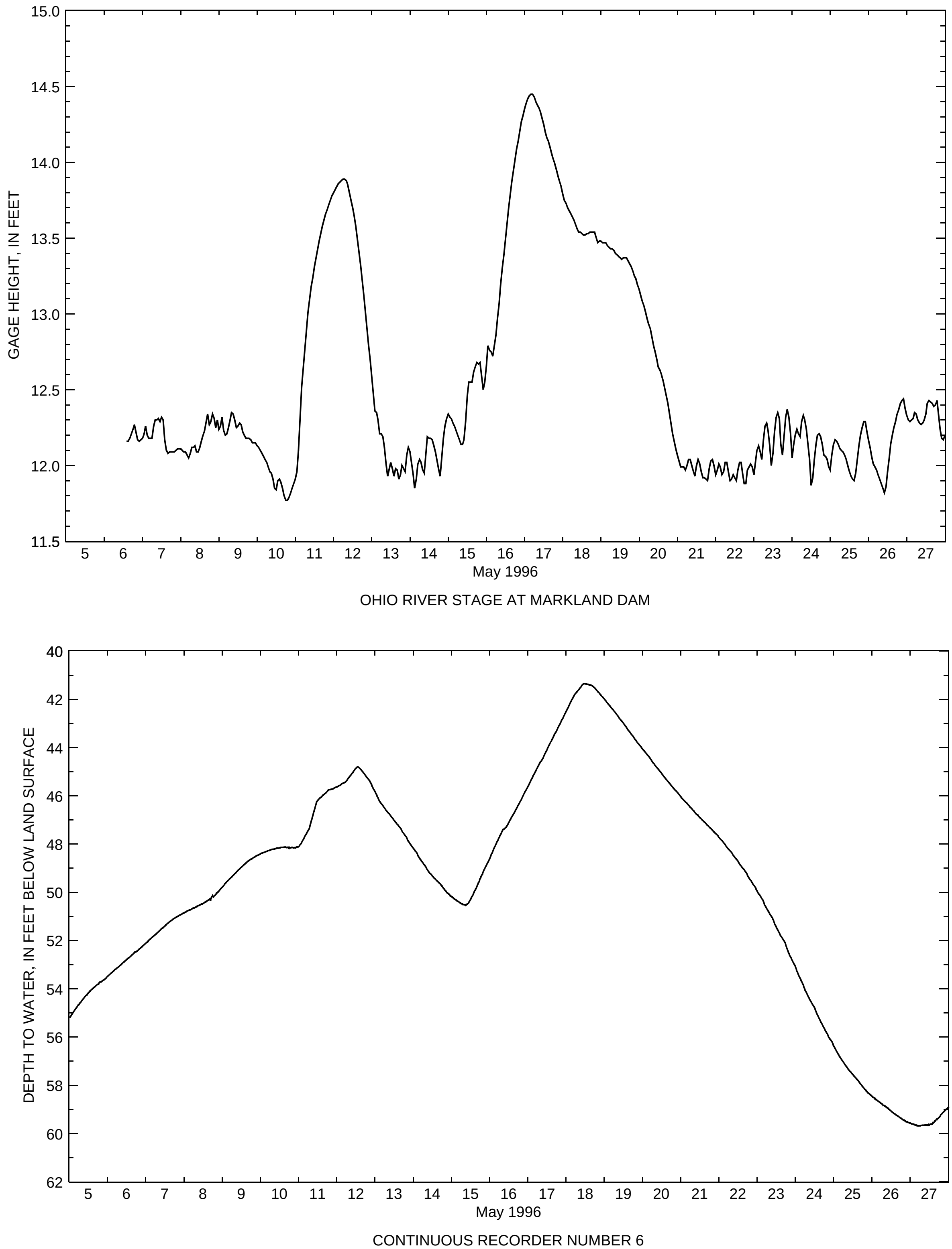

Figure 7. Response of water levels in the alluvial aquifer to an Ohio River flood pulse in a non-stressed area.

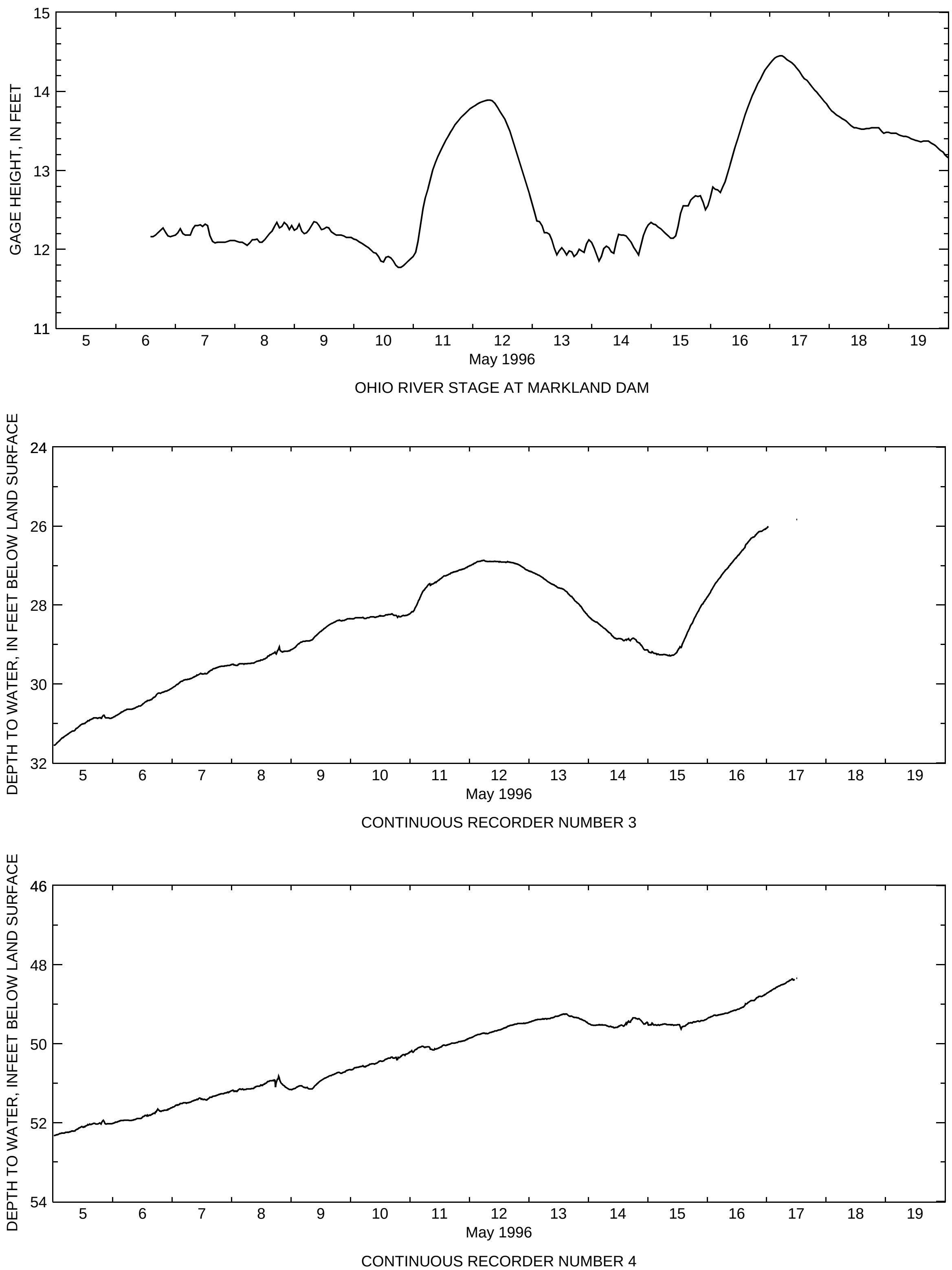

Figure 8. Response of water levels in the alluvial aquifer to an Ohio River flood pulse in a heavily pumped area.

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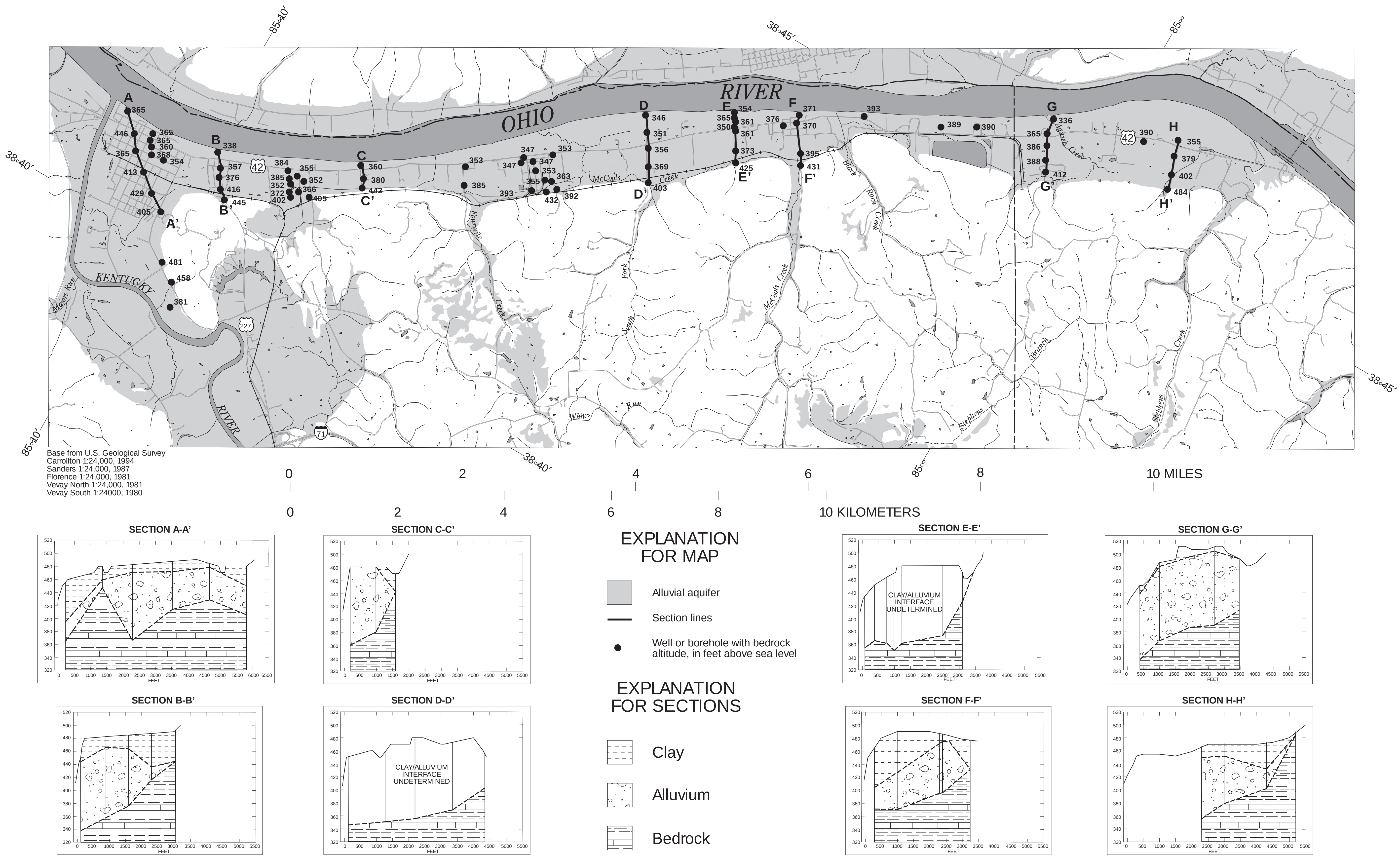

Figure 9. Altitude of bedrock surface near Carrollton, Kentucky.

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Ohio River

A system of locks and dams controls the navigational channel and stage for the Ohio River through a series of pools. The McAlpine Dam at Louisville creates a pool that extends upstream for approximately 75 mi to Markland Dam. Markland Dam is at the upstream boundary of the study area (fig. 1). The water level in the pool at Carrollton is normally maintained at about 421 ft above sea level.

Under natural conditions, the Ohio River is a discharge point or sink for the ground-water-flow system. Hydrographs for several observation wells in the study area show ground-water flow to be toward the river during periods of normal pool elevation (figs. 7 and 8). During periods of high water on the Ohio River, gradients may “flatten out” or reverse as water from the river becomes a source of recharge to the alluvial aquifer (fig. 6). Induced infiltration from the Ohio River is evident from hydrographs from observation wells in areas of high ground-water pumpage near the river (fig. 8). Cones of depression extend toward the river, thereby gaining an additional source of recharge.

CONCEPTUAL MODEL OF THE GROUND-WATER-FLOW SYSTEM

A preliminary step in designing a ground-water-flow model is to devise a conceptual model of the flow system. The conceptual model is a simplified representation of the important hydrogeologic conditions of the natural flow system. Field-based data such as aquifer characteristics, ground-water levels, and infiltration rates are measured or estimated to provide a clear and easily understood physical picture of the flow system. Errors in the development of the conceptual model can result in the failure of the mathematical model to make accurate predictions.

Gallaher and Price (1966) visualized the Ohio River Valley as a huge water container where water is stored on or flows across the valley surface in the Ohio River and its tributaries with additional amounts of water present beneath the land surface. The container was formed as a trench cut out of the surrounding bedrock formations by meltwaters from glaciers, then part filled with water-deposited sediments of gravel, sand, silt, and clay. Gradual down cutting by the Ohio River since the retreat of the last glacier has shaped the surface of the valley to its present level.

From the concept of a trench-shaped container, the model design treats the alluvial aquifer as a single layer. The layer is bounded on the bottom and along the length of the container by the bedrock. The open ends of the trench allow the flow of the Ohio and Kentucky Rivers, which are partially penetrating streams, to enter and exit the flow system. The Ohio and Kentucky Rivers are partially penetrating streams. The bedrock underlying the alluvial deposits is a mixture of shales and limestones and is considered impermeable, thus forming a no-flow boundary.

The single-layer representation of the alluvial aquifer receives recharge from precipitation, discharge from the valley walls, and natural and induced infiltration from the Ohio River. Discharges from the ground-water-flow system include water withdrawn by production wells and natural discharge to the Ohio River. Two distinct flow patterns exist within the ground-water-flow system. Under natural conditions, regional flow patterns are predominantly horizontal, from points of recharge along the valley walls toward the Ohio River, a discharge zone; this pattern is interrupted by the effects of withdrawals at wells and well fields. Cones of depression formed in the potentiometric surface at the wells extend to the river; gradients are reversed and flow is induced from the Ohio River, thus making it a source of recharge. The Ohio River and other area streams may become additional sources of water to the alluvial aquifer during periods of high water. Floodwaters can percolate downward and contribute water to the ground-water-flow system.

SIMULATION OF GROUND-WATER FLOW IN THE ALLUVIAL AQUIFER

A finite-difference model was used to simulate ground-water flow in the alluvial aquifer at Carrollton, Ky., and the surrounding area. The objectives of the modeling were to test the conceptual model of the ground-water-flow system, generate the required data sets for particle-tracking analysis, and provide a regional-scale tool for water-resources investigations. The modular, finite-difference computer program, MODFLOW (McDonald and Harbaugh, 1988), was used to construct a regional, two-dimensional, steady-state model of the ground-water-flow system in the alluvial aquifer. Output from the MODFLOW program is used by the particle-tracking program, MODPATH (Pollock, 1989, 1994), to simulate ground-water-flow directions and travel times. The combination of the MODFLOW simulation and the application of the results through the MODPATH program provides an investigative tool for area water-resources managers.

Equation Development

The ground-water-flow model is formed from a set of partial-differential equations—governing equation, boundary conditions, and initial conditions. Numerical methods are used to solve a set of algebraic equations generated by approximating these equations. A general form of the partial-differential equation governing two-dimensional, steady-state ground-water flow in a heterogeneous, isotropic, unconfined aquifer is:

$$\frac{\partial}{\partial_x}\left(T\frac{\partial_h}{\partial_x}\right) + \frac{\partial}{\partial_y}\left(T\frac{\partial_h}{\partial_y}\right) = W, \qquad (1)$$

where

$T\frac{\partial_h}{\partial_x}, T\frac{\partial_h}{\partial_y}$ are the values of transmissivity along the *x* and *y* axes, which are assumed parallel to the major axes of hydraulic conductivity (L^2T^{-1}),

h is the hydraulic head (L), and

W is a volumetric flux per unit volume representing sources and (or) sinks of water (LT^{-1}).

Boundary conditions and initial conditions were selected to represent hydraulic conditions as formulated in the conceptual model. The governing equation, boundary conditions, and initial conditions were combined in a set of finite-difference equations and solved numerically using the MODFLOW code.

Model Assumptions

The ground-water-flow model was designed in accordance with the following assumptions and simplifications:

1. The shaley limestones beneath the alluvial deposits do not contribute flow to the alluvial aquifer; therefore, they are not included in the model design as an active layer.
2. Ground-water levels during the months of November 1994 and 1995 approximate average water levels for the modeled area during periods of the least amount of changing hydrologic stresses. The ground-water-flow system is considered at steady state during this period, meaning no net gain or loss of water occurs.
3. All simulated wells fully penetrate the alluvial deposits.
4. Horizontal hydraulic conductivity is uniform throughout the study area.
5. Infiltration from precipitation is at a constant rate and does not vary areally.
6. The Ohio River is hydraulically connected to the alluvial aquifer throughout its course in the study area.

Model Grid

The grid design used to represent the conceptual model of the ground-water-flow system is shown in figure 10. The grid comprises 36 rows and 207 columns and simulates an area of 12,800 ft by 74,900 ft, or approximately 34.1 mi^2. Cell sizes vary from 200 by 200 ft in areas within the industrial well fields to 1,000 by 1,500 ft for cells near the model boundaries. The grid rows are oriented parallel to the reach of the Ohio River within the study area and perpendicular to the regional ground-water-flow direction from the conceptual model. The alluvial aquifer is modeled as a single layer.

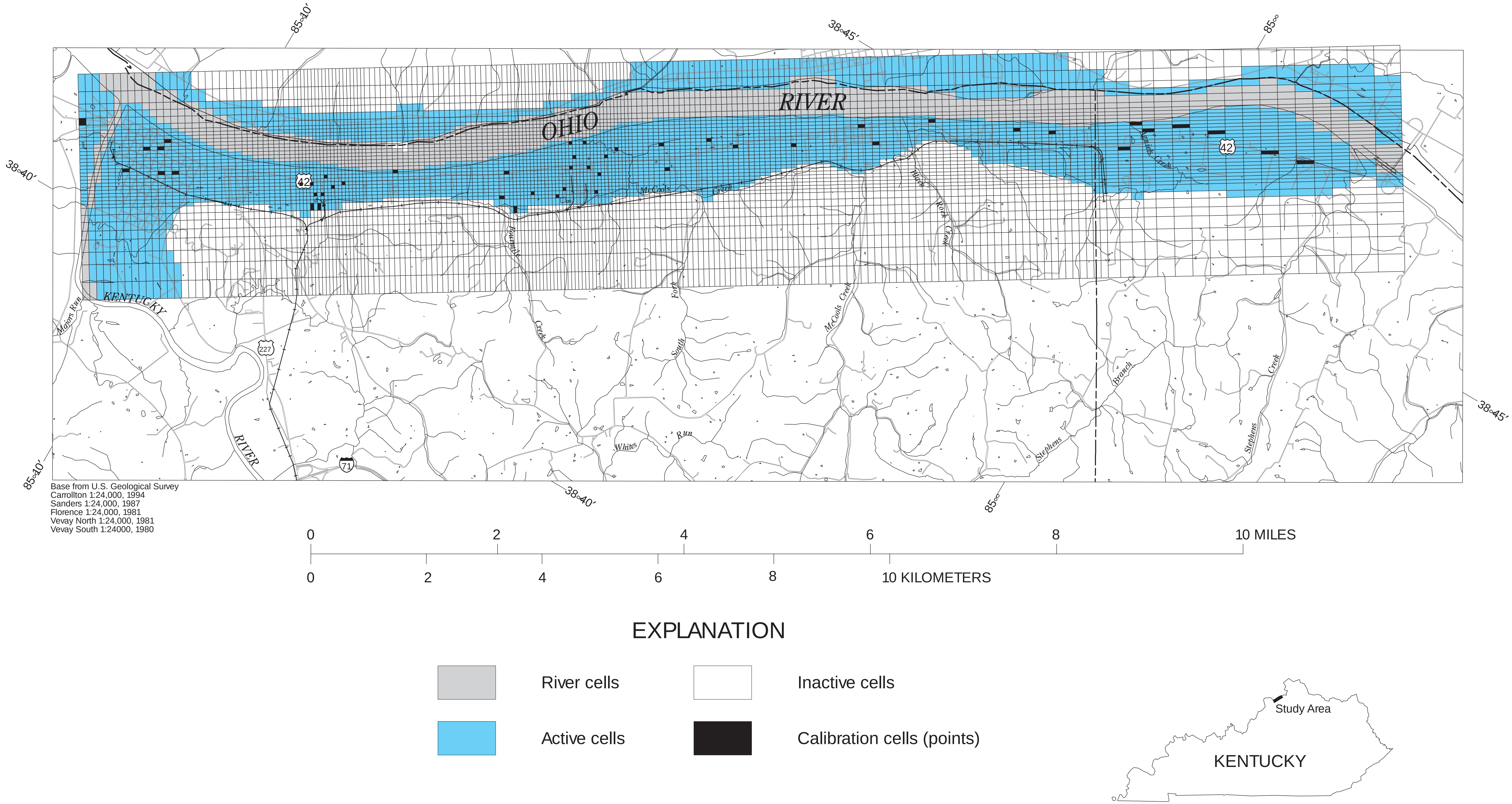

Figure 10. Extent of finite-difference model grid and location of model-calibration cells.

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Model Boundaries

Conceptually, the bedrock forms the sides and bottom of the ground-water container—the alluvial aquifer. The bedrock beneath the alluvial aquifer is assumed to be a non-contributor of water to the flow system and simulated as a no-flow boundary. The sides of the container, or the bedrock valley walls, however, are considered contributors to the flow system and are modeled as general head boundaries. Flow across general head boundaries depends upon the head difference between an active model cell and an adjacent external source.

Precipitation infiltration forms a specified-flux boundary for the top of the model layer, which is simulated with the recharge package of the MODFLOW code.

Input Parameters

Initial input parameters for the ground-water-flow model were derived from reviews of previous studies, available records from area ground-water users, and data-collection activities conducted as part of this investigation. Input parameters included recharge from precipitation, hydraulic conductivity of the alluvial deposits, boundary conditions of the bedrock and valley walls, and initial ground-water levels and reported pumpage. Input parameters also included characteristics of the Ohio River such as river stage, altitude of the riverbed, and the hydraulic conductivity of the riverbed deposits. Input parameters were systematically varied over respective ranges of acceptable values until simulated water levels for the alluvial aquifer approximated the water levels from the November 1995 synoptic measurement.

Recharge to the alluvial aquifer was simulated as leakage across the fine-grained alluvial deposits. Rorabaugh (1956) estimated the recharge to the alluvial aquifer in Louisville to be 6 to 12 percent of the annual precipitation; this range was assumed to be reasonable for the Carrollton area because the study areas are similar. The annual precipitation for Carrollton during the period July 1994 to June 1995 was 42.05 in., which resulted in a test range of 2.52 to 5.05 in. recharge; during calibration, the amount of recharge from precipitation was varied over this range. The best approximation of recharge to simulate the November 1995 water levels was 4.63 in/yr. The recharge was distributed evenly throughout the model area for the simulation.

The altitude of the Ohio River stage was simulated at 421 ft on the basis of data from the USGS gaging station at the Markland Locks and Dam and measurements from an auxiliary gage on the Kentucky River just above its confluence with the Ohio River. Riverbed altitude was held constant at 385 ft. The hydraulic conductivity of the riverbed material was held at 0.65 ft/d based on estimates from Grubb (1975). Streambed conductance varied because of the area of the cells representing the river. River stage, hydraulic conductivity, and elevation of the riverbed were not varied as part of the calibration process.

The hydraulic conductivity of the alluvial deposits was assumed to range from 300 to 350 ft/d based on area aquifer tests conducted for previous investigations or by private industry. Because measurements of anisotropy were not available, a lateral isotropy was assumed for the simulation. A horizontal hydraulic conductivity of 350 ft/d provided the best simulation of the measured water levels.

The valley walls, which form boundaries for the ground-water-flow system, were simulated as head-dependent flux boundaries because of the potential for flow from the limestone beds. An external boundary head altitude of 600 ft was assumed for each cell of the boundary. Conductance between the external source and the aquifer was held at 10 ft/d. The model simulation was not very sensitive to changes in the conductance during the calibration process.

Other input parameters used for the simulation (but not varied) included altitude of the bedrock surface and ground-water pumpage. Available depth-to-bedrock measurements and additional data collected during this investigation revealed a fairly flat bedrock surface (ranging in altitude from 340 to 350 ft) beneath the alluvial aquifer. Ground-water pumpage was simulated for 29 wells at 6 installations in the study area; locations and pumpage amounts were verified for November 1995.

Model Calibration and Water Budget

The calibration of a model is the procedure used to reduce the difference between simulation results and observed data by adjusting input parameters of the model until an acceptable range of differences is achieved. For this simulation, three input parameters were adjusted to meet the predetermined calibration criteria: the recharge rate from precipitation, hydraulic conductivity of the alluvial deposits, and the conductance value for the general head-boundary configurations. Rorabaugh (1956) determined a range of infiltration from precipitation for the alluvial aquifer at Louisville of 6 to 12 percent of the annual precipitation. This range of values was used to determine the extent to which the recharge rate could vary because the study area at Carrollton is similar to the region around Louisville. Less is known about the variations in conductance values for the riverbed and valley-wall configurations.

The root-mean-square error (RMSE) of the measured and simulated heads was used to determine the effect of an adjustment. The RMSE is calculated as:

$$\mathrm{RMSE} = \sqrt{\left(\sum_{i=1}^{N}\right)\frac{(h_{cal_i} - h_{m_i})^2}{N}}\,, \qquad (2)$$

where

h_{cal_i} is the simulated head,

h_{m_i} is the measured head, and

N is the number of measurements used in error computations.

Decreases in the RMSE as a result of the calibration process indicated an improvement in the overall fit of the simulation to the observed conditions. Flow paths were checked to ensure compliance with the conceptual model.

The calibration criteria were based on an observed range of ground-water levels assuming steady-state conditions. The steady-state simulation of the alluvial aquifer at Carrollton represents a period during which the ground-water-flow system was in equilibrium, meaning that the rate of recharge to the system is equal to the rate of discharge from the system. True steady-state conditions probably never exist for the aquifer because of various and almost continual changes in recharge (river stage, precipitation, and flow from the valley wall) and discharge (river stage and ground-water withdrawals). But ground-water-level synoptic measurements, continuous ground-water-level records, and Ohio River stage hydrographs indicate that the alluvial aquifer was generally near steady-state conditions during November 1994 and November 1995. For the purposes of this investigation, it was assumed that the aquifer was at steady-state during these periods and the ground-water-flow conditions during November 1995 were chosen as the target levels for calibration of the model. The hydrograph from recorder 2 (fig. 4) shows the ground-water levels at the beginning of November 1994 and 1995 to be stable, showing no significant changes to any system stresses.

The calibration criteria were dependent on water levels measured in 48 observation wells. The average difference of water levels for the 48 wells was 1.43 ft from November 1994 to November 1995; the differences ranged from 0.0 to 4.46 ft. Based on these measurements, the calibration criteria selected were a maximum difference of 4.46 ft and an average difference of 1.43 ft between simulated and observed water levels for November 1995.

After calibration, the maximum difference between simulated and observed water levels for November 1995 is 4.43 ft. The simulated and observed water levels differed by less than 4 ft in 98 percent of the wells, less than 3 ft in 88 percent, less than 2 ft in 77 percent, and less than 1 ft in 48 percent of the wells. The average difference in water levels for the 48 wells was 1.43 ft; the RMSE for the simulation was 1.80. Figure 11 shows the comparison between observed and simulated heads for the model calibration.

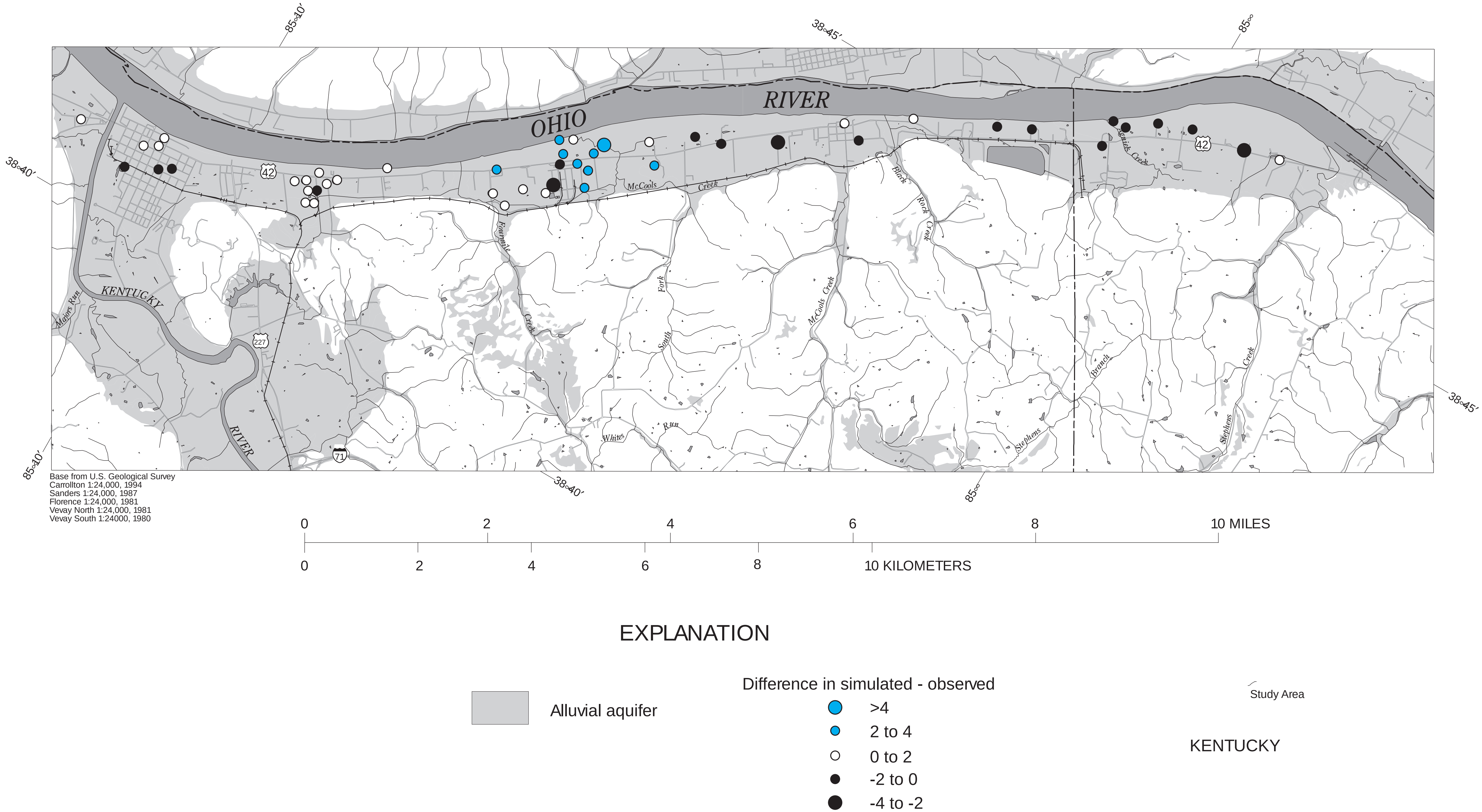

Figure 11. Model calibration by use of root-mean-square-error (RMSE) results.

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The simulation also provided a ground-water budget for the aquifer. In terms of volume of water, the model calculated a total water budget of 3,034,800 ft^3. The simulation indicated that, of the total recharge to the alluvial aquifer, induced infiltration of water from the Ohio River provided approximately 32 percent (983,900 ft^3), water from area streams provided 25 percent (752,500 ft^3), flow from the bedrock valley wall contributed 24 percent (723,000 ft^3), and recharge from precipitation provided about 19 percent (575,400 ft^3). The portion of recharge attributed to infiltration of water from the Ohio River could be greater during times of flooding. Computation of recharge that would be derived from the Ohio River during flooding was not considered as part of the calibration of a steady-state model. Simulation results indicate that a seemingly large percentage of the system's recharge originates from the bedrock-valley wall. Rorabaugh (1949) estimated that as much as 28,600 ft^3/d of recharge per mile of bedrock-valley wall is contributed to the ground-water-flow system at Louisville. The average amount calculated from this simulation of the Carrollton area is 27,800 ft^3/d per mile of bedrock-valley wall.

Withdrawals from area wells accounted for 83 percent (2,511,400 ft^3) of the total discharge from the alluvial aquifer, with the remaining 17 percent (520,800 ft^3) discharging to the Ohio River.

Sensitivity Analysis

Sensitivity analysis is a procedure used to assess how responsive the calibrated model is to systematic changes in each input parameter. The analysis determines which parameters exert the most control over the model solution and possibly generate the largest error when varied over their respective range of test values. Parameters that were varied in the sensitivity analysis include the hydraulic conductivity of the alluvial deposits, recharge, river stage, river conductance, and terms associated with general head boundaries. Each input parameter was varied a specified amount from the calibrated value used in the steady-state simulation. The amount of variance was determined by estimates of the probable range of data. Because each change in parameter value was tested separately, the additive effects of changes for different combinations of parameter values were not considered.

Simulated hydraulic heads at 49 wells were compared statistically to the water levels measured in November 1995. Head responses are reported as the RMSE of residuals. The results of the sensitivity analysis in terms of percentage of change in RMSE are shown in figure 12. An increase in the percentage of change in RMSE indicates that the match between measured and simulated heads from a sensitivity-analysis run is worse that the match of the calibrated model. The magnitude of the percentage of change in RMSE indicates the relative sensitivity of the model to that change in the model parameter.

The sensitivity of the model to changes in hydraulic conductivity was evaluated by varying the conductivity (350 ft/d) within a range of +/- 50 percent. The results of the analysis indicate that the head residuals are slightly more sensitive to decreases in hydraulic conductivity than to increases.

Recharge to the ground-water-flow system from precipitation was estimated at 4.63 in/yr (0.00106 ft/d), or approximately 11 percent of the annual precipitation, for the calibrated model. For the sensitivity analysis, the amount of recharge was varied from 4 to 16 percent of the annual precipitation. Hydraulic heads simulated by the model were not very sensitive to changes in the amount of recharge from precipitation infiltration.

The Ohio River is the dominant hydrologic feature in the study area. It is a constant source of recharge for nearby pumping wells and a point of discharge for the alluvial aquifer in areas unaffected by pumpage. For the calibrated model, the river stage altitude was 421 ft. Even though the river stage is monitored closely and the accuracy of the measurements is known, stage was varied +/- 10 ft to evaluate the sensitivity of the model. As shown in figure 12, the model is very sensitive to changes in the river stage, emphasizing the river's importance in the hydrologic system.

The hydraulic conductivity of the riverbed material was varied from +/- 10 percent of the calibrated value (0.65 ft/d). The hydraulic heads simulated by the model were very sensitive to this change in river characterization.

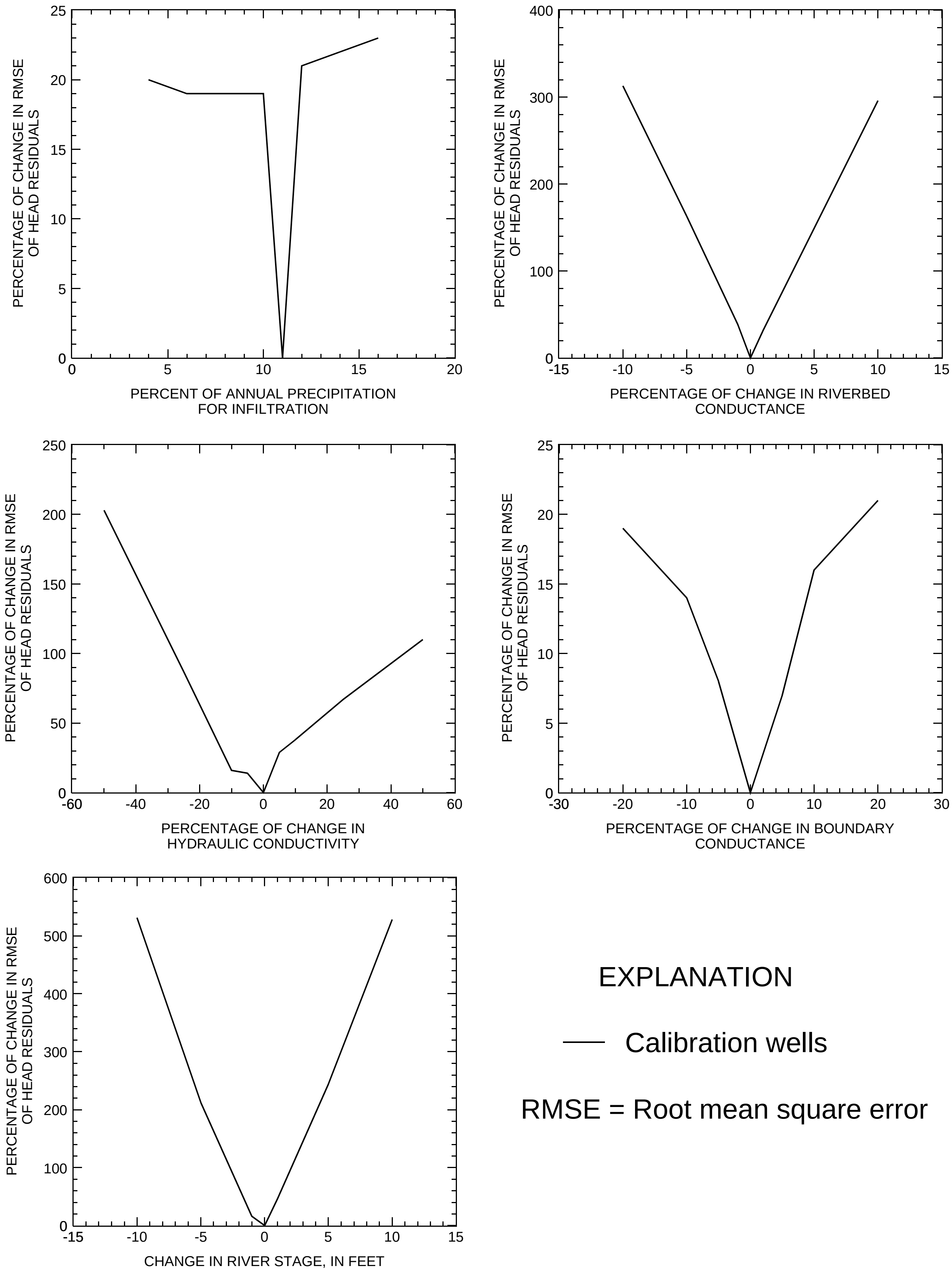

Figure 12. Sensitivity of simulated heads to changes in precipitation infiltration, riverbed conductance, hydraulic conductivity, boundary conductance, and river stage, Carrollton area, Kentucky.

The valley walls on both sides of the Ohio River were simulated as general head boundaries. Hydraulic conductivity of the interface between the aquifer cell and the boundary was varied +/- 20 percent for the sensitivity analysis. The effects of these changes did not vary greatly, generally less than 20 percent change in RMSE.

Limitations of the Model

Limitations of the ground-water-flow model and the interpretation of subsequent simulation results must be known and fully considered for appropriate application of the model and accurate simulation of the natural flow system. The amount and detail of hydrogeologic knowledge of the natural flow system, the initial scale of the ground-water-flow model, and the inherent limitations of numerical models restrict applications of the model. With proper application and an understanding of the limitations, however, the ground-water-flow model is a useful investigative tool capable of simulating regional ground-water flow through the alluvial aquifer.

Grid design, boundary conditions, and calibration all rely on knowledge of the hydrogeologic characteristics of the natural flow system. For this assessment of hydrogeologic conditions, a series of synoptic water-level measurements were made for model calibration. Boundary conditions and surface-water/ground-water interaction, particularly regarding the Ohio River, were based on published data, county/project file data, continuous water-level recordings, and the conceptual model. The grid design was based on the anticipated ground-water flow as formulated by the conceptual model and on the spatial distribution of available control points. Hydrogeologic characterization of the natural flow system will improve with the incorporation of additional data.

Scale limitations also should be considered when using the model to predict the response of the ground-water-flow system to changes in applied stresses or hypothetical situations such as the migration routes of hazardous-material releases. The response of the ground-water-flow system to large-scale changes, such as a 50-percent increase in pumpage or the addition of 1 in. of recharge from precipitation infiltration, can be simulated with a limited degree of accuracy. The response of the ground-water-flow system to small-scale changes, such as rearranging withdrawals within a well field, could not be accurately simulated; a more site-specific model would be required for this type of application.

The ground-water-flow model is an attempt to represent numerically the natural flow system. User-defined numerical approximations and convergence tolerances—the predetermined error criterion for model solutions—allow the model to simulate the natural flow system and its response to changes in stresses within a predetermined range of accuracy. No ground-water-flow model can completely recreate the natural flow system in a numerical representation.

APPLICATION OF THE GROUND-WATER-FLOW MODEL

The calibrated ground-water-flow model was used to delineate recharge and discharge boundaries and to estimate flowpaths and travel times of particles placed in the flow system. The cell-by-cell flow terms from the calibrated steady-state model were used as input to MODPATH, a particle-tracking program (Pollock, 1989, 1994). The MODPATH program computes particle locations and travel times in three dimensions based on advective flow in a uniformly porous medium. MODPATH can track particles forward in time and space in the direction of ground-water flow or backward toward recharge areas (Robinson and others, 1997).

To delineate discharge areas, one particle, representing an infinitesimal volume of ground water, was placed at the center of all active cells in the model grid. Each particle progressed forward in time and space through the ground-water-flow system until a discharge boundary was encountered. Cells discharging to the same boundary were grouped to produce a map identifying the contributing areas (fig. 13). Discharge boundaries include area ground-water-withdrawal wells and the Ohio River. Likewise, particles were placed at the center of all active cells and allowed to progress backward in time and space to recharge boundaries (fig. 14).

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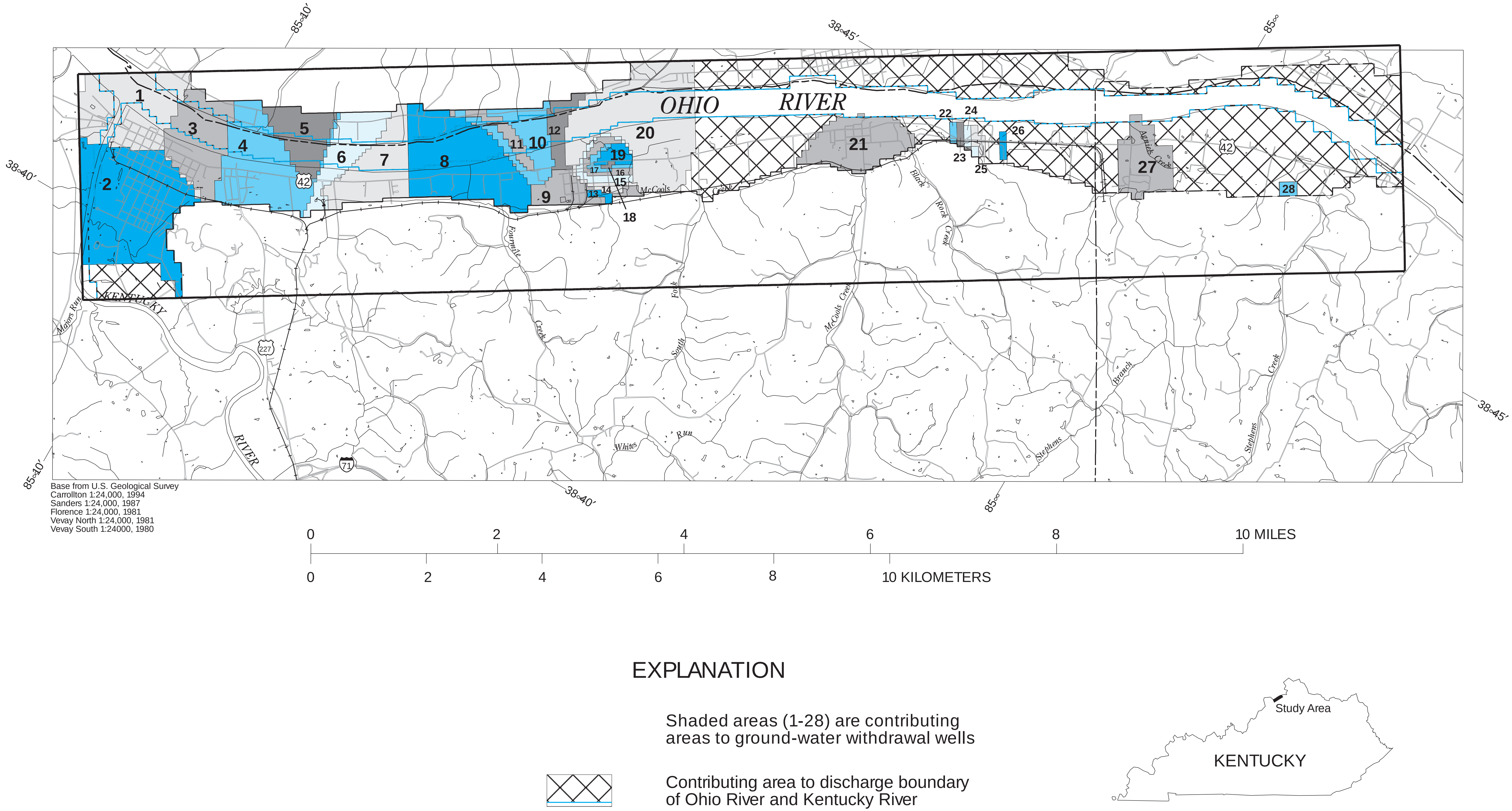

Figure 13. Simulated contributing areas to discharge boundaries of the alluvial aquifer.

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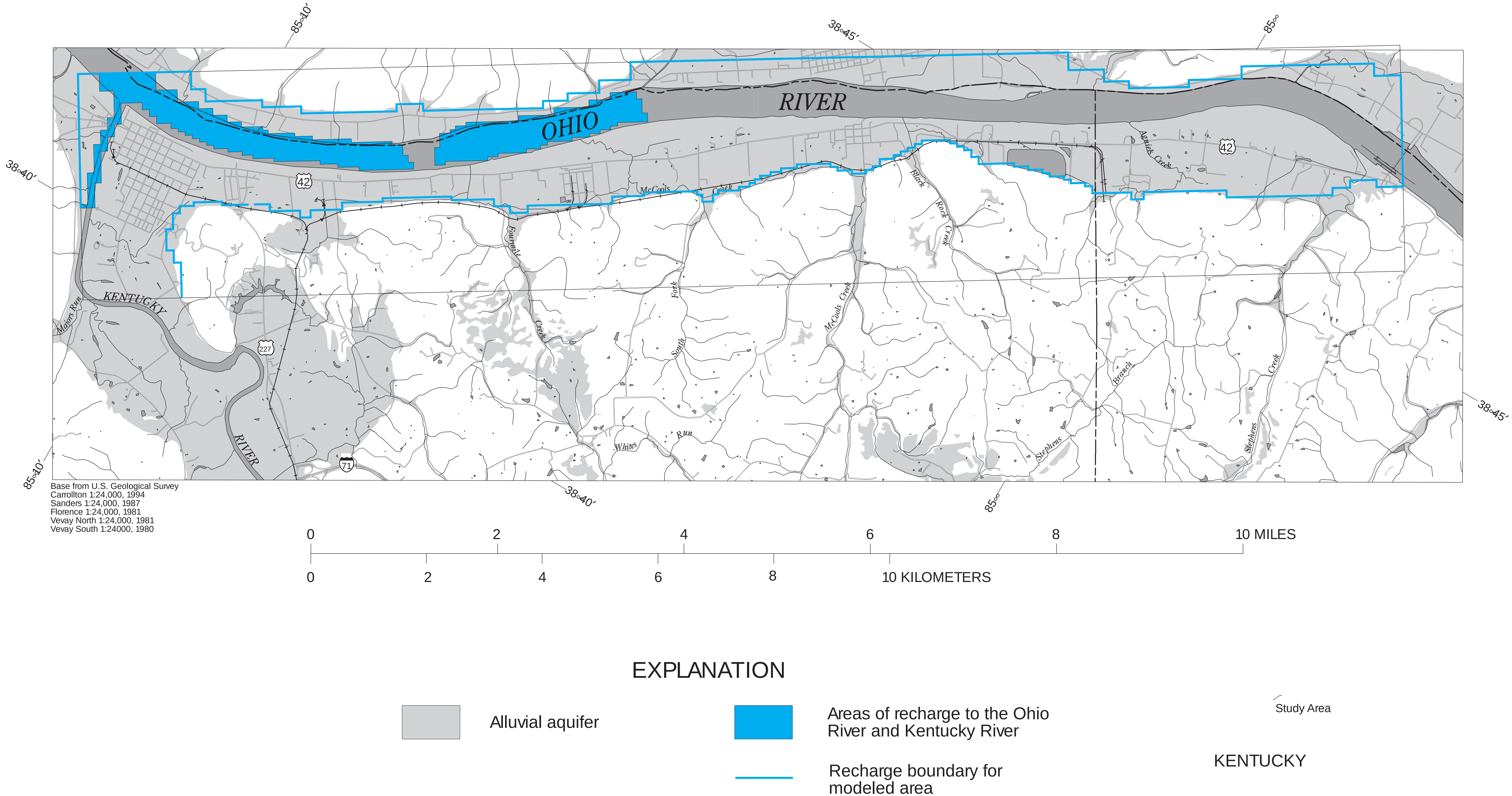

Figure 14. Simulated recharge areas and boundaries of the alluvial aquifer.

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Recharge boundaries for the model include the valley walls, surface streams, and the Ohio and Kentucky Rivers. Typical ground-water velocities ranged from about 0.025 to 31.43 ft/d. The average residence time is about 2,044 days. Ground-water velocities for particles simulating induced infiltration from the Ohio River ranged from about 0.313 ft/d in lightly pumped areas such as downtown Carrollton to about 15.30 ft/d for well fields servicing industrial plants. A porosity of 0.20 was used for the particle-tracking analysis (Bell, 1966).

To estimate flowpaths and travel times for a specific well, particles were placed at the center of the model cell representing a public water supply in near Ghent, Ky. The particles were traced backward in time and space to delineate the possible contributing area for this particular well. Figure 15 shows the extent of the modeled contributing area and the calculated times of travel contours. Estimations of contributing areas to wells, the delineation of flowpaths, and the calculation of time of travel for particles are subject to error. The limitations of particle tracking are directly related to the uncertainty in parameter estimations and incorrect model design. Contributing areas to wells are approximated because assumptions are made in estimating parameters characterizing the alluvial deposits, and a limited number of particles are used for the traces.

Particle-tracking analysis also can be used to delineate the extent and travel times for a plume originating from a potential contaminant source within the study area. For illustrative purposes, particles were placed in a cell to represent a potential contaminant source and allowed to progress forward in time and space, thus delineating the extent of the contaminant-plume migration (fig. 16). Time-of-travel estimates can then be plotted on the trace of the plume to predict breakthrough times at different points along the flowpaths. Physical, chemical, and biological processes that attenuate chemical constituents in ground water are not considered, and the dissolved contaminant is assumed to not appreciably alter the density of the ground water. MODPATH cannot be used to predict solute transport (Robinson and others, 1997).

Additional applications of the model include hypothetical pumping situations to determine the development potential of the aquifer for current users, the addition of new pumping centers and the potential effects of these new stresses on water availability, and the overall “safe yield” of the aquifer for resource management. Such issues and situations may be addressed with proper application of the model and understanding of the model assumptions, but are beyond the scope of this investigation.

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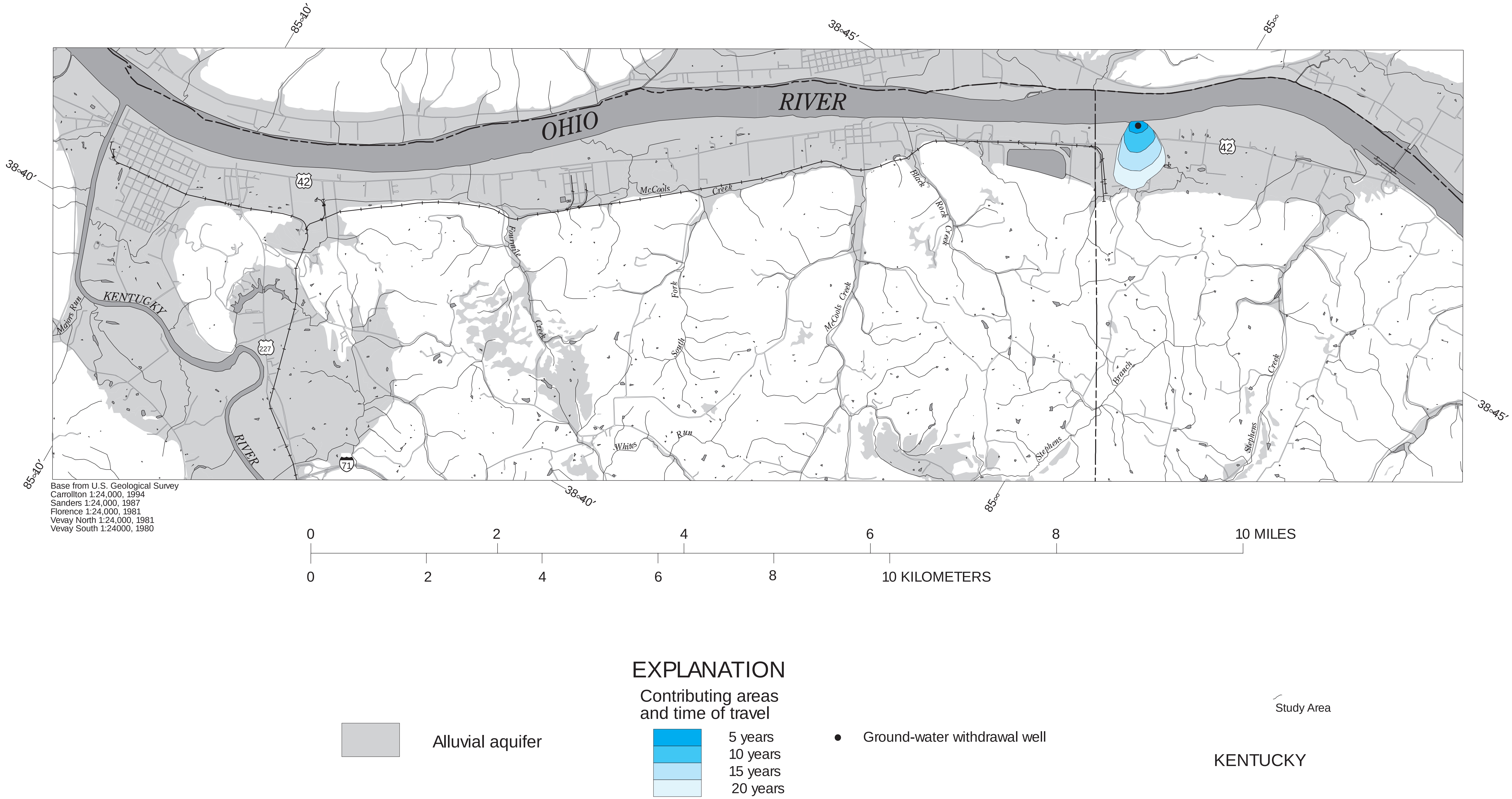

Figure 15. Simulated contributing area and time of travel to a withdrawal well near Ghent, Kentucky.

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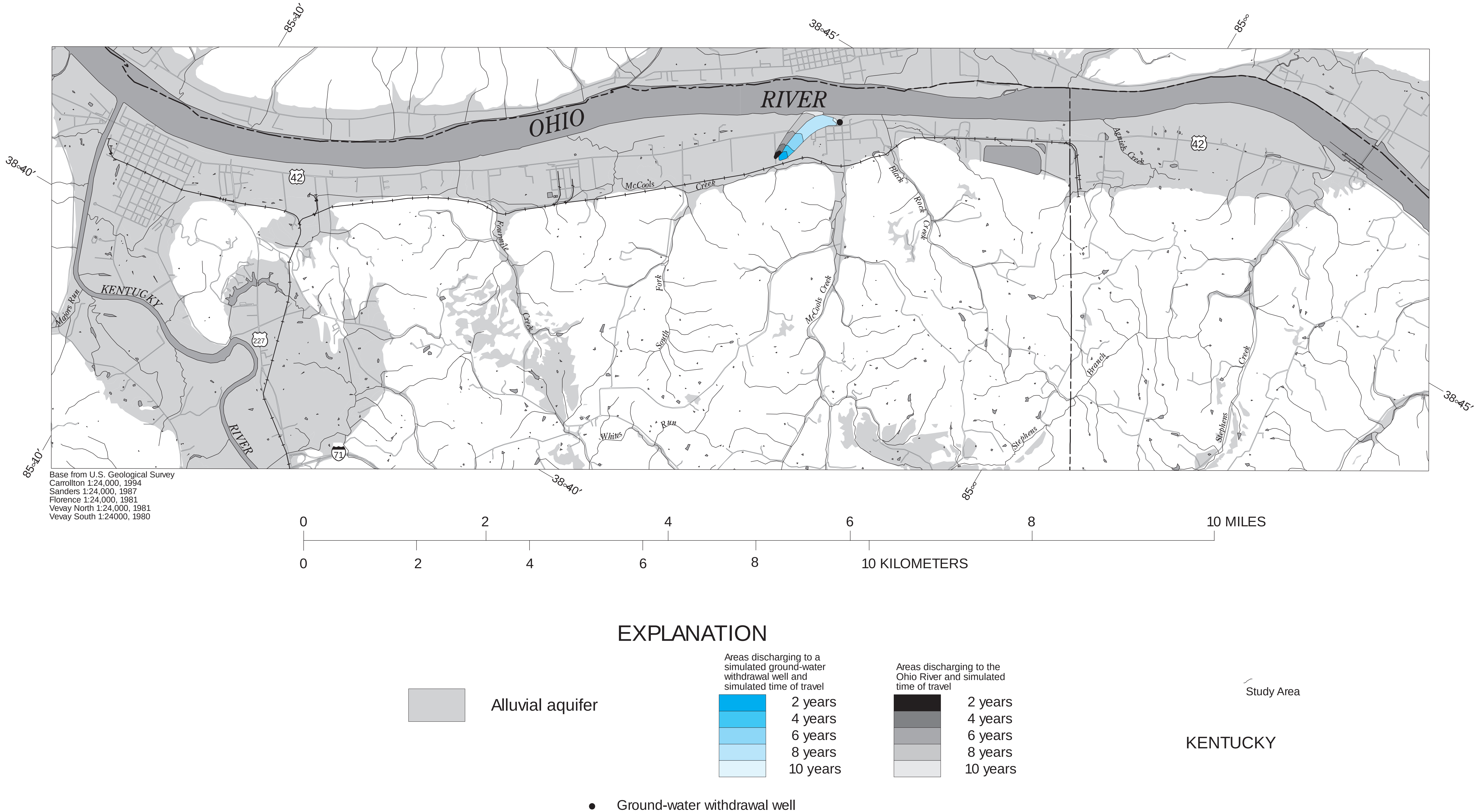

Figure 16. Simulated flowpaths and time of travel for a simulated contaminant release from a hypothetical hazardous-materials storage facility.

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SUMMARY AND CONCLUSIONS

The alluvial aquifer at Carrollton, Ky., consists of glacial-outwash deposits of Wisconsin Age underlain by shales and limestones of Ordovician Age. The glacial outwash is composed of medium- to coarse-grained sand with lenses of gravel in the lower part capped by a thick layer of fine-grained sand and silt. A layer of silt and clay covers the glacial-outwash deposits throughout the study area. The direction of ground-water flow in the aquifer is predominantly from the bedrock valley walls toward the Ohio River and pumping wells.

The alluvial aquifer receives natural recharge from the following sources: (1) direct infiltration of precipitation; (2) subsurface flow from the consolidated rocks along the valley walls; (3) flow from small streams; and (4) flow from the Ohio River to the aquifer when the stage of the river is higher than the adjacent ground-water levels. Additional recharge to the alluvial aquifer occurs as pumping wells close to the Ohio River induce flow from the river to the aquifer. Water discharges from the alluvial aquifer by flow to the Ohio River and to pumping wells. The aquifer was assumed to be at or near steady-state conditions in November 1995.

A two-dimensional, single-layer, finite-difference model of the alluvial aquifer was calibrated by comparing the computed hydraulic heads with corresponding measured water levels in 49 area wells for steady-state conditions. The model simulation indicates that ground water enters the system primarily from induced infiltration from the Ohio River (32 percent), and from smaller streams (25 percent), flow from the valley walls (24 percent), and infiltration of precipitation (19 percent). The water exits the system through pumped wells (83 percent) and by flow to the Ohio River (17 percent). A sensitivity analysis of the model indicated it is most responsive to changes in the stage of the Ohio River and changes in the conductance of the riverbed material.

Recharge and discharge boundaries for the model area were identified and contributing areas to ground-water withdrawal wells and time of travel for particles were estimated on the basis of head gradients and ground-water velocities as simulated by the model.

The ground-water-flow model of the Carrollton area is an attempt to numerically represent the natural flow system. The simulations in this report were designed on the basis of general hydrologic conditions. Results of the simulations provide only an estimate of the components of the ground-water budget in the alluvial aquifer and are not intended for well-field design or placement. The accuracy of the simulations would be improved by the acquisition and incorporation of more information characterizing and quantifying boundary conditions, surface-water/aquifer interaction, and hydraulic conductivity estimations. Additional study to quantify the water quality of the alluvial aquifer and to characterize solute-transport mechanisms would be beneficial to water-resource managers.

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