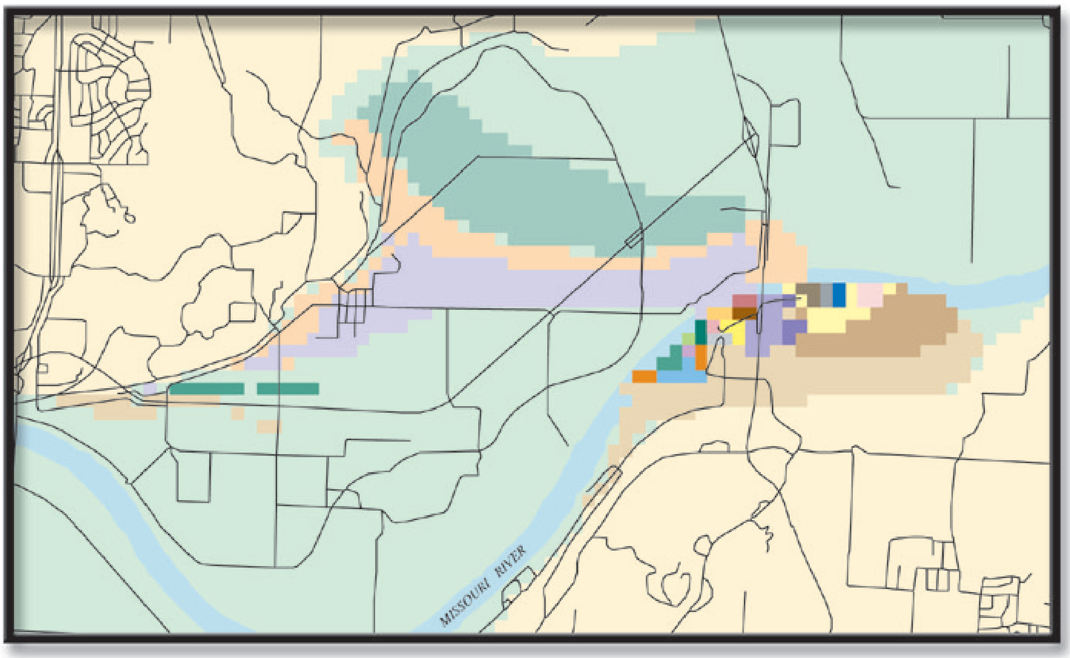
Ground-Water Flow Simulation and Chemical and Isotopic Mixing Equation Analysis to Determine Source Contributions to the Missouri River Alluvial Aquifer in the Vicinity of the Independence, Missouri, Well Field

Water-Resources Investigations Report 02–4208



Prepared in cooperation with the
City of Independence, Missouri

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

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Ground-Water Flow Simulation and Chemical and Isotopic Mixing Equation Analysis to Determine Source Contributions to the Missouri River Alluvial Aquifer in the Vicinity of the Independence, Missouri, Well Field

by Brian P. Kelly

Abstract

The city of Independence, Missouri, operates a well field in the Missouri River alluvial aquifer. Steady-state ground-water flow simulation, particle tracking, and the use of chemical and isotopic composition of river water, ground water, and well-field pumpage in a two-component mixing equation were used to determine the source contributions of induced inflow from the Missouri River and recharge to ground water from precipitation in well-field pumpage.

Steady-state flow-budget analysis for the simulation-defined zone of contribution to the Independence well field indicates that 86.7 percent of well-field pumpage is from induced inflow from the river, and 6.7 percent is from ground-water recharge from precipitation. The 6.6 percent of flow from outside the simulation-defined zone of contribution is a measure of the uncertainty of the estimation, and occurs because model cells are too large to uniquely define the actual zone of contribution. Flow-budget calculations indicate that the largest source of water to most wells is the Missouri River.

Particle-tracking techniques indicate that the Missouri River supplies 82.3 percent of the water to the Independence well field, ground-water recharge from precipitation supplies 9.7 percent, and flow from outside defined zones of contribution supplies 8.0 percent. Particle tracking was used to determine the relative amounts of source water to total well-field pumpage as a function of traveltime from the source. Well-field pumpage that traveled 1 year or less from the source was 8.8 percent, with 0.6 percent from the Missouri River, none from precipitation, and 8.2 percent between starting cells. Well-field pumpage that traveled 2 years or less from the source was 10.3 percent, with 1.8 percent from the Missouri River, 0.2 percent from precipitation, and 8.3 percent between starting cells. Well-field pumpage that traveled 5 years or less from the source was 36.5 percent, with 27.1 percent from the Missouri River, 1.1 percent from precipitation, and 8.3 percent between starting cells. Well-field pumpage that traveled 10 years or less from the source was 42.7 percent, with 32.6 percent from the Missouri River, 1.8 percent from precipitation, and 8.3 percent between starting cells. Well-field pumpage that traveled 25 years or less from the source was 71.9 percent, with 58.9 percent from the Missouri River, 4.7 percent from precipitation, and 8.3 percent between starting cells.

Results of chemical (calcium, sodium, iron, and fluoride) and isotopic (oxygen and hydrogen) analyses of water samples collected from the Missouri River, selected monitoring wells around the Independence well field, and combined well-field pumpage were used in a two component mixing equation to estimate the relative amount of Missouri River water in total well-field pumpage. The relative amounts of induced inflow from the Missouri River in well-field pumpage ranged from 49 percent for sodium to 80 percent for calcium, and sensitivities ranged from 0 percent for iron to plus or minus 35 percent for naturally occurring stable isotope (^{18}O). The average of all mixing equation results indicated that 61 percent of well-field pumpage was from induced inflow from the Missouri River.

All methods used in the study indicate that more than one-half of the water in well-field pumpage was inflow from the Missouri River. River inflow estimates from ground-water simulation methods are larger and error values are smaller than those using chemical and isotopic data in the mixing equation, although substantial uncertainties exist for both estimation methods. Because of the complex hydrology of the aquifer near the Independence well field, the source estimates using particle tracking probably are the most reliable of the ground-water simulation methods. Mixing equation results are less reliable than those of the ground-water simulation for this study. However, more reliable results can be obtained from the mixing equation by increasing the number of samples and collecting samples for a longer period of time, and during different flow conditions. In the absence of a calibrated ground-water flow simulation, the mixing equation can provide a reasonable estimate of the sources of water to a well field at relatively low cost, if sources of error are clearly understood.

INTRODUCTION

The city of Independence, Missouri, operates a well field within the city limits of Sugar Creek, Missouri, in the Missouri River alluvial aquifer (fig. 1). The well field supplies an average of 27 million gallons of water per day and serves about 250,000 people in several communities.

Previous studies by the U.S. Geological Survey (USGS) have determined the hydrogeology of, and ground-water flow in, the Missouri River alluvial aquifer in the Kansas City metropolitan area and contributing recharge areas to public water-supply well fields, including the Independence well field (Kelly and Blevins, 1995; Kelly, 1996a). Results from these studies indicate that pumping the well field alters the natural pattern of ground-water flow from the valley walls toward the Missouri River and down the river valley. Pumping causes ground water to flow beneath the Missouri River and induces a substantial inflow from the Missouri River. The USGS and the city of Independence, Missouri, also completed a comprehensive study of ground-water flow to the Independence well field (Kelly, 1996b). Results of the study included types and locations of potential ground-water contamination source areas, prediction of changes in ground-water flow, ground-water traveltimes and contributing recharge areas from planned well-field expansion, and the design of a ground-water monitoring network for the Independence well field.

Monitoring well nomenclature, as used in this report, is based on a well cluster number and a designation of the simulated ground-water traveltime from the screened interval of each monitoring well to the well field (Kelly, 1996b). For example, well 1-5yr is part of well cluster 1 and has a 5-year simulated ground-water traveltime from the monitoring well to the production well field. Well 24-3yr is part of well cluster 24 and has a 3-year simulated ground-water traveltime from the well to the well field. Monitoring well cluster locations and numbers are shown in figure 1.

The quality of the river water affects the quality of well-field pumpage because a substantial part of the total well-field pumpage is induced inflow from the Missouri River; however, the relative amounts of induced inflow from the Missouri River and well-field pumpage derived from ground-water recharge from precipitation were unknown at the start of this study. Knowledge of these relative amounts can be used to guide responses to possible contamination of the water supply from both ground- and surface-water sources. The objective of this study was to determine the relative contributions of induced inflow from the Missouri River and ground-water recharge from precipitation to the total pumpage of the Independence well field.

The purpose of this report is to present the results of ground-water flow simulation and the use of chemical and isotopic (isotopes of oxygen and hydrogen) analyses of river water, ground water, and well-field pumpage in a two-component mixing equation to determine contributions to well-field pumpage from the Missouri River and recharge from precipitation. Geologic and hydrologic data used for the ground-water simulation were compiled or collected between 1991 and 2001. Chemical and isotopic data were obtained between 1998 and 2001.

GROUND-WATER FLOW SIMULATION

Ground-water flow was simulated using the three-dimensional finite-difference ground-water-flow modeling program MODFLOW-96 (Harbaugh and McDonald, 1996). The simulation was calibrated to steady-state and transient conditions using an earlier

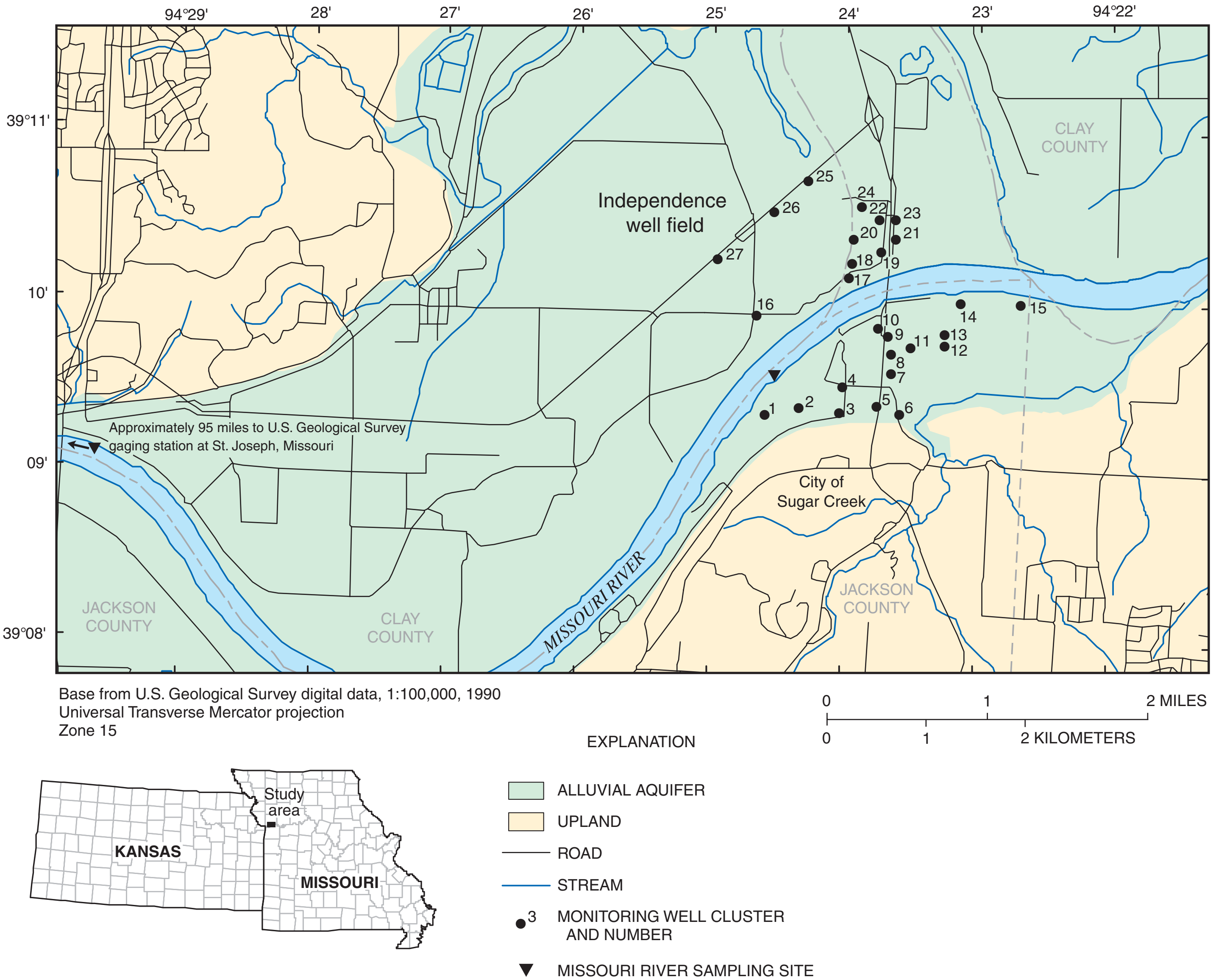


Figure 1. Location of study area and ground-water monitoring well network for the Independence, Missouri, well field.

version of the program MODFLOW (McDonald and Harbaugh, 1988) during a previous study of the Missouri River alluvial aquifer (Kelly, 1996a). This previous simulation was used to determine steady-state ground-water flow and the contributing recharge areas to public water-supply well fields for various pumping rates and river stages. The area simulated included the Independence well field. A complete description of the simulation is presented by Kelly (1996a); a brief description follows.

The simulation used uniform cell areas of 150 by 150 meters and contained 310,400 cells in 160 rows, 485 columns, and 4 layers. Layer 1 corresponded to the upper part of the aquifer where clay, silt, and fine-grained sand are dominant. Layers 2 and 3 corresponded to the middle part of the aquifer where sand and gravelly sand are dominant. Layer 4 corresponded to deep parts of the aquifer where gravel and sandy gravel are present. The thickness of each layer was variable. All four layers are present in the area of interest around the Independence well field. Unconfined ground-water flow was simulated in layer 1, and confined ground-water flow was simulated in layers 2, 3, and 4.

The bedrock was simulated as a no-flow boundary because its hydraulic conductivity is several orders of magnitude less than the hydraulic conductivity of the alluvial aquifer (Kelly, 1996a). The channel bottoms of the Missouri and Kansas Rivers were simulated in layer 2 because they intersect the sand and gravel that correspond to layer 2. The bottoms of small rivers were placed in layer 1. Small streams and drainage ditches were simulated as drains that receive water from the aquifer, but do not supply water to the aquifer.

A steady-state calibration was performed using quasi-steady-state hydraulic head data from a January 1993 synoptic water-level measurement of 155 wells. River stage, precipitation rate, and well pumping are variable with time, and true steady-state conditions probably never exist in the simulated area. Transient conditions were calibrated using hydraulic head data collected during the August 1993 flood, and synoptic water-level measurements from 123 wells in October 1993 and from 98 wells in February 1994.

Available information and the steady-state calibration were used to obtain initial estimates of transient simulation parameters. The more rigorous transient calibration was used to refine the steady-state and transient parameters through prolonged drainage of water from the alluvial aquifer after the August 1993 flood to February 1994, when river stage and ground-water levels had approached typical conditions for that time of year. The root mean square error in simulated hydraulic head was 1.15 meters for the steady-state calibration, 0.71 meter for October 1993 in the transient calibration, and 0.8 meter for February 1994 in the transient calibration. A sensitivity analysis indicated that the simulation is most sensitive to changes in calibrated hydraulic conductivity values and least sensitive to decreases in vertical conductance between layers 1 and 2 and to increases in river conductance.

For this study, steady-state ground-water flow was simulated using average annual ground-water flow conditions determined from average annual river stage data and an average annual rate of recharge from precipitation (Kelly, 1996b). Average annual recharge was calculated as 20 percent of the annual precipitation of 0.91 meter (36 inches) and varied spatially depending on the vertical permeability of the soils (Kelly, 1996a). Pumping rates for all active wells in the simulation were set at average annual rates (Missouri Department of Natural Resources, 2000). Locations of supply wells used in the simulation for the Independence well field are shown in figure 2, and pumping rates are listed in table 1.

The USGS particle-tracking program MODPATH (Pollock, 1994) was used to determine steady-state traveltimes and contributing recharge areas (CRAs) of the Independence well field. MODPATH uses hydraulic head and cell flow data from MODFLOW to calculate flow paths and traveltimes of imaginary particles of water moving through the simulated ground-water flow system. Knowledge of the limitations of particle-tracking analysis is necessary to correctly interpret MODPATH results and are given in detail in Pollock (1994). Particle-tracking limitations specific to this simulation are discussed in Kelly (1996a).

The USGS post-processing program ZONEBUDGET (Harbaugh, 1990) was used to calculate water budgets for selected subregions of the simulation. ZONEBUDGET calculates subregional water budgets using cell to cell flow data from MODFLOW. Groups of cells defined by the user are ZONEBUDGET subregions.

Simulation Flow Boundaries

MODFLOW calculates and records a ground-water flow budget for each simulation that can be used to determine the total quantity of water and rate of water flow across simulated hydrologic boundaries. Hydrologic boundaries include river and lake beds, stream beds and ditches, the water table, the boundary between alluvial valley walls and bedrock, assigned flow boundaries, and pumped wells (fig. 3). Ground-water flow boundaries are simulated as specified head, specified flux, head-dependent flow (mixed boundary), or a free surface (Franke and others, 1984). The hydraulic head is maintained at a fixed value as a function of time and position at a specified-head boundary, and ground-water flow across the boundary is proportional to the difference in hydraulic head at the boundary and in the simulated aquifer. The volume of water that flows across a specified-flow boundary is a function of time and position, and hydraulic head varies as a function of flow. The volume of flow across a head-dependent flow boundary varies as a function of hydraulic head at the boundary. The position of a free-surface boundary varies with time.

Rivers and lakes are represented in the simulation as head-dependent flow boundaries. Flows across these boundaries are recorded in the simulation budget as river leakage. Small streams and drainage ditches are represented as head-dependent flow boundaries but, unlike the simulated rivers, do not supply water to the aquifer. Flows across these boundaries are recorded as flows to drains. The water table, the upper boundary of

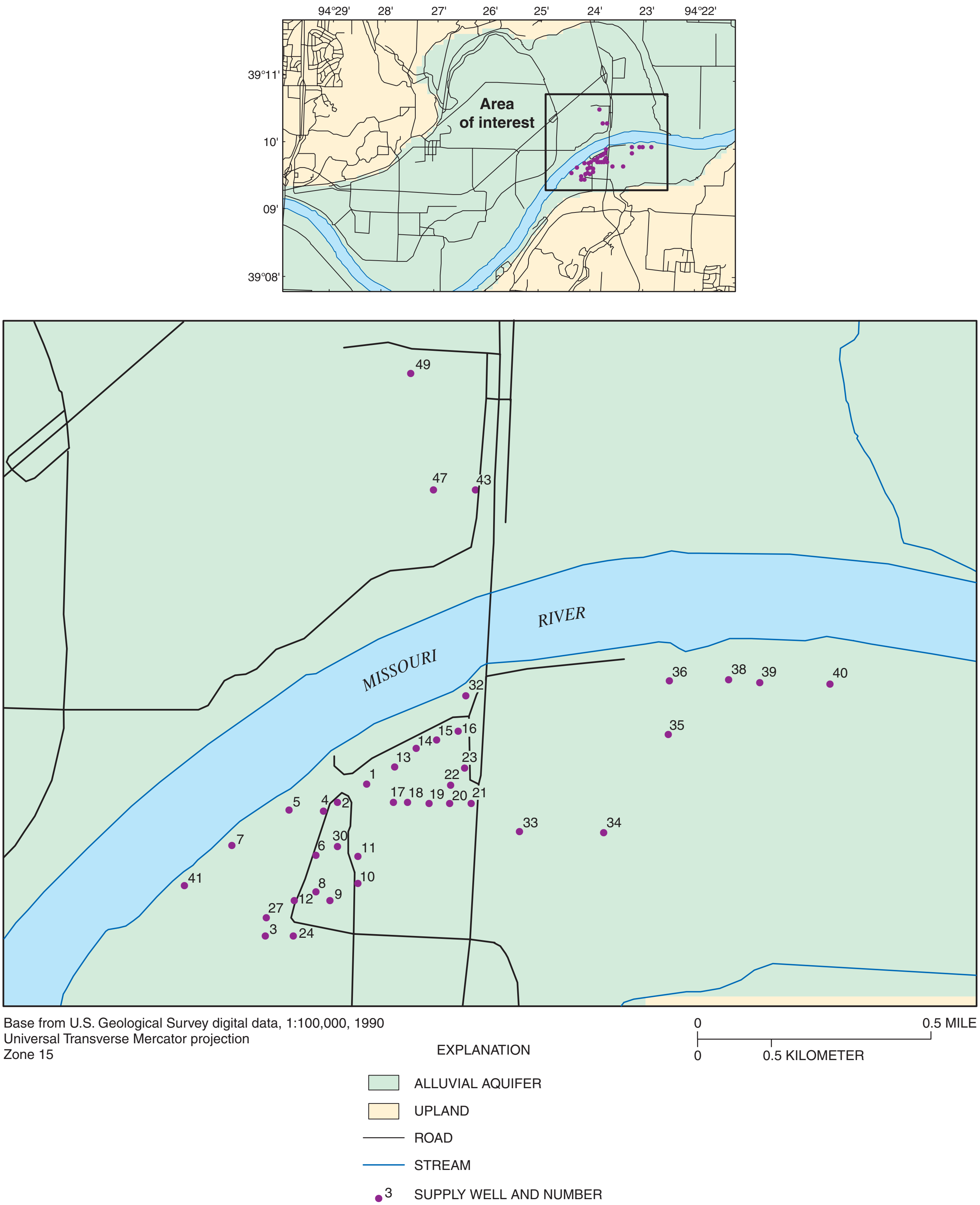


Figure 2. Location of supply wells in the Independence, Missouri, well field.

Table 1. Pumping rates for supply wells in the Independence, Missouri, well field

Well number (fig. 2)	Pumping rate (cubic meters per day)	Well number (fig. 2)	Pumping rate (cubic meters per day)
1	2,855.07	20	1,843.12
2	1,076.56	22	4,297.94
3	2,717.39	23	2,128.99
4	2,844.88	24	2,084.29
5	3,224.62	27	2,273.92
6	1,396.92	30	8,047.24
7	1,135.80	32	4,562.14
8	3,256.51	33	1,749.67
9	3,800.57	34	1,787.28
10	6,303.44	35	2,002.83
11	5,361.39	36	2,309.30
12	2,611.01	38	2,137.15
13	1,085.53	39	2,002.83
14	3,497.53	40	1,988.53
15	2,886.24	41	18,082.82
16	4,069.93	43	2,899.78
17	2,494.78	47	2,899.78
18	3,488.79	49	2,899.78
19	2,380.46		

the alluvial aquifer, was simulated as a free-surface boundary across which areally-distributed recharge from precipitation entered the aquifer. Flows across this boundary are recorded in the simulation budget as recharge. The alluvial valley walls and bedrock were simulated as no-flow boundaries, a form of the specified flow boundary. Flow does not cross this boundary and is not recorded in the simulation budget. Several boundaries of the simulation do not represent actual physical or ground-water flow boundaries of the alluvial aquifer, but are located where the aquifer intersects the simulation boundary. Flow across these boundaries is recorded in the simulation budget as general head boundary fluxes. Pumped wells are internal boundaries where water is removed at a specified rate equal to the discharge of each well. Flows from these boundaries are recorded in the simulation budget as well discharges.

Estimates of Source Contributions

Ground-water flow simulations were used to obtain estimates of source contributions to the Independence well-field pumpage from the Missouri River and recharge from precipitation. Estimates were made using: (1) boundary-flow budgets; (2) simulation-defined zone of contribution for the Independence well field zone; (3) simulation-defined zones of contribution for individual wells or groups of wells; and (4) particle-tracking analysis.

Boundary-Flow Budgets

Sources of water to the Independence well field were determined by subtracting boundary flow components of a steady-state simulation with all wells pumped (pumping scenario) from a steady-state simulation with all wells pumped except for the Independence well field (no-pumping scenario). The difference between these flow budgets indicates the effect of pumping from the Independence well field on the flow budget (table 2). The percentage of flow across a particular boundary type can be calculated by dividing each budget category by the total flow into the simulation. Using this method indicates that for the pumping scenario, 67.6 percent of the flow into the simulation is inflow from rivers, 31.4 percent is ground-water recharge from precipitation, and 1.0 percent is from head-dependent boundaries. Outflow calculations indicate that 49.1 percent of the flow out of the simulation is to wells, 38.7 percent is to rivers, 11.2 percent is to drains, and 1.0 percent is to head-dependent boundaries.

Pumping from the Independence well field increased the rate of flow into the simulation from river leakage by 114,700 cubic meters per day, and the rate of flow out of the simulation from well discharge by 122,475 cubic meters per day (table 2). Dividing the increased river leakage by the increased well discharge indicates that 93.7 percent of Independence well-field pumpage is derived from induced inflow from the Missouri River. Pumped wells from the Independence well field intercepted ground water that otherwise would discharge to either the Missouri River, or to drains in the simulation. Dividing the sum of the decreased dis-

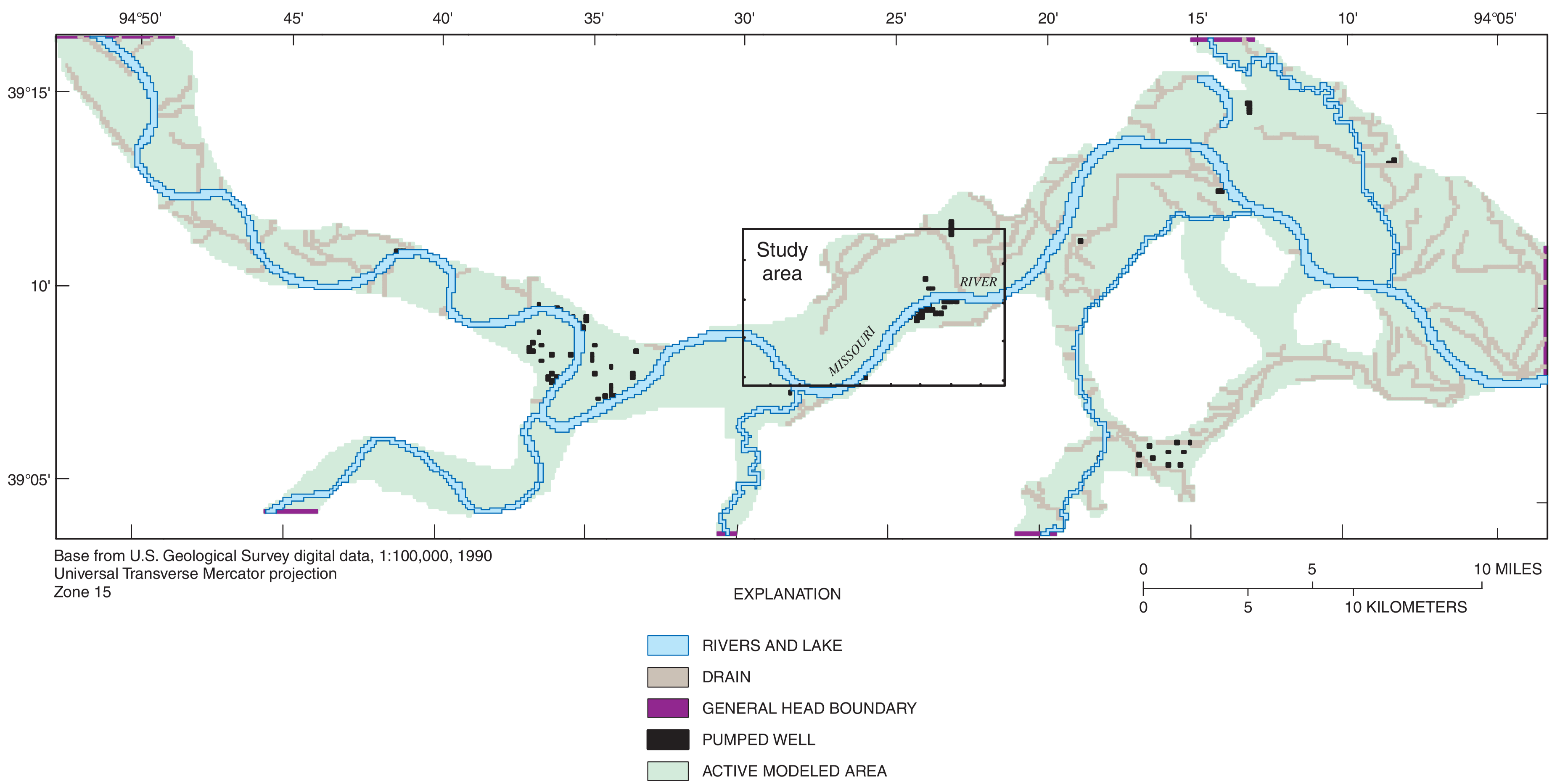


Figure 3. Hydrologic boundaries in the ground-water flow simulation.

Table 2. Boundary flow components for the pumping scenario and no-pumping scenario for the Independence, Missouri, well field

[na, not applicable]

Budget category	Pumping scenario (cubic meters per day)	No-pumping scenario (cubic meters per day)	Pumping scenario minus no-pumping scenario (cubic meters per day)
Flow into simulated area			
All wells	0	0	0
Discharge to drains	0	0	0
Inflow from river	499,399	384,699	114,700
Head-dependent boundaries	7,547	7,547	0
Recharge from precipitation	231,891	231,891	0
Total in	738,837	624,137	114,700
Flow out of simulated area			
All wells	362,300	239,825	122,475
Discharge to drains	83,038	83,039	-1
Discharge to river	285,654	293,428	-7,774
Head-dependent boundaries	7,275	7,275	0
Recharge from precipitation	0	0	0
Total out	738,267	623,567	114,700
Total			
Flow in minus flow out	570	570	0
Percent discrepancy	0	0	na

charges to drains and rivers by the increased well discharge indicates that 6.3 percent of Independence well-field pumpage is derived from intercepted ground water. The source of water for the intercepted ground water was assumed to be recharge to the aquifer from precipitation. The no-pumping scenario alters ground-water hydraulic heads and gradients; therefore, other nearby well fields may obtain more water from induced inflow from the Missouri River or ground-water recharge from precipitation than would occur when water is pumped from the Independence well field. This would result in a larger inflow either from the river or recharge budget term for the no-pumping scenario that would introduce some error in the results obtained using this method.

Simulation-Defined Zone of Contribution for the Independence Well Field

To more accurately determine the sources of water to the Independence well field, the simulated flow budget was calculated within the zone of contribution (ZOC) of the Independence well field. The ZOC is the three-dimensional region of an aquifer from which a well, river, or other area of ground-water discharge obtains its water. The simulation-defined ZOC for the Independence well field was determined using MODPATH. Simulation-defined ZOCs for the Independence well field have been determined previously (Kelly, 1996a, 1996b). However, ZOCs change with the addition of pumped wells, changes in pumping rate, changes in river stage, or changes in recharge from precipitation; therefore, a revised simulation-defined ZOC based on 2001 pumping conditions was determined. Simulation-defined ZOCs for the Missouri River, the Liberty, Missouri, well field, and an industrial well field southwest of the Independence well field also were determined because of their proximity and interaction with the Independence well field simulation-defined ZOC. The ZOCs for the Independence, industrial, and Liberty well fields are presented in figure 4 for each layer of the ground-water flow simulation. The ZOC for the Missouri River consisted of a few model cells that also represented the simulated Missouri River and are not shown in figure 4.

To construct the simulation-defined ZOCs, an imaginary particle of water was placed in the center of each active cell in each layer of the steady-state flow simulation and tracked forward in time to its eventual discharge point. The starting location of each particle that discharged to a simulated supply well in the Independence, Liberty, or the industrial well field was used to determine simulation-defined ZOCs. This method was used to ensure that each cell was assigned to only one source of discharge. However, flow from any one cell can travel to more than one discharge point. By placing the particle in the center of the cell, the discharge point with the most effect on flow from that cell was assumed to be the point to where that particle traveled. Ground-water flow divides in the simulation rarely coincide with cell edges, and flow from a cell that contains a ground-water flow divide can travel to different discharge points.

The ZOCs for which flow budgets can be determined using ZONEBUDGET can only be defined in the simulation using groups of cells; therefore, flow budgets for simulation-defined ZOCs have a component of flow out of the ZOC and a component of flow into the ZOC. For this report, ZOCs will be differentiated between simulation-defined ZOCs and actual ZOCs. Flow is recorded between simulation-defined ZOCs that are adjacent to each other. However, the relative amounts of water sources to a simulation-defined ZOC may not be reflected in the water that flows to another simulation-defined ZOC. This is caused by the location of simulation-defined ZOCs with respect to the river and each other, and the location of pumped wells within each simulation-defined ZOC with respect to the location of pumping wells in the other simulation-defined ZOCs. For example, if simulation-defined ZOC-1 obtains one-half of its water from the river and one-half from recharge from precipitation, and water from simulation-defined ZOC-1 provides water to simulation-defined ZOC-2, the original source of water from the part of simulation-defined ZOC-1 that provides water to simulation-defined ZOC-2 may be all from recharge from precipitation, all from the river, or some combination of the two. Therefore, flows recorded between simulation-defined ZOCs are a measure of the uncertainty in the ZOC flow-budget calculation because the original source of the water is unknown.

The simulated water budget for the Independence well field simulation-defined ZOC is listed in table 3. The relative amounts of flow from different sources within the simulation-defined ZOC indicate that 92.8 percent of well-field pumpage is from induced inflow from the river, and 7.2 percent is ground-water recharge from precipitation. The relative amounts of flow from sources inside and outside of the simulation-defined ZOC indicate that 86.7 percent of Independence well-field pumpage is from induced inflow from the river, 6.7 percent is from recharge to the alluvial aquifer from precipitation, and 6.6 percent is flow from the other simulation-defined ZOCs. Differences in total inflow and total outflow of the simulation-defined ZOC probably are caused by differences between ground-water flow divides and edges of cells used to define ZOCs.

Simulation-Defined Zones of Contribution for Individual Wells or Groups of Wells

Knowledge of the sources of water and the actual ZOCs to individual wells within the Independence well field is important for proper management of the well field. Sources of water to simulation-defined ZOCs of individual wells or groups of wells within the Independence well field were determined using flow budgets calculated with ZONEBUDGET. Simulation-defined ZOCs were calculated using MODPATH in the same manner as previously discussed. Each ZOC corresponds to a single cell that contains the location of one or more simulated wells. The simulation-defined ZOC for each well or group of wells is presented in figure 5 for each layer of the simulation. Substantial differences in the size of individual simulation-defined ZOCs are apparent. Well 7 and well 5 did not have simulation-defined ZOCs because particles used to define ZOCs were intercepted by other wells.

Wells that are near the Missouri River obtain most of their water from induced inflow from the river and have smaller simulation-defined ZOCs because the

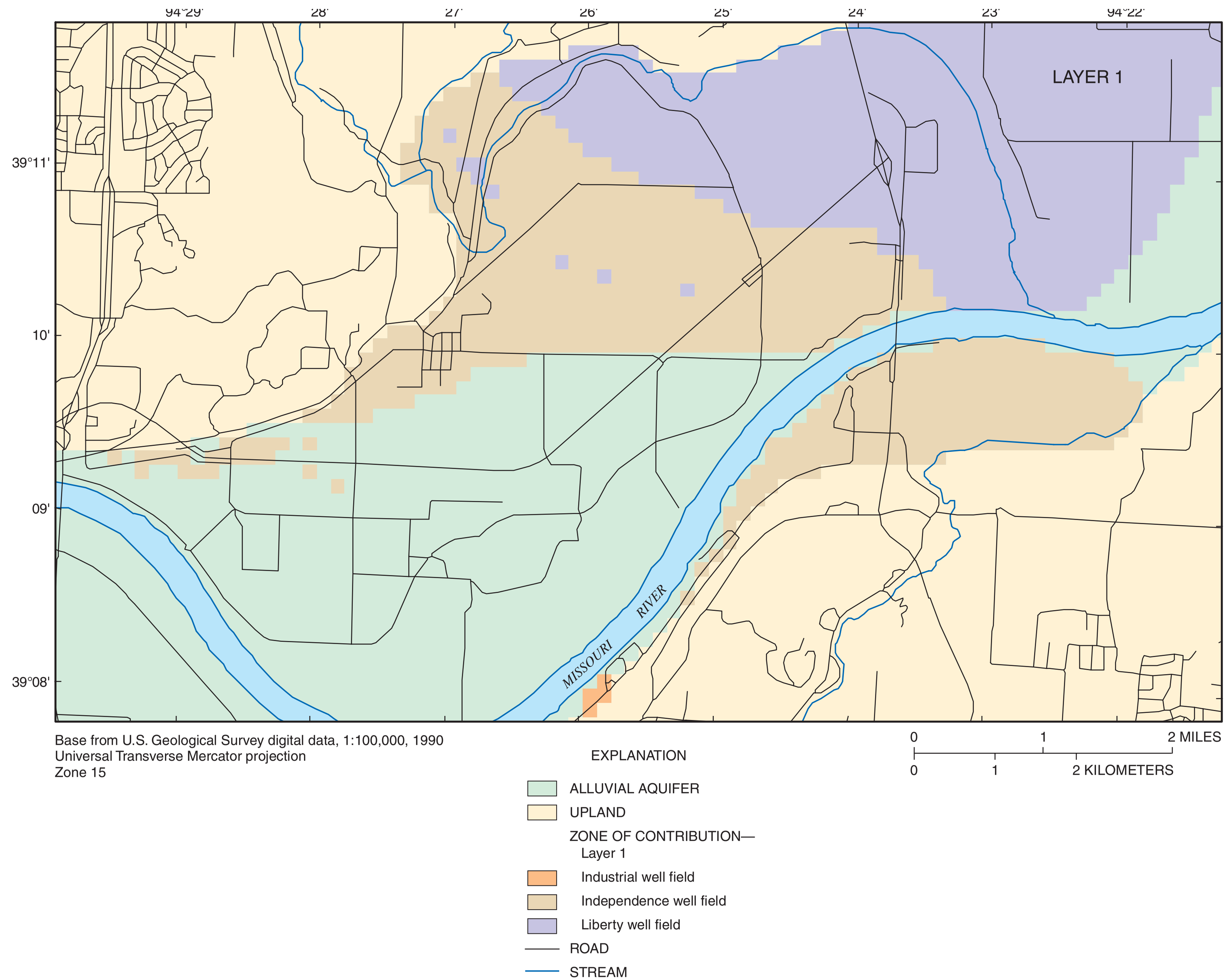


Figure 4. Simulation-defined zone of contribution for the Independence, Missouri, well field for each layer of the ground-water flow simulation.

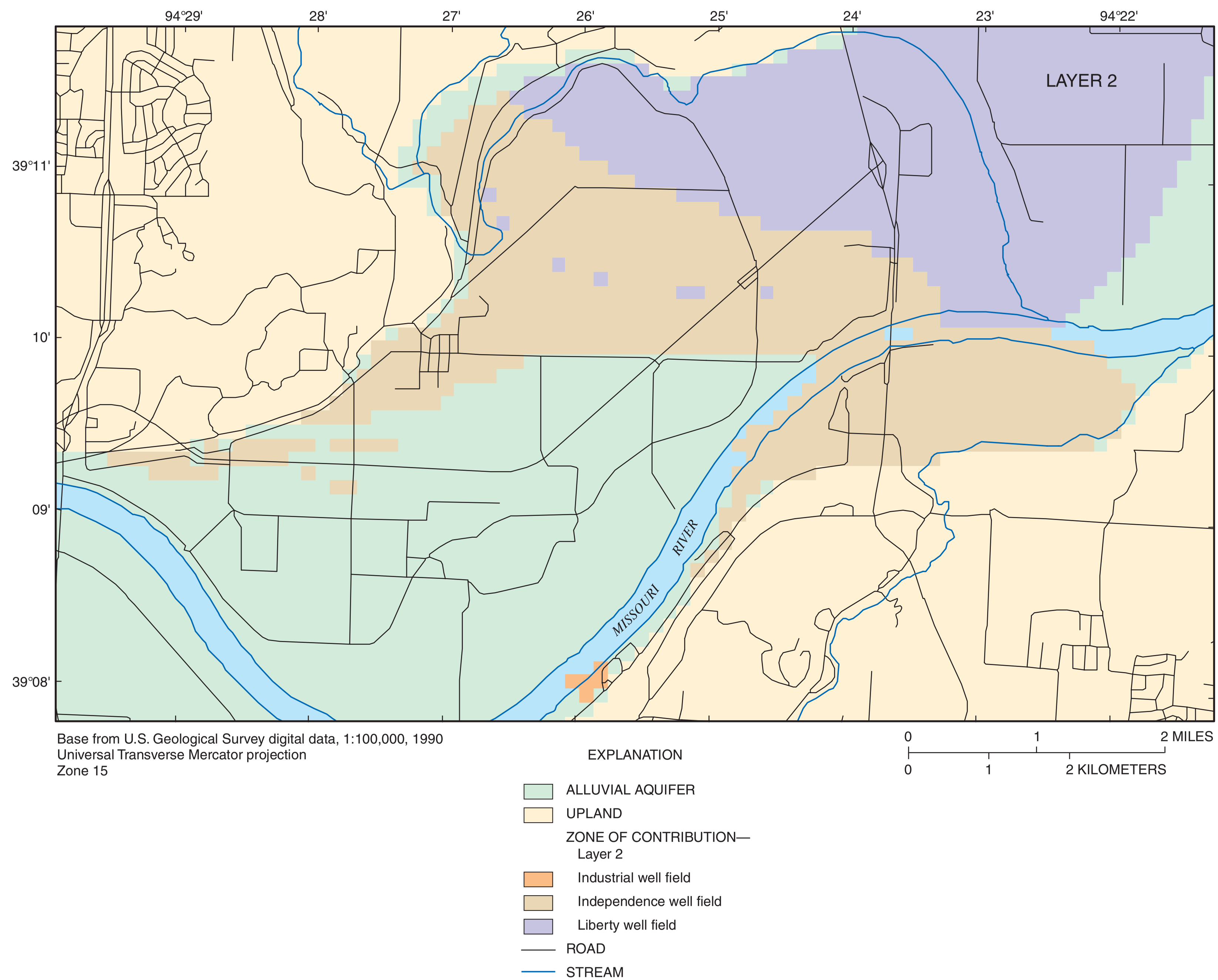


Figure 4. Simulation-defined zone of contribution for the Independence, Missouri, well field for each layer of the ground-water flow simulation—Continued.

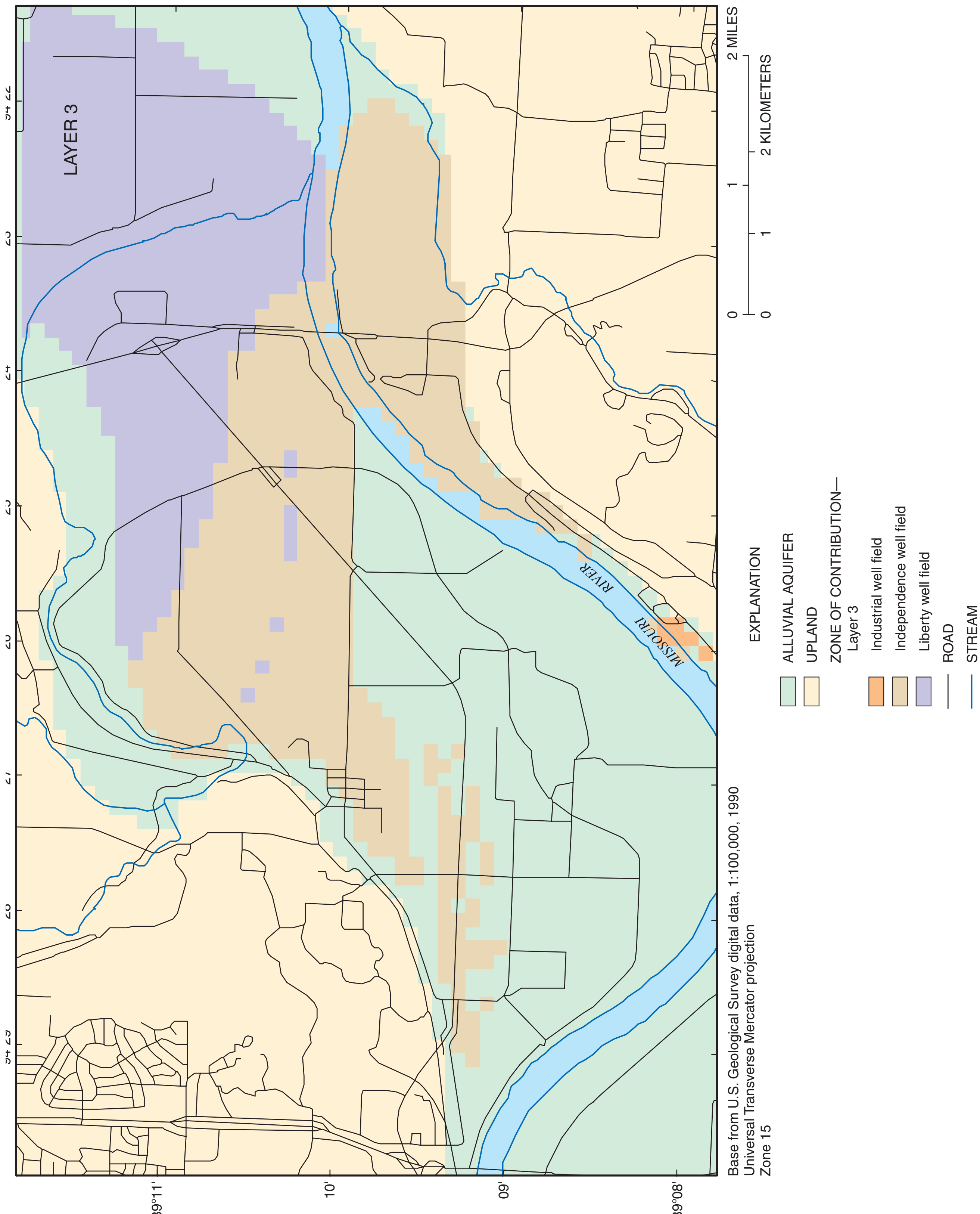


Figure 4. Simulation-defined zone of contribution for the Independence, Missouri, well field for each layer of the ground-water flow simulation—Continued.

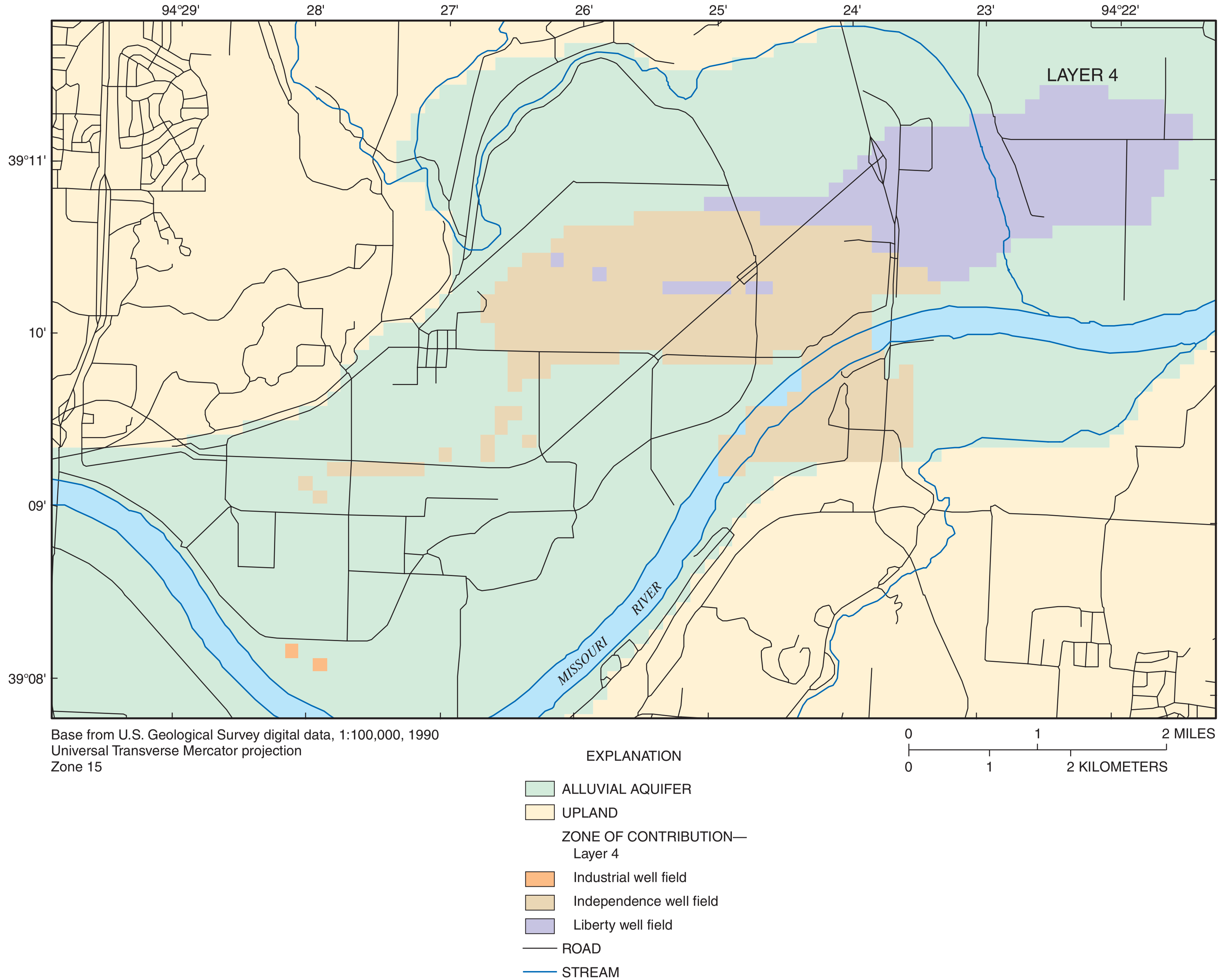


Figure 4. Simulation-defined zone of contribution for the Independence, Missouri, well field for each layer of the ground-water flow simulation—Continued.

Table 3. Simulated flow budget for the simulation-defined zone of contribution for the Independence, Missouri, well field

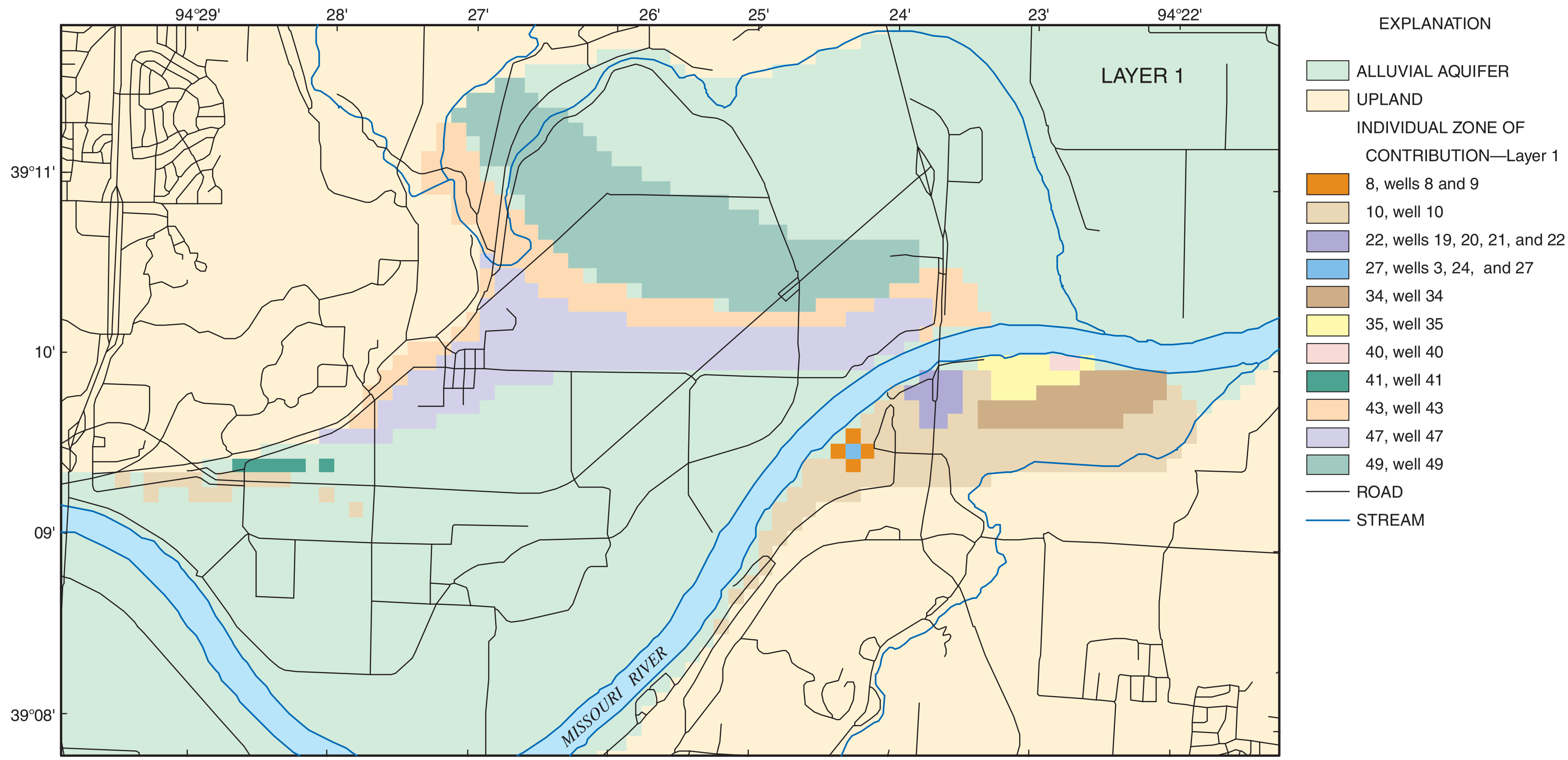
[ZOC, zone of contribution; m^3/day, cubic meters per day; na, not applicable]

Budget category (source, sink, or simulation-defined ZOC)	Inflow to simulation-defined ZOC (m^3/day)	Outflow from simulation-defined ZOC (m^3/day)	Sources and sinks within simulation-defined ZOC		Sources and sinks within simulation-defined ZOC and flow between simulation-defined ZOCs	
			Percent inflow from sources	Percent outflow to sinks	Percent inflow from sources	Percent outflow to sinks
Constant head	0	0	0.0	0.0	0.0	0.0
Wells	0	122,470	0.0	100.0	0.0	93.2
Drains	0	0	0.0	0.0	0.0	0.0
Rivers	114,070	0	92.8	0.0	86.7	0.0
Head-dependent boundaries	0	0	0.0	0.0	0.0	0.0
Recharge from precipitation	8,796	0	7.2	0.0	6.7	0.0
Flow between the Missouri River simulation-defined ZOC and the Independence well field simulation-defined ZOC	4,945	5,201	na	na	3.8	4.0
Flow between the industrial well field simulation-defined ZOC and the Independence well field simulation-defined ZOC	36	1	na	na	0.0	0.0
Flow between the Liberty well field simulation-defined ZOC and the Independence well field simulation-defined ZOC	3,727	3,697	na	na	2.8	2.8
Total flow to and from the Independence well field simulation-defined ZOC	131,574	131,369	na	na	na	na

river can supply a relatively unlimited amount of water to the well. Wells that are farther from the river or located such that other pumped wells intercept induced inflow from the river can have large simulation-defined ZOCs because recharge rates are relatively small per unit area and a larger area is needed to supply water to the well. For example, ZOC 41 corresponds to well 41, a horizontal collector well that has one of the largest pumping rates (18,082 cubic meters per day). However, ZOC 41 is one of the smaller simulation-defined ZOCs because most of its water is from induced inflow from the river. Conversely, ZOC 49 (well 49) has a much lower pumping rate (2,899 cubic meters per day), but is one of the larger simulation-defined ZOCs because it obtains more of its water from recharge from precipitation than from induced inflow from the river.

Flow-budget results were grouped between the rest of the simulation and the simulation-defined ZOCs of individual wells or groups of wells of the Independence well field and are listed in table 4, at the back of this report. Sources of water to the simulation-defined ZOCs were determined using ZONEBUDGET and indicate the relative percentages of source water to wells. The largest source of water within simulation-defined ZOCs for most wells in the Independence well field is the Missouri River; however, recharge from precipitation is the largest source of water within the simulation-defined ZOCs for wells 43, 47, and 49.

For 17 of the 25 simulation-defined ZOCs for the Independence well field, flow from other simulation-defined ZOCs accounted for most of the flow into the ZOC. All flow into the simulation-defined ZOCs of wells 11, 17, and 30 came from other simulation-



Base from U.S. Geological Survey digital data, 1:100,000, 1990
Universal Transverse Mercator projection
Zone 15

0 1 2 MILES
0 1 2 KILOMETERS

Figure 5. Simulation-defined zone of contribution for wells or groups of wells in the Independence, Missouri, well field for each layer of the ground-water flow simulation.

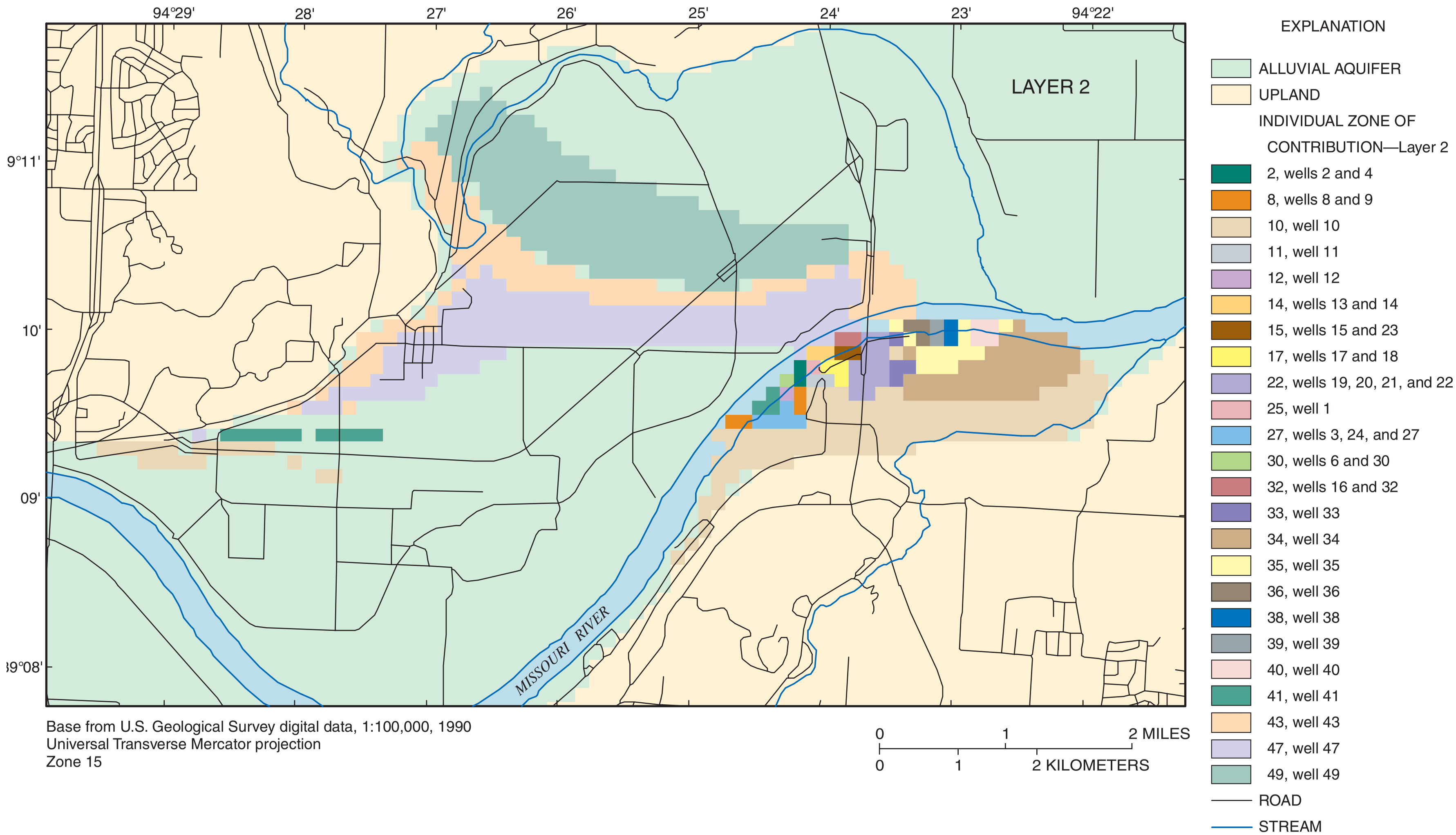
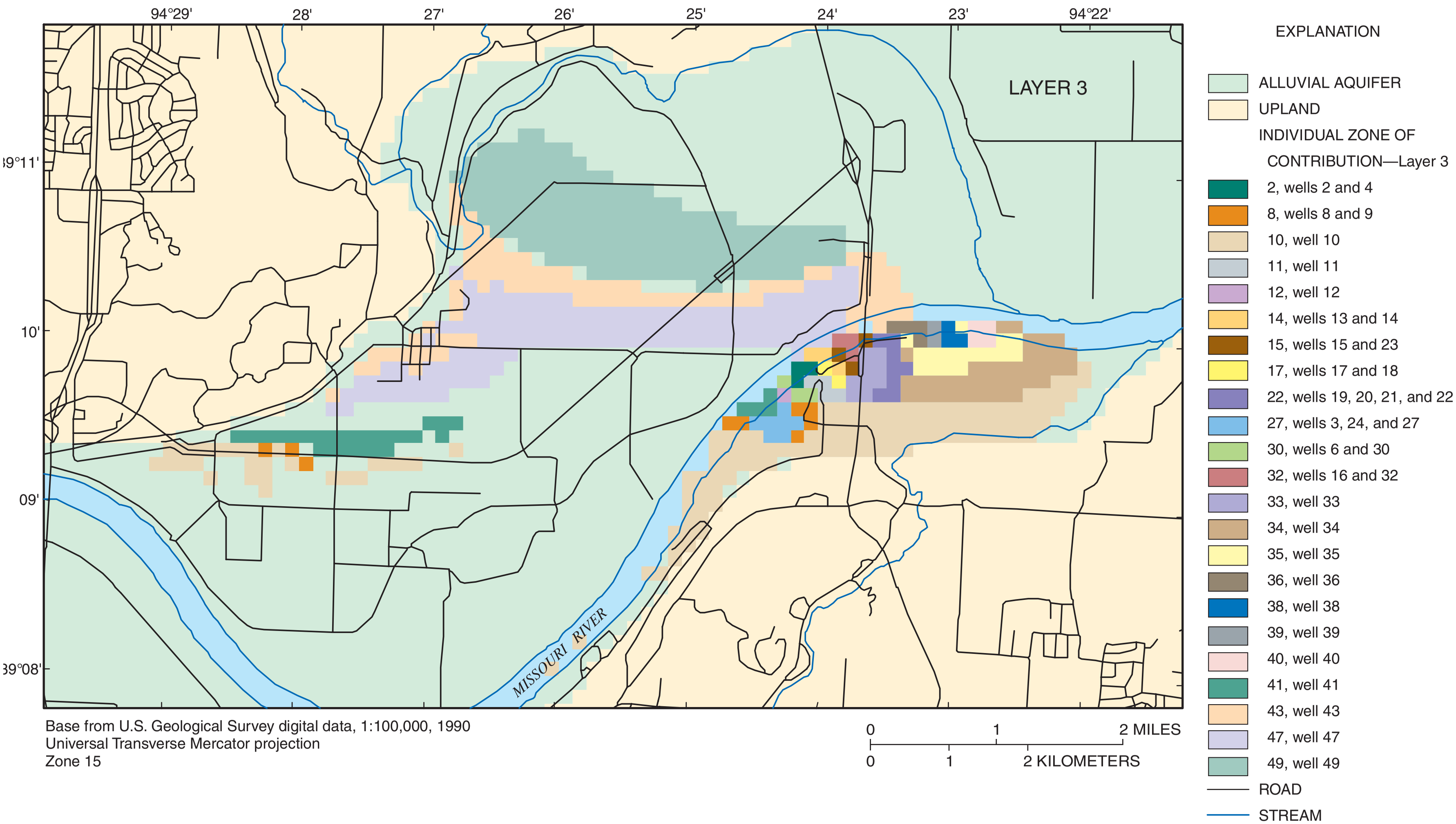


Figure 5. Simulation-defined zone of contribution for wells or groups of wells in the Independence, Missouri, well field for each layer of the ground-water flow simulation—Continued.



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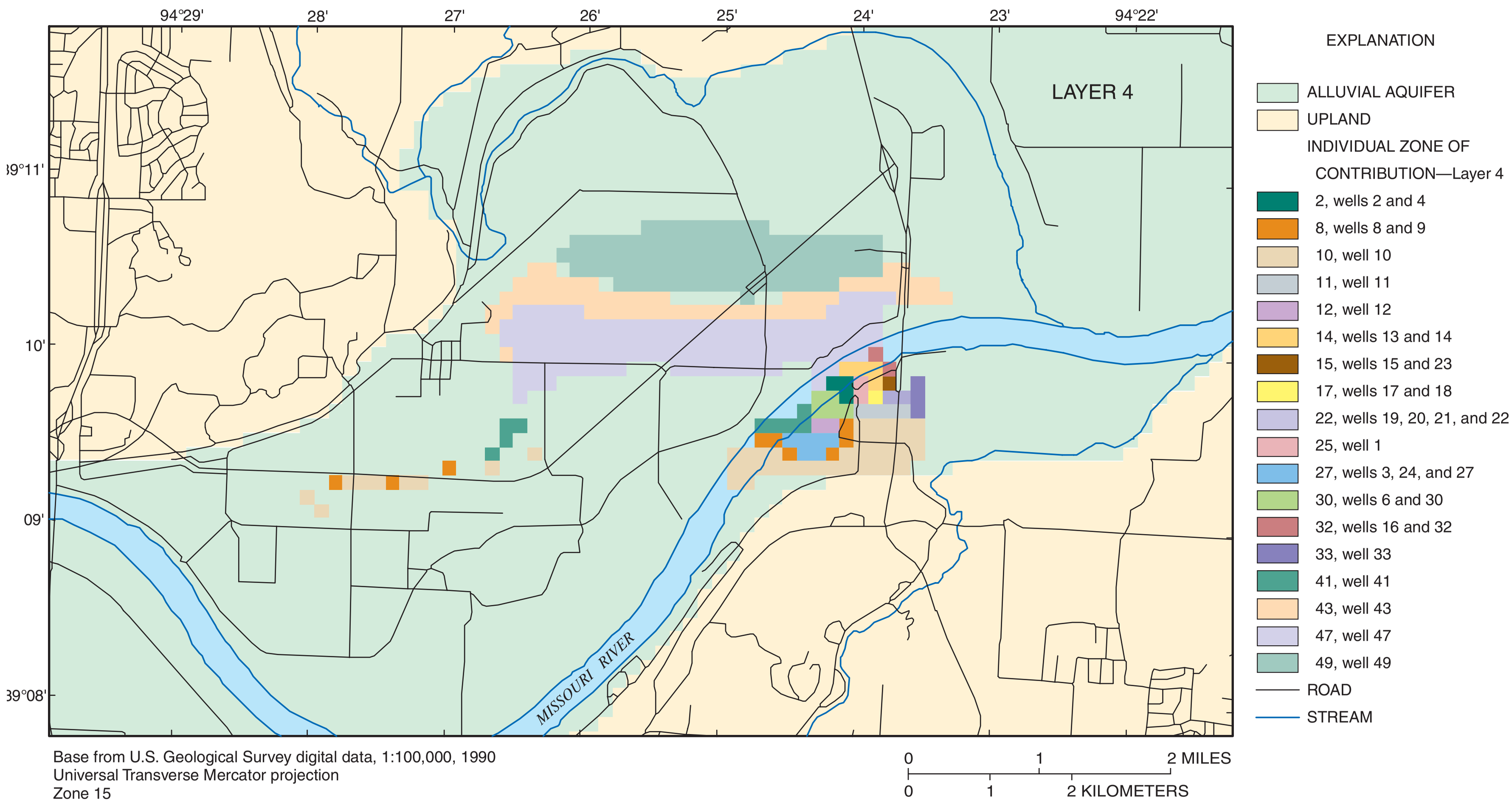

Figure 5. Simulation-defined zone of contribution for wells or groups of wells in the Independence, Missouri, well field for each layer of the ground-water flow simulation—Continued.

defined ZOCs. As previously discussed, the source of water is not indicated by ZONEBUDGET for flow between simulation-defined ZOCs.

Particle-Tracking Analysis

Particle tracking with MODPATH was used to calculate the relative amounts of source water to wells in the Independence well field. This method was used to decrease the flow-budget errors caused by the flow of water between simulation-defined ZOCs and to ensure that all pumped wells were included in the analysis. A three-dimensional (4x4x4) grid of particles (64 total particles) was placed within each cell that contained one or more pumped wells of the Independence well field. Particles were then tracked backward in time in a steady-state simulation to river or recharge source cells until all particle movement ended. The minimum traveltime for the particles was about 5 days, and the maximum was about 206 years. The pathline of the particles between source cells and well cells of the Independence well field is shown in figure 6.

The relative amounts of source water were estimated by dividing the number of particles that ended in either a river or recharge source cell by the number of particles placed in the cell containing the pumped well (the starting cell). For example, if 32 particles ended in river source cells and 32 particles ended in recharge source cells, then one-half of the source water to the cell containing the pumped well was from the river and one-half was from ground-water recharge from precipitation. This method does not uniquely identify cells as belonging to only one simulation-defined ZOC, because particles from more than one starting cell can travel to the same source cell. Flow between cells that contained pumped wells was recorded with this method only when particles placed within a cell containing a pumped well were intercepted by another cell containing a pumped well. This usually occurred when cells containing pumped wells were adjacent to one another, or the cell containing the pumped well also contained a source of water such as the Missouri River. Results of this analysis are listed in table 5.

Compared to the flow-budget analysis for simulation-defined ZOCs of individual wells within the Independence well field, the use of particle tracking more precisely defined the relative amounts of source water for each individual well or group of wells. However, the overall error for the entire well field is about the same. The particle tracking analysis indicated that the Missouri River supplied 82.3 percent of the water to the entire Independence well field, ground-water recharge from precipitation supplied 9.7 percent, and flow between starting cells containing pumping wells supplied 8.0 percent.

Knowledge of the source of water to the Independence well field is important for proper well-field management. However, the traveltime between the source of water and the pumped wells within the Independence well field may be equally important. The number of particles that reached river or recharge source cells in 1, 2, 5, 10, and 25 years and for the entire simulation were recorded and compared to the total number of particles initially placed within pumped well cells to determine the relative amounts of source water that reached pumped well cells within those times. Results of this analysis for individual wells or groups of wells by ZOCs are listed in table 6, at the back of this report.

The relative amounts of source water to total well-field pumpage as a function of traveltime from the source are illustrated in figure 7. The amount of water in total well-field pumpage that traveled for 1 year or less from the source was 8.8 percent, with 0.6 percent of the water in total well-field pumpage from the Missouri River, none from precipitation, and 8.2 percent between starting cells. The amount of water in total well-field pumpage that traveled 2 years or less from the source was 10.3 percent, with 1.8 percent of the water in total well-field pumpage from the Missouri River, 0.2 percent from precipitation, and 8.3 percent between starting cells. The amount of water in total well-field pumpage that traveled 5 years or less from the source was 36.5 percent, with 27.1 percent of the water in total well-field pumpage from the Missouri River, 1.1 percent from precipitation, and 8.3 percent between starting cells. The amount of water in total well-field pumpage that traveled 10 years or less from the source was 42.7 percent, with 32.6 percent of the water in total well-field pumpage from the Missouri River, 1.8 percent from precipitation, and 8.3 percent between starting cells. The amount of water in total well-field pumpage that traveled 25 years or less from the source was 71.9 percent, with 58.9 percent of the water in total well-field pumpage from the Missouri River, 4.7 percent from precipitation, and 8.3 percent between starting cells. Flow between starting cells usually occurred when those cells were adjacent to each other. Flow between starting cells remained about 8 percent for all traveltimes listed because all particles captured by adjacent cells had traveltimes less than 2 years, and most had traveltimes less than 1 year.

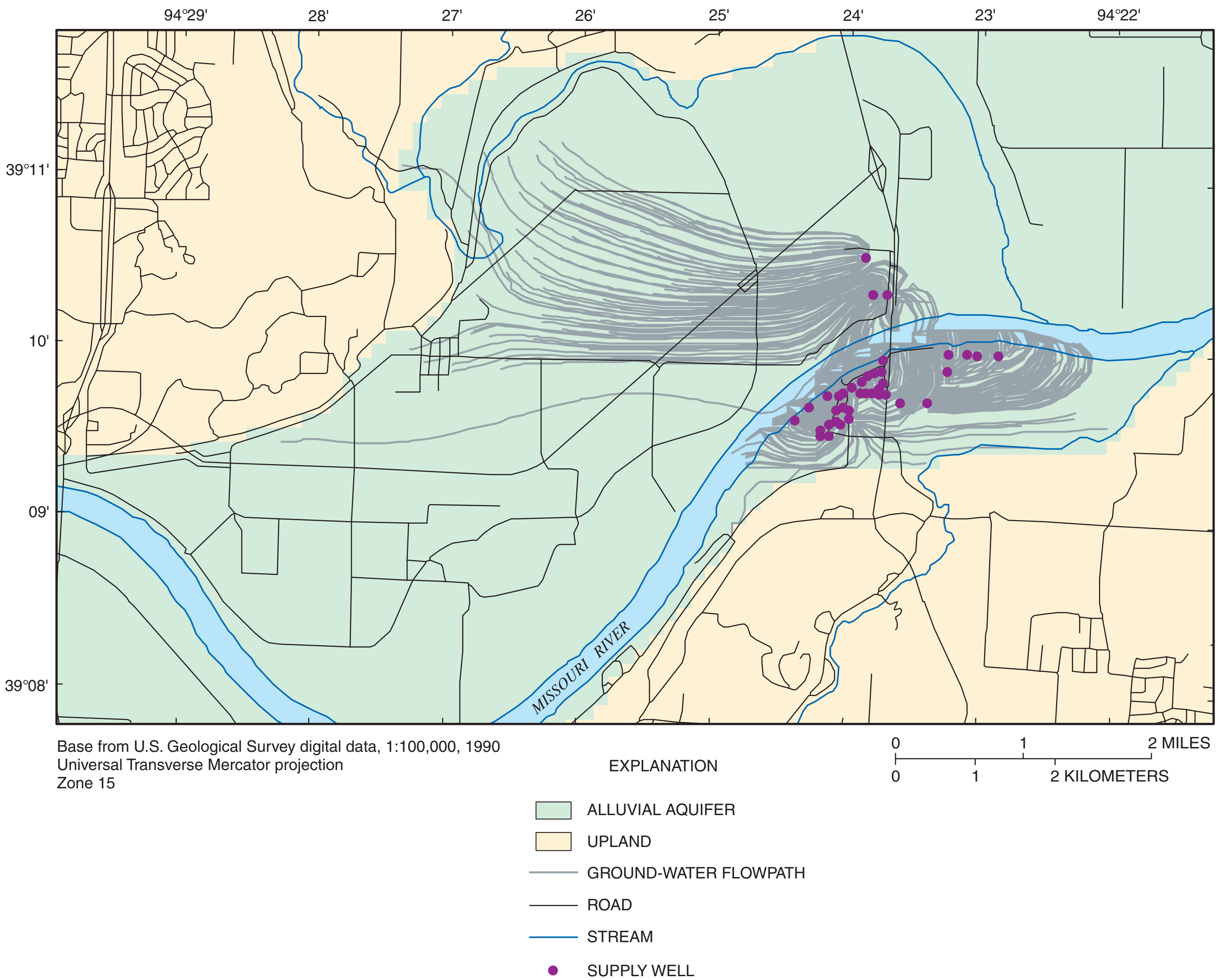

Figure 6. Pathlines of particles between source cells and well cells of the Independence, Missouri, well field.

Limitations of Estimates

Ground-water simulation techniques indicate that 82 to 94 percent of well-field pumpage is induced inflow from the Missouri River. However, simulation limitations affect the accuracy of the pumpage estimates. All the ground-water simulation techniques used to estimate sources of water to the Independence well field are based on steady-state ground-water flow simulations. The results of the simulations are subject to the accuracy of the simulation calibration. As previously stated, river stage, precipitation rate, and well pumping are variable with time, and true steady-state conditions probably never exist in the simulated area. During periods of high river stage, induced flow from the river to the well field likely will be greater than during low river stage. Steady-state ground-water flow represents long-term or average flow conditions; the relative amounts of source water to the well field calculated in this study also represent long-term conditions.

Another limitation affects the calculation of the ZOCs. By definition, a ZOC is the three-dimensional region within an aquifer that supplies all water to a well, well field, or other sink. However, flow between

Table 5. Particle tracking results indicating the relative amounts of source waters to the individual wells and groups of wells within the Independence, Missouri, well field

[na, not applicable]

Wells	Particles ending at river source	Percent of river source	Particles ending at recharge from precipitation source	Percent of recharge from precipitation source	Particles from other starting cells	Percent of flow from other starting cells	Percent total
1	53	82.8	0	0.0	11	17.2	100
2, 4	64	100.0	0	0.0	0	0.0	100
3, 24, 27	52	81.3	0	0.0	12	18.7	100
5	64	100.0	0	0.0	0	0.0	100
6, 30	57	89.1	0	0.0	7	10.9	100
7	64	100.0	0	0.0	0	0.0	100
8, 9	50	78.1	0	0.0	14	21.9	100
10	38	59.4	12	18.7	14	21.9	100
11	47	73.4	0	0.0	17	26.6	100
12	64	100.0	0	0.0	0	0.0	100
13, 14	64	100.0	0	0.0	0	0.0	100
15, 23	37	57.8	0	0.0	27	42.2	100
16, 32	64	100.0	0	0.0	0	0.0	100
17, 18	46	71.9	0	0.0	18	28.1	100
19, 20, 21, 22	56	87.5	0	0.0	8	12.5	100
33	64	100.0	0	0.0	0	0.0	100
34	52	81.3	12	18.7	0	0.0	100
35	57	89.1	4	6.2	3	4.7	100
36	64	100.0	0	0.0	0	0.0	100
38	64	100.0	0	0.0	0	0.0	100
39	64	100.0	0	0.0	0	0.0	100
40	64	100.0	0	0.0	0	0.0	100
41	64	100.0	0	0.0	0	0.0	100
43	33	51.6	29	45.3	2	3.1	100
47	24	37.5	40	62.5	0	0.0	100
49	0	0.0	64	100.0	0	0.0	100
Well field total	na	82.3	na	9.7	na	8.0	100

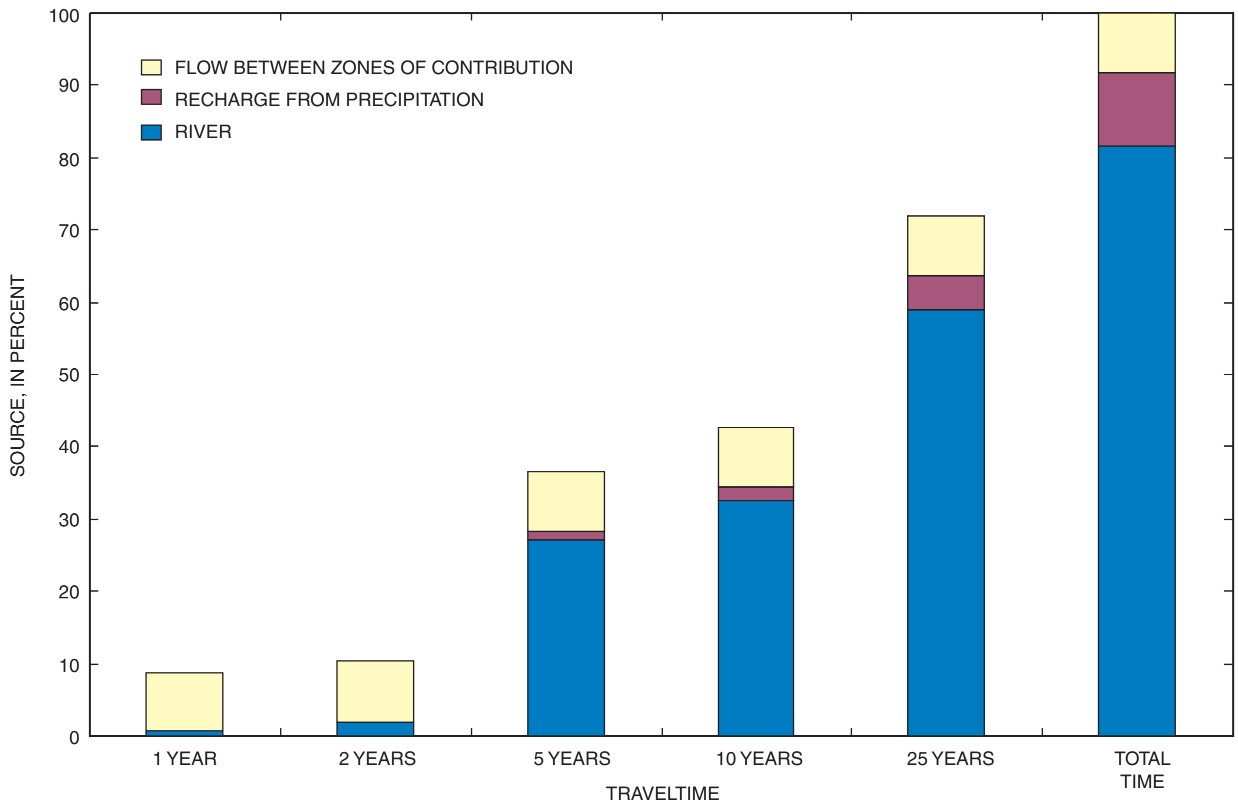

Figure 7. Relative amount of source water to total Independence, Missouri, well-field pumpage as a function of traveltime from the source.

ZOCs in the simulation is caused by cells that are too large to precisely define each ZOC. The source of water simulated as flow between ZOCs is either the river or recharge from precipitation, but the relative amounts of each are unknown. Therefore, the estimated amounts of induced inflow from the river or ground-water recharge from precipitation represent minimum estimates, and the flow from other ZOCs, when added to the estimates, represents maximum estimates for each source.

CHEMICAL AND ISOTOPIC MIXING EQUATION ANALYSES

Differences in constituent concentrations of source waters can be used to determine their relative amounts in a mixture. Water samples were collected from selected monitoring wells around the Independence well field (ground-water source), from the USGS continuous streamflow gaging station at St. Joseph, Missouri (river source), and from combined well-field pumpage (mixture) using methods described in Kelly (2002). Combined well-field pumpage water samples also were collected by the Independence Water Department from four raw-water mixing tanks. The samples were analyzed for common constituents (calcium, magnesium, potassium, sodium, iron, sulfate, chloride, and fluoride) using methods described in Kelly (2002). Samples collected by the Independence Water Department were analyzed for all common constituents except potassium and sodium at the Independence Water Department laboratory. Results of these analyses are listed in table 7, at the back of this report.

Water samples from selected monitoring wells around the Independence well field, from combined well-field pumpage, from the Missouri River at St. Joseph, and from the Missouri River near the Independence well field were analyzed for naturally occurring stable isotopes of oxygen (^{18}O and ^{16}O) and hydrogen (^{2}H or deuterium and ^{1}H). The stable isotope values are expressed in delta notation (δ), which compares the ratio between heavy and light isotopes of a sample to that of a reference standard. Delta values are expressed as per mil (parts per thousand) differences relative to the standard known as Vienna Standard Mean Ocean Water (VSMOW) and normalized (Gonfiantini, 1984;

Hut, 1987; Coplen, 1988 and 1994) on scales so that $\delta^{18}O$, $^{18}O/^{16}O$, and δD (deuterium/hydrogen) values of Standard Light Antarctic Precipitation (SLAP) are -55.5 per mil and -428 per mil, respectively.

Values of $\delta^{18}O$ for water samples were measured using the carbon dioxide equilibration technique (25 degrees Celsius) of Epstein and Mayeda (1953). Hydrogen-isotope-ratio analyses were performed using a hydrogen equilibration technique (at 30 degrees Celsius) (Coplen and others, 1991). The hydrogen equilibration technique measures deuterium activity. The 2-sigma uncertainty of $\delta^{18}O$ analyses is 0.2 per mil, and the uncertainty of δD analyses is 2 per mil.

The ^{18}O and D are slightly heavier than the more abundant ^{16}O and hydrogen atoms and evaporation enriches surface water with respect to ^{18}O and D because the lighter atoms more readily evaporate, and the heavier atoms are left behind. Most rainfall is from the evaporation of seawater and is depleted with respect to ^{18}O and D. The relation of $\delta^{18}O$ to δD values for precipitation is linear; a graph of this relation is known as the meteoric water line (Craig, 1961). Evaporated surface waters can also become enriched with respect to ^{18}O and D as the lighter atoms are removed. Water that condenses at lower temperatures is lighter (more depleted) than water that condenses at higher temperatures.

The use of $\delta^{18}O$ and δD values to determine the relative amounts of source water to Independence well-field pumpage initially was considered because water is retained in the flood control reservoirs of the upper Missouri River for a long time, which can result in an enrichment of ^{18}O and D through evaporation. Conversely, precipitation is a substantial source of ground-water recharge and, as a result, ground water should be depleted in ^{18}O and D. However, isotopic analyses indicate that Missouri River water is more depleted in both ^{18}O and D than ground water near the Independence well field (fig. 8). Although evaporation of water within the upstream reservoirs undoubtedly takes place, the water in those reservoirs condensed at lower temperatures, resulting in the net depletion of ^{18}O and D observed. Values of $\delta^{18}O$ and δD are listed in table 8, at the back of this report.

Estimates of Source Contributions

Chemical and isotopic analyses of water from different sources can be used to estimate the relative amounts of those source waters in a receiving body of water if each source has a different chemical or isotopic signature. Combined pumpage from the Independence well field is a mixture of Missouri River water and ground water. A two component mixing equation (Katz, 1998) was used to estimate the relative amount of Missouri River water in total well-field pumpage. For a two-component mixture, the fraction of Missouri River water (F_{moriv}) is defined as:

$$F_{moriv} = (C_{wellfield} - C_{gw})/(C_{moriv} - C_{gw}) \qquad (1)$$

where:

$C_{wellfield}$ = the concentration of the constituent in the well field (mixture);

C_{gw} = the concentration of the constituent in ground water (ground-water source); and

C_{moriv} = the concentration of the constituent in the Missouri River (river source).

The precision of this method depends on the variability of the constituent concentrations in water from the Missouri River and the difference in concentration of the constituent between the Missouri River and ground water. The sensitivity of this method is determined with the following equation (Payne, 1983):

$$Sensitivity = +/-STDEV_{moriv}/(C_{moriv}-C_{gw}) \qquad (2)$$

where $+/-STDEV_{moriv}$ is the variation (one standard deviation) of the constituent concentration in the Missouri River. If the variation of the constituent concentration in the Missouri River is large, or if no substantial difference is present in constituent concentrations between ground water and the Missouri River, then the method will not be reliable.

Results for the common constituent analyses were grouped into Missouri River samples (river source), ground-water samples from monitoring wells (ground-water source), and combined well-field-pumpage samples (mixture), and were used to determine the suitability of each for use in the mixing equation (fig. 9). Of the common constituents analyzed in water samples, calcium, sodium, iron, and fluoride were chosen for use in the mixing equation described previously. Other constituents either had large concentration variations in the Missouri River or had concentrations not sufficiently dissimilar in both river water and ground water.

The $\delta^{18}O$ and δD values were grouped into Missouri River samples, ground-water samples, and combined well-field-pumpage samples, and their suitability

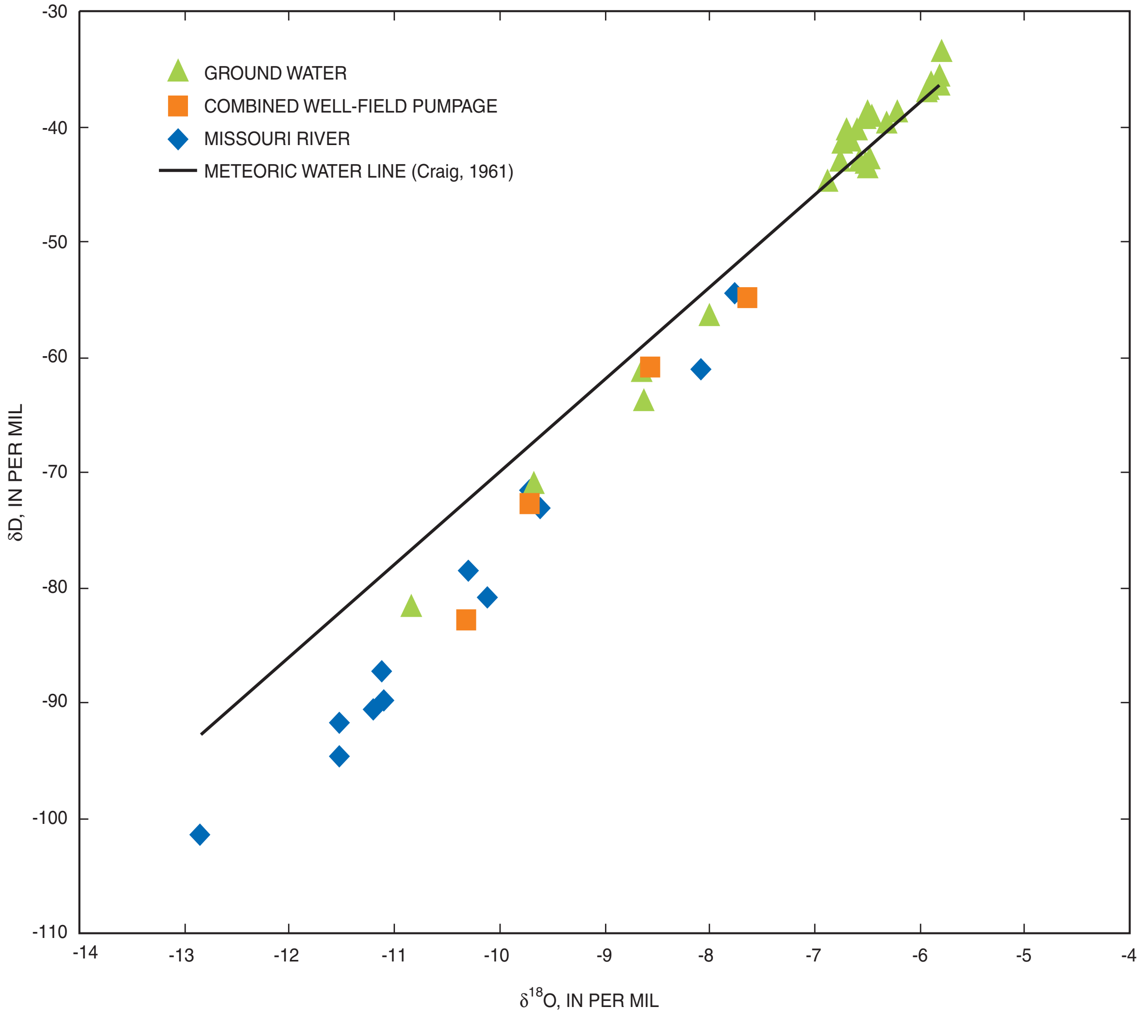

Figure 8. $\delta^{18}O$ and δD values for ground water, combined well-field pumpage, and Missouri River water and the meteoric water line.

for use in the mixing equation (fig. 10) was determined. Both ^{18}O and D are depleted in Missouri River samples. Ground water is less depleted in ^{18}O and D than Missouri River samples and, as can be seen in figure 10, a well-defined isotopic signature is present for each source of water to the Independence well field.

Results of the mixing equation for the common ions, $\delta^{18}O$, and δD are listed in table 9. Median concentrations of each constituent were determined, and these values were used in equation 1. The relative amounts of induced inflow from the Missouri River in well-field pumpage ranged from 49 percent for sodium to 80 percent for calcium, and sensitivities ranged from 0 percent for iron to +/- 35 percent for $\delta^{18}O$. The small sensitivity for iron was caused by the consistently low concentration of iron in river water samples, and the large sensitivity for $\delta^{18}O$ and δD was caused by the high variability of these isotopes in river water samples. The average of all mixing equation results indicated that 61 percent of well-field pumpage was from induced inflow from the Missouri River.

Limitations of Estimates

Several limitations are associated with using the mixing equation. When river water and ground water mix in the alluvial aquifer, it causes the chemical and isotopic character of the river water and ground water to become more similar to each other than would be the case if no mixing occurred. This causes the mixing equation to underestimate the component of river water in well-field pumpage. Conversely, much of the flow in

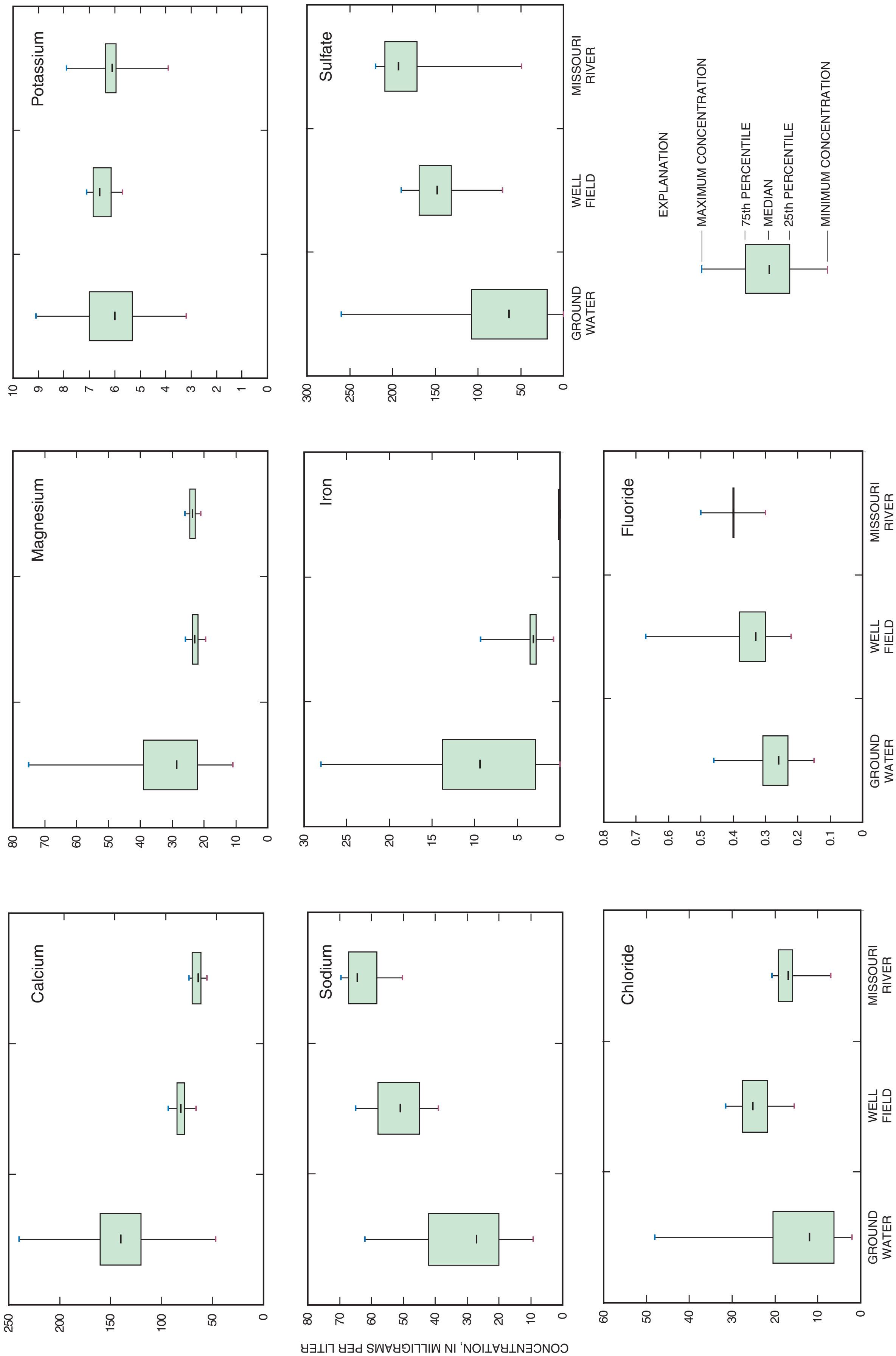

Figure 9. Maximum, median, minimum, and quartiles of analyses for common constituents in ground water, well-field pumpage, and Missouri River samples.

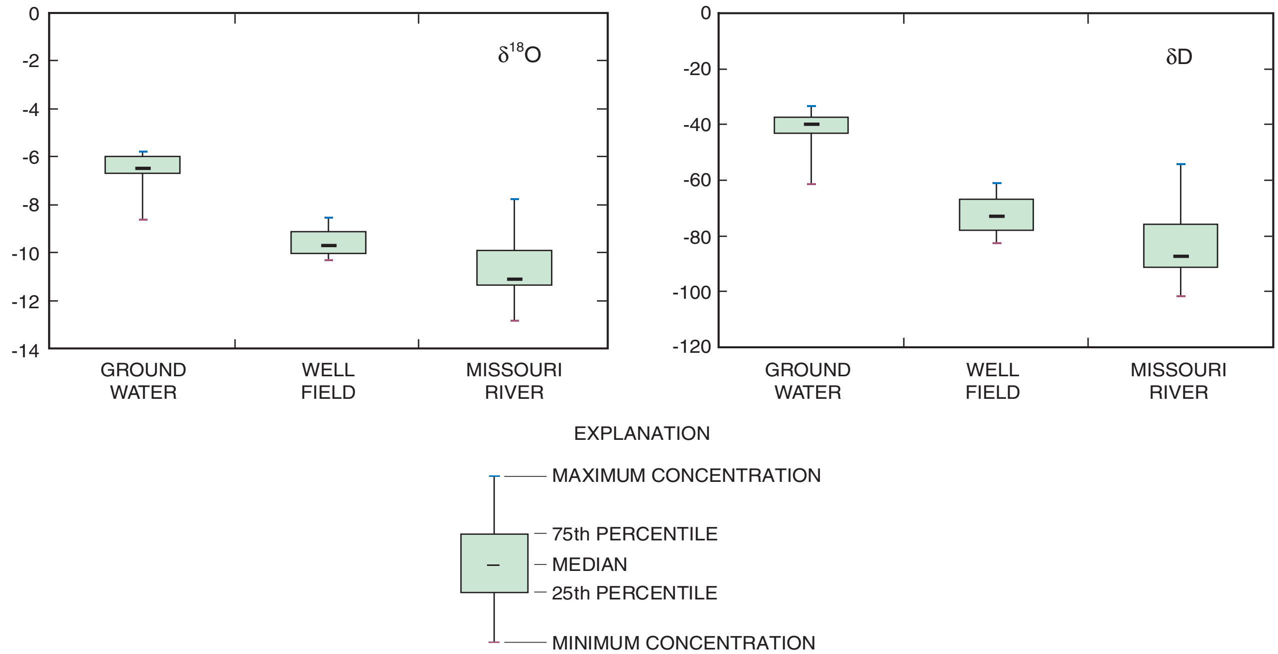

Figure 10. Maximum, median, minimum, and quartiles of analyses for $\delta^{18}O$ and δD in ground water, well-field pumpage, and Missouri River samples.

Table 9. Results of mixing equation for common constituents, $\delta^{18}O$ and δD

[+/-, plus or minus]

Constituent	Number of samples: Missouri River	Number of samples: Well field	Number of samples: Ground water	Relative amount of Missouri River source in well-field pumpage, in percent	Sensitivity, in percent (+/-)	Range, in percent
Calcium	15	127	46	80	7	73 to 87
Sodium	15	3	46	49	24	25 to 73
Iron	12	127	46	62	0	62
Fluoride	15	127	46	50	27	23 to 77
$\delta^{18}O$	12	4	27	63	35	28 to 98
δD	12	4	27	60	33	27 to 93

the Missouri River is base flow from the alluvial aquifer. During periods of extended low flow, the chemical characteristics of Missouri River samples may become closer to those of ground water. This would cause the mixing equation to overestimate the component of river water in well-field pumpage. Mixing of these waters also can occur during seasonal flooding when large areas are inundated, and river water infiltrates into the aquifer along the same path that recharge from precipitation infiltrates into the aquifer. Another limitation is the change in chemical characteristics of river water or ground-water recharge from precipitation after it infiltrates into the alluvial aquifer. Long traveltimes from the source to the well field increase the length of time water is in contact with the alluvial aquifer. Dissolution of aquifer materials into the source water as the water moves through the aquifer causes the water to acquire the chemical characteristics of ground water. In addition, the long traveltime of some induced flow from the river to the wells and potential differences in past river water chemistry may affect the results of the mixing equation.

The values of $\delta^{18}O$ and δD generally are unaffected by interactions between minerals and ground water after they enter the ground-water system. However, for this study, the large variation of $\delta^{18}O$ and δD values for Missouri River samples increased the amount of error associated with their use in the mixing equation.

Another limitation is that different areas of the aquifer contribute different amounts of water to the total well-field pumpage. The water from areas that contribute the most to the well field may have different chemical characteristics than water from other areas that do not contribute as much. The effects of spatial variability of the chemical and isotopic characteristics of ground water can be decreased by obtaining samples from all regions of the contributing recharge area of the well field. However, if most of the water that supplies the well field flows through limited regions of the aquifer, the assumption that a median value, as used in the mixing equation, represents the composition of the river water or ground water that actually supplies the well field per unit of time may either overestimate or underestimate the component of river water or recharge from precipitation in well-field pumpage.

SYNOPSIS OF CONTRIBUTION OF THE MISSOURI RIVER TO THE INDEPENDENCE WELL FIELD

Flow budgets from ground-water simulation results, the Independence well field ZOC, the ZOCs of individual wells or groups of wells of the Independence well field, particle tracking, and chemical and isotopic analyses of water from the Missouri River, the Independence well field, and ground-water monitoring wells were used to determine the relative amount of Missouri River water in total Independence well-field pumpage. The estimate, maximum, and minimum error of the relative amount of Missouri River water in well-field pumpage for each of these methods are shown in figure 11.

All of the methods used in the study indicate that more than one-half of the water in well-field pumpage is from induced inflow from the Missouri River. Generally, the estimates from the ground-water simulation methods for river inflow to the well field are larger and error values are smaller than those produced using chemical and isotopic data in the mixing equation. However, substantial overlap exists between the ranges of estimates from both methods. The difference between estimates from the two methods may exist because the steady-state ground-water simulation estimated long-term flows to the well field, whereas the data used in the mixing equation are more representative of current hydrologic conditions near the well field. Estimate ranges for the ground-water simulation methods were calculated by adding the flow between simulation-defined ZOCs to the estimated value. Estimate ranges for the chemical and isotopic mixing equation estimates were calculated by adding or subtracting the sensitivity to or from the estimate value. Substantial and unquantified uncertainties exist for both estimation methods. The greatest sources of error in the ground-water simulation techniques were from the spatial discretization of the simulation. A simulation with smaller cells should decrease this source of error. The greatest source of uncertainty in the mixing equation is the variability of the chemical and isotopic data that represent the sources of water (river water and ground-water recharge from precipitation) to the aquifer. Increasing the number, span of time, and variability of flow conditions of samples from the river water, ground water, and well-field pumpage should decrease the uncertainty associated with using the mixing equation. However, annual and seasonal variability of constituents in river water, and long ground-water traveltimes, may continue to introduce sources of error.

Using flow-budget analysis to determine the relative amounts of source water to a well field by subtracting a no-pumping scenario from a pumping scenario is a relatively simple technique once a ground-water simulation is constructed and calibrated. This technique is most appropriate where a single well or well field is simulated. Flow-budget analysis in more complex systems with multiple well fields may require that the effects of a single well or well field be isolated from over-all simulation results. To extract flow budgets of single wells or well fields within a simulation, different areas of interest can be defined by the user or by using particle tracking with MODPATH, and budgets can be calculated for each area using ZONEBUDGET. However, if simulation-defined ZOCs of well fields border each other, flow between them will cause errors in the results. In hydrologically complex systems, similar to the alluvial aquifer near the Independence well field, particle-tracking analysis can be used to more precisely determine the relative amounts of

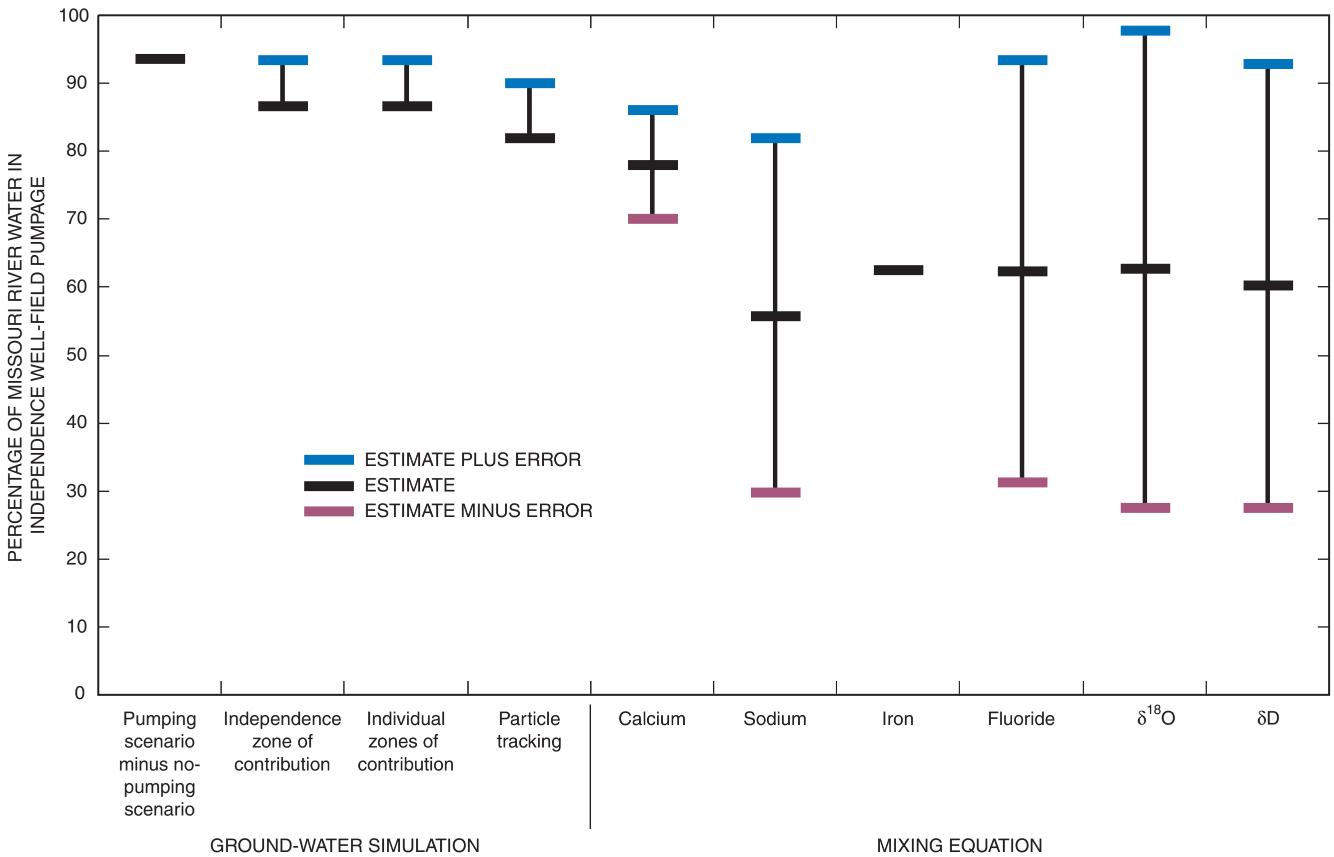

Figure 11. Estimates of the relative amount of Missouri River water in the Independence, Missouri, well-field pumpage and the maximum and minimum error for ground-water simulation and mixing equation methods.

source water for individual wells or in total well-field pumpage because the error (flow between simulation-defined ZOCs) is smaller than the error for flow-budget analysis results. Therefore, because of the complex hydrology of the aquifer near the Independence well field, the estimates for the relative amounts of Missouri River water and ground-water recharge from precipitation in Independence well-field pumpage from particle-tracking analysis probably are the most reliable of the ground-water simulation methods.

Source water estimates using the mixing equation are less reliable than those of the ground-water simulation for this study because the estimate errors are larger than the estimate errors of the ground-water simulation. However, more reliable results can be obtained from the mixing equation by increasing the number of samples from source and mixed waters, collecting samples for a longer time, and collecting samples during different flow conditions. In the absence of a calibrated ground-water flow simulation, the mixing equation can provide a reasonable estimate of sources of water to a well field at relatively low cost, if sources of error are clearly understood.

SUMMARY

The city of Independence, Missouri, operates a well field within the city limits of Sugar Creek, Missouri, in the Missouri River alluvial aquifer. Results from previous studies indicate that pumping of the well field induces inflow from the Missouri River as a substantial percentage of the total well-field pumpage. The objective of this study was to determine the relative contributions of induced inflow from the Missouri River and ground-water recharge from precipitation to the total pumpage of the Independence well field using an existing ground-water flow simulation and compar-

isons of chemical and isotopic (oxygen and hydrogen) analyses of river water, ground water, and well-field pumpage.

Sources of water to the Independence well field were estimated by comparing boundary flow components of a steady-state simulation with all wells being pumped (pumping scenario) to a steady-state simulation with all wells being pumped except for the Independence well field (no-pumping scenario). This method yielded estimates of flow into the simulated area of the aquifer of 67.6 percent from rivers, 31.4 percent from recharge from precipitation, and 1.0 percent from head-dependent boundaries. Flows out of the simulated area of the aquifer were estimated as 49.1 percent to wells, 11.2 percent to drains, 38.7 percent to rivers, and 1.0 percent to head-dependent boundaries. Results indicated that 93.7 percent of Independence well-field pumpage was derived from induced inflow from the Missouri River and 6.3 percent was derived from ground-water recharge from precipitation. The no-pumping scenario alters ground-water hydraulic heads and gradients; therefore other nearby well fields may obtain more water from induced inflow from the Missouri River or ground-water recharge from precipitation than would occur when water is pumped from the Independence well field. This would result in a larger inflow either from the river or recharge budget term for the no-pumping scenario that would introduce some error in the results obtained using this method.

To more accurately determine the sources of water to the Independence well field, the simulated flow budget was calculated within the simulation-defined zone of contribution (ZOC) of the Independence well field. The relative amounts of flow from different sources within the simulation-defined ZOC indicate that 92.8 percent of well-field pumpage is from induced inflow from the river, and 7.2 percent is from ground-water recharge from precipitation. The relative amounts of flow from sources inside and outside of the simulation-defined ZOC indicate that 86.7 percent of Independence well-field pumpage is from induced inflow from the river, 6.7 percent is from recharge to the alluvial aquifer from precipitation, and 6.6 percent is flow from the other simulation-defined ZOCs. The original source of water (river or recharge from precipitation) for the flow from other simulation-defined ZOCs is unknown; thus, the 6.6 percent of flow is a measure of the uncertainty of the estimates. Differences in total inflow and total outflow for the simulation-defined ZOC probably are caused by differences between ground-water flow divides and edges of cells used to define ZOCs.

Sources of water to individual wells or groups of wells within the Independence well field were determined using flow budgets calculated for individual simulation-defined ZOCs. The largest source of water within simulation-defined ZOCs for most wells in the Independence well field is the Missouri River. However, recharge from precipitation is the largest source of water within the simulation-defined ZOCs for three wells located north of the river. For 17 of the 25 simulation-defined ZOCs in the Independence well field, flow from other simulation-defined ZOCs accounted for most of the flow. The combined flow budget calculated for all the individual simulation-defined ZOCs in the Independence well field is the same as that calculated for the entire Independence simulation-defined ZOC.

Another method to calculate the relative amounts of source waters to wells in the Independence well field used particle tracking to decrease the flow budget errors caused by the flow of water between simulation-defined ZOCs and to ensure that all pumped wells were included in the analysis. The relative amounts of source water were estimated by dividing the number of particles from each starting cell that ended in either a river or recharge source cell with the number of particles placed in the starting cell. The particle-tracking technique indicated that the Missouri River supplied 82.3 percent of the water to the Independence well field, ground-water recharge from precipitation supplied 9.7 percent, and flow between starting cells supplied 8.0 percent.

Knowledge of the traveltime between the source of water and individual wells of any ZOC within the Independence well field is important for proper well-field management. Particle tracking was used to determine traveltimes from the sources to the well field. Total well-field pumpage that traveled 1 year or less from the source was 8.8 percent, with 0.6 percent of the water from the Missouri River, none from precipitation, and 8.2 percent between starting cells. Total well-field pumpage that traveled 2 years or less from the source was 10.3 percent, with 1.8 percent of the water from the Missouri River, 0.2 percent from precipitation, and 8.3 percent between starting cells. Total well-field pumpage that traveled 5 years or less from the source was 36.5 percent, with 27.1 percent of the water from the Missouri River, 1.1 percent from precipitation, and 8.3

percent between starting cells. Total well-field pumpage that traveled 10 years or less from the source was 42.7 percent, with 32.6 percent of the water from the Missouri River, 1.8 percent from precipitation, and 8.3 percent between starting cells. Total well-field pumpage that traveled 25 years or less from the source was 71.9 percent, with 58.9 percent of the water from the Missouri River, 4.7 percent from precipitation, and 8.3 percent between starting cells. Flow between starting cells usually occurred when those cells were adjacent to one another. Flow between starting cells remained about 8 percent for all traveltimes listed because all particles captured by adjacent cells had traveltimes less than 2 years, and most had traveltimes less than 1 year.

Results of chemical and isotopic analyses of water samples collected from the Missouri River, selected monitoring wells around the Independence well field, and combined well-field pumpage were used in a two-component mixing equation to estimate the relative amount of Missouri River water in total well-field pumpage. The relative amounts of induced inflow from the Missouri River in well-field pumpage ranged from 49 percent for sodium to 80 percent for calcium; sensitivities ranged from 0 percent for iron to plus or minus 35 percent for $\delta^{18}O$. The average of all mixing equation results indicated that 61 percent of well-field pumpage was from induced inflow from the Missouri River.

All of the methods used in the study indicate that more than one-half of the water in well-field pumpage is from induced inflow from the Missouri River. In general, the estimates from the ground-water simulation methods for river inflow to the well field are larger, and error values are smaller than those produced using chemical and isotopic data in the mixing equation. However, substantial overlap exists between the ranges of estimates from both methods. The difference between estimates from the two methods may exist because the steady-state ground-water simulation estimated long-term flows to the well field, whereas the data used in the mixing equation were more representative of current hydrologic conditions near the well field. Because of the complex hydrology of the aquifer near the Independence well field, the estimate for the relative amounts of Missouri River water and ground-water recharge from precipitation in Independence well-field pumpage from particle tracking results probably are the most reliable of the ground-water simulation methods. Mixing equation estimates are less reliable than those of the ground-water simulation for this study. However, more reliable results can be obtained from the mixing equation by increasing the number of samples, collecting samples for a longer period of time, and collecting samples during different flow conditions. In the absence of a calibrated ground-water flow simulation, the mixing equation can provide a reasonable estimate of sources of water to a well field at relatively low cost, if sources of error are clearly understood.

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