science for a changing world

Prepared in cooperation with
MUSCATINE POWER AND WATER,
MUSCATINE, IOWA

Simulation of Ground-Water Flow and Delineation of Areas Contributing Recharge to Municipal Water-Supply Wells, Muscatine, Iowa

Water-Resources Investigations Report 02–4004

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

Simulation of Ground-Water Flow and Delineation of Areas Contributing Recharge to Municipal Water-Supply Wells, Muscatine, Iowa

By Mark E. Savoca, Keith J. Lucey, and Brian D. Lanning

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02–4004

Prepared in cooperation with
MUSCATINE POWER AND WATER,
MUSCATINE, IOWA

Iowa City, Iowa
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
P.O. Box 1230
Iowa City, Iowa 52244

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Denver Federal Center
Denver, CO 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
foot per day(ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.0929	meter squared per day
million gallons per day (Mgal/d)	3,785	cubic meters per day
gallon per minute (gal/min)	0.06309	liter per second
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day

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.

Simulation of Ground-Water Flow and Delineation of Areas Contributing Recharge to Municipal Water-Supply Wells, Muscatine, Iowa

By Mark E. Savoca, Keith J. Lucey, *and* Brian D. Lanning

Abstract

Mississippi River alluvium in the Muscatine, Iowa, area provides large quantities of good quality ground water for municipal, industrial, and agricultural supplies. Three municipal well fields for the City of Muscatine produce a total of about 27 million gallons per day from the alluvium. A previously published steady-state ground-water flow model was modified, and results from the model were used with particle-tracking software to delineate approximate areas contributing recharge to Muscatine Power and Water municipal supply wells and to determine zones of transport within the areas contributing recharge.

Under steady-state conditions and 1998 pumpage, primary sources of inflow to the ground-water flow system are recharge through infiltration of precipitation and upland runoff (53 percent) and Mississippi River leakage (41 percent). The primary components of outflow from the ground-water flow system are pumpage (39.6 percent), flow to drainage ditches in Illinois (32.9 percent), and Muscatine Slough leakage (24.7 percent).

Several sources of water are present within estimated areas contributing recharge to Muscatine Power and Water municipal well fields including ground water from the alluvial aquifer, Mississippi River water, and recharge originating as runoff from two unnamed creeks in the northern part of the study area. Recharge originating from the Mississippi River accounts for about 46 percent of the total water discharged from the municipal well fields. The average simulated traveltime of particles tracked from recharge to discharge at the municipal well fields was 13.6 years. Particle-tracking results illustrate the influence of nearby industrial supply wells on the shape and size of the area contributing recharge to Muscatine Power and Water wells. Two large embayments into the area contributing recharge to municipal wells are present along the Mississippi River. These areas represent ground water that is unavailable to municipal wells due to withdrawals by industrial supply wells. Recharge originating from the Mississippi River accounts for about 98 percent of the total water discharged from the Muscatine Power and Water Main well field. However, recharge originating from the Mississippi River accounts for less of the total discharge from the Progress Park and Grandview municipal well fields (12 and 34 percent, respectively).

The effects of changing climatic conditions on the size and shape of the 10-year zone of transport to Muscatine Power and Water municipal well fields were simulated by decreasing and increasing recharge from precipitation to the ground-water model to demonstrate the variability inherent in delineating these areas. Locations of potential sources of contamination within the zones of transport also are identified.

INTRODUCTION

The sands and gravels of the Mississippi River alluvium in the Muscatine, Iowa, area provide large quantities of good quality ground water for municipal, industrial, and agricultural supplies. Three municipal well fields contain 26 water-supply wells that produce about 27 Mgal/d from the alluvial aquifer for the City of Muscatine. The general plan for development of the ground-water resource calls for doubling municipal withdrawals during the next 20 years (J. Doering, Muscatine Power and Water, oral commun., December 1996). The highly permeable nature of the alluvium and varied land use in the area result in a ground-water supply potentially vulnerable to contamination.

A cooperative study of the Mississippi River alluvium near Muscatine, Iowa, was conducted by Muscatine Power and Water (MPW) and the U.S. Geological Survey (USGS) from 1992 to 1995. Hydrogeology and water quality were investigated in an 80-mi^2 area in Muscatine and Louisa Counties in Iowa and Rock Island and Mercer Counties in Illinois (fig. 1), and the results were documented in a report by Lucey and others (1995). A ground-water flow model was constructed by Lucey and others (1995) using the USGS computer program MODFLOW (McDonald and Harbaugh, 1988) to simulate February 1993 hydrologic conditions, which were considered to be an acceptable estimate of the ground-water system at equilibrium (steady-state condition). Steady-state conditions occur when inflow to the ground-water flow system equals outflow, resulting in a relatively stable water-table surface and a constant amount of water in storage in the aquifer. The ground-water flow model consists of three layers to represent the alluvium and part of the bedrock. A 30-row by 24-column grid was used to discretize each model layer into 2,000-ft by 2,000-ft cells. Model results were used to develop an improved understanding of the complex ground-water flow system and to quantify sources of water to the alluvium. Lucey (1997) used this model to describe effects of hypothetical future pumping scenarios on water levels and sources of water in the Mississippi River alluvium.

There is a need to delineate areas contributing recharge to municipal water-supply wells in the study area described by Lucey and others (1995) to aid in the development of a wellhead protection plan (WHPP) for the Muscatine area. A WHPP helps protect a municipal ground-water supply from contamination and can provide many benefits that include: (1) protection of public health by preventing contamination of the water supply, (2) protection of the community's investment in its water supply, (3) ensuring a clean water supply necessary for continued economic growth, (4) preserving the ground-water resource for future generations, and (5) the possible reduction in regulatory water-quality monitoring costs (State of Ohio Environmental Protection Agency, 1994). To help address this need, the USGS, in cooperation with MPW, initiated a study in 1999 to delineate areas contributing recharge to municipal water-supply wells and to determine the 2-, 5-, and 10-year zones of transport within the areas contributing recharge.

Results of the study can aid water managers in directing wellhead protection efforts within technically defensible areas contributing recharge to municipal water-supply wells. Knowledge will be gained about ground-water flow and areas contributing recharge in alluvium and about the application of simulation techniques used to delineate areas contributing recharge to wells constructed in alluvium.

Purpose and Scope

The purpose of this report is to describe the methods used to delineate areas contributing recharge to municipal water-supply wells in Muscatine, Iowa, and to present the results of those delineations for 1998 pumping conditions. The steady-state ground-water flow model constructed by Lucey and others (1995) was modified to discretize the three model layers into 200-ft by 200-ft cells. Smaller cell size provides a more accurate representation of the ground-water flow system, which improves the accuracy of contributing areas determined by model simulation. Smaller cell size allows for a more detailed representation of model features such as drains, streams, and rivers and provides a more accurate representation of the spatial distribution of well withdrawals by eliminating the need to simulate multiple wells in a single larger cell. Results from the modified flow model were used with the particle-tracking software MODPATH (Pollock, 1994) to delineate approximate areas contributing recharge to wells and to determine 2-, 5-, and 10-year zones of transport within the areas contributing recharge. The report also presents delineations based on less-than-average and greater-than-average recharge conditions to demonstrate the variability inherent in delineating areas contributing recharge to wells. Locations of potential sources of contamination within the zones of transport are identified.

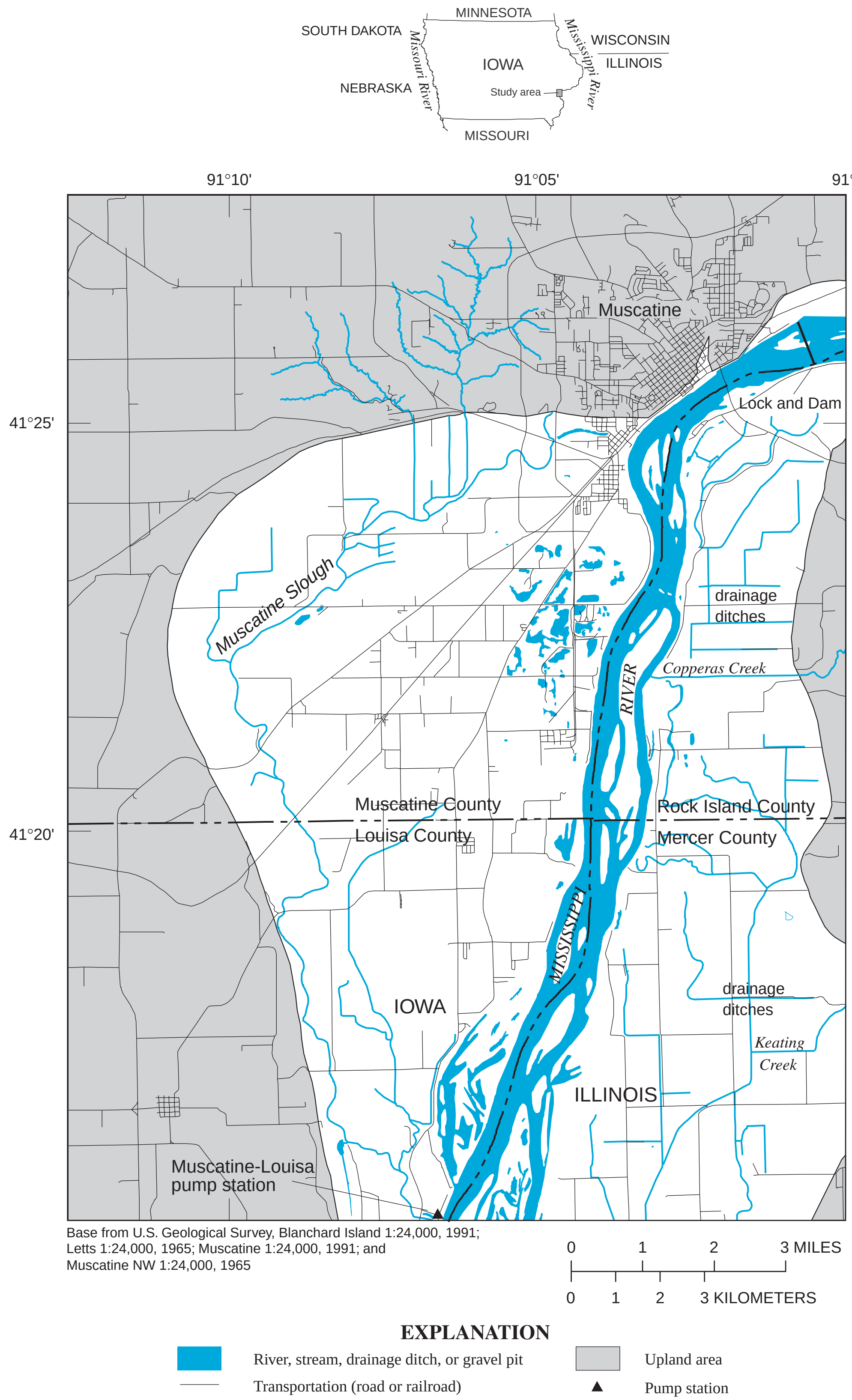

Figure 1. Location of study area.

Description of Study Area

The study area covers approximately 80 mi^2 in southeast Iowa and northwest Illinois and includes parts of Muscatine and Louisa Counties in Iowa and Rock Island and Mercer Counties in Illinois (fig. 1). The relatively flat alluvial plain of the Mississippi River Valley in this area generally has an altitude of 535 to 550 ft above sea level and gradually rises to 590 ft at the base of bluffs on either side of the valley. These steep bluffs separate the valley from the upland areas that rise to 750 ft. Alluvium overlies bedrock consisting of limestone, dolomite, and shale in the Mississippi River Valley, and the thickness of the alluvium varies from about 40 ft in the northeast to more than 140 ft in the southern and western parts of the study area. Glacial till (predominantly clay) overlies bedrock units in the upland areas. Detailed descriptions of aquifer characteristics, geology, and hydrology of the study area are given by Hansen and Steinhilber (1977) and Lucey and others (1995).

The U.S. Army Corps of Engineers controls the Mississippi River stage with a series of lock and dam structures, and channel depth is maintained by dredging operations to facilitate commercial navigation. The Muscatine Slough and its associated tributaries drain 52.3 mi^2 in Iowa. Streamflow and stage in the slough are controlled by a pump station located at the south end of the slough (fig. 1). The lowlands in the river valley are protected from Mississippi River flooding by a levee complex extending along both sides of the Mississippi River.

Land use in the Mississippi River valley is primarily agricultural. Sandy soils on the Iowa side of the river often require supplemental irrigation, which uses ground-water withdrawals. Industrial activity includes manufacturing, electric power generation, and sand and gravel extraction.

Acknowledgments

Information and assistance were provided by MPW during this study. A field inventory of potential sources of contaminants was conducted by MPW personnel, and the cooperation and assistance of property owners during the field inventory is appreciated. Water-supply well withdrawals for 1998 were obtained from records provided by Grain Processing Corporation, Iowa-Illinois Gas and Electric Power Company, Monsanto Corporation, and MPW.

METHODS OF INVESTIGATION

The ground-water flow model constructed by Lucey and others (1995) to simulate February 1993 steady-state conditions was modified for this study. In the modified model, the model cell size was decreased from 2,000 ft by 2,000 ft to 200 ft by 200 ft, hydraulic conductivity for selected cells was changed, a larger number of drainage ditches in Illinois and tributaries to Muscatine Slough in Iowa were simulated, and gravel pits were simulated. Results for the modified model were verified for similarity to results for the model constructed by Lucey and others (1995) after a model calibration process. The calibrated model was then further modified to simulate average 1998 municipal and industrial pumpage for delineation of areas contributing recharge to MPW municipal water-supply wells and to determine the 2-, 5-, and 10-year zones of transport within the areas contributing recharge.

Ground-water samples were collected from three MPW wells. Sample collection followed USGS protocols (Koterba and others, 1995). Prior to sample collection, wells were purged of at least three well casing volumes using a submersible pump. Pumping continued until field measurements of water temperature, pH, specific conductance, and dissolved oxygen stabilized, at which time water samples were collected for the analysis of tritium (Ostlund and Dorsey, 1977) and chlorofluorocarbons (Busenberg and Plummer, 1992). Tritium- and CFC-based ground-water recharge dates were compared to model-simulated traveltimes to evaluate model performance.

SIMULATION OF GROUND-WATER FLOW

Model Description and Boundary Conditions

The model consists of three layers to represent the alluvium and part of the bedrock. The relation between the geologic units and the equivalent layers in the ground-water flow model is described in Lucey and others (1995). The alluvium is divided into layers 1 and 2, which represent the upper and lower alluvium, respectively. Layer 3 represents the bedrock. The alluvium is modeled in this manner because the ground-water withdrawals at the pumping centers are from the lower alluvium and because differences in hydraulic conductivities between the upper and lower alluvium are interpreted from geologic data (Lucey and others, 1995). Flow in layer 1 is modeled as unconfined (under water-table conditions), whereas flow in layers 2 and 3 is modeled as confined. Shale in the northeast part of the study area (Lucey and others, 1995, fig. 4) forms a confining unit, where present in layer 3.

A 305-row by 250-column grid was used to divide the area of study into a grid of 200-ft by 200-ft cells. The grid was used to discretize each of the model layers. The cell area was identical in each layer, but its vertical dimension varied with layer thickness. The active cells of the model coincide with the river valley (where the alluvium is present) and the inactive cells coincide with the upland areas. Previous modeling (Lucey and others, 1995) has shown that the upland areas contribute insignificant amounts of ground water to the alluvial ground-water flow system. Therefore, upland areas are modeled as inactive or no-flow cells. The model code calculates a hydraulic head (ground-water-level altitude) at the center, or node, of each active cell and a ground-water flux across each cell face based on water-level gradients between cells. Cells are identified by a row, column, layer designation.

The Mississippi River, Copperas Creek, and Keating Creek are simulated by river cells that allow leakage through the river bottom to or from layer 1 based on the difference in hydraulic heads (between river and layer 1) and riverbed conductance (fig. 2). Conductance is the product of the vertical hydraulic conductivity of the bed material, and the length and width of the reach in the cell, divided by bed-material thickness (McDonald and Harbaugh, 1988). An estimated bed-material thickness of 1 ft was used for river, drain, and stream cells. The vertical hydraulic conductivity of bed materials was initially estimated based on expected lithologies and modified during model calibration. A river cell will provide or receive as much water as the model requires to reach a mathematical solution. These perennial streams are expected to continue to flow even if the water table in the alluvium is lower than the river bottom. A riverbed thickness of 1 ft was assumed. Riverbed vertical hydraulic conductivities of 1 ft/d and 0.5 ft/d were used for cells representing the Mississippi River and cells representing the creeks, respectively. A larger vertical hydraulic conductivity was used for the Mississippi River because of periodic dredging operations to maintain a navigation channel.

Drainage ditches in Illinois are simulated by drain cells that allow leakage only from layer 1 to the drain. It is assumed that the stage in the drain reflects the altitude of the water table and that flow in these drainage ditches is predominantly from ground water. A drainbed thickness of 1 ft and a vertical hydraulic conductivity of 5 ft/d were used for the drainbed conductance calculation.

The Muscatine Slough is represented by stream cells and is simulated using a computer code that calculates leakage between layer 1 and the slough while accounting for streamflow entering or leaving each defined stream cell (Prudic, 1989). Stream cells function like river cells by allowing leakage from or to layer 1 based on the difference in water levels. However, stream cells can cease to flow rather than provide an infinite supply of water like a river cell. Large ground-water withdrawals could cause parts of Muscatine Slough or its associated tributaries to cease flowing during periods of low recharge to the alluvium. Stream cells give the model the flexibility to simulate this situation. A streambed thickness of 1 ft and a streambed vertical hydraulic conductivity of 5 ft/d were used in the streambed conductance calculation. Detailed descriptions of channel location, length, width, stage, and discharge estimates or measurements for the Mississippi River, Copperas Creek, Keating Creek, drainage ditches in Illinois, and Muscatine Slough are given in Lucey and others (1995). Stage was assigned to previously undefined drain and slough cells based on stage measurements obtained by Lucey and others (1995) and estimates from USGS 7.5-minute topographic maps.

The upper boundary of the model area is a free surface that represents the water table. A specified-flux boundary is used to represent areal recharge to layer 1. No-flow boundaries are used to simulate the limits of the model area where ground-water flow is assumed to be insignificant or in areas where aquifer material is absent. The bottom of the modeled system is at the top of the relatively impermeable Maquoketa Formation and is represented by a no-flow boundary at the bottom of layer 3. The lateral hydrologic boundaries formed by the relatively impermeable glacial till adjacent to the alluvium (layers 1 and 2) establish logical hydrologic limits for modeling ground-water flow in the alluvium. These boundaries are modeled as no-flow boundaries. A no-flow boundary was used across the narrow part of the Mississippi River Valley in the northeast part of the model area because subsurface flow from the north is considered insignificant to the overall water budget (Lucey and others, 1995).

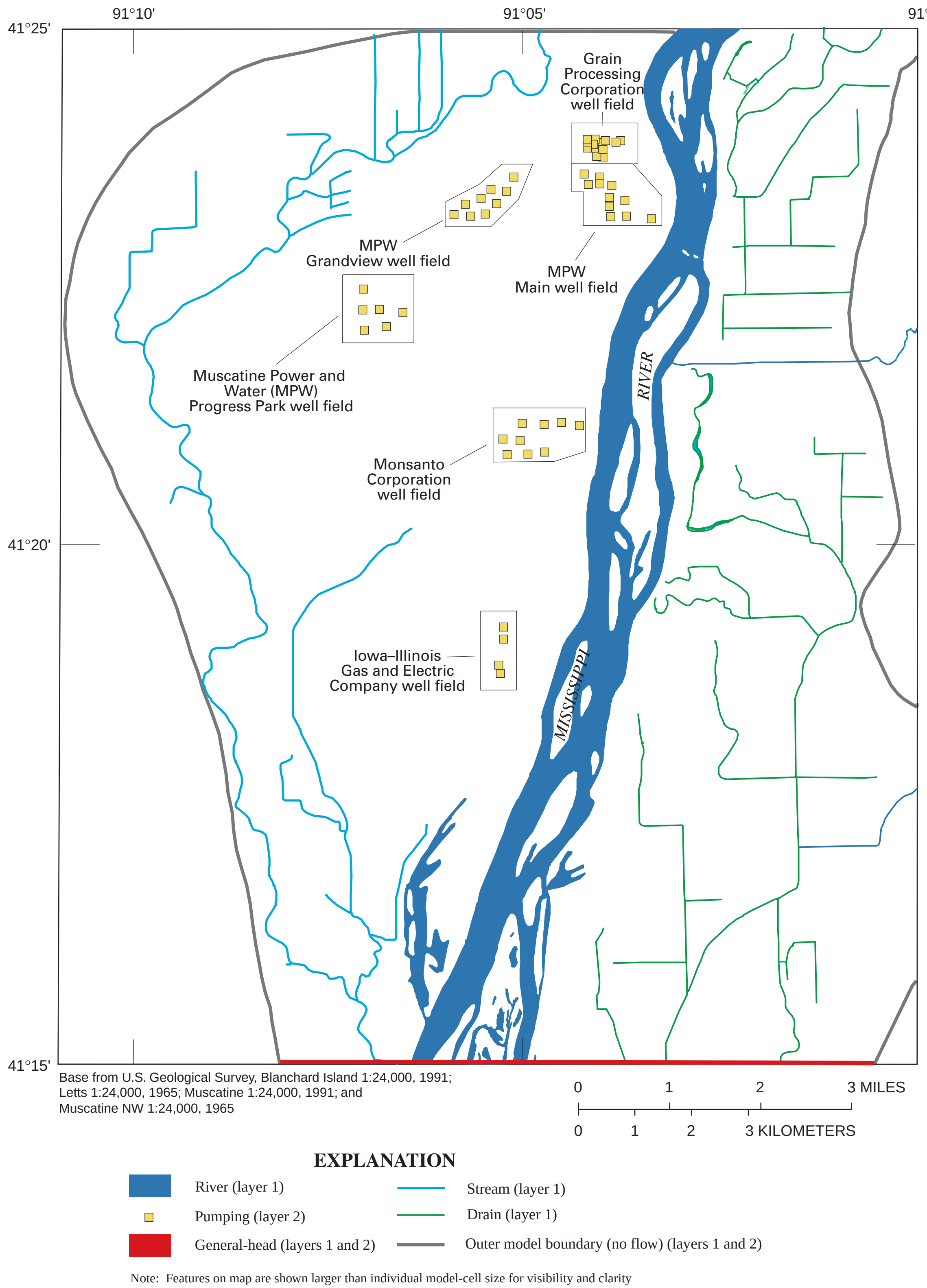

Figure 2. Model boundary conditions for layers 1 and 2.

The model area is not a closed hydrologic system, and general-head boundaries are used to simulate lateral model boundaries where ground water enters or leaves the system. Flow across the boundary is proportional to the differences between hydraulic head in the cells at the model boundary and hydraulic head assigned at a distance outside the model. General-head boundaries are used at the southern limits of layers 1 and 2 to simulate subsurface flow out of the study area through the alluvium down the Mississippi River Valley. General-head boundaries also are used at the perimeter of layer 3 to represent ground water entering or leaving the system through the bedrock in proportion to relative hydraulic head differences between the cells at the model boundary and the regional potentiometric surface outside the model. In both cases, a constant-head source is placed 5 miles from the closest active cell in the model, and the hydraulic conductivity of the laterally adjacent unit is used in the computation of ground-water flux across the boundary. The ground-water level at the boundary was derived by projecting regional ground-water gradients in the alluvium for layers 1 and 2 and in the bedrock for layer 3.

Model Parameters

Individual cells of the model were assigned values for each of the parameters used by the model to solve the ground-water flow equations. Parameters are specified at the node of each active cell and represent an average for the entire cell. Spatial variation in parameter value is represented by assigning appropriate values to individual cells in the model array. Spatially distributed parameters used in the model include the geometry of the model layers, horizontal and vertical hydraulic conductivity, recharge from infiltration of precipitation and of runoff from upland areas, and ground-water pumpage. The model code uses transmissivity to solve equations and simulate ground-water flow. Horizontal hydraulic conductivity is multiplied by the layer thickness to calculate transmissivity at each node throughout the model grid. Alternatively, a transmissivity can be assigned to model cells.

A uniform transmissivity of 0.3 ft^2/d was assigned to nodes in layer 3 (bedrock) and calculated by assuming a thickness of 300 ft and a hydraulic conductivity of 0.001 ft/d. A uniform transmissivity was selected on the basis of slug-test results (Lucey and others, 1995, table 4) and limited hydrogeologic information about the bedrock. Shale in the northeast part of the study area is modeled as a confining unit beneath the alluvium, so horizontal flow in that unit is not represented in the model.

The initial hydraulic conductivity distributions used in the model arrays for layers 1 and 2 were derived from the calibrated model of Lucey and others (1995) and were based on lithology and expected ranges of hydraulic conductivity values determined from the literature and aquifer-test analyses (Lucey and others, 1995, table 4, figs. 13 and 14). Initial values were modified during model calibration, and final hydraulic conductivities used in the model arrays for the upper and lower alluvium ranged from 150 to 1,000 ft/d. The final hydraulic conductivity distributions closely resemble those of Lucey and others (1995), the major difference being several cells within the “gravel and coarse sand” area of the upper alluvium in which initial hydraulic conductivity values of 600 ft/d were increased to 1,000 ft/d. Gravel pits were simulated in the modified model. The water table is exposed at several active and abandoned gravel pits in the northeast part of the study area (fig. 1). Large hydraulic conductivities (10,000 ft/d) were assigned to cells in layers 1 and 2 that represent gravel pits. The smaller cell size in the modified model facilitates simulation of gravel pits and provides a more realistic simulation of ground-water flow paths near these features.

Vertical leakance is required by the model to simulate ground-water flow between layers. Vertical leakance between two adjacent model layers is calculated from the thickness of each layer between its node and the common layer contact and the vertical hydraulic conductivity of each layer (McDonald and Harbaugh, 1988, eq. 51). Vertical leakance between two model layers with an intervening confining unit is calculated with the above properties and the vertical hydraulic conductivity and thickness of the confining unit (McDonald and Harbaugh, 1988, eq. 52). Vertical hydraulic conductivities used to calculate vertical leakance ranged from 1.5 to 10 ft/d in the alluvium, 1 ft/d in the limestone and dolomite, and 0.005 ft/d in the shale. Calculation of vertical leakance in the alluvium assumed that the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity was 1 to 100. The small hydraulic conductivity for the alluvium in the vertical direction compared to the horizontal direction represents impediment to flow from intervening clay or silt layers and small-scale depositional features. The larger vertical than horizontal hydraulic conductivity in the limestone and dolomite is used to simulate the effective hydraulic connection with the overlying alluvium. Vertical flow through the shale is accounted for with a small vertical leakance between layers 2 and 3 where the confining unit is present in the northeast part of the study area.

Inflow to the ground-water system includes infiltration of precipitation, infiltration of runoff from upland areas to the river valley, leakage from rivers and streams, and flow across general-head boundaries. The model calculates leakage from rivers and streams and subsurface flow across outer boundaries. An array to represent inflow from infiltration of precipitation and infiltration of runoff from upland areas was prepared as model input. A daily net inflow rate from precipitation of 0.003 ft/d was used in the model to simulate the assumed steady-state February 1993 conditions. Runoff from upland areas was accounted for by increasing the precipitation inflow rate at the model cells along the boundary between the river valley and the upland area. Methods used to compute precipitation and runoff inflow rates are described in Lucey and others (1995). Infiltration of precipitation and the infiltration of runoff from upland areas will be referred to as recharge from precipitation in this report.

Outflow from the ground-water system includes pumpage, leakage to rivers, streams, and drains, and subsurface flow across outer boundaries. The model calculates all of these fluxes except pumpage, for which an array was constructed for input to the model. Average daily withdrawals from the ground-water system during February 1993 (6,150,000 ft^3/d, or about 46 Mgal/d) were assigned to cells containing pumping wells (fig. 2). Average daily pumpage during February 1993 was obtained from records provided by well-field operators.

Model Calibration

The smaller cell size in the modified model resulted in some changes in the representation of hydrologic features when compared to the model constructed by Lucey and others (1995). Gravel pits were simulated in the northeast part of the study area, a larger number of drainage ditches in Illinois and tributaries to Muscatine Slough in Iowa were simulated, and the extent of the Mississippi River and associated island areas were represented in greater detail. These changes required a calibration of the modified model to the assumed February 1993 steady-state conditions described in Lucey and others (1995).

The steady-state model was calibrated through an iterative process by varying hydraulic conductivity, vertical leakance, recharge from precipitation, and drainbed, streambed, and riverbed conductance during numerous simulations. As these parameters were adjusted within reasonable limits, model output was analyzed to ascertain whether the adjustment improved the match between measured (February 26, 1993) and simulated ground-water levels and measured (February 1993) and simulated discharge from Muscatine Slough. The goal of the model calibration process is to minimize differences between the measured and simulated values while maintaining realistic values of hydraulic properties. The calibration process continued until further incremental adjustments to model input parameters produced no perceivable improvement in model results.

During the calibration process, improvements in the model output were evaluated by calculating the average head difference (AVEH) and the root mean squared error (RMSE) between measured and simulated ground-water levels. The AVEH is a measure of systematic error; it approaches zero when the sum of the differences between measured and simulated ground-water levels that are greater than zero equals the sum of the differences that are less than zero. The RMSE is a measure of the magnitude of error between measured and simulated ground-water levels over the entire model area (Anderson and Woessner, 1992).

A total of 60 comparisons of measured and simulated water levels were made—39 in layer 1, 15 in layer 2, and 6 in layer 3. The calibration values of AVEH and RMSE were, respectively, 0.1 ft and 0.9 ft in layers 1 and 2, 1.4 ft and 3.6 ft in layer 3, and 0.2 ft and 1.4 ft in all three model layers. The RMSE for all three model layers represents 8.6 percent of the range of measured water levels (16.2 ft).

The calibration process also attempted to minimize the percentage of error between estimated and simulated mean daily discharge for February 1993 from the Muscatine Slough. The mean daily discharge from Muscatine Slough simulated by the calibrated model is 4,042,000 ft^3/d, which is 20 percent less than the amount estimated from pump operation time and rated pump capacity (5,080,000 ft^3/d). Model input data that affect flow to the slough, such as streambed conductance, vertical leakance, horizontal hydraulic conductivity, and recharge from precipitation, have been adjusted through a reasonable range of hydrologic values during calibration to maximize simulated flow in the slough while minimizing AVEH and RMSE.

A comparison of measured and simulated ground-water-level altitudes shows how accurately the calibrated model simulates the ground-water system. The water-table surface and general flow directions (interpreted from water-level contours) in the upper alluvium are similar for maps prepared from simulated (fig. 3) and measured (February 26, 1993, fig. 4) water levels. Flow is approximately perpendicular to water-table contours in the direction of decreasing hydraulic head. The influent nature (losing reach) of Copperas Creek as it enters the river valley from the adjacent upland area is apparent in each case. A ground-water divide located between the southern part of Muscatine Slough and the cone of depression caused by the pumping centers also is apparent in each case. Flow is toward the pumping centers north of the ground-water divide in Iowa and toward the drainage ditches in Illinois.

Differences between the water-table surface in the upper alluvium constructed from measured and simulated data are most apparent east of the Mississippi River in Illinois. There are few measured water levels in Illinois, resulting in a more detailed depiction of the simulated water-table surface than is possible from the measured data. Differences between the simulated water-table surface in the upper alluvium from Lucey and others (1995, fig. 15) and the modified model (fig. 3) also are apparent east of the Mississippi River in Illinois. The smaller cell size used in the modified model allows for a more accurate depiction of changes in drain elevation and nearby water levels.

The calibrated model calculates a ground-water flux between cells from which a simulated water budget was computed (table 1). Differences between this budget and the budget from Lucey and others (1995) are attributed to the greater extent and detail to which the drain, slough, and river networks are represented in the modified model as a result of decreased cell size. Increased slough and drain outflows and increased river inflows in the calibrated model support this explanation.

The steady-state model was considered calibrated when the following criteria were met:

1. Incremental changes in model input parameters did not produce an AVEH closer to zero or a smaller RMSE for all layers in the model;
2. The RMSE represented a small percentage of the range in measured ground-water levels;
3. Incremental changes in model input parameters did not decrease the percentage difference between estimated and simulated discharge from the Muscatine Slough; and
4. Simulated lateral ground-water flow directions closely resembled flow directions interpreted from the water-table map in the upper alluvium constructed using water levels measured on February 26, 1993.

Sensitivity Analysis

The calibrated model is influenced by uncertainty resulting from limited knowledge of the spatial variation of parameter values and uncertainty associated with the definition of boundary conditions. A sensitivity analysis establishes the effect of parameter uncertainty on the calibrated model by documenting the response of the model (simulated water levels and discharge) to incremental changes in parameter values. The model is sensitive to a parameter when changes in the parameter value produce substantial changes in model response. If improvement in the model is desired, additional data collection could be directed toward refining the most sensitive parameters.

Simulated water-level response to incremental changes in selected input parameters is shown in figure 5. The RMSE is plotted against the multiplication factor used to vary the parameter. The calibrated model parameters are used as comparison and are represented by a multiplication factor of 1. The multiplication factor was applied uniformly to the entire model for the indicated parameter and ranged from 0.1 to 2.0. The parameter being tested was adjusted while the remaining model parameters were held at the calibrated values. Water levels were most sensitive to horizontal hydraulic conductivity in layers 1 and 2 and to recharge from precipitation. Water levels were insensitive to transmissivity in layer 3, drainbed and streambed conductance, riverbed conductance, and vertical leakance.

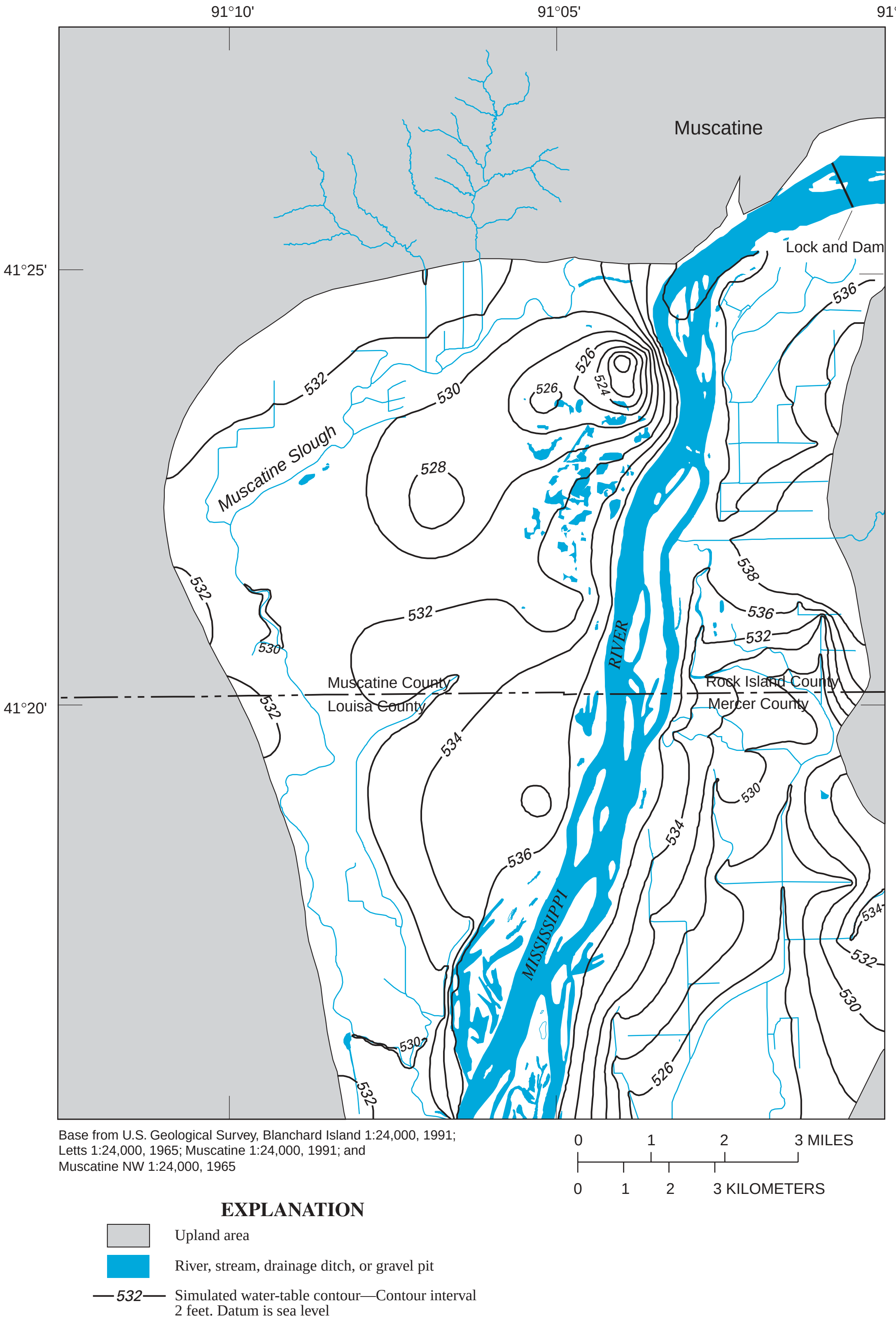

Figure 3. Simulated water-table surface in upper alluvium, February 1993 (modified model with 1993 package).

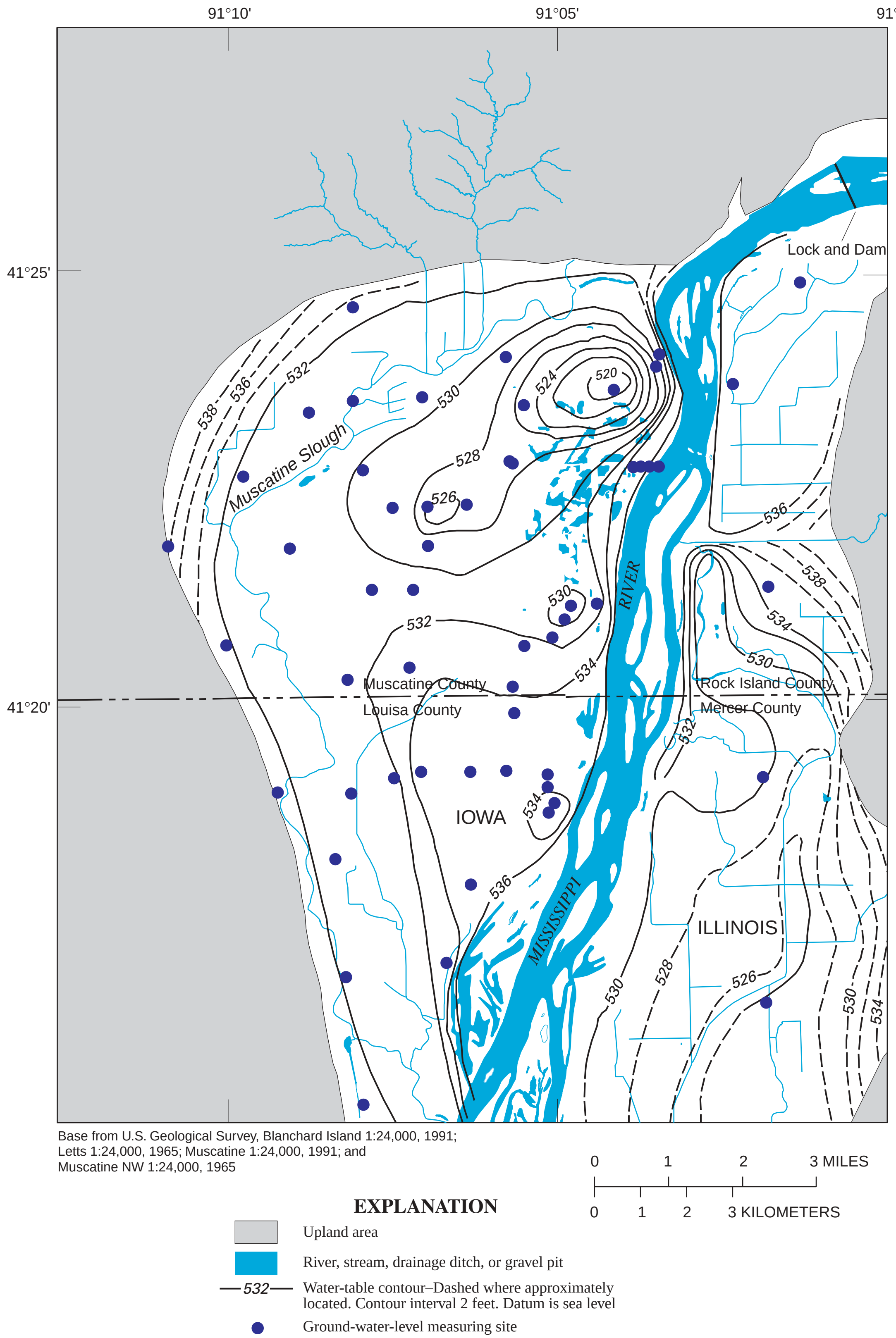

Figure 4. Measured water-table surface in upper alluvium, February 26, 1993 (from Lucey and others, 1995).

Table 1. Simulated water budgets

[Inflow, water added to the ground-water system; ft^3/d, cubic feet per day; outflow, water removed from the ground-water system; slough leakage, from or to Muscatine Slough and its associated drain network in Iowa; pumpage—municipal, ground-water withdrawals by Muscatine Power and Water; pumpage—industrial, ground-water withdrawals by Grain Processing Corporation, Iowa-Illinois Gas and Electric Company, and Monsanto Corporation; drain leakage, to the drainage ditch network in Illinois]

Budget component	Lucey and others (1995)	Modified model (calibrated)	Modified model (1998 pumpage)
	Inflow (ft^3/d)		
Recharge from precipitation	9,025,000	9,022,000	9,022,000
River leakage—Mississippi River	5,411,000	6,938,000	7,066,000
River leakage—Copperas and Keating Creeks	236,000	360,000	360,000
Slough leakage	425,000	680,000	682,000
Subsurface flow across outer boundaries	[a]5.0	22,000	22,000
Pumpage—Municipal	0	0	0
Pumpage—Industrial	0	0	0
Drain leakage	0	0	0
Total inflow	**[a]15,097,000**	**17,022,000**	**17,152,000**
	Outflow (ft^3/d)		
Recharge from precipitation	0	0	0
River leakage—Mississippi River	121,000	303,000	288,000
River leakage—Copperas and Keating Creeks	291,000	69,000	69,000
Slough leakage	3,360,000	4,722,000	4,252,000
Subsurface flow across outer boundaries	155,000	121,000	121,000
Pumpage—Municipal	3,136,000	3,195,000	3,602,000
Pumpage—Industrial	2,955,000	2,955,000	3,193,000
Drain leakage	5,095,000	5,651,000	5,651,000
Total outflow	**15,113,000**	**17,016,000**	**17,176,000**

[a]Total not precise due to rounding.

The sensitivity of simulated river leakage was evaluated by varying model input parameters and determining the proportion of simulated inflow to the ground-water system obtained from river leakage. The proportion of simulated inflow obtained from river leakage was most sensitive to recharge from precipitation and horizontal hydraulic conductivity in layers 1 and 2, whereas transmissivity of layer 3, drainbed and streambed conductance, changing vertical leakance, and riverbed conductance had less of an effect (fig. 6).

An evaluation of the sensitivity of simulated discharge from Muscatine Slough was made by varying horizontal hydraulic conductivity in layers 1 and 2, drainbed and streambed conductance, recharge from precipitation, and vertical leakance. Of these parameters, simulated discharge from Muscatine Slough was most sensitive to recharge from precipitation and horizontal hydraulic conductivity in layers 1 and 2.

The sensitivity of the general-head boundaries to changes in hydraulic conductivity affecting flow entering or leaving the model through the bedrock was evaluated. The hydraulic conductivity was increased, and the flow contributed by the general-head boundary was compared to the total amount of ground-water flow entering the model. The calibrated model uses a hydraulic conductivity of 0.001 ft/d for the bedrock and general-head boundary, and flow entering the model from the general-head boundary is less than 0.2 percent of the total. Even by increasing the hydraulic conductivity to 100 ft/d, which is unreasonably large for the limestone and dolomite bedrock in this area (Lucey and others, 1995), the ground-water contribution from the bedrock remains less than 3 percent of the total.

Model Limitations

The ground-water flow model constructed by Lucey and others (1995) and modified for use in this study estimates the effects of ground-water withdrawals from the alluvium. However, several model limitations should be considered. Model input parameters, such as horizontal and vertical hydraulic conductivity and recharge from precipitation, are specified at the node of each active cell and represent an average for the entire cell. The assumptions of uniformity for the entire cell introduce inaccuracies because of the heterogeneous nature of geologic materials and the variability of climatic conditions. The steady-state model assumes that inflows to the ground-water system equal outflows. If this was not the case in February 1993, the resultant change in ground-water storage would be a source of model error. For example, water levels could have been either rising or falling during the assumed equilibrium conditions. The steady-state flow model does not account for dynamic (transient) conditions (natural or anthropogenic). The steady-state model does not indicate time needed to reach equilibrium conditions. Attaining equilibrium might take a substantial period of time and is complicated by varying climatic and hydrologic conditions, noncontinuous pumping and pumping that is cycled among well fields, and changing and seasonally varying irrigation pumpage (not included in this model).

Results of Simulation

The calibrated model was modified to simulate 1998 municipal and industrial supply well withdrawals from the ground-water system. Average daily withdrawals during 1998 (6,795,000 ft^3/d, or about 51 Mgal/d) represent an increase of 11 percent since 1993 and reflect recent ground-water usage. It was assumed that steady-state conditions (February 1993) described in Lucey and others (1995) are still an appropriate representation of the system. Therefore, 1998 ground-water levels, and river, slough, and drain stages were not collected.

The model calculates a ground-water-level altitude at the node of each 200-ft by 200-ft cell from which a simulated water-table surface in the upper alluvium (fig. 7) was constructed. The model also calculates a ground-water flux between cells from which a simulated water budget was computed (table 1, 1998 pumpage). Ground-water flow directions derived from analysis of the computed

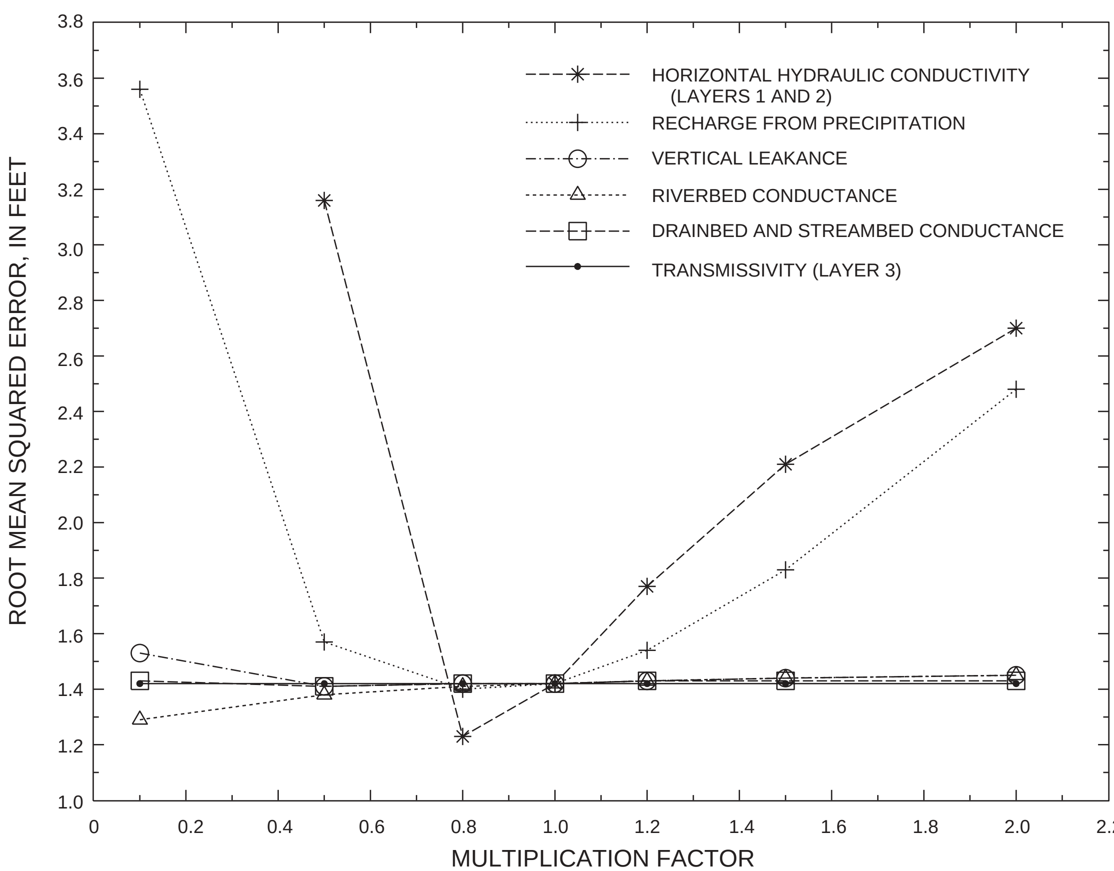

Figure 5. Root mean squared error between measured and simulated water levels as a result of varying model input parameters.

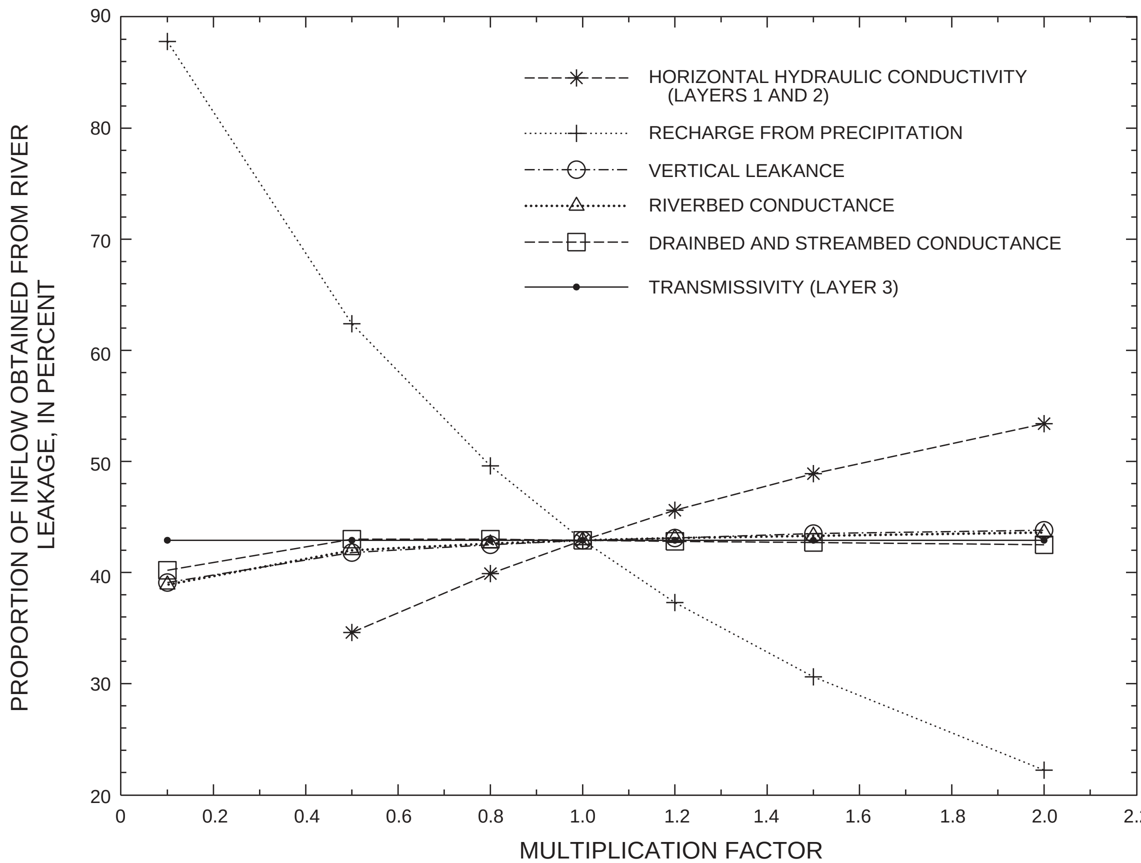

Figure 6. Proportion of simulated inflow obtained from river leakage as a result of varying model input parameters.

ground-water-level altitudes, and inflows and outflows quantified in the water budget, assist in developing an improved understanding of the ground-water system. The sources of water recharging the alluvium can be identified from an analysis of the water budget (table 1). Under assumed steady-state conditions and 1998 pumpage, the model calculated 17,152,000 ft^3/d of inflow to the ground-water system and 17,176,000 ft^3/d of outflow from the system. There is a 0.14 percent discrepancy between the calculated inflow and outflow due to model error in approximating a solution to the mathematical equations.

Primary sources of inflow are infiltration of precipitation and upland runoff (53 percent) and Mississippi River leakage (41 percent). Minor amounts of inflow occur through leakage from Muscatine Slough and its associated drainage network (3.9 percent) and through leakage from Copperas and Keating Creeks (2.0 percent) in Illinois. All of these sources of inflow enter the system through the upper alluvium.

The primary components of outflow from the ground-water system are pumpage (39.6 percent), flow to drainage ditches in Illinois (32.9 percent), and slough leakage (24.7 percent). Pumpage is from the lower alluvium, whereas drain and slough leakage leave the system from the upper alluvium. Flow across the general-head boundaries of the model, which primarily represents subsurface flow through the alluvium down the river valley, accounts for less than 1.0 percent of the total.

Differences in simulated water budgets (table 1) for the calibrated model (1993 pumpage) and the model with 1998 pumpage illustrate model response to increased pumpage. Average daily supply-well withdrawals during 1998 (6,795,000 ft^3/d) represent an increase of 11 percent (645,000 ft^3/d) since 1993. Increased pumpage (outflow) from the ground-water system results in an increased inflow from the Mississippi River (128,000 ft^3/d) and Muscatine Slough (2,000 ft^3/d) and a reduction in outflow from the Mississippi River (15,000 ft^3/d) and Muscatine Slough (470,000 ft^3/d).

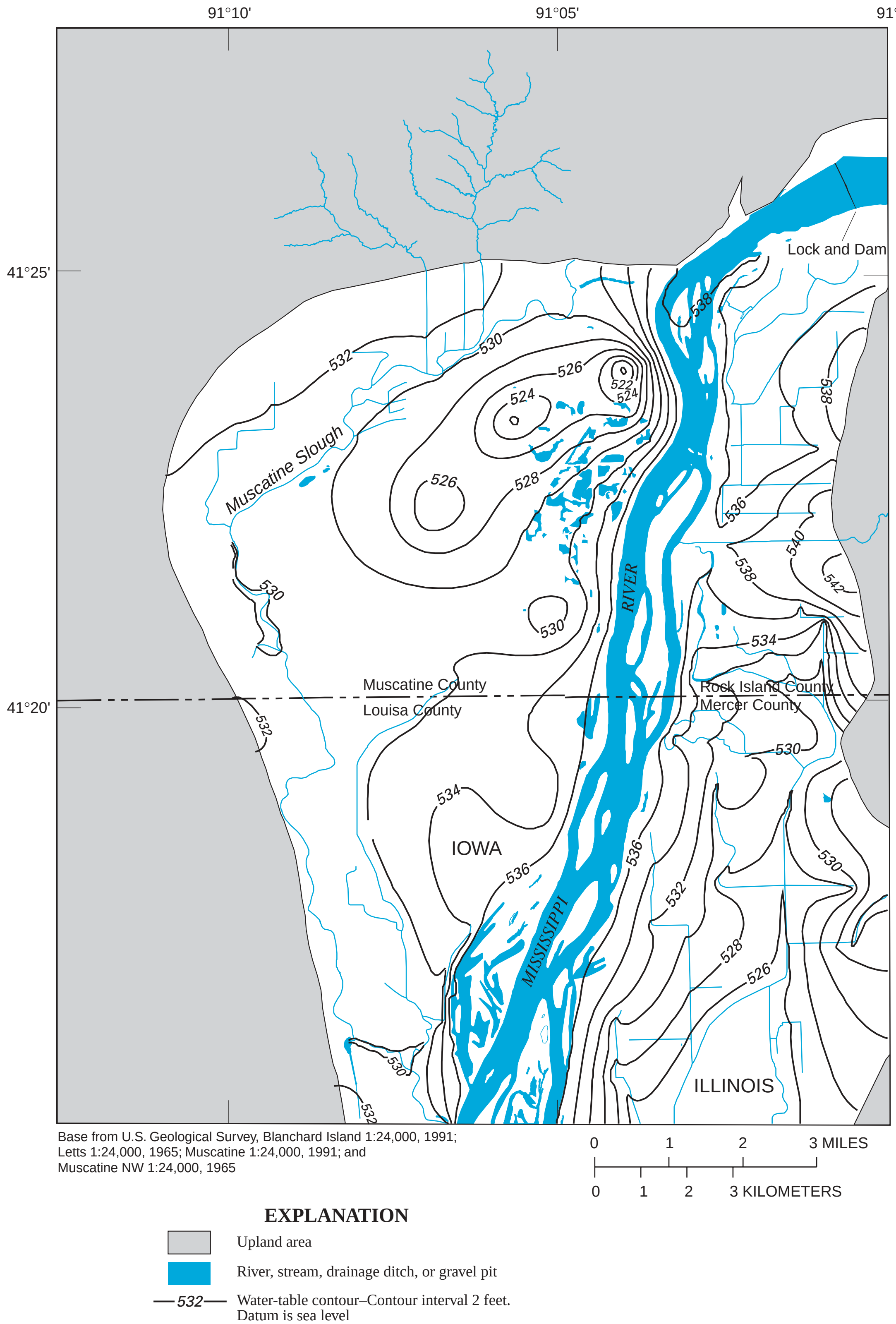

Figure 7. Simulated water-table surface in upper alluvium, February 1993 (modified model with 1998 pumpage).

DELINEATION OF AREAS CONTRIBUTING RECHARGE

Results from the ground-water flow model (MODFLOW) were used with the particle-tracking software MODPATH (Pollock, 1994) to delineate approximate areas contributing recharge to MPW well fields and to determine the 2-, 5-, and 10-year zones of transport under steady-state conditions and 1998 pumpage within contributing areas. MODPATH calculates flow paths and traveltimes for hypothetical water particles in the saturated zone using a velocity distribution derived from simulated ground-water-level altitudes and flow rates (MODFLOW results) and estimates of aquifer effective porosity. Limitations of particle-tracking analysis are discussed by Pollock (1994) and are largely dependent on the accuracy of the ground-water levels and flow rates computed by the ground-water flow model. Particle flow paths and traveltimes calculated by MODPATH are based on advective ground-water flow and do not reflect the effects of dispersion, diffusion, or chemical and microbial retardation, which would be required to fully describe contaminant transport.

Estimates of effective porosity were assigned to model cells based on lithology and published values of porosity (Freeze and Cherry, 1979; Driscoll, 1986). Estimates of effective porosity ranged from 0.15 to 0.24 in layer 1 and 0.15 to 0.20 in layer 2. A constant effective porosity value of 0.03 was assigned to cells in layer 3. Hypothetical water particles were distributed on the faces of each cell containing an active MPW municipal water-supply well, and a backward-tracking analysis was conducted in which particles were tracked backward in time along flow paths to their points of recharge (for example, water table, river, or other model boundary). The final location of particles defines the approximate extent of the area contributing recharge to the cell containing the pumping well.

Several sources of water are present within estimated areas contributing recharge to MPW municipal well fields including ground water from the alluvial aquifer, Mississippi River and Muscatine Slough water, and recharge originating as runoff from two unnamed creeks in the northern part of the study area (fig. 8). Recharge originating from the Mississippi River accounts for about 46 percent of the total water discharged from the municipal well fields. The average simulated traveltime of particles tracked from recharge to discharge at the MPW municipal well fields was 13.6 years. Average simulated traveltimes of particles were compared to ground-water recharge dates determined from chlorofluorocarbon (CFC) and tritium analyses of water samples from three MPW wells (table 2). The presence of modern water (recharged since the 1950's) as indicated by CFC and tritium analyses supports the simulated traveltimes.

Particle-tracking results illustrate the influence of nearby industrial supply wells on the shape and size of the area contributing recharge to MPW wells. Two large embayments into the area contributing recharge to MPW wells are present along the Mississippi River (fig. 8). These areas represent ground water that is unavailable to MPW wells due to withdrawals by Grain Processing Corporation (in the north) and Monsanto Corporation (in the south) supply wells. Differences in the source of recharge water to MPW wells due to the influence of industrial supply wells on the shape and size of the area contributing recharge may affect water quality at individual MPW well fields. Recharge originating from the Mississippi River accounts for about 98 percent of the total water discharged from the MPW Main well field. However, recharge originating from the Mississippi River accounts for less of the total discharge from the Progress Park and Grandview municipal well fields (12 and 34 percent, respectively).

Zones of Transport and Potential Sources of Contamination

The simulated 2-, 5-, and 10-year zones of transport for particles discharging at MPW municipal well fields (fig. 9) were computed by MODPATH using ground-water velocities and particle path lengths. The locations of potential sources of contamination were determined within the 2-, 5-, and 10-year zones of transport for the Grandview, Main, and Progress Park well fields (figs. 10, 11, and 12, respectively) by MPW personnel. Potential sources of contamination also were located within the drainage basins of two creeks (fig. 13) that discharge water to the alluvial aquifer within the 5- and 10-year zones of transport for the Grandview well field. Information about National Pollution Discharge Elimination System (NPDES) permitted sites within the zones of transport and drainage basins was obtained from the Iowa Department of Natural Resources. USGS personnel determined the horizontal location (latitude and longitude) of potential sources of contamination by using a hand-held global positioning system (GPS) unit.

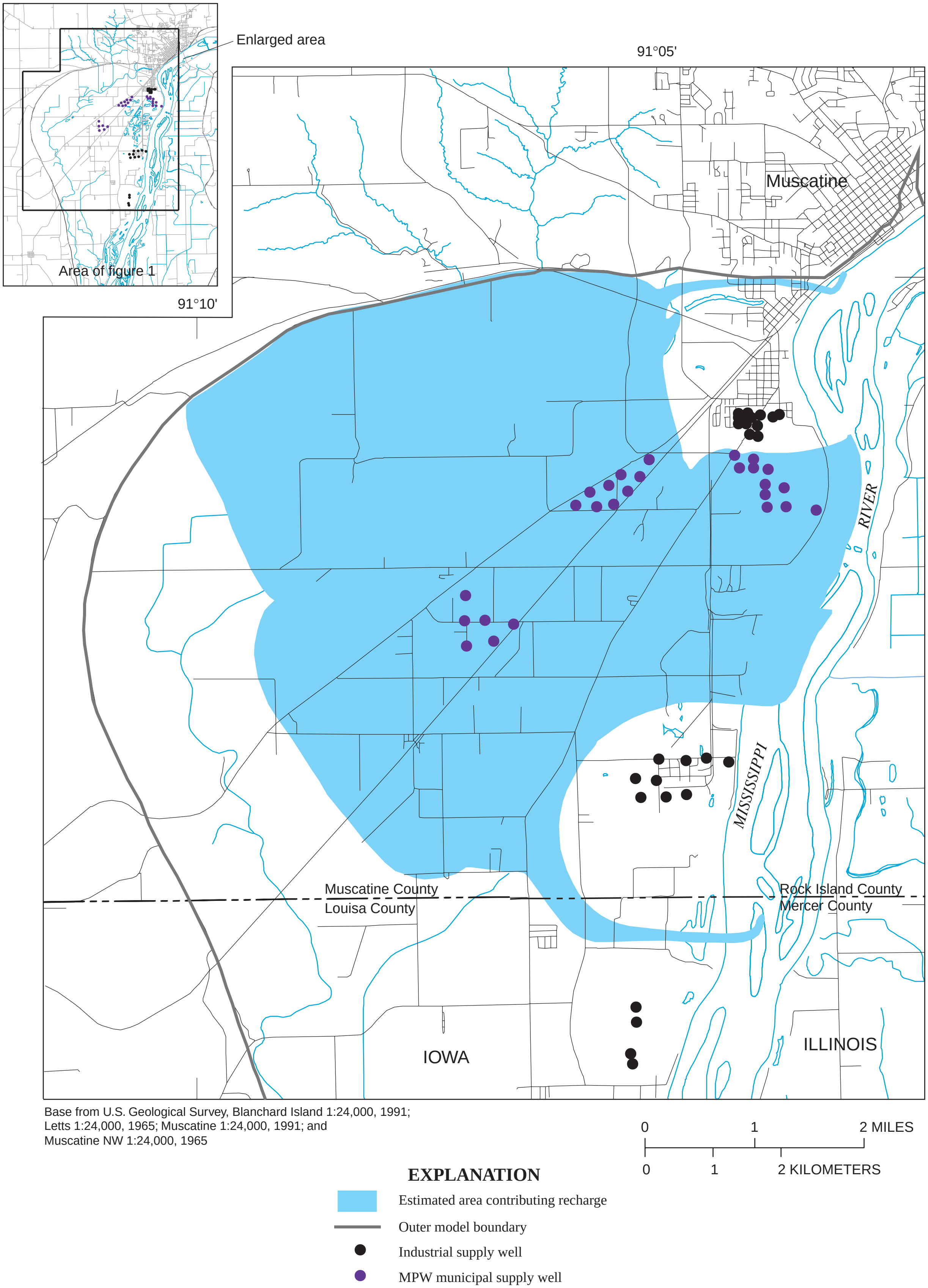

Figure 8. Estimated areas contributing recharge to municipal well fields under 1998 pumping conditions.

Table 2. Comparison of simulated traveltime and ground-water recharge date determined from chlorofluorocarbon and tritium analyses for samples collected May 4–7, 1999

[ft, feet below land surface; simulated traveltime, average traveltime for all particles from well; CFC, chlorofluorocarbons; M, Main; PP, Progress Park; GV, Grandview]

Site ID / site name / well field	Well depth (ft)	Geologic unit	Simulated traveltime[1] (years)	Ground-water recharge date CFC[2] / tritium[3]
412329091041301 / MPW19 / M	83	Alluvium	9.6	Mid-1980's / Post-1950's
412215091065601 / MPW23 / PP	125	Alluvium	20.9	About 1990 / Post-1950's
412331091051201 / MPW29 / GV	130	Alluvium	17.4	Early 1980's / Post-1950's

[1]Based on results of MODPATH simulation.
[2]E. Busenberg, U.S. Geological Survey, written commun., 2000.
[3]Plummer and others (1993).

Potential point sources of contamination were grouped by type into residential and industrial/commercial sites. The contamination potential associated with residential sites can originate from improperly functioning septic tanks and the rapid downward movement of surface water (and possible contaminants) into the underlying aquifer at improperly constructed domestic wells. Activities associated with industrial/commercial sites often include the handling and storage of a variety of chemicals and fuels. Waste streams from industrial/commercial processes (such as manufacturing and dry cleaning) also may create a potential for contamination if improperly handled.

The potential for contamination of the alluvial aquifer within the 2-, 5-, and 10-year zones of transport also occurs along roads and railroads and from the Mississippi River and mining operations (gravel pits). Truck, train, and barge traffic often include the transport of chemicals and hazardous waste, and the unintended release of these materials could affect water quality. The presence of agricultural chemicals (pesticides and nitrogen fertilizers), derived from upland runoff into the Mississippi River, also could affect water quality in areas where pumpage from MPW well fields originates as recharge induced from the river. Open gravel pits may facilitate rapid infiltration of contaminants.

The delineation of zones of transport for MPW wells and the identification of potential contaminant sources within those zones provide important information that can be used in the development of a WHPP for MPW municipal wells. Additional efforts on the part of MPW to protect municipal water quality include the development and implementation of a ground-water and surface-water monitoring program (Jerry Doering, Muscatine Power and Water, written commun., 1998). Ground water from a network of observation wells located within areas contributing recharge to MPW wells and surface water from nearby streams will be periodically sampled and analyzed for a variety of anthropogenic constituents.

Effects of Changing Climatic Conditions on Areas Contributing Recharge

The delineation of areas contributing recharge to MPW municipal well fields is influenced by uncertainty resulting from limited knowledge of the parameter values, boundary conditions, and hydrologic stresses used in MODFLOW. The effects of less-than- and greater-than-normal recharge from precipitation on the size and shape of the 10-year zone of transport to MPW municipal well fields were simulated by decreasing and increasing precipitation to the ground-water model by 20 percent. The resultant 10-year zones of transport (less-than- and greater-than-normal recharge from precipitation) were compared to the 10-year zone of transport for normal recharge from precipitation used in the calibrated model (fig. 14). Areas where changes in the location of the 10-year zone of transport were determined are denoted in blue in figure 14. Decreasing the amount of recharge from precipitation reduces the amount of water available (per unit area) for municipal withdrawal and requires a 2-percent increase in the size of the 10-year zone of transport to maintain the same rate of withdrawal. Increasing the amount of recharge from precipitation has the opposite effect, resulting in a 3-percent reduction in the size of the zone of transport. This relation between recharge from precipitation and the size of the zone of transport is illustrated in areas A, B, and C of figure 14.

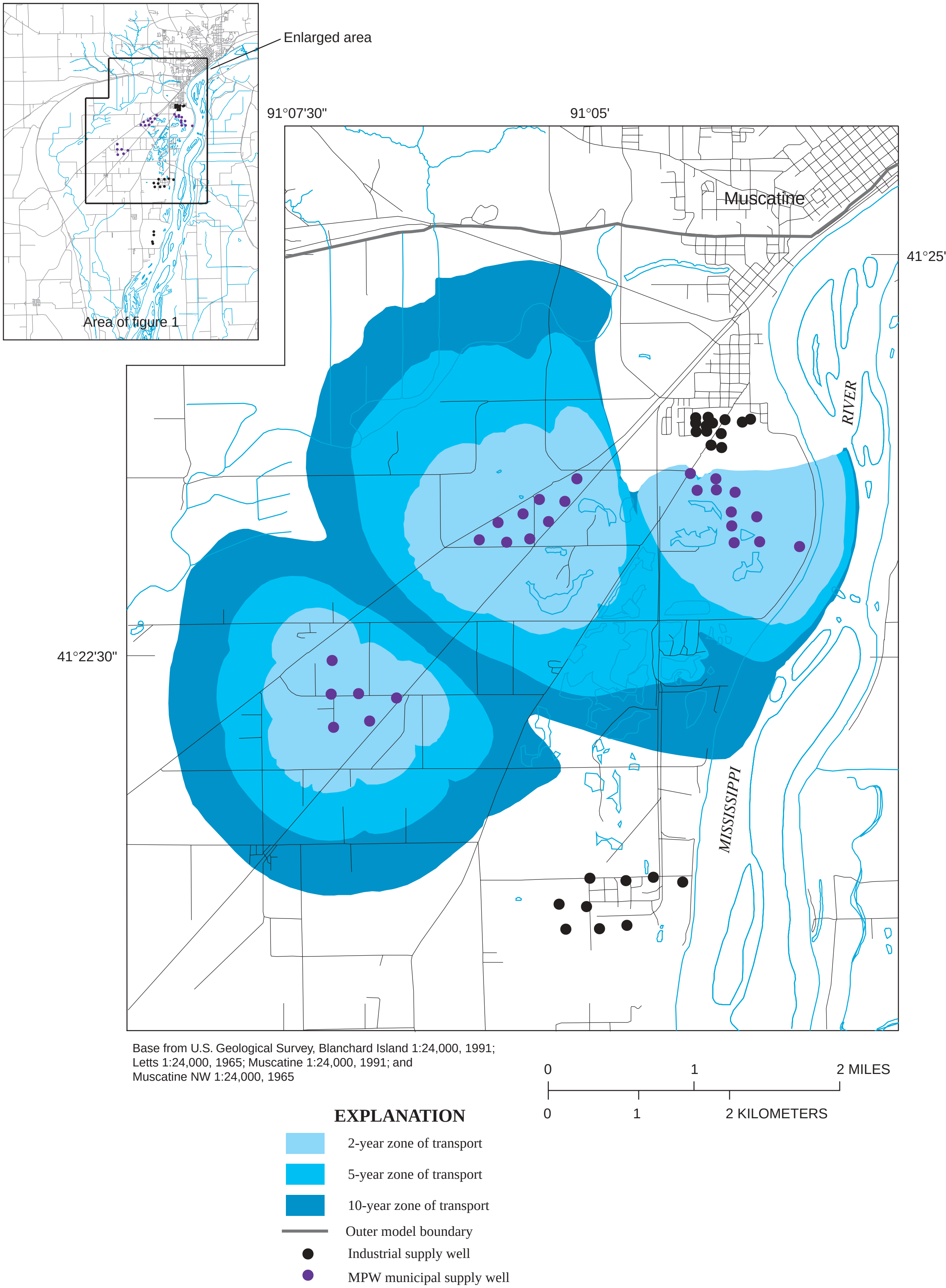

Figure 9. Estimated 2-, 5-, and 10-year zones of transport for municipal well fields.

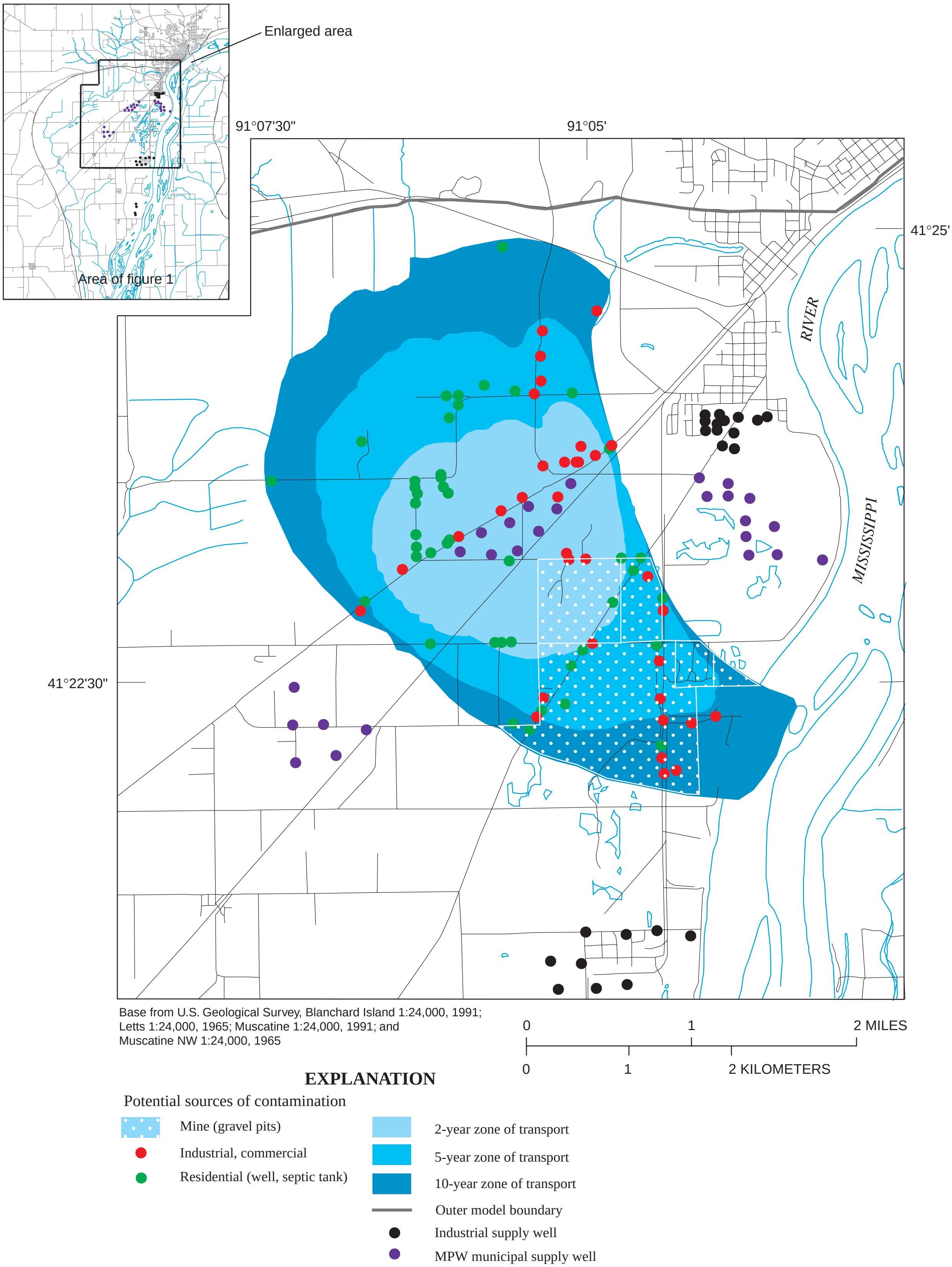

Figure 10. Estimated 2-, 5-, and 10-year zones of transport for wells in the Grandview well field and potential sources of contamination.

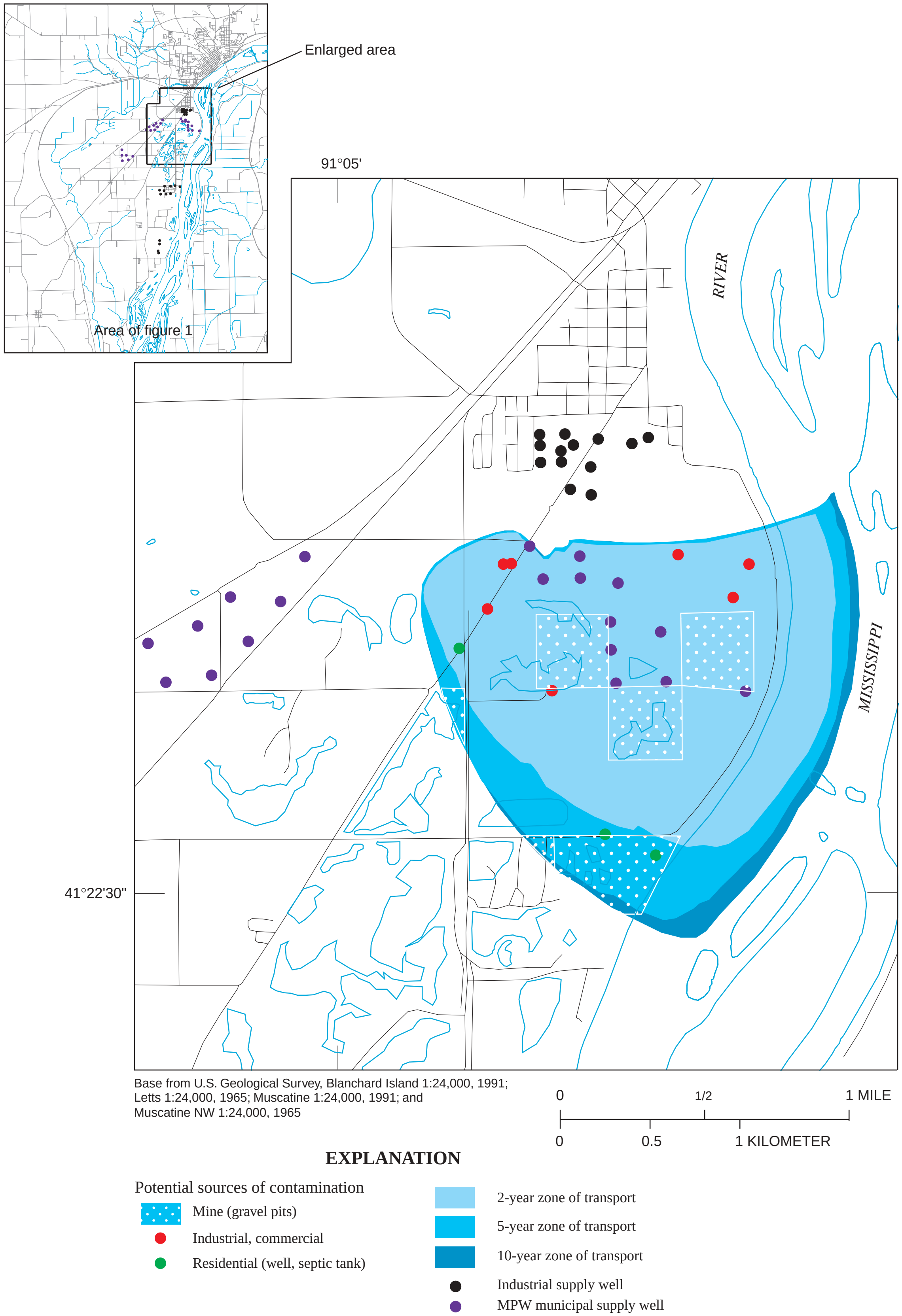

Figure 11. Estimated 2-, 5-, and 10-year zones of transport for wells in the Main well field and potential sources of contamination.

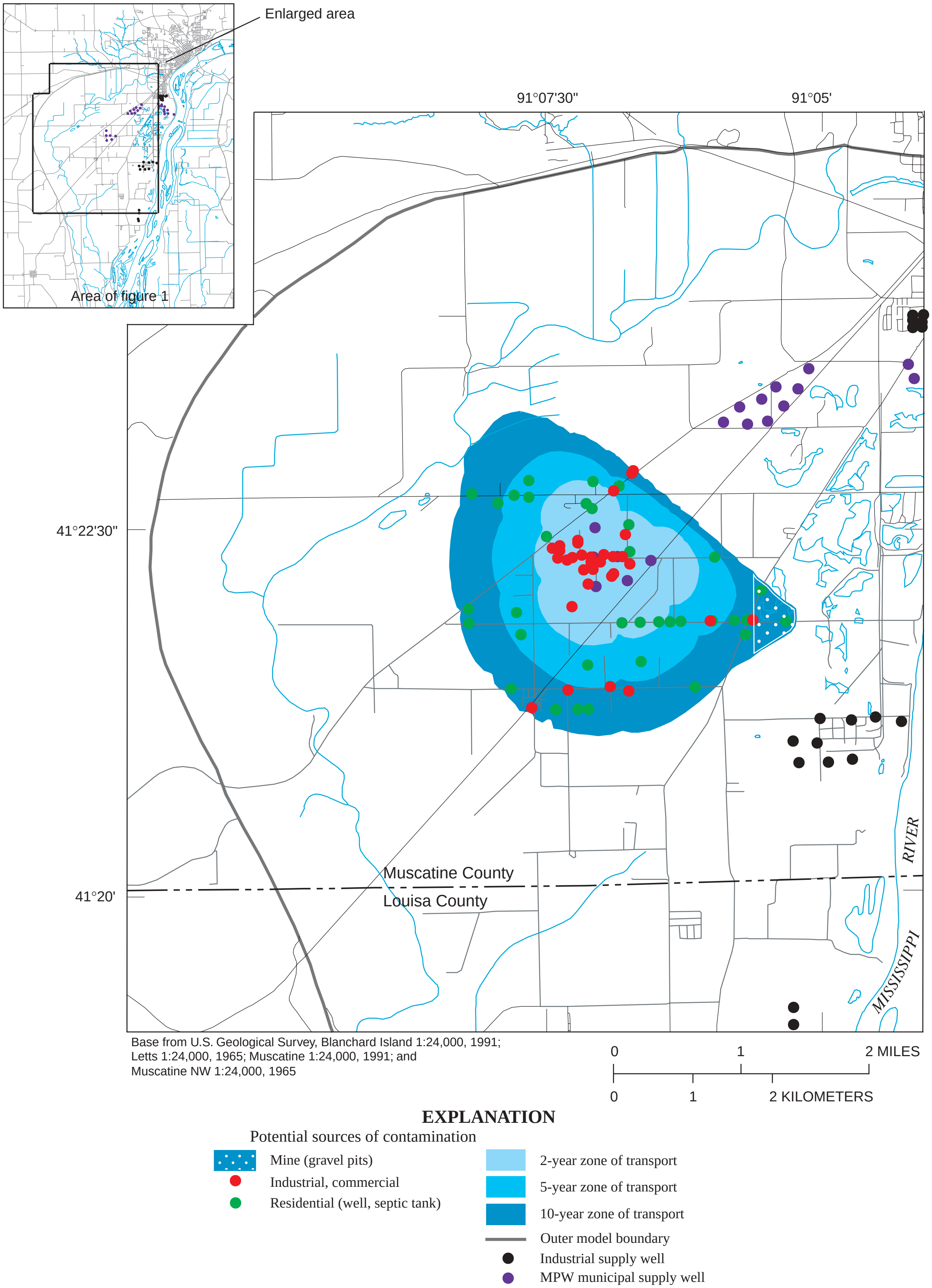

Figure 12. Estimated 2-, 5-, and 10-year zones of transport for wells in the Progress Park well field and potential sources of contamination.

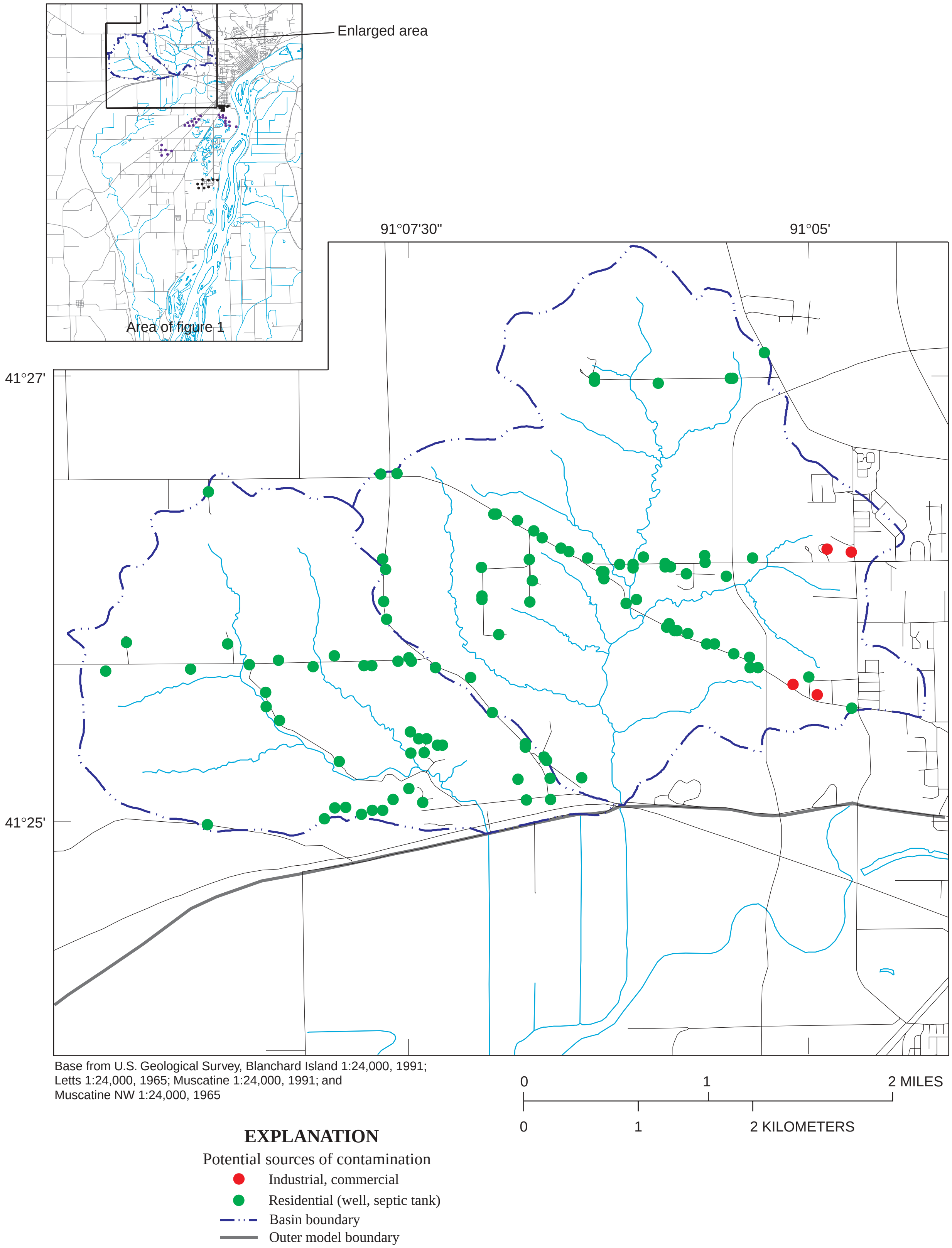

Figure 13. Drainage basins of creeks within areas contributing recharge to the Grandview well field and potential sources of contamination.

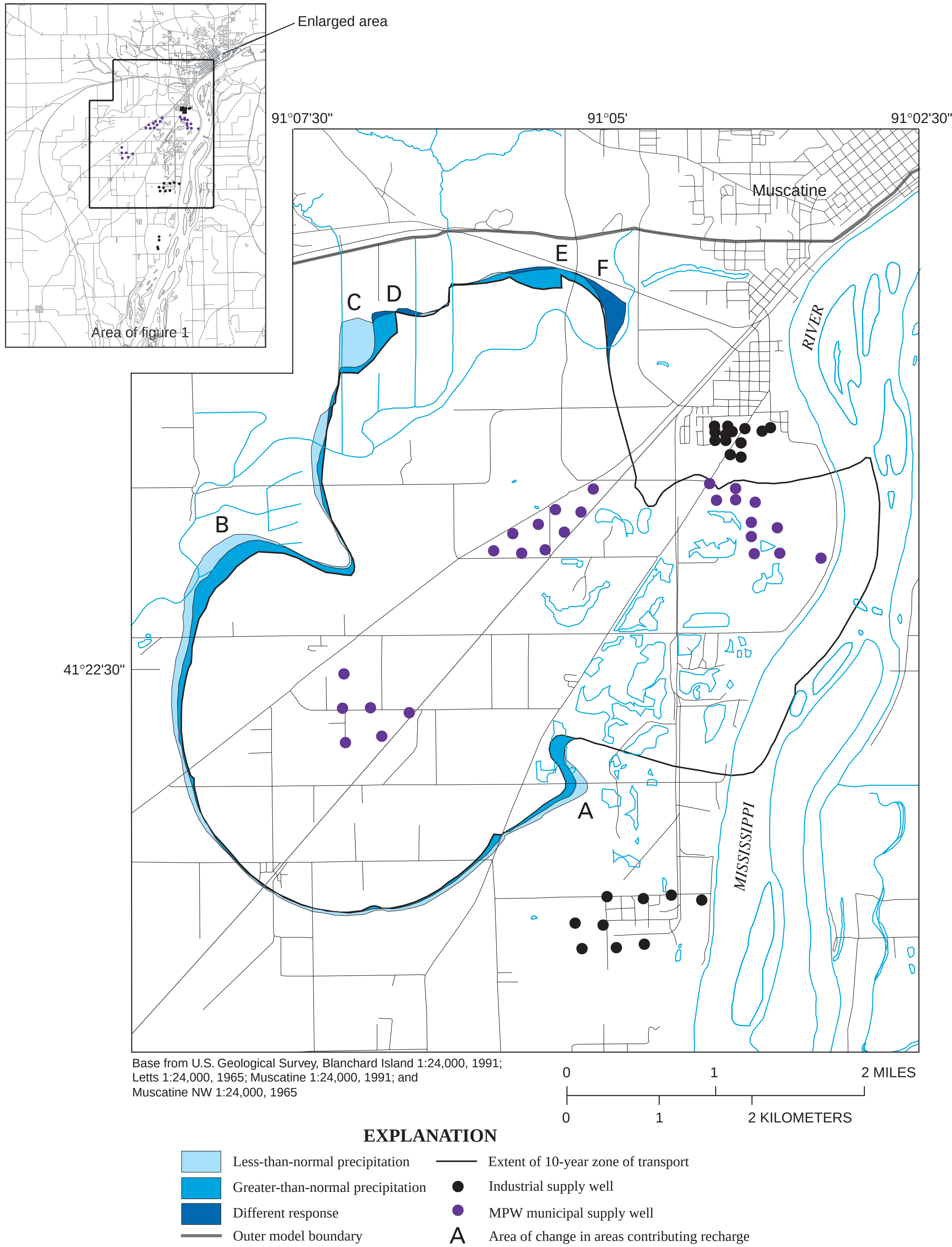

Figure 14. Estimated areas contributing recharge to municipal well fields under less-than- and greater-than-normal recharge from precipitation.

A different response to changing climatic conditions was indicated in areas D, E, and F of figure 14. In these areas, the 10-year zone of transport for normal recharge from precipitation either extends beyond the zone of transport for the less-than-normal condition or is exceeded by the zone of transport for the greater-than-normal condition. Areas of such response most likely result from model uncertainty and the complex nature of model response to changing parameter values or proximity to model boundaries. Changes in the location of the 10-year zone of transport were not apparent to the east (fig. 14) in areas where ground water is either unavailable to MPW wells due to nearby industrial withdrawals or the Mississippi River provides abundant recharge.

The Mississippi River is a major surface-water feature in the study area, and its stage has an important effect on ground-water levels in the Mississippi River alluvium (Lucey and others, 1995, fig. 10). An investigation of the potential effects of changing Mississippi River stage on areas contributing recharge to MPW well fields is beyond the scope of this study. However, it should be noted that river-induced changes in ground-water levels may alter model-calculated particle flow paths and traveltimes and affect the delineation of areas contributing recharge to MPW well fields.

SUMMARY

Mississippi River alluvium in the Muscatine, Iowa, area provides large quantities of good quality ground water for municipal, industrial, and agricultural supplies. Three municipal well fields for the City of Muscatine produce about 27 Mgal/d from the alluvium. The general plan for development of the ground-water resource calls for doubling municipal withdrawals during the next 20 years (J. Doering, Muscatine Power and Water, oral commun., December 1996). The highly permeable nature of the alluvium and varied land use in the area result in a ground-water supply potentially vulnerable to contamination. There is a need to delineate areas contributing recharge to municipal water-supply wells in the study area, described by Lucey and others (1995), to aid in the development of a wellhead protection plan (WHPP) for the Muscatine area.

A steady-state ground-water flow model constructed by Lucey and others (1995) was modified, and results from the model were used with the particle-tracking software MODPATH (Pollock, 1994) to delineate approximate areas contributing recharge to Muscatine Power and Water (MPW) municipal supply wells and to determine zones of transport within the areas contributing recharge. The model consists of three layers to represent the upper and lower alluvium and the bedrock. A 305-row by 250-column grid was used to divide the area of study into an array of 200-ft by 200-ft cells. A uniform horizontal hydraulic conductivity of 0.001 ft/d was used in the model layer representing the bedrock. Horizontal hydraulic conductivities for the upper and lower alluvium ranged from 150 to 1,000 ft/d.

Under steady-state conditions and 1998 pumpage, primary sources of model inflow are recharge through infiltration of precipitation and upland runoff (53 percent) and Mississippi River leakage (41 percent). The primary components of outflow from the ground-water flow system are pumpage (39.6 percent), flow to drainage ditches in Illinois (32.9 percent), and slough leakage (24.7 percent).

Several sources of water are present within estimated areas contributing recharge to MPW municipal well fields including ground water from the alluvial aquifer, Mississippi River water, and recharge originating as runoff from two unnamed creeks in the northern part of the study area. Recharge originating from the Mississippi River accounts for about 46 percent of the total water discharged from the municipal well fields. The average simulated traveltime of particles from recharge to discharge at the MPW municipal well fields is 13.6 years. Particle-tracking results illustrate the influence of nearby industrial supply wells on the shape and size of the area contributing recharge to MPW wells. Two large embayments into the area contributing recharge to MPW wells are present along the Mississippi River. These areas represent ground water that is unavailable to MPW wells due to withdrawals by industrial supply wells. Recharge originating from the Mississippi River accounts for about 98 percent of the total water discharged from the Muscatine Power and Water Main well field. However, recharge originating from the Mississippi River accounts for less of the total discharge from the Progress Park and Grandview municipal well fields (12 and 34 percent, respectively).

The effects of changing climatic conditions on the size and shape of the 10-year zone of transport to MPW municipal well fields were simulated by decreasing and increasing recharge from precipitation to the ground-water model by 20 percent to demonstrate the uncertainty inherent in delineating these areas. Potential sources of contamination within the 2-, 5-, and 10-year zones of transport to MPW municipal well fields were located and characterized. The delineation of zones of transport for MPW wells and the location of potential contaminant sources within those zones provide information used in the development of a WHPP for MPW municipal wells. Additional efforts on the part of MPW to protect municipal water quality include the development and implementaion of a ground-water and surface-water monitoring program.

REFERENCES

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling—Simulation of flow and advective transport: San Diego, Academic Press, Inc., 381 p.

Busenberg, Eurybiades, and Plummer, L.N., 1992, Use of chlorofluorocarbons (CCl_3F and CCl_2F_2) as hydrologic tracers and age-dating tools—Example, The alluvium and terrace system of central Oklahoma: Water Resources Research, v. 28, p. 2257–2283

Driscoll, F.G., 1986, Groundwater and wells: St. Paul, Minnesota, Johnson Filtration Systems Inc., 1089 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, 604 p.

Hansen, R.E., and Steinhilber, W.L., 1977, Geohydrology of Muscatine Island, Muscatine County, Iowa: Iowa City, Iowa Geological Survey, Water-Supply Bulletin 11, 60 p.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95–399, 113 p.

Lucey, K.J., 1997, Evaluation of drawdown and sources of water in the Mississippi River alluvium caused by hypothetical pumping, Muscatine, Iowa: U.S. Geological Survey Water-Resources Investigations Report 97–4162, 18 p.

Lucey, K.J., Kuzniar, R.L., and Caldwell, J.P., 1995, Hydrogeology and water quality of the Mississippi River alluvium near Muscatine, Iowa, June 1992 through June 1994: U.S. Geological Survey Water-Resources Investigations Report 95–4049, 74 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 576 p.

Ostlund, H.G., and Dorsey, H.G., 1977, Rapid electrolytic enrichment of hydrogen gas proportional counting of tritium: Proceedings of International Conference on Low Radioactivity Measurement and Applications, High Tatras, Czechoslovakia, October, 1975, 6 p.

Plummer, L.N., Michel, R.L., Thurman, E.M., and Glynn, P.D., 1993, Environmental tracers for age dating young ground water, *in* Alley, W.M., ed., Regional ground-water quality: New York, Van Nostrand Reinhold, p. 255–294.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3—A particle-tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94–464, 249 p.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using the modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 88–729, 113 p.

State of Ohio Environmental Protection Agency, 1994, What is wellhead protection?: Columbus, State of Ohio Environmental Protection Agency Fact Sheet.

Savoca and others—Simulation of Ground-Water Flow and Delineation of Areas Contributing Recharge To Municipal Water-Supply Wells, Muscatine, Iowa

USGS/WRIR 02–4004

Printed on recycled paper