

Ground-Water Flow Model of the Boone Formation at the Tar Creek Superfund Site, Oklahoma and Kansas



Prepared in cooperation with the
U.S. Environmental Protection Agency, Region VI

Scientific Investigations Report 2006-5097

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

Front cover: View looking west from top of chat pile on east side of the town of Picher, Oklahoma, overlooking the town and the adjacent chat piles derived from decades of lead-zinc mining. Photograph by John B. Czarnecki, U.S. Geological Survey.

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By T.B. Reed and John B. Czarnecki

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Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi ²)	2.590	square kilometer (km ²)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft ³ /s)	0.0283	cubic meter per second (m ³ /s)
cubic foot per day (ft ³ /d)	0.0283	cubic meter per day (m ³ /d)
pound per cubic foot (lb/ft ³)	0.0129	kilogram per cubic meter (kg/m ³)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD of 1983)

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Abstract

Extensive mining activities conducted at the Tar Creek Superfund site, one of the largest Superfund sites in the United States, pose substantial health and safety risks. Mining activities removed a total of about 6,000,000 tons of lead and zinc by 1949. To evaluate the effect of this mining on the ground-water flow, a MODFLOW 2000 digital model has been developed to simulate ground-water flow in the carbonate formations of Mississippian age underlying the Tar Creek Superfund site. The model consists of three layers of variable thickness and a grid of 580 rows by 680 columns of cells 164 feet (50 meters) on a side. Model flux boundary conditions are specified for rivers and general head boundaries along the northern boundary of the Boone Formation. Selected cells in layer 1 are simulated as drain cells. Model calibration has been performed to minimize the difference between simulated and observed water levels in the Boone Formation. Hydraulic conductivity values specified during calibration range from 1.3 to 35 feet per day for the Boone Formation with the larger values occurring along the axis of the Miami Syncline where horizontal anisotropy is specified as 10 to 1. Hydraulic conductivity associated with the mine void is set at 50,000 feet per day and a specific yield of 1.0 is specified to represent that the mine void is filled completely with water. Residuals (the difference between measured and simulated ground-water altitudes) has a root-mean-squared value of 8.53 feet and an absolute mean value of 7.29 feet for 17 observed values of water levels in the Boone Formation.

The utility of the model for simulating and evaluating the possible consequences of remediation activities has been demonstrated. The model was used to simulate the emplacement of chat (mine waste consisting of fines and fragments of chert) back into the mine. Scenarios using 1,800,000 and 6,500,000 tons of chat were run. Hydraulic conductivity was reduced from 50,000 feet per day to 35 feet per day in the model cells corresponding to chat emplacement locations. A comparison of the simulated baseline conditions and conditions after simulated chat emplacement revealed little change in water levels, drainage and stream flux, and ground-water flow velocity.

Using the calibrated flow model, particle tracks were simulated using MODPATH to evaluate the simultaneous movement of particles with water in the vicinity of four potential sites at which various volumes of chat might be emplaced in the

underground mine workings as part of potential remediation efforts at the site. Particle tracks were generated to follow the rate and direction of water movement for a simulated period of 100 years. In general, chat emplacement had minimal effect on the direction and rate of movement when compared to baseline (current) flow conditions. Water-level differences between baseline and chat-emplacement scenarios showed declines as much as 2 to 3 feet in areas immediately downgradient from the chat emplacement cells and little or no head change upgradient. Chat emplacements had minimal effect on changes in surface-water flux with the largest simulated difference in one cell between baseline and chat emplacement scenarios being about 3.5 gallons per minute.

Introduction

The mined area that includes the Tar Creek Superfund site (hereafter referred to as the "site") straddles the eastern part of the Oklahoma-Kansas State Line, in Ottawa County, Oklahoma, and Cherokee County, Kansas (fig. 1). Lead and zinc ores were mined extensively in this area from about 1904 to the 1970's from mines in the site extending to 385 feet in depth below land surface (Playton and others, 1980, p. 2). Mining activities at the site in the Picher, Oklahoma, area resulted in large piles of mine waste (chat) and open underground mine workings capable of transmitting ground water; mining activities removed about 6,000,000 tons of lead and zinc by 1949 (Reed and others, 1955, p. 23). Throughout the mining era, water had to be pumped from the mines to keep the water level below the mine drifts. These activities, for example, removed up to 1,730,000 cubic feet of water per day from the Boone Formation in 1932 (Reed and others, 1955, p. 53). With the cessation of mining, the mines filled with an estimated 100,000 acre-feet of water by 1976 (Playton and others, 1980, p. 24). This mined area, while now abandoned, constitutes one of the largest Superfund sites by area in the United States (U.S. Environmental Protection Agency, 1994). As a Superfund site, the consequences of past mining pose substantial health and safety risks. These include mine collapse, exposure to mining wastes, and potential ground-water and surface-water contamination (U.S. Environmental Protection Agency, 1994). Potential remediation efforts involving the emplacement of chat back into the

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mines may pose substantial hydrologic issues. To help address these concerns, the U.S. Geological Survey (USGS) in cooperation with the U.S. Environmental Protection Agency, Region VI, developed a digital ground-water flow model for the area.

Purpose and Scope

The purpose of this report is to describe a ground-water flow model of the Boone Formation and investigate the potential effects that emplacement of various volumes of chat would have on the direction, quantity, and velocity of ground-water flow for selected potential remediation scenarios. This report describes the hydrogeologic framework; the hydrogeology of the model area, specifically in relation to application of model boundary conditions and hydraulic properties; model development and calibration; and results of model simulations of ground-water flow in the vicinity of the site. Particle-tracking analyses for the different scenarios are presented and compared.

Description of Model Area

The model area (fig. 1) covers about 380 square miles in the vicinity of the Tar Creek mined area near Picher in Ottawa County, Oklahoma, and Cherokee County, Kansas. The principal named streams interior to the model area are Tar Creek and Lytle Creek. Relief in the area generally consists of gently rolling terrain. Land-surface altitude (fig. 2) ranges from about 925 feet on the north to about 750 feet at the confluence of the Neosho and Spring Rivers in the Grand Lake of the Cherokees. A topographic high reaching over 900 feet is present to the east of the mined area and along the Spring River. Local relief occurs as cliffs along the Spring and Neosho Rivers and chat piles (mine tailings), which can rise several hundred feet above the surrounding area.

Previous Studies

Numerous investigations have been made of the geologic units in the vicinity of the site and of the underlying Roubidoux Formation and older geologic units. The focus of many of these studies has been the extensive lead and zinc mines in Ottawa County. Reed and others (1955) conducted an extensive investigation of the ground-water resources of Ottawa County, which included aquifer test data for the Roubidoux Formation and pumping data for the Boone Formation. McKnight and Fischer (1970) extensively discussed the geology and mining history of the lead and zinc mines. Marcher and Bingham (1971) described the water resources of much of northeastern Oklahoma. Playton and others (1980) conducted a study of the water within the abandoned lead and zinc mines in the region. Marcher and others (1984) reported on the hydrology of the coal area encompassing the model area. Luza (1986) evaluated problems related to mine collapses. Parkhurst (1987) reported on the chemical constituents found in water from Tar Creek and the

Picher mining area. Spruill (1987) assessed water resources including water levels in the northern part of the model area. Imes and Emmett (1994) discussed the regional geohydrology and presented a regional scale numerical model that encompasses the vicinity of the model area. Christenson and others (1994) discussed the geohydrology of the Roubidoux aquifer, conducted an aquifer test, and produced a digital model of the cone of depression of the Roubidoux aquifer in the vicinity of Miami, Oklahoma. DeHay and others (2004) assessed ground-water and surface-water altitudes and chemical constituents in the mined area in 2002-2003.

Hydrogeologic Setting and Conceptual Model

The model area is in a relatively flat prairie in Oklahoma and southeastern Kansas. The model area extends southward, westward, and eastward to natural hydrologic boundaries at the Spring and Neosho Rivers and the Grand Lake of the Cherokees. The model area encompasses the active model area that is bounded on the east by the Spring River and bounded on the west by the Neosho River which flows in a southeasterly direction across the model area into the Grand Lake of the Cherokees. The model area is bounded on the south and west by the Neosho River. The Neosho and Spring Rivers serve as surface-water drains and have eroded deep valleys up to 200 feet below the surrounding area. Other streams flowing across the model area, which interact directly with the mine, are Tar and Lytle Creeks. There are other streams that do not interact directly with the mine.

The regional dip of the rocks is 15 to 25 feet per mile to the northwest, although locally the dip may vary. The most prominent structural feature in the model area is the Miami Syncline which has a general trend of N. 26 degrees E. The Miami Syncline or Miami Trough is described by McKnight and Fischer (1970, p. 74) as a linear combination of syncline and graben except that the synclinal sag, with or without accompanying faults, prevails over the true graben block faulting. This and other such features may affect the flow of ground water.

The presence of underground mines is an important component of the ground-water flow system. A generalized geologic section shows the relations of rock formations to water-filled mines (fig. 3). Mine maps (Luza, 1986) were used to define the extent of the underground-mine workings and associated conditions within the ground-water flow model.

Carbonate rocks predominate in the model area. The uppermost units considered in this report are the largely shale units of the Krebs Group of Pennsylvanian age which range in thickness from 9 to 200 feet in Ottawa County (Reed and others, 1955, p. 63) and beneath them the units of the Chester series of Mississippian age which include the Hindville Limestone and the calcareous sandstone of the Batesville Sandstone. Together these units represent the bedrock of post-Boone Formations exposed throughout much of the model area (Reed and others,

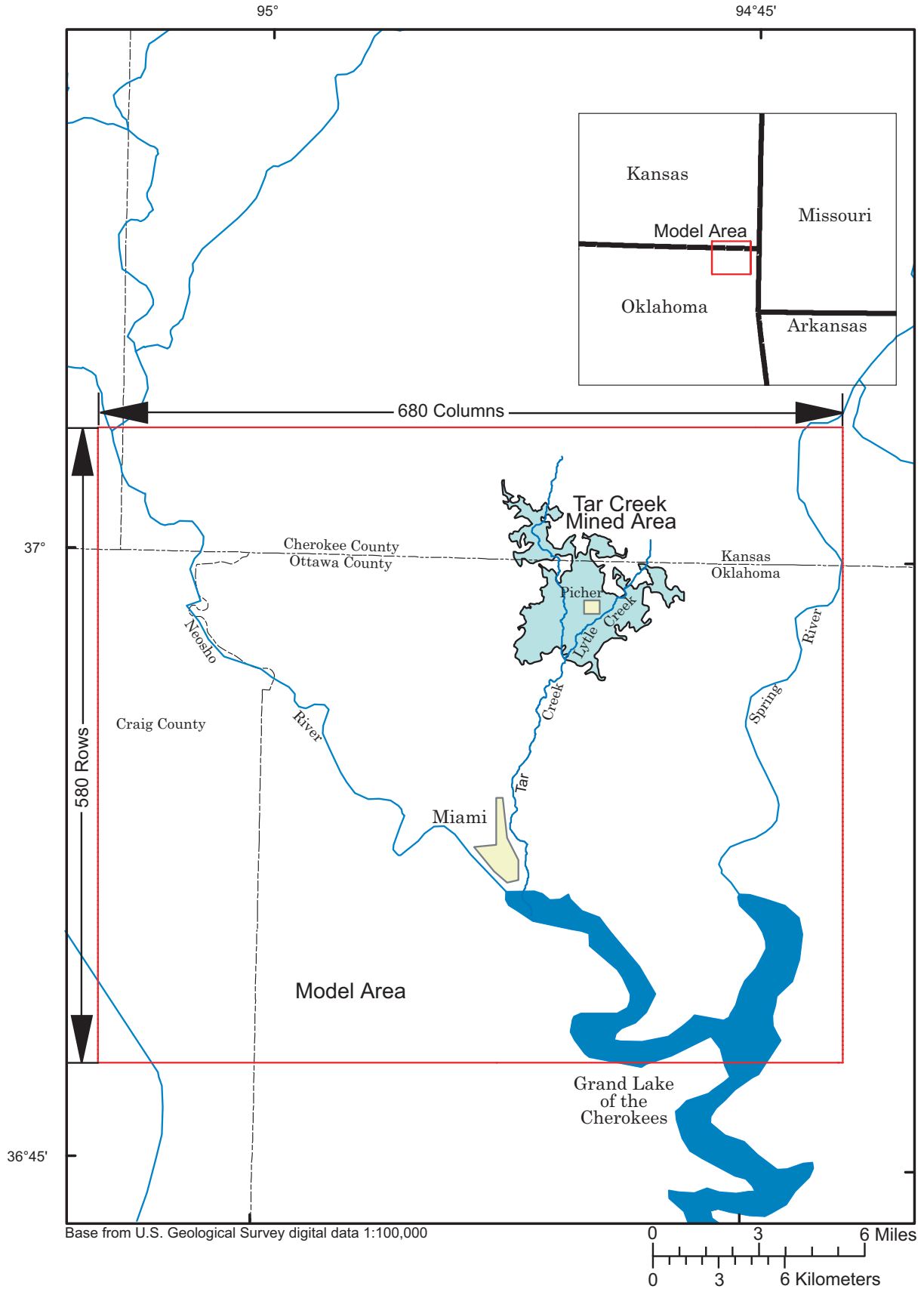


Figure 1. Location of model are.

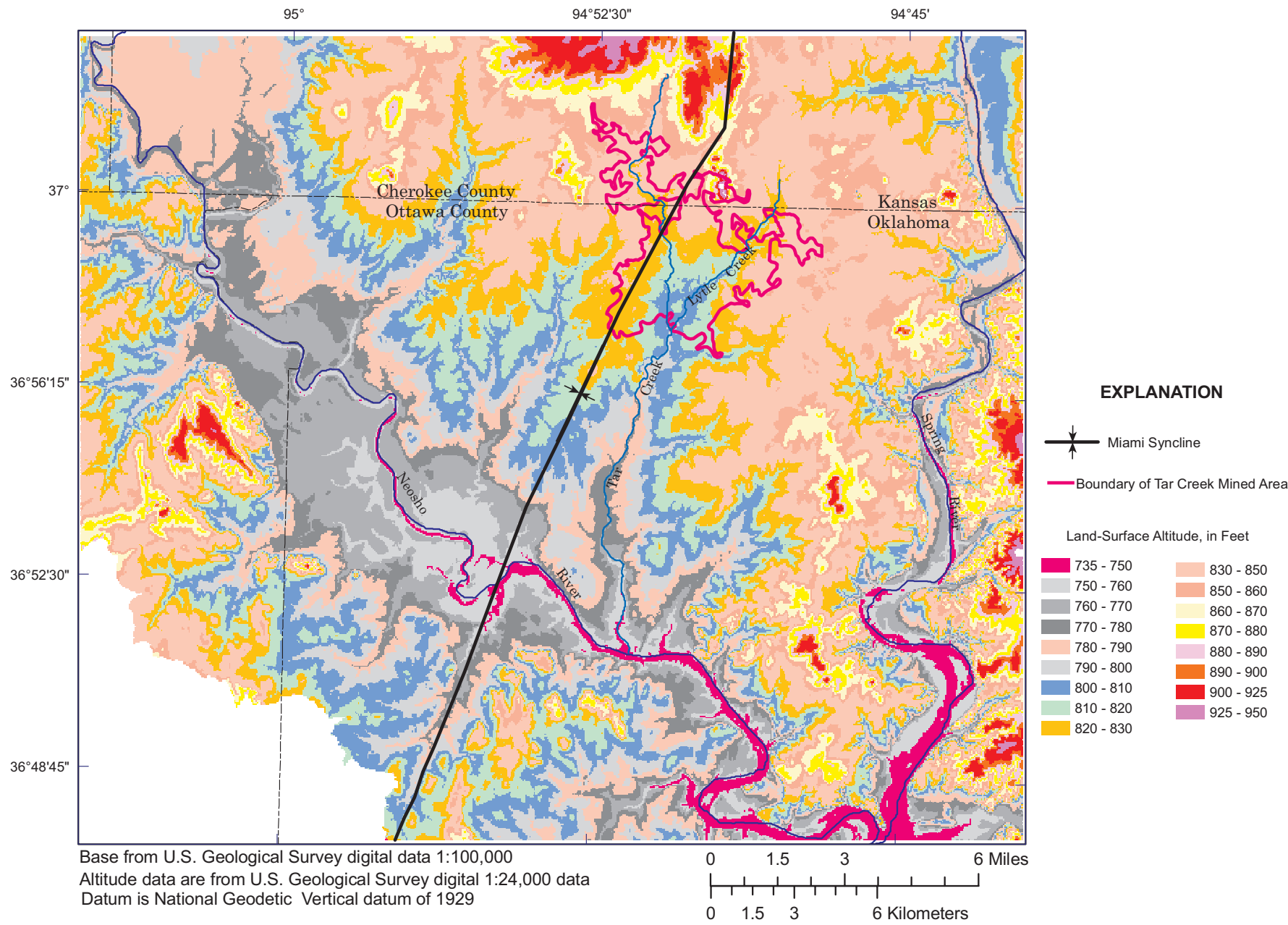


Figure 2. Land-surface altitude in the model area.

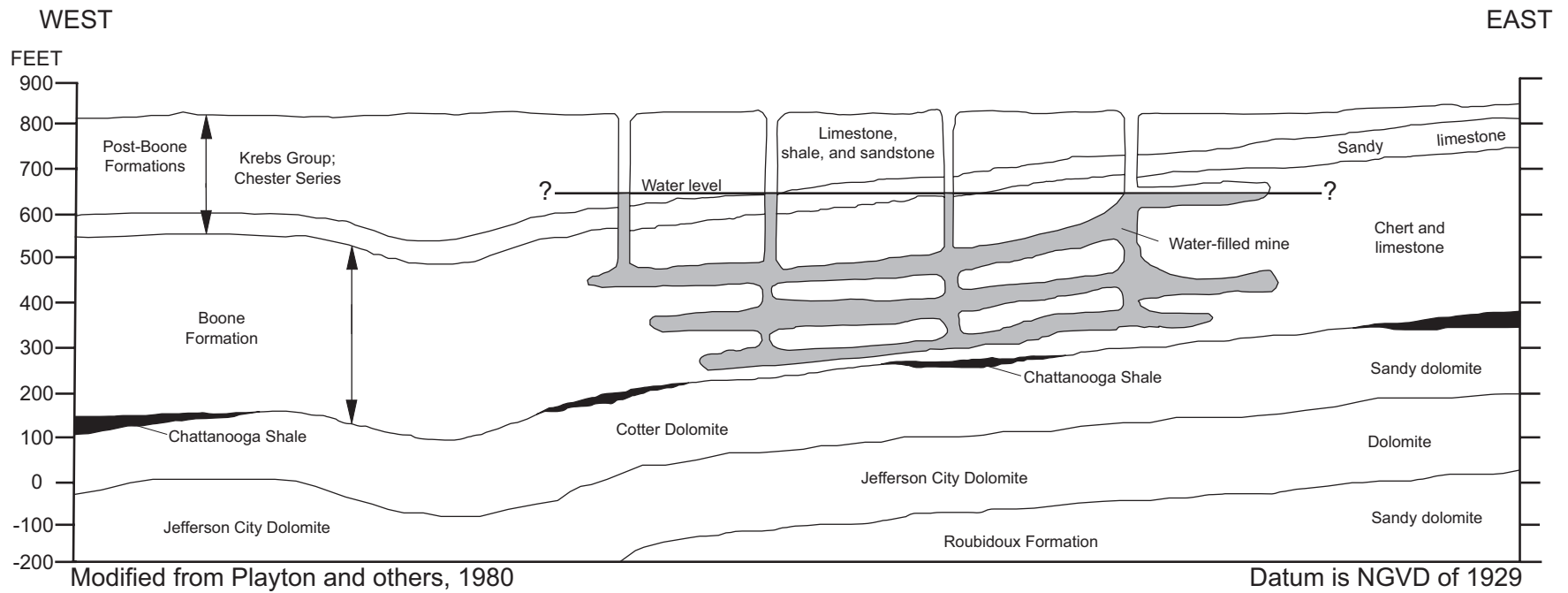


Figure 3. Generalized geologic section showing relations of rock formations to water-filled mines.

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1955, plate) and comprise about 300 feet of limestone, shale, sandstone, and siltstone. Beneath these units and exposed in portions of the model area is the Boone Formation (Reed and others, 1955, plate 1), a carbonate unit of Mississippian age, composed of chert and limestone and ranging in thickness from about 270 to 470 feet thick in the model area (fig. 4). The abandoned mines are in the Boone Formation. Wells in the Boone Formation yield as much as 750 gallons per minute (Christenson and others, 1994, table 1). The altitude of the bottom of the Boone Formation slopes upward towards the east (fig. 5). The Boone Formation is underlain at depth by the Chattanooga Shale which is from 0 to 8 feet thick in the study area and is a non-water bearing unit. The water-yielding characteristics of the other units between the Chattanooga Shale and the Boone Formations are unknown (Christenson and others, 1994, table 1). The Chattanooga Shale is underlain by the Cotter and Jefferson City Dolomites (fig. 3), which are mainly cherty dolomites with sandstone lenses (Christenson and others, 1994, p. 7). These units combined are about 500 feet thick in the study area. The Cotter Dolomite may yield up to 380 gallons per minute (Christenson and others, 1994). The Cotter and Jefferson City Dolomites are underlain by the Roubidoux Formation which consists of cherty dolomite and is about 105 to 180 feet thick in the study area. The Roubidoux Formation contains the Roubidoux aquifer, a potentially important component of the ground-water flow system and the principal aquifer in northeastern Oklahoma with well yields ranging from 100 to over 1,000 gallons per minute (Christenson and others, 1994, table 1). The Roubidoux Formation is underlain by the Gasconade Dolomite, a cherty dolomite, which is found at depths of 1,050 to 1,130 feet in Ottawa County (Reed and others, 1955, p. 40) and which is not known to yield substantial amounts of water in its upper portions (Christenson and others, 1994) and as such may be relatively impermeable.

Ground-Water Altitudes in the Boone Formation

In the spring of 2004, depths to water in 17 wells and air shafts in the Boone Formation within the model area were measured with a steel or electric tape by USGS personnel (table 1). The ground-water depths generally were shallow, usually less than 20 feet below land surface. Because there is little indication of areally extensive confining units within the Boone Formation or in overlying units (Reed and others, 1955), ground water is considered to be unconfined in the Boone Formation within the model area. After the cessation of mining in the late 1970's, ground-water levels in the mine voids have risen. From about 1975 to about 1980 after mine pumps were turned off, ground water within the mines rose from an altitude of about 650 feet to about 800 feet above National Geodetic Vertical Datum (NGVD) of 1929 (Playton and others, 1980, figure 3). Ground-water altitudes for wells measured in spring 2004 range from a high of 830.6 feet to a low of 762.0 feet (fig. 6). Ground-water altitudes were contoured in figure 6 using both measured values and land-surface data. In the absence of surface water the

land-surface altitude provides an upper limit to the ground-water altitude. Ground-water altitudes throughout the mined area were similar (about 800 feet) in spring 2004, in spring 2003 (DeHay, 2004), and in 1981 (Spruill, 1987). This indicates a very well connected network of mine voids and fractures providing a nearly level water surface. Ground-water altitudes for five wells east of the mined area were higher than 800 feet, the highest (830.6 feet) occurring along the topographic high, which corresponds approximately with a local ground-water divide, between the Spring River and Tar Creek. In the area west of this local divide, including the mined area, ground water flows generally from the topographically high areas in the north and east to the south and southwest toward the Neosho River in the southwestern part of the model area. In the area east of this local divide, ground water generally flows east towards the Spring River. The range in ground-water altitude in the model area is about 80 feet from the northern boundary to the Neosho and Spring Rivers.

Boundaries, Sources, and Sinks of Water

Generally, boundaries of the ground-water flow system correspond to physical boundaries such as streams or lithologic contacts. The exception to this is the northern boundary of the model, which was arbitrarily selected such that ground-water flow specified across it would be sufficiently distant from the central part of the model where the mines are specified. As a result, water levels in these areas where the chat emplacements in the remediation scenarios will be placed will not be sensitive to boundary flows. Each of the boundaries will be discussed in the following sections.

Upper Boundary—Areal Recharge

The upper boundary of the model occurs at land surface, at which recharge derived from atmospheric precipitation occurs. Precipitation averages 42 inches per year (Christenson and others, 1994, p. 3), some of which seeps through the overlying units into the Boone Formation. Recharge in the model area to the aquifer is equal to precipitation less (1) runoff into streams, (2) direct evaporation, and (3) evapotranspiration or direct interception from plants in the soil zone. Areal recharge can vary spatially and is an important model variable for simulating observed water levels.

Lower Boundary—Hydrologic Interchange with Underlying Formations

The Gasconade Dolomite, which underlies the Roubidoux Formation, is not known to yield substantial amounts of water other than from the Gunter Sandstone Member of the Gasconade Dolomite (Christenson and others, 1994, table 1). Therefore, vertical ground-water flow from or to the Roubidoux Formation from below is likely to be low.

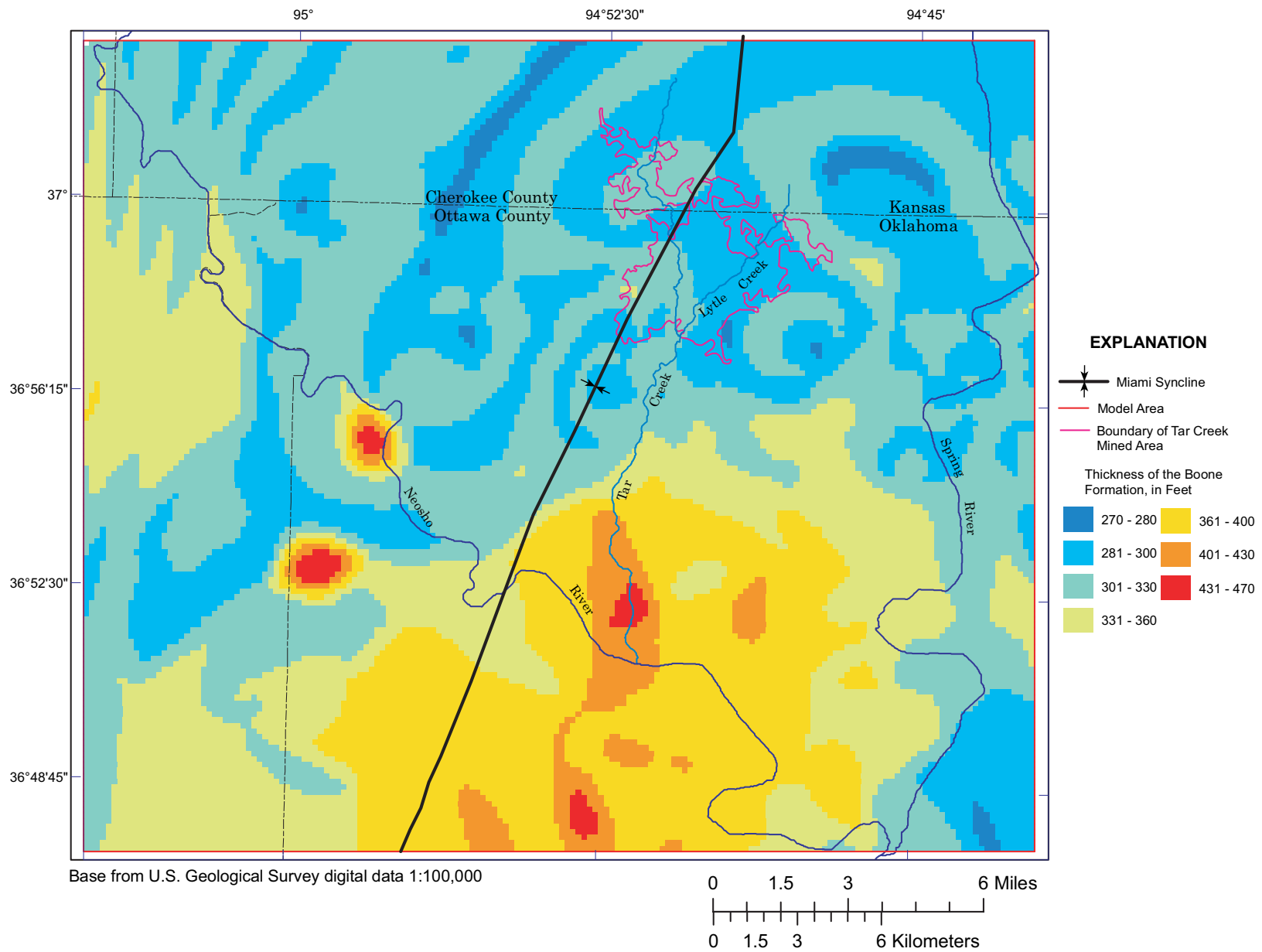


Figure 4. Thickness of the Boone Formation.

Table 1. Information pertaining to measured and simulated water levels at wells and airshafts in the Boone Formation

[Well number refers to location on figure 12; Station name and site identification number are assigned by the U.S. Geological Survey according to the methods of the National Water Information System; ddmss, degrees, minutes, seconds; horizontal coordinate information is referenced to the North American Datum of 1983 (NAD of 1983); NGVD of 1929 refers to the National Geodetic Vertical Datum of 1929; water levels at all wells were measured using a steel tape, except well 2 was measured using an electric tape; Residual water level is the difference between the measured water-level altitude and simulated water-level altitude; --, no data]

Well number	Station name	Site identification number	Latitude (ddmss)	Longitude (ddmss)	Surface datum altitude (feet above NGVD of 1929)	Well depth (feet below land-surface datum)	Measured depth to water (feet below land-surface datum)	Measured water-level altitude (feet above NGVD of 1929)	Date of measurement	Simulated water-level altitude (feet above NGVD of 1929)	Residual water level (feet)
1	29N23E17BCD1	365942094504201	365942	945042	828.0	116	28.5	799.5	4/13/2004	804.0	-4.5
2	OKOT-27	365428094441701	365428	944417	790.0	165	27.0	763.0	4/27/2004	779.1	-16.1
4	29N23E30CDD1	365732094513201	365734	945127	827.4	289	26.1	801.3	4/13/2004	797.0	4.3
6	35S22E10CDD1	370012094591501	370012	945915	803.0	306	14.4	788.6	4/28/2004	795.3	-6.7
23	29N23E22BCB1	365855094484501	365855	944845	828.5	--	25.7	802.8	4/13/2004	805.3	-2.5
24	29N23E20CBB1	365846094505401	365846	945054	817.5	--	14.8	802.7	4/13/2004	796.4	6.3
25	28N22E02BCC1	365612094544601	365612	945446	799.0	--	12.5	786.5	4/13/2004	772.0	14.5
26	29N24E21BCB1	365857094431801	365857	944318	805.0	--	14.0	791.0	4/13/2004	796.7	-5.7
27	29N22E20AAA1	365910094562101	365911	945622	806.0	--	2.2	803.8	4/13/2004	793.3	10.5
28	29N22E19AAA1	365911094573401	365911	945734	815.0	--	15.0	800.0	4/13/2004	797.0	3.0
29	29N22E19AAA2	365911094573402	365911	945734	815.0	--	15.3	799.7	4/13/2004	797.0	2.7
31	27N23E12ABA1	365031094463201	365031	944632	855.0	--	24.4	830.6	4/14/2004	823.6	7.0
32	29N23E24AAD1	365859094453301	365859	944533	840.0	--	11.4	828.6	4/14/2004	813.9	14.7
33	28N23E11CBB1	365517094481901	365517	944819	851.0	--	40.0	811.0	4/20/2004	806.9	4.1
34	28N23E11CBB2	365517094481601	365517	944816	852.0	--	41.7	810.3	4/20/2004	807.8	2.5
35	27N23E24ACB1	364832094464201	364832	944642	840.0	--	78.0	762.0	4/27/2004	769.0	-7.0
36	27N24E06ACC1	365059094453301	365059	944534	835.0	--	24.5	810.5	4/27/2004	798.5	12.0

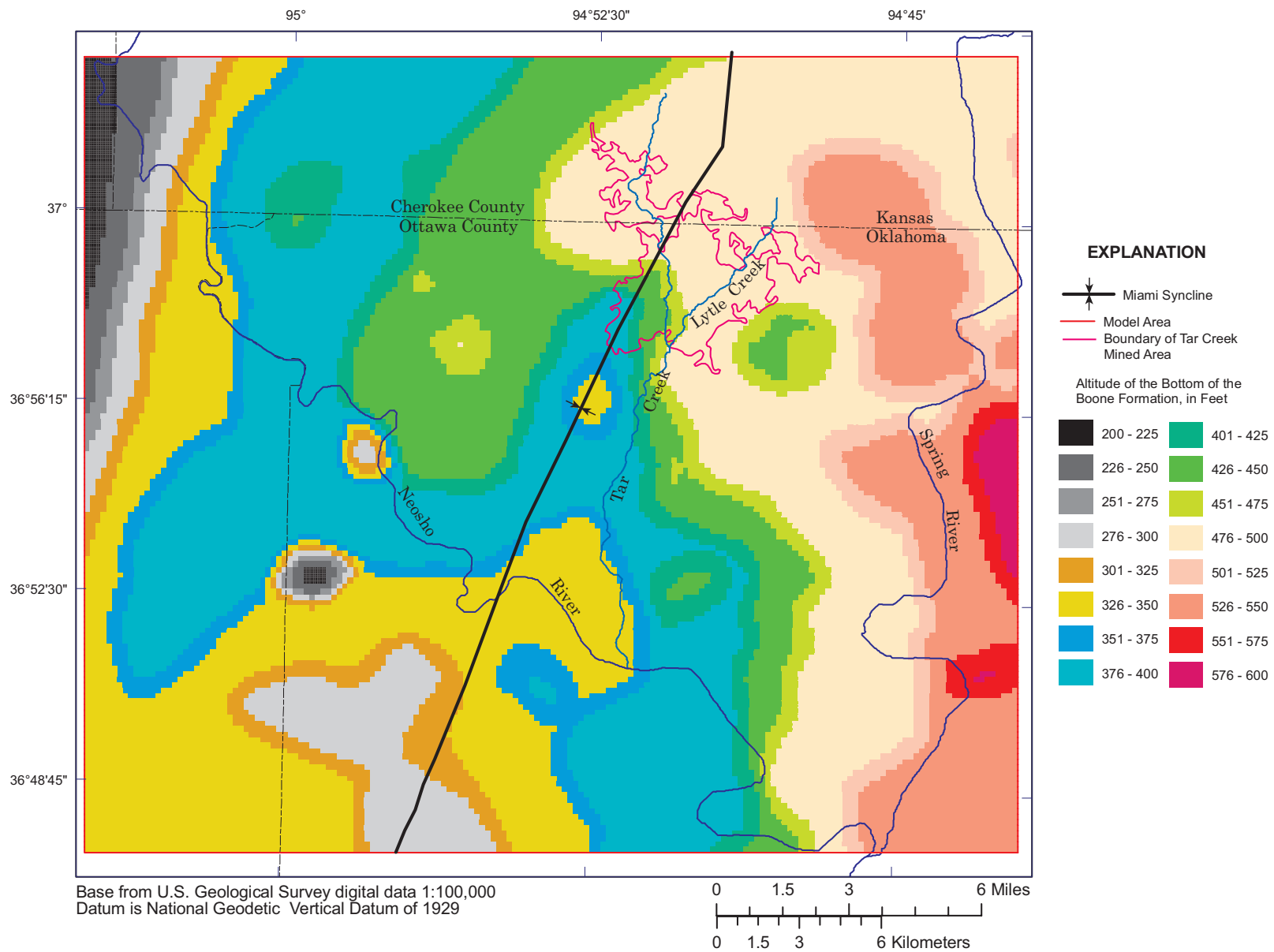


Figure 5. Altitude of the bottom of the Boone Formation.

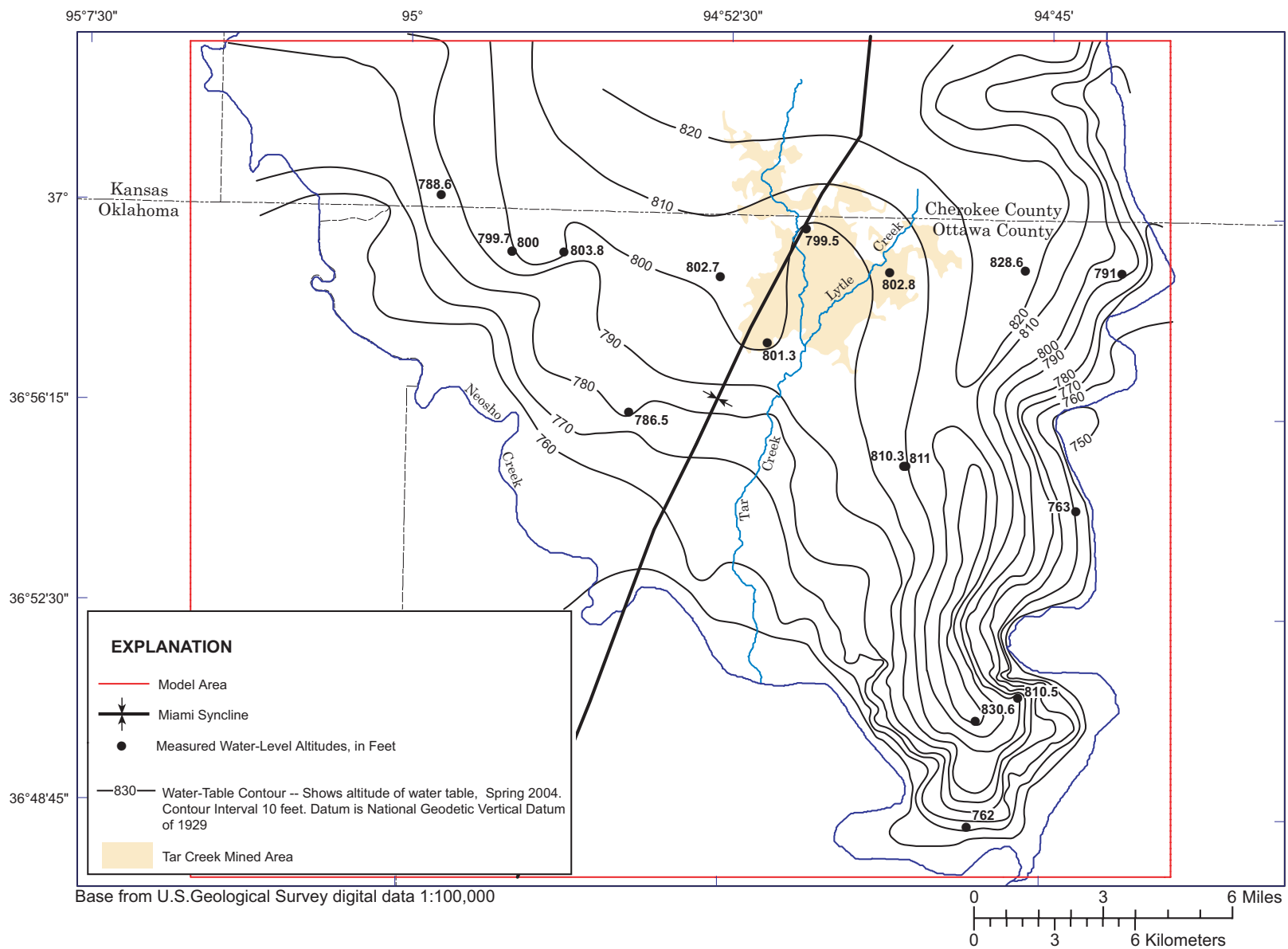


Figure 6. Water-level altitudes in Boone Formation in spring 2004.

Streams

A number of streams flow across the model area and exchange water with the Boone Formation. The flow of water through streambeds is dependent on the transmissive properties of the streambed and the difference between the head in the aquifer and the stream stage. Streams such as the Spring River and the Neosho River are presumed to have a good hydraulic connection with the Boone Formation because they are deeply incised into the Boone Formation or overlying units. Two other perennial streams in the model area are Tar and Lytle Creeks. Observations indicate that stages in these streams are both above and below observed ground-water altitudes at various locations (DeHay and others, 2004).

Lateral Flow from North

Although water-level data were not available to the north of the modeled area, land-surface altitudes increase in that direction. Water-level altitudes in a shallow aquifer generally may follow topography (Spruill, 1987, p. 13). Therefore, for model calibration purposes, the assumption was made that water-level altitudes along the northern border of the modeled area generally follow topography and are higher than those to the south.

Hydrologic Properties

Carbonate rocks predominate in the model area and consist mostly of dolomites and limestones. The Boone Formation yields as much as 750 gallons per minute (Christenson and others, 1994, p. 6). Efforts to dewater the Boone Formation to enable mining in 1932 resulted in an average of about 1,730,000 cubic feet of water per day (about 20 cubic feet per second) being pumped (Reed and others, 1955, p. 53). The hydrologic properties of carbonates will vary greatly, particularly because of post-depositional erosion and fracturing. The ground-water contours (fig. 6) are highly variable with steeper contours along the topographic high area along the eastern part of the model area and flatter contours further west in the area around the Miami Syncline. Areas of relatively large horizontal hydraulic gradients may be associated with lower values of vertical or horizontal hydraulic conductivity. Values of horizontal hydraulic conductivity, or horizontal anisotropy, may be larger along the axis of the Miami Syncline because of fracturing. The presence of the mined zone may be related to fracturing along the Miami Syncline that may have contributed to hydrothermal deposits of lead and zinc ore (McKnight and Fischer, 1970, p. 142-145). Preferential flow caused by anisotropy also may occur along the axis of the Miami Syncline.

Description of Ground-Water Flow Model

Ground-Water Modeling Tool

The USGS finite-difference, three-dimensional, ground-water flow model MODFLOW-2000 (Harbaugh and others, 2000) was used to develop and calibrate the ground-water flow models for the site. MODFLOW-2000 was used to solve finite difference ground-water flow equation approximations for spatial distributions of hydraulic head over time with certain simplifying assumptions. The head is calculated at the middle of each model cell and flux is calculated into or out of each cell in the three flow directions (X and Y, horizontal vectors; and Z, vertical vector) across the six cell faces (Pollock, 1994). The Preconditional-Conjugate-Gradient (PCG) solver was used to solve the finite-difference equation. The calibrated model was used to simulate ground-water flow in the aquifer and to evaluate the range of plausible values for hydrologic characteristics.

Preliminary Ground-Water Flow Model

A preliminary model of the ground-water flow system was developed by the present authors that included the Boone and the Roubidoux Formations. This preliminary model was used to evaluate whether (1) mine voids could be modeled in a regional ground-water flow model, and (2) whether there was substantial flow between the Roubidoux and Boone Formations. This model covered the same area as the present model but was divided into a coarser grid with cells four times wider (200 meters) than those of the present model. Also, the model was divided into an additional two layers representing the Roubidoux Formation and the units between the Boone and Roubidoux Formations. This model successfully simulated mine voids with high horizontal conductivities. When calibrating the cones of depression formed by pumping in the Roubidoux Formation it became necessary to restrict flow by adding the Miami Syncline as a barrier to flow and to restrict flow from above into the Roubidoux Formation. The latter results also indicate minimal flow from the Roubidoux Formation upwards into the Boone Formation justifying a no-flow boundary at the bottom of the present model.

Simplifying Assumptions for Boone Model

By definition, a model is a simplification of a process or a system. In that regard all the units above the Boone Formation were lumped into a single layer (layer 1). The underlying Boone Formation was simulated as two layers (layers 2 and 3) with the upper 40 feet comprising the mined zone (layer 2) and the rest of the formation simulated by the lower layer (layer 3). The northern boundary of the model was simulated as a general-head boundary. The base of the Boone Formation was modeled as a no-flow boundary (consistent with preliminary model findings).

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As ground-water withdrawals within the Boone Formation are considered to be negligible because municipalities rely on better-quality water from the underlying Roubidoux Formation, no ground-water withdrawals were simulated. Recharge is considered to be constant over the period of simulation. Variations in hydraulic conductivity within cells and across areas of the model are considered to be of negligible importance to the ground-water flow system. Fracture and dissolution openings are extensive enough in both areal and vertical distribution that the hydrogeologic units can be simulated as porous media.

Model Specifications

Finite-Difference Grid

The model grid was subdivided into a horizontally uniform cell network of 580 rows and 680 columns (fig. 1). Each cell was 164 feet (50 meters) on a side. Vertically the model was divided into three layers of variable thickness. The first layer represents all of the post-Boone Formation units and is absent in the southeastern part of the model area where the Boone Formation is exposed at land surface and the upper units have been removed by erosion. The second and third layers represent the Boone Formation with the second layer, a uniform 40 feet thick, representing the mined zone of the formation, and the third layer representing the remainder of the Boone Formation. The active model area includes the 230,203 cells between the Neosho and Spring Rivers (fig. 7).

Initial Hydraulic-Head Values

Initial hydraulic-head values for the Boone Formation were derived from the mean values of historic water-level altitudes from observation wells over the whole period of record from data from the U.S. Geological Survey (2006). Initial hydraulic-head values of the other layers for which no historic data were available were estimated or derived from these heads.

Stress Period Discretization

The model was calibrated by specifying one steady-state stress period (stress period 1), in which no changes in storage take place and the simulated hydraulic head results from the hydrologic system being in equilibrium with specified boundary conditions. The absence of pumping from any of the simulated units made it unnecessary to simulate transient conditions with hydraulic head changing over time. In subsequent simulations of selected potential remediation scenarios, hydraulic head was allowed to vary with time, requiring specification of an additional transient stress period (stress period 2) representing 100 years.

Flow-Boundary Conditions

Areal Recharge

Areal recharge is that portion of precipitation that is not lost to runoff, direct evaporation, evapotranspiration, or direct interception by plants. Given that chat piles, ponds, and open shafts into the mines cover portions of the model area, areal recharge is not likely to be spatially uniform. For this model, a uniformly distributed recharge rate of 0.0012 foot per (5.3 inches per year) was specified across the uppermost active layer.

Streams

The Spring and the Neosho Rivers, with their confluence in the Grand Lake of the Cherokees, were simulated as the major discharge locations for the Boone Formation using the MODFLOW river package (Harbaugh and others, 2000). Tar and Lytle Creeks, which flow across the mined area, also were simulated as streams. The stream stages were estimated from land-surface altitudes (fig. 2), and the stream cells were placed in layers 1 and 2 (fig. 7). The conductance of the streambed is calculated as the surficial area of the stream covered by the model cell multiplied by the vertical hydraulic conductivity of the streambed material divided by the thickness of the streambed. Streambed conductances were adjusted during model calibration to match observed water levels and specified for the Neosho and Spring Rivers as 25,000 feet-squared per day; values for Tar and Lytle Creek were 500 and 100 feet-squared per day, respectively.

Drains

Flow accumulation methodologies using ARCGIS software (Environmental Sciences Research Institute, 2006) were used with land-surface altitude data to locate topographically low areas in layers 1 and 2 where surface flow would accumulate. These areas coincide with intermittent creeks on maps and were simulated with drains with altitudes set at land-surface values (figs. 2 and 7). When simulated heads within the top layer exceed the land-surface altitude, the model simulates discharge. Drain conductance is calculated as a uniform 9999.1 feet-squared per day. Thus, projection scenarios may be simulated and the model will account for any resulting induced surface flow from the ground-water flow system.

Lateral Fluxes

To simulate ground-water flow from the north, general-head boundary cells were specified along all three layers. The heads for these cells were selected to best represent the water-level altitudes in the north. Values of hydraulic heads were specified as 10 feet below the land-surface altitude (fig. 2) along

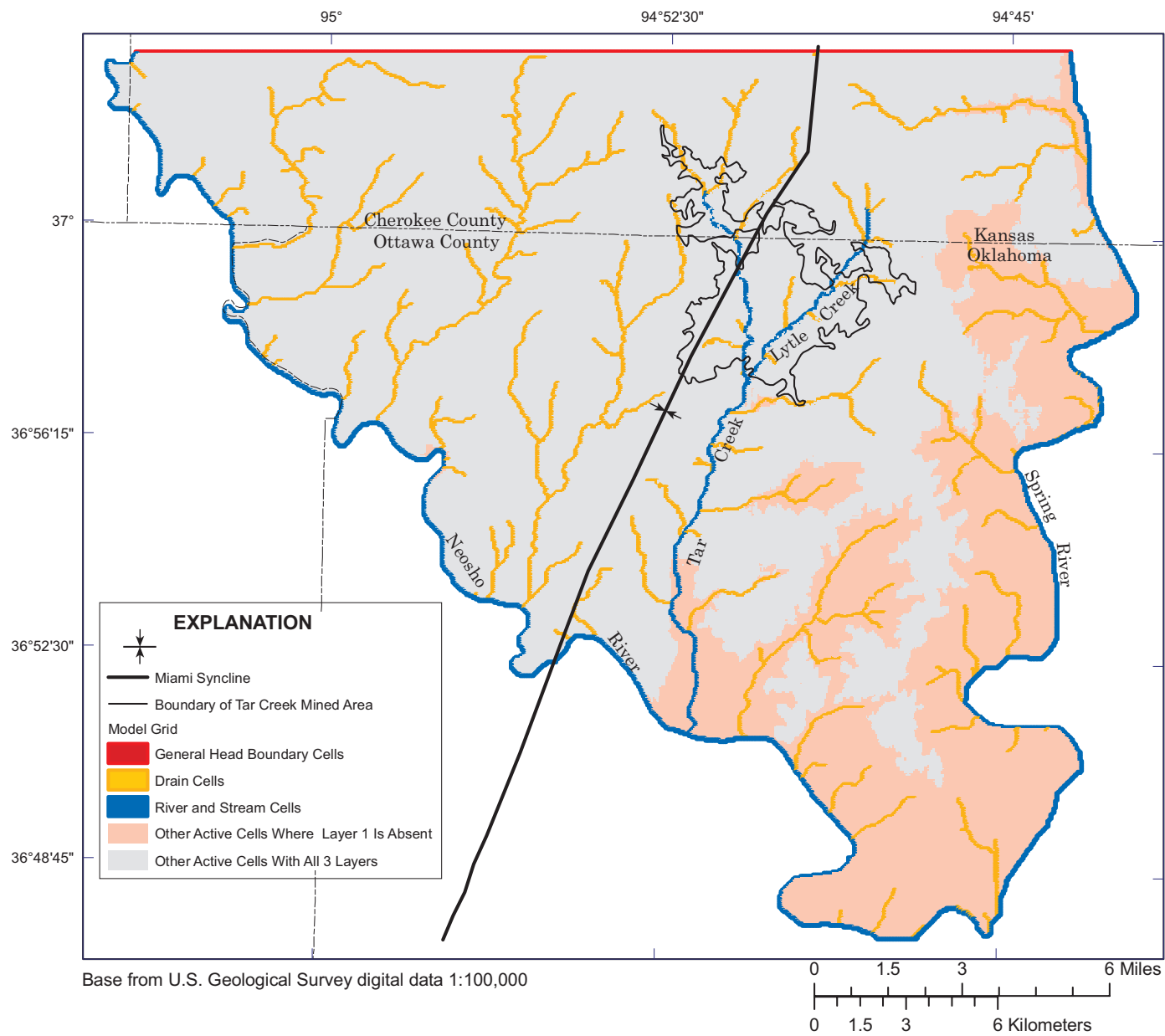


Figure 7. Finite difference grid of active cells of the model showing river cells and general head boundary cells.

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most of the northern boundary with depths below land surface gradually tapering to zero at the Spring and Neosho Rivers. Conductance terms for the general-head boundary cells were adjusted during model calibration, which was specified as 25 feet-squared per day after calibration.

Water Use

Water-use data from 2000 (Andrew Scurlock, Oklahoma Water Resources Board, written commun., 2004; Robert Tortorelli, U.S. Geological Survey, written commun., 2004) were used during the construction of an earlier version of the model developed by the present authors that included the Roubidoux Formation. These data indicated no substantial withdrawals from the Boone Formation. All public supply wells in the model area are completed in the Roubidoux Formation (David Cates, Oklahoma Department of Environmental Quality, oral commun., 2005). Therefore, no well withdrawals from the Boone Formation were simulated in the model.

Hydrologic Properties

Horizontal Hydraulic Conductivity

Hydraulic-test data and estimates of horizontal hydraulic conductivity for the Boone Formation were unavailable for the model area. Freeze and Cherry (1979, p. 29) provide general ranges of hydraulic conductivity from about 0.0005 to 0.60 feet per day for limestones and dolomites and about 0.1 to 2,000 feet per day for karst limestone. Given the large variability in ground-water gradients (fig. 6), it is likely that there is large variation in hydraulic conductivity in the Boone Formation and overlying units. Hydraulic conductivity was zoned along the axis of the Miami Syncline with a central zone close to the fault containing most of the mined zones. Separate zones of hydraulic conductivity were used on the east and west flanks of the central zone (fig. 8). Further zonation was based on hydraulic gradients, some of which appear to be related to the Miami Syncline. This zonation was used in all layers. Horizontal and vertical hydraulic conductivity as well as horizontal anisotropy were adjusted during model calibration. Hydraulic conductivity may be higher along the axis of the Miami Syncline than across it because of faulting. Layer 2 consists of that portion of the Boone Formation containing the mined zone (fig. 8). Hydraulic conductivity in model cells coinciding with the mapped spatial extent of the mined zone were specified with a horizontal hydraulic conductivity of 50,000 feet per day. The orientation of the horizontal anisotropy is north-south within the model grid, which approximates an orientation along the axis of the Miami Syncline. Excluding the mined zone, horizontal hydraulic conductivity in the calibrated model ranges from 1.3 to 7 feet per day near the Spring River where a larger hydraulic gradient exists and from 10 to 35 feet per day throughout much of the rest of the active model area (fig. 8). The horizontal anisotropy in

the central zone along the axis of the Miami Syncline was 10 to 1 after calibration.

Vertical Hydraulic Conductivity

Vertical hydraulic conductivity was assumed to be less than horizontal hydraulic conductivity. Vertical flow likely occurs predominantly within vertical fractures connecting horizontal bedding planes. For limestone and dolomite formations, interbedded layers of less permeable material such as clay or shale may further reduce the vertical hydraulic conductivity. Vertical hydraulic conductivity was specified through use of a vertical anisotropy term to be 2 percent giving a vertical hydraulic conductivity 2 percent the value of the horizontal hydraulic conductivity for all cells except for within the mined zone. The voids in the mined layer were assumed to be isotropic, in which a 1:1 ratio of vertical to horizontal hydraulic conductivity was used.

Storage

For the calibrated model, steady-state conditions were specified; hence, no storage terms were specified. Storage properties were specified in the subsequent potential remediation scenarios using the calibrated model with an additional transient stress period. Specific storage for all layers was specified as 0.00001, which is the amount of water released from storage because of the compressibility of the rock matrix and the expansion of water for a unit decline in hydraulic head under confined conditions. The specific yield for layers 1 through 3 was set as 0.20, which represents the amount of water released from storage for a unit decline in hydraulic head under unconfined or water-table conditions. For model cells representing the mined zone, specific yield was set to 1.0. Storage values are needed for the particle-tracking analysis (Pollock, 1994) (see Simulation of Selected Potential Remediation Scenarios' section later in this report).

Faults

Reed and others (1955, p. 109) concluded from pumping tests that the Miami Syncline (fig. 2) was a barrier to ground-water flow perpendicular to the syncline axis, likely caused by accompanying faults. As such the Miami Syncline was simulated in layer 3 using horizontal flow barrier cells (Harbaugh and others, 2000). The calibrated hydraulic conductivity across the faults, represented by the Miami Syncline axis in figure 7, was 1×10^{-6} feet per day.

Model Calibration

Model calibration was performed through manual adjustment of model variables to minimize the differences between measured and simulated water-level altitudes at 17 wells and

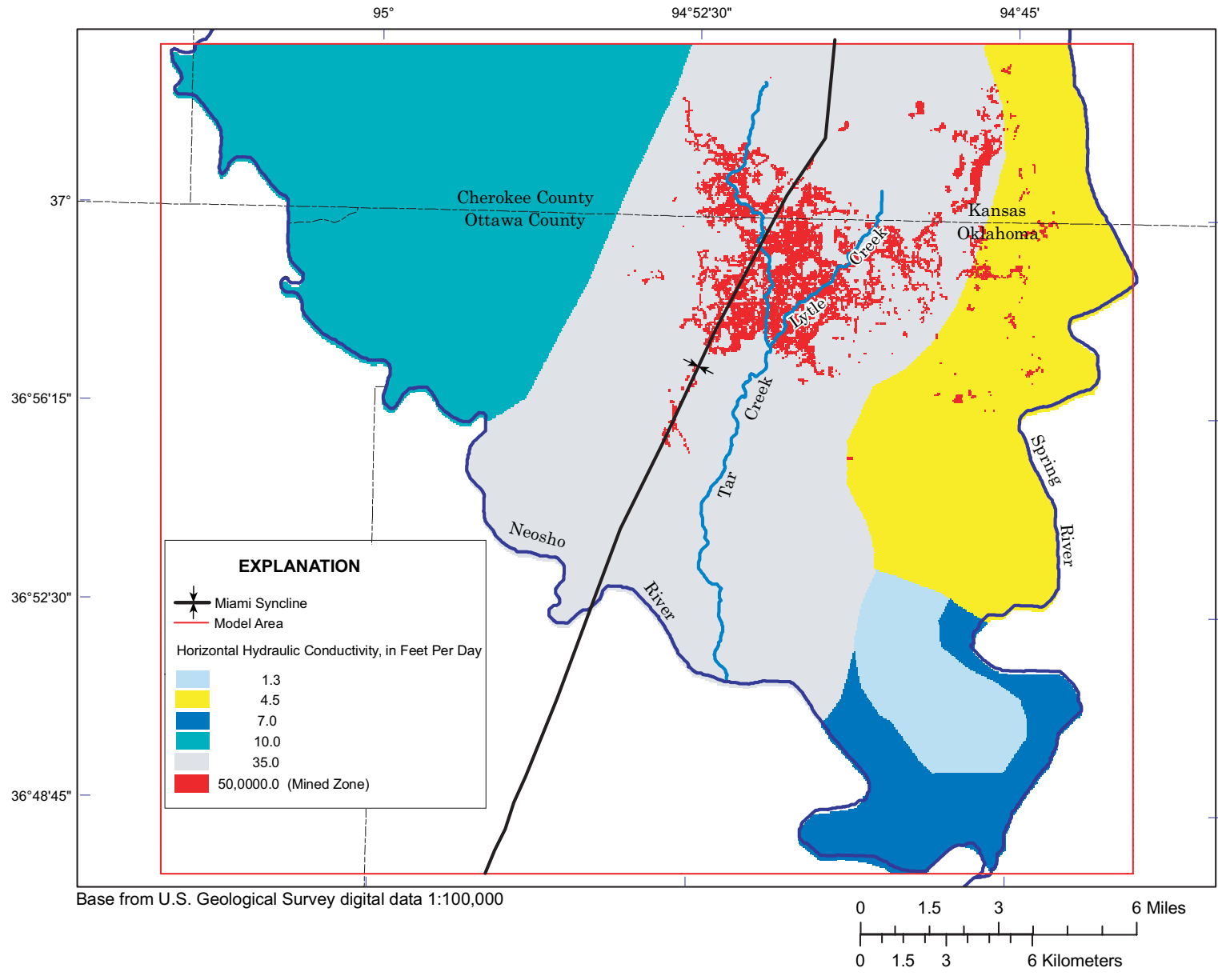


Figure 8. Selected zones used for uniform horizontal hydraulic conductivity with final calibration values.

airshafts (fig. 6, table 1). The variables for recharge, specific storage, specific yield, and conductance terms for general-head boundaries, rivers, drains, and faults were applied uniformly throughout the relevant layers or cells. Horizontal hydraulic conductivity and vertical and horizontal anisotropy were varied over specified zones. In particular, the horizontal hydraulic conductivity in all layers except for the mined zone in layer 2 was varied in the different zones shown in figure 8 with larger values specified in the central zone along the axis of the Miami Syncline and smaller values specified along the east and west model areas.

Model Evaluation

The mass balance of the calibrated model represents the simulated sources and sinks to and from the model. The mass balance values show that water mostly enters the model from areally distributed recharge, and discharges by way of streams or drains (fig. 9). These model fluxes reflect model mass balance error with slightly different fluxes simulating entering or leaving the model. Figure 10 shows simulated ground-water fluxes at the end of stress period 2 for general head boundary cells in all layers along the northern boundary, the total stream fluxes, and the total drain fluxes. Positive values indicate flow into the model, negative values indicate flow out of the model. Fluxes generally were positive along the northern boundary except along the extreme west. Fluxes generally were negative along streams except along the upper reaches of Tar and Lytle Creeks.

Simulated water-level altitudes in layer 3 at the end of stress period 1 generally were highest along the northern boundary and decreased southwards and eastward toward the Neosho and Spring Rivers and their confluence (fig. 11). These results generally are consistent with the described geohydrological setting. The simulated water-level altitudes for layer 3 were shown because only the model cells in layer 3 were continuous throughout the model. The heads in layers 1 and 2 generally were less than 2 feet different from the heads in layer 3 except near stream boundaries and drains.

Measured water levels in 17 wells and airshafts were used as a basis for calibrating the flow model. Figure 12 shows the distribution of residuals (the difference between measured and simulated water levels) for the 17 observation wells and airshafts used in model calibration. Table 1 shows data for these wells. Negative residuals indicate that measured water-level altitudes were lower than those simulated; positive residuals indicate that measured water-level altitudes were higher than those simulated. Residuals had a root-mean-squared value of 8.53 feet and an absolute mean value of 7.29 feet. These values are relatively small when compared with the range in simulated head of about 80 feet and indicate a generally reasonable fit to the observed water levels.

The maximum residual is 14.7 feet and the minimum is -16.1 feet. The minimum residual is in an area of large hydraulic gradients. The mean of the residuals is 2.3 feet and the median value is 3.04 feet. The distribution of residuals is reasonably well distributed indicating minimal model bias. (fig. 13). Spatially, negative residuals are found more in the east than elsewhere.

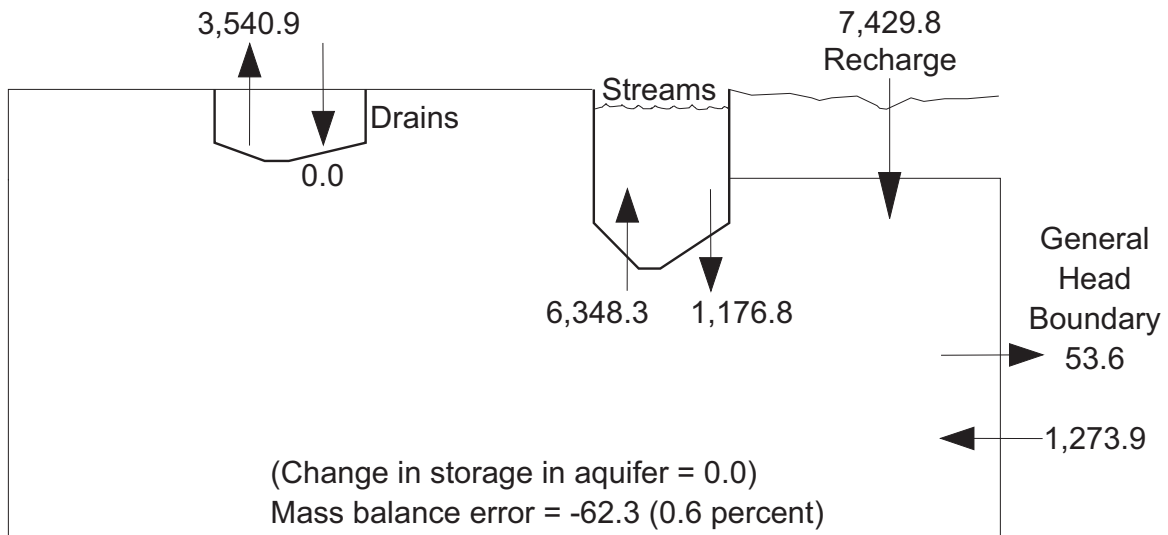


Figure 9. Volumetric budget components, in cubic feet per day, for the first stress period.

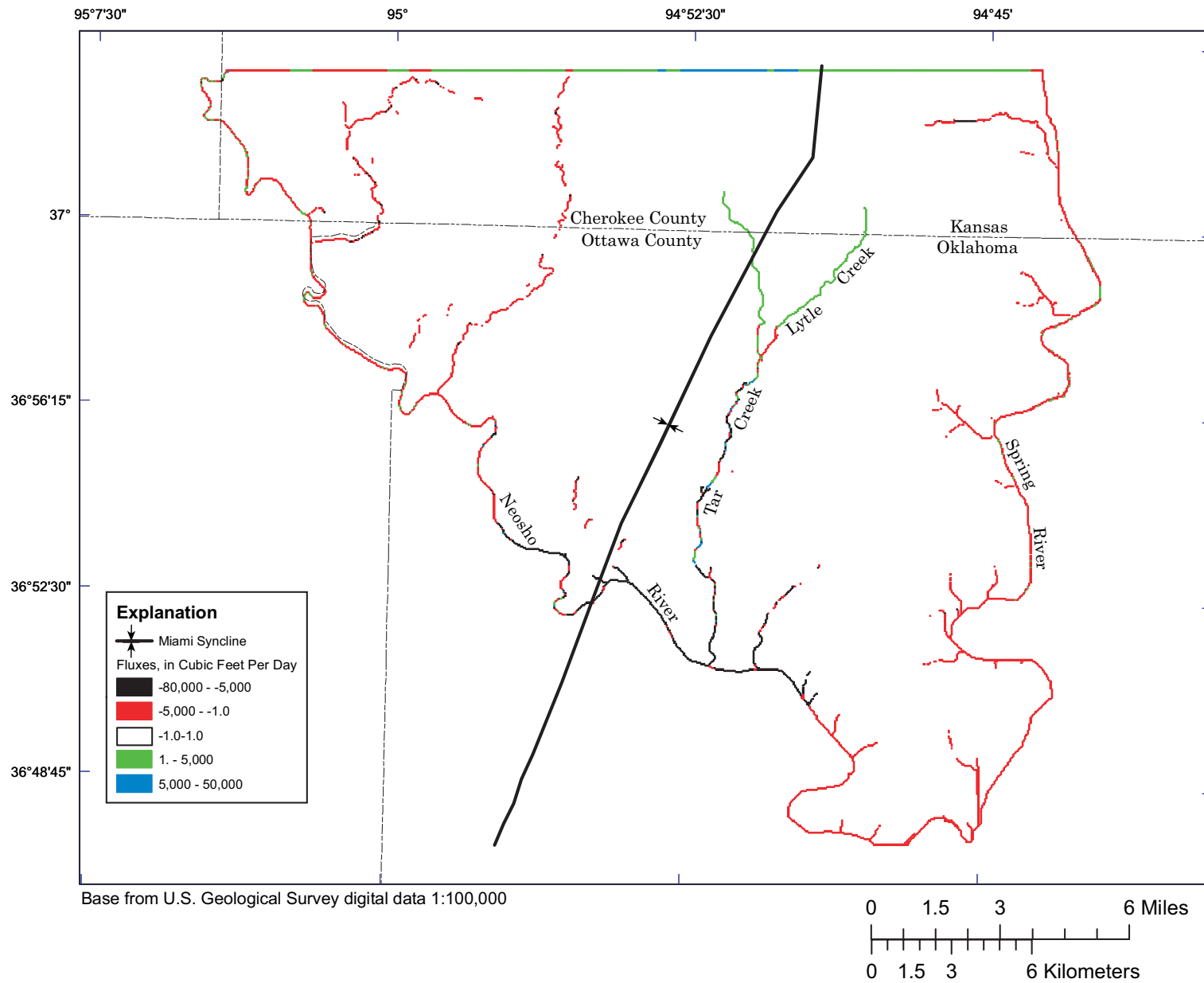


Figure 10. Streams, constant head, and drain fluxes in the Boone Formation at the end of stress period 1.

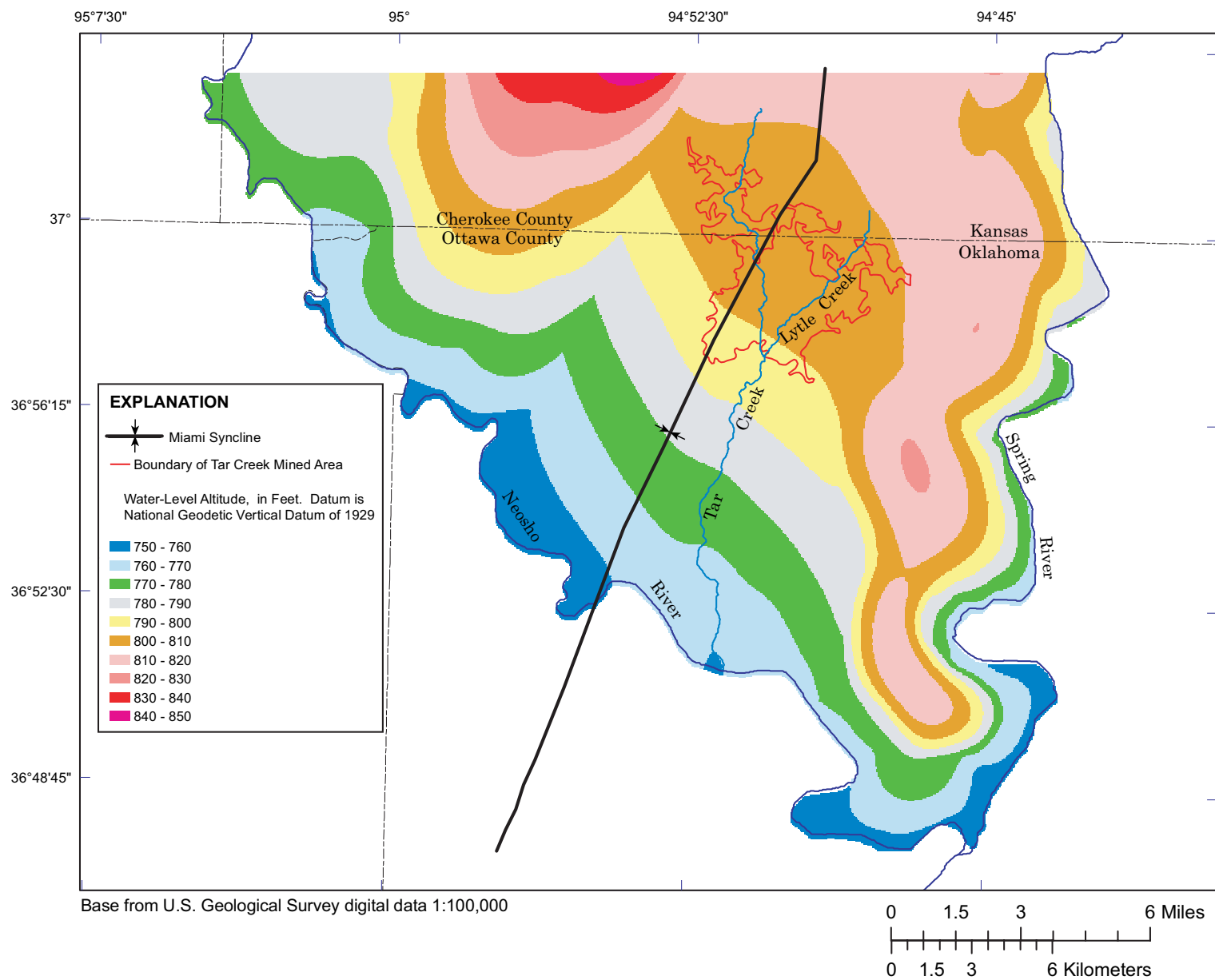


Figure 11. Simulated water-level altitudes in Boone Formation in layer 3 at the end of stress period 1.

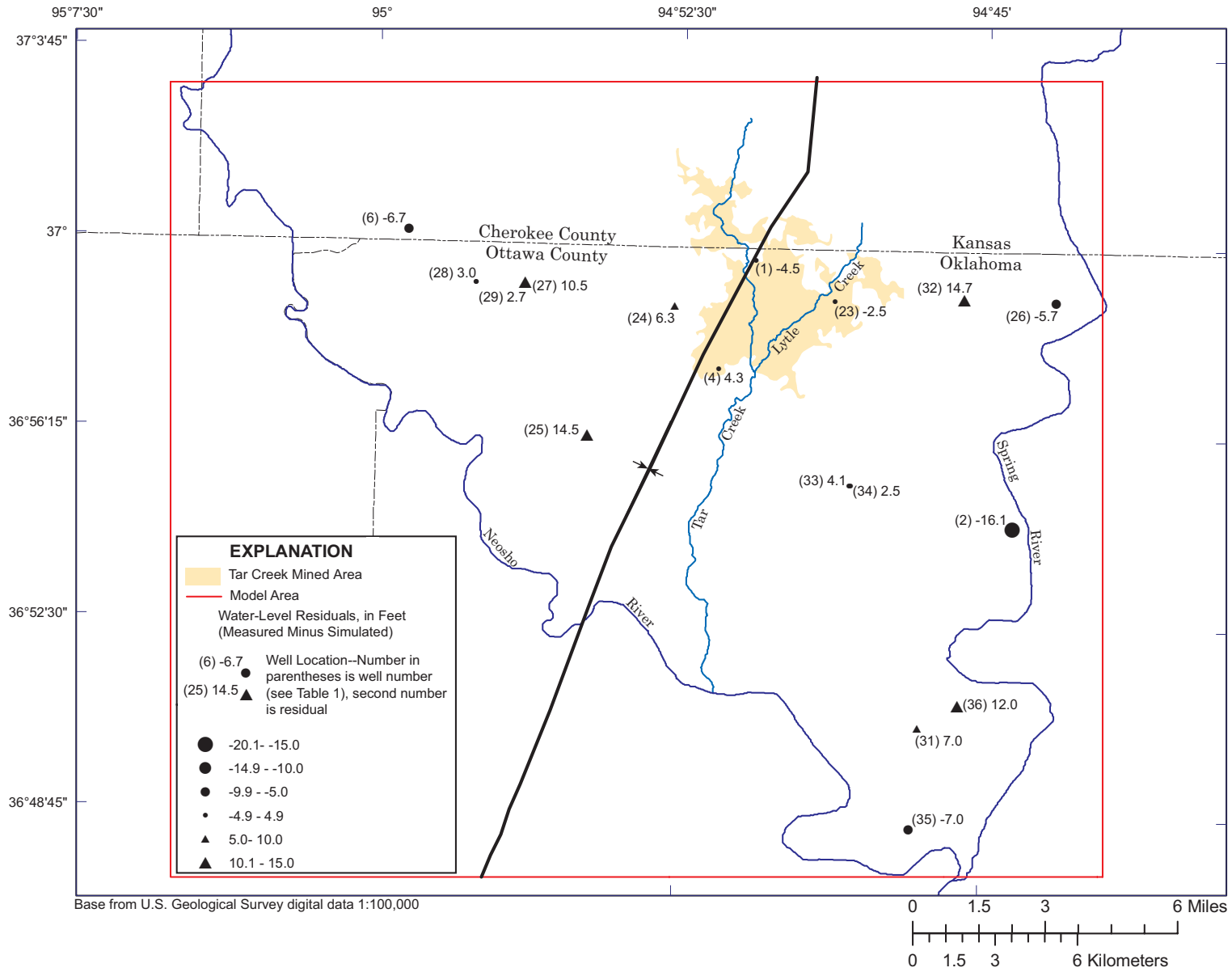


Figure 12. Water-level residuals for observation wells in the Boone Formation at the end of stress period 1.

A comparison was made of the sum of simulated surface discharge from river cells from the confluence of Tar and Lytle Creeks and the measured values for USGS gage 07185095 on Tar Creek at Miami, Okla. (Robert L. Tortorelli, U.S. Geological Survey, written commun., March 15, 2006). The simulated value was about 5.7 cubic feet per second as compared to a value of 2.58 cubic feet per second that was observed to be equaled or exceeded 90 percent of the time at the gage, and a value of 5.72 cubic feet per second that was observed to be equaled or exceeded 70 percent of the time at the gage. Differences in the simulated surface-water discharge and the observed streamflow may be attributed to uncertainty in the streambed conductance term used in the model or simulating a hydraulic head in the aquifer beneath the stream channel that is higher than the actual value.

Calibrated horizontal hydraulic conductivity values for the Boone Formation (layers 2 and 3) ranged from 1.3 to 35 feet per day (excluding the mined zone). Spatial distribution of these horizontal hydraulic conductivity values is shown in figure 8. The higher value of 35 feet per day was specified along the central axis of the model that encompasses most of the mined zone and follows the axis of the Miami Syncline. Also, horizontal anisotropy was specified equal to 10 along this central axis (excluding the mined zone) and 1 elsewhere including the mined zone. Thus, the north-south hydraulic conductivity tensor is 350 feet per day in cells in the central axis associated with the Miami Syncline area, which might be expected in an intensely fractured zone. Vertical hydraulic conductivity was specified as 2 percent of horizontal hydraulic conductivity

throughout the model. Specific yield was specified equal to 0.20 throughout the model and specific storage was 0.00001.

Sensitivity Analyses

The sensitivity of the model-simulated water levels at observation wells to changes in specific model variables was examined by performing successive model simulations and varying the value of the model variable. This was accomplished by using successive multipliers applied to the variable being analyzed, and comparing the mean absolute value of the water-level residuals from each simulation to that of the baseline values of the original calibrated model. The model variables analyzed were: (1) horizontal hydraulic conductivity along the central axis of the Boone Formation (fig. 8), (2) horizontal hydraulic conductivity within the mined zone (fig. 8), (3) river conductance terms in the Neosho and Spring Rivers, (4) river conductance terms in Tar and Lytle Creeks, (5) vertical anisotropy in the second layer that contains the mined zone (but excluding the mine cells); and (6) horizontal anisotropy along the central axis. The effect of these variables on water-level residuals is shown in figure 14. These sensitivity analyses show that the model is relatively insensitive to changes in these variables. Of the model variables tested, the largest sensitivity was associated with horizontal hydraulic conductivity and horizontal anisotropy along the central axis. The sensitivity analysis shows that changing the horizontal hydraulic conductivity a horizontal anisotropy along the central axis by factors of 2 and 0.5 has the effect of increasing change in average absolute resi-

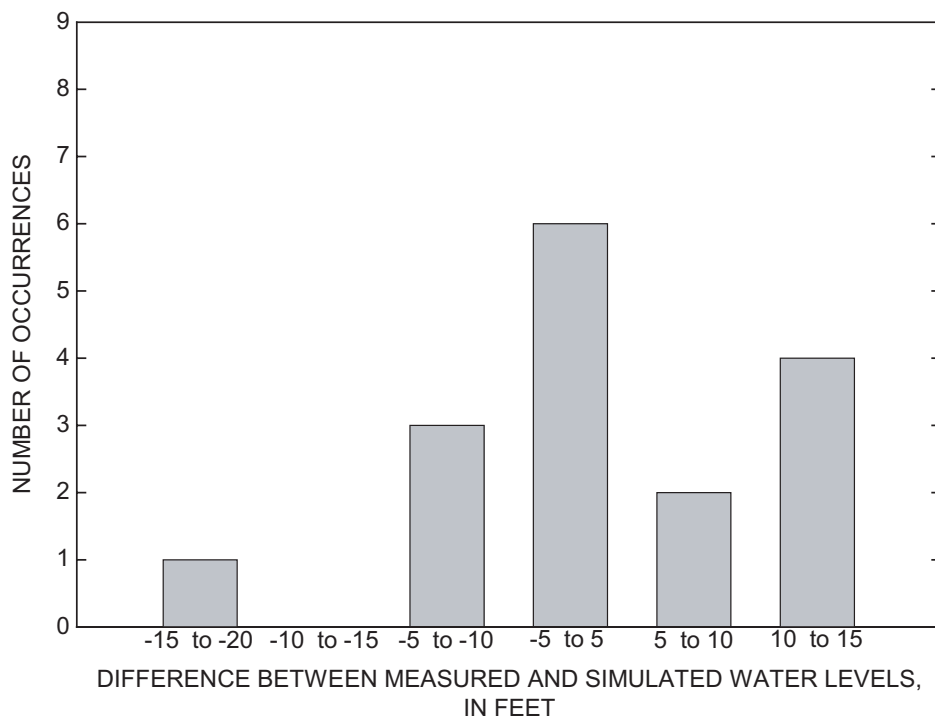


Figure 13. Difference between measured and simulated water levels in the Boone Formation at the end of stress period 1.

dual from that of the baseline values of the calibrated model by as much as 3 feet. Changing the other model variables rarely changed the average absolute residual by more than 0.50 foot.

Model Limitations

The ground-water flow model described in this report is useful in evaluating the flow system in the model area. However, the model results represent a simplification of the system, and the following limitations should be considered. Flow in the Boone Formation mainly is through secondary porosity and modeling this flow as equivalent to flow through a uniformly porous media may add error especially with regard to travel time. The steady-state simulation used for the initial head conditions assumes that flows into and out of the model area were equal. If this were not so, the change in ground-water storage (that is, if water levels were actually rising or falling) would be a source of model error. The lack of data relating to streamflows or hydrologic properties of the aquifer adds further uncertainty. Model input parameters are applied over extended areas and assumptions of uniformity for heterogeneous geologic materials may produce inaccuracies. The particles used in particle tracking in the simulation of potential remediation scenarios (see Simulation of selected Potential Remediation Scenarios section) do not simulate chemical reactions, and, as such, the pathlines and time of travel cannot simulate sorption, dispersion, and diffusion and will not accurately reflect the movement of chemically active material.

Simulations of Selected Potential Remediation Scenarios

The calibrated model was used to simulate the flow system for hypothetical scenarios in which portions of the mine were filled completely with chat. Simulations were run such that an additional transient stress period (stress period 2) was added to the model and was set to a length of 100 years. The flow model results were used in conjunction with MODPATH (Pollock, 1994), a computer program to compute ground-water flow paths, thus permitting the analysis of flow paths and the time of travel for ground water to flow to a point along a flow path. Hydraulic-property distributions from the calibrated model were used in a baseline transient model of the site, from which subsequent scenarios involving various hydraulic-property distributions associated with chat emplacement in the mines could be compared. Two additional transient model scenarios were used to simulate these chat emplacements.

The hydraulic properties were altered to simulate the emplacement of chat into the mined zone in four locations. Figures 15 and 16 show these four locations as well as the portions of the mine filled during the scenarios. Potential chat emplacement sites Rmb#3, Frye, and Fcb2 are located within a mile of each other within the main body of the mine, while site

Occ#3 is located in an outlier of the mine about 3 miles southwest of the other three sites. To model chat emplacements, mine-cell properties in cells that would be filled with chat were assigned the same hydraulic conductivity and storage values as the surrounding Boone Formation. This assignment was considered to represent the largest impedance to ground-water flow by material introduced into the mine. The flow model then was run with a simulation time of 100 years.

Two scenarios were simulated in which successively larger portions of the mine were filled with chat material at four sites (figs. 15-16). In the first scenario, mine-cell properties were modified to reflect the emplacement of a total quantity of about 1,800,000 tons of chat (mine waste consisting of fines and fragments of chert) distributed over the four sites, by changing the hydraulic properties assigned to either seven or eight cells at each site (depending if sufficient cells were available at a site). In the second scenario, the amount of chat was increased to about 6,500,000 tons by changing 25 to 28 cells at each site. To assess the number of cells that this weight of chat would occupy in the model, an average density of about 100 pounds per cubic foot (Fogt, 2005) was assumed, the volume of which was distributed within cells with an average thickness of 40 feet within the mined zone. The volume of each mined cell was about 1,000,000 cubic feet. The locations of cells within layer 2 at each site that were modified to reflect chat emplacement are shown in figures 15 and 16. Mine cells associated with the Frye chat emplacement site were combined with those of Fcb2 for convenience in model property assignment in Scenario 1 resulting in cell assignments occurring somewhat to the south of the Frye site.

Water-Level Altitude Differences

Differences in water-level altitudes between the baseline transient model and the two chat emplacement scenarios generally are not large (figs. 17 and 18). Because less flow occurs through the chat, water levels declined for a mile or more immediately downgradient from the chat emplacements by as much as 2 feet in scenario 1 and 3 feet in scenario 2. Hydraulic-head changes in layer 2 cells north of the three chat emplacements indicate a small rise in head of 0.25 feet or less over the mined area in both scenarios 1 and 2 (figs. 17 and 18). Along Tar Creek, south of the confluence with Lytle Creek, the head difference is generally between -0.02 and 0.02 foot for both scenarios. As 0.02 foot is the head closure criteria used in the model, the consequent simulated flux changes along this portion of Tar Creek are within the numerical error range of the model. The regular curvilinear structures apparent throughout figures 17 and 18 are artifacts of the model and have no hydrologic significance. In general, chat emplacement had minimal effect on the direction and rate of movement of ground water when compared to baseline, or current flow, conditions.

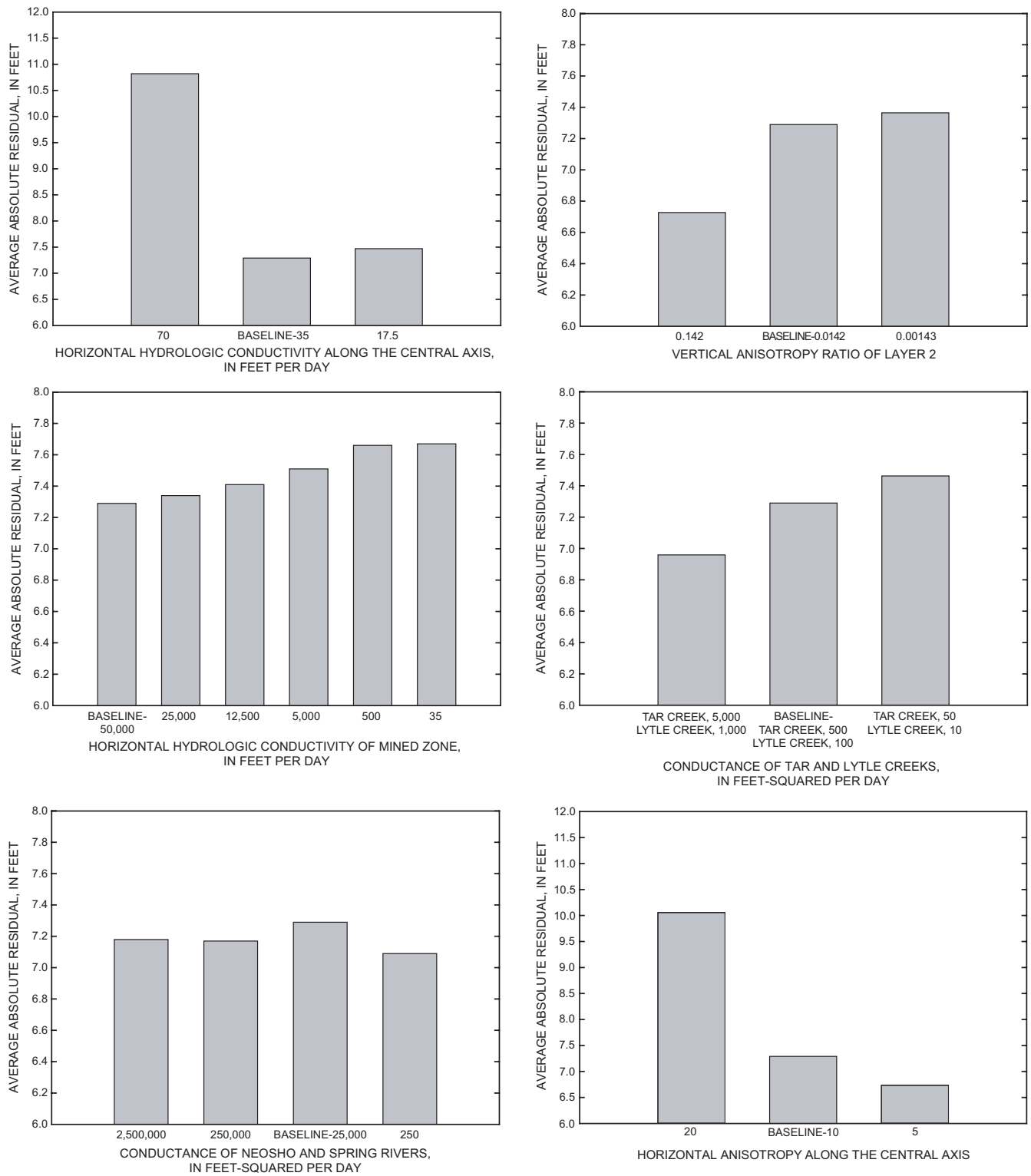


Figure 14. Sensitivity analysis for input model variables.

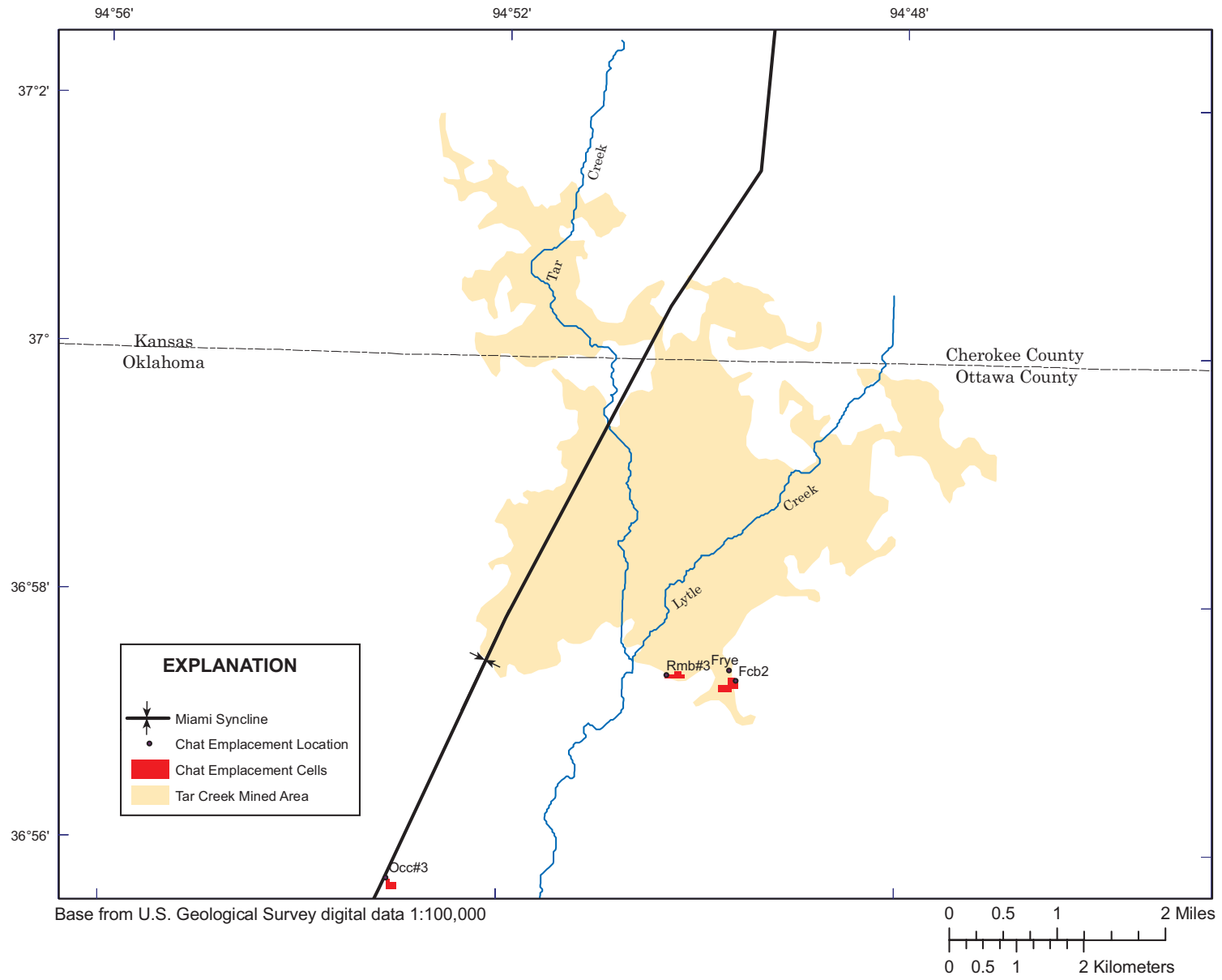


Figure 15. Location of chat emplacements for scenario 1.

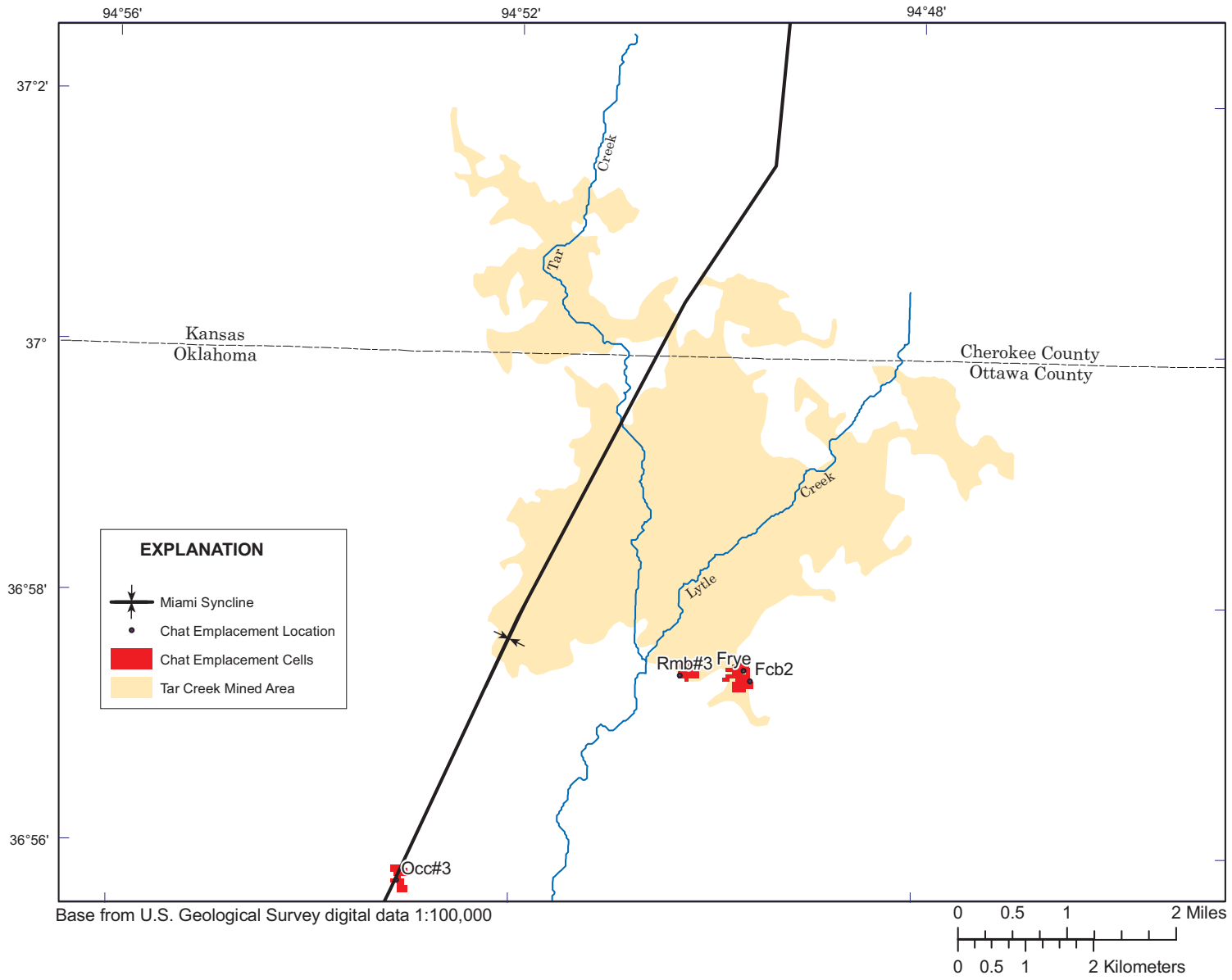


Figure 16. Location of chat emplacements for scenario 2.

Surface Flux from Drains and Streams

The changes in drain and stream fluxes from the baseline model to the two scenarios are small and are illustrated in figures 19 and 20 in gallons per minute rather than cubic feet per day to help illustrate this point. One gallon per minute equals 192.5 cubic feet per day. The flux change shown in figure 19 or 20 rarely exceeds 0.10 gallon per minute, and the maximum flux is about 3.5 gallons per minute distributed over a model cell face that is 164 feet by 164 feet. The fluxes shown in Tar Creek, south of its confluence with Lytle Creek, cross areas in figures 17 and 18 where the head change is within -0.02 and 0.02 foot. As 0.02 foot is the head closure for the model simulation, any lesser head change will not be accurately simulated. However, the head changes north of the confluence represent reliably simulated results. As heads increased north of the chat emplacement, the head difference between stream stages and the simulated head fell resulting in reduced stream flux into the model as shown in figures 19 and 20. Likewise, the areas of largest difference in stream flux between scenarios 1 and 2 are south of the confluence, and, thus, are not based on reliably simulated heads.

Surface flux changes between the baseline model and scenarios 1 and 2 rarely exceeded 100 cubic feet per day or about 1 gallon per minute for any of the model cells (figs. 19 and 20). Given that surface flux and water-level altitude in a cell are related, these differences are consistent with the calculated differences in simulated water-level altitudes between the baseline and chat-emplacement scenarios.

Ground-Water Velocity

Estimates were made of ground-water velocity in the mined zone using the simulated fluxes from the model. Two horizontal flux vectors and one vertical flux vector were added, divided by the area of the cell faces, and the result divided by the specific yield of 0.20 to provide the ground-water velocity (Pollock, 1994). The mean simulated velocity in 9,336 cells in the mined zone was 3.20 feet per day for the baseline scenario, 3.15 feet per day for scenario 1, and 3.12 feet per day for scenario 2. The differences in these distributions of ground-water velocity in the baseline model and the two scenarios is not large (fig. 21) and probably represent minor numerical inaccuracies in the models rather than physical realities.

The uncertainty of simulated values of velocity within the mined zone is reflected by the uncertainties of the simulated hydraulic gradient and of the specified hydraulic conductivity of the mine void. The hydraulic gradient in the mine void is expected to be very small but not zero. Flow around corners in the mined zone of the model can lead to larger simulated gradients and consequently larger velocities. Given the lack of actual measurements of water levels throughout the extent of the mine, the actual hydraulic gradient is difficult to quantify. With regard to mine hydraulic conductivity, a value was chosen that was several orders of magnitude larger than for the host rock of the mine. Neither value is well known, and, hence, there likely is

considerable uncertainty as to the actual magnitude of velocity, which could be in error by as much as an order of magnitude from those presented. This uncertainty also affects the resultant flow path analysis presented later in the report.

Particle Tracking

Using the particle-tracking routine, MODPATH, simulated particles were released in the center of cells in layer 1 along a row, north of the chat-emplacement with a porosity of 0.20, to simulate the introduction of material above the mined zone. For the Frye, Fcb2, and Rmb#3 sites, these simulated particles were released along a row about 8,000 feet long about a mile north of the Frye site. For the Occ#3 site, simulated particles were released along a row about 4,000 feet long just north of that site. These particles simulate the hypothetical movement of particles after 100 years of being released to follow the rate and direction of ground-water movement. There is relatively little difference in horizontal flow paths (direction and travel time) between the baseline scenario and the chat emplacement scenarios (fig. 22).

Vertically the particles move downward through the mined zone into layer 3 and then upwards towards the cells representing the Neosho River in layers 1 and 2 towards the end of the simulation. At 100 years (red colored portion of particle path), many particles from the Occ#3 site have traveled to discharge points along the Neosho River.

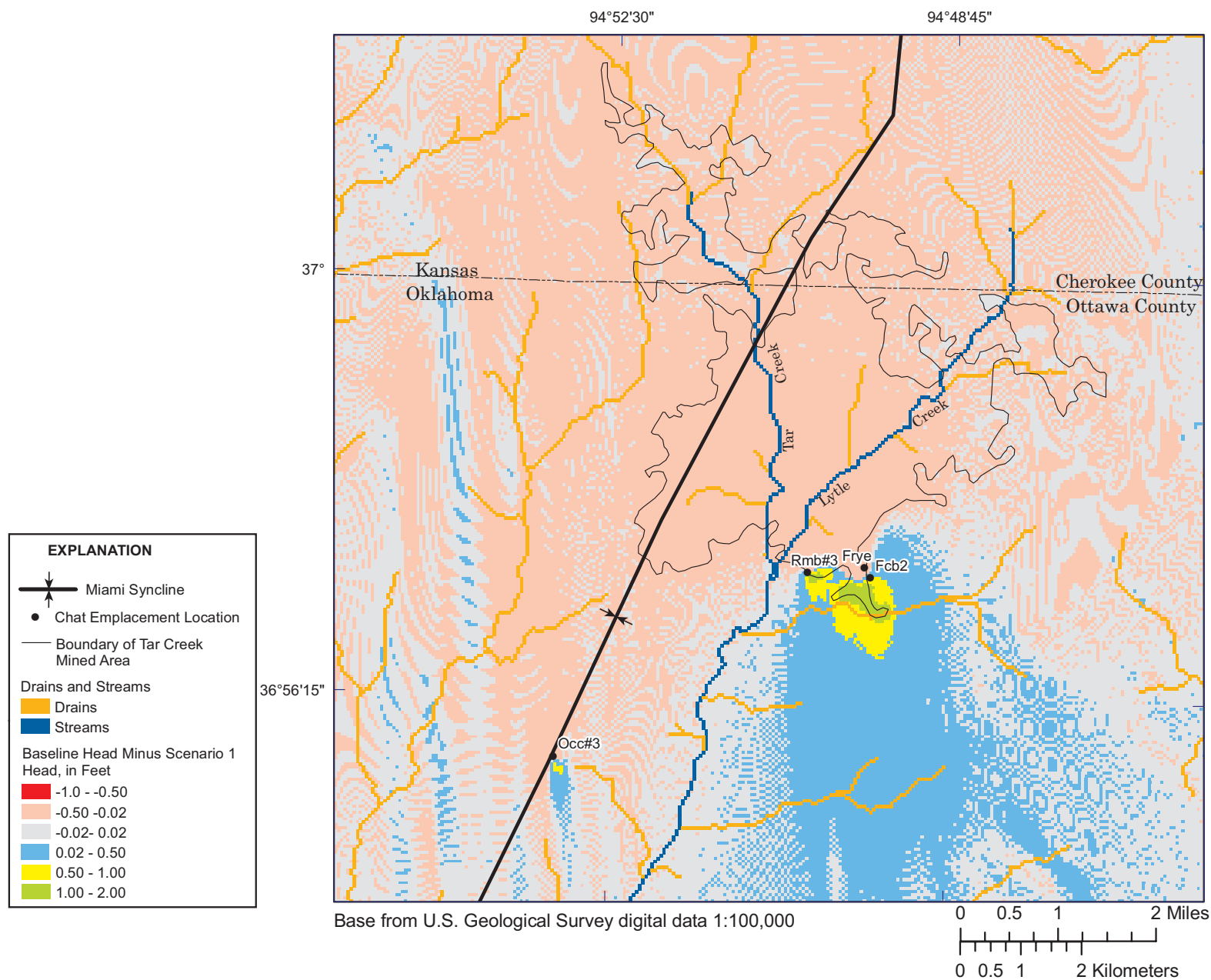


Figure 17. Water-level altitude differences between baseline and scenario 1.

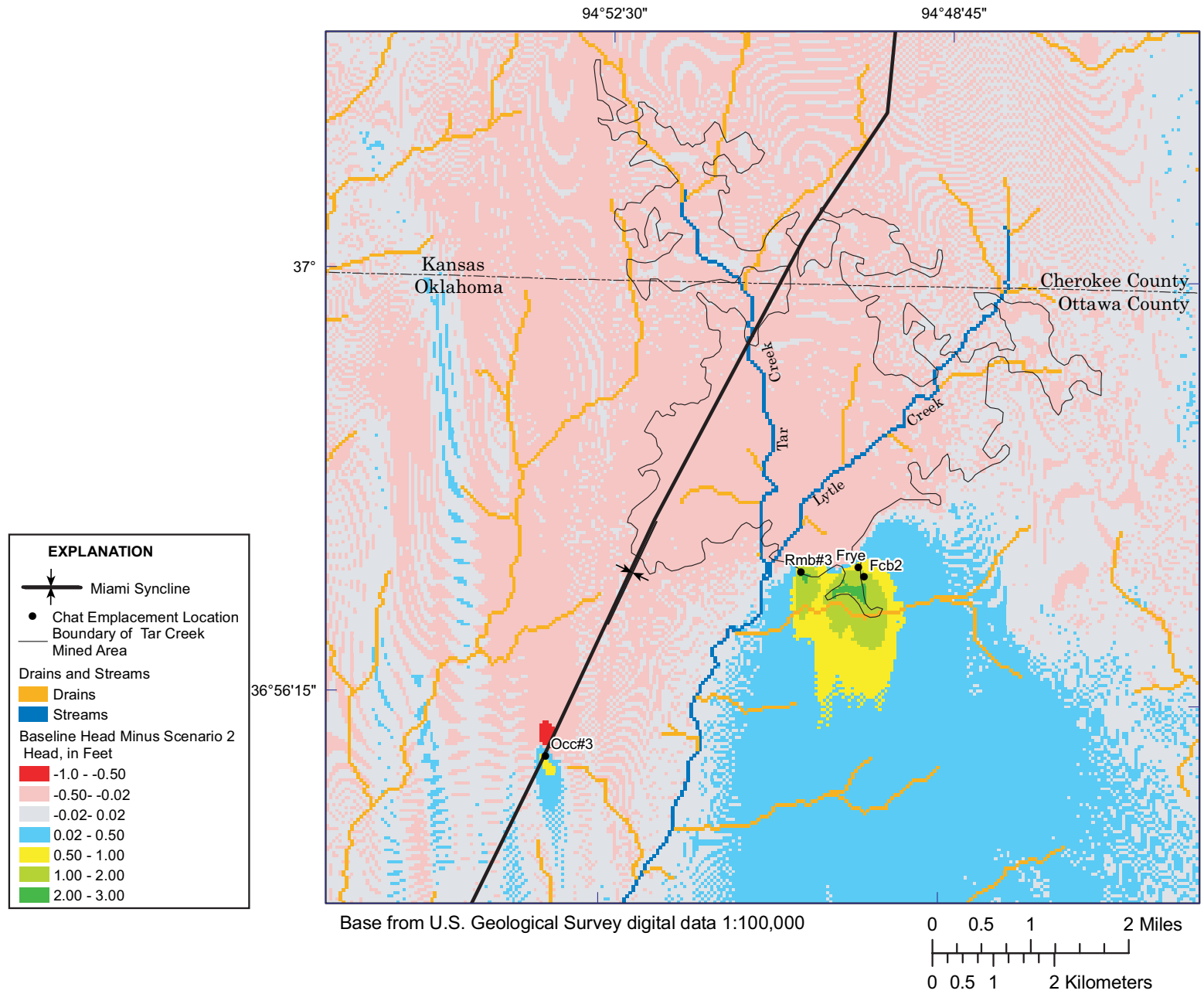


Figure 18. Water-level altitude differences between baseline and scenario 2.

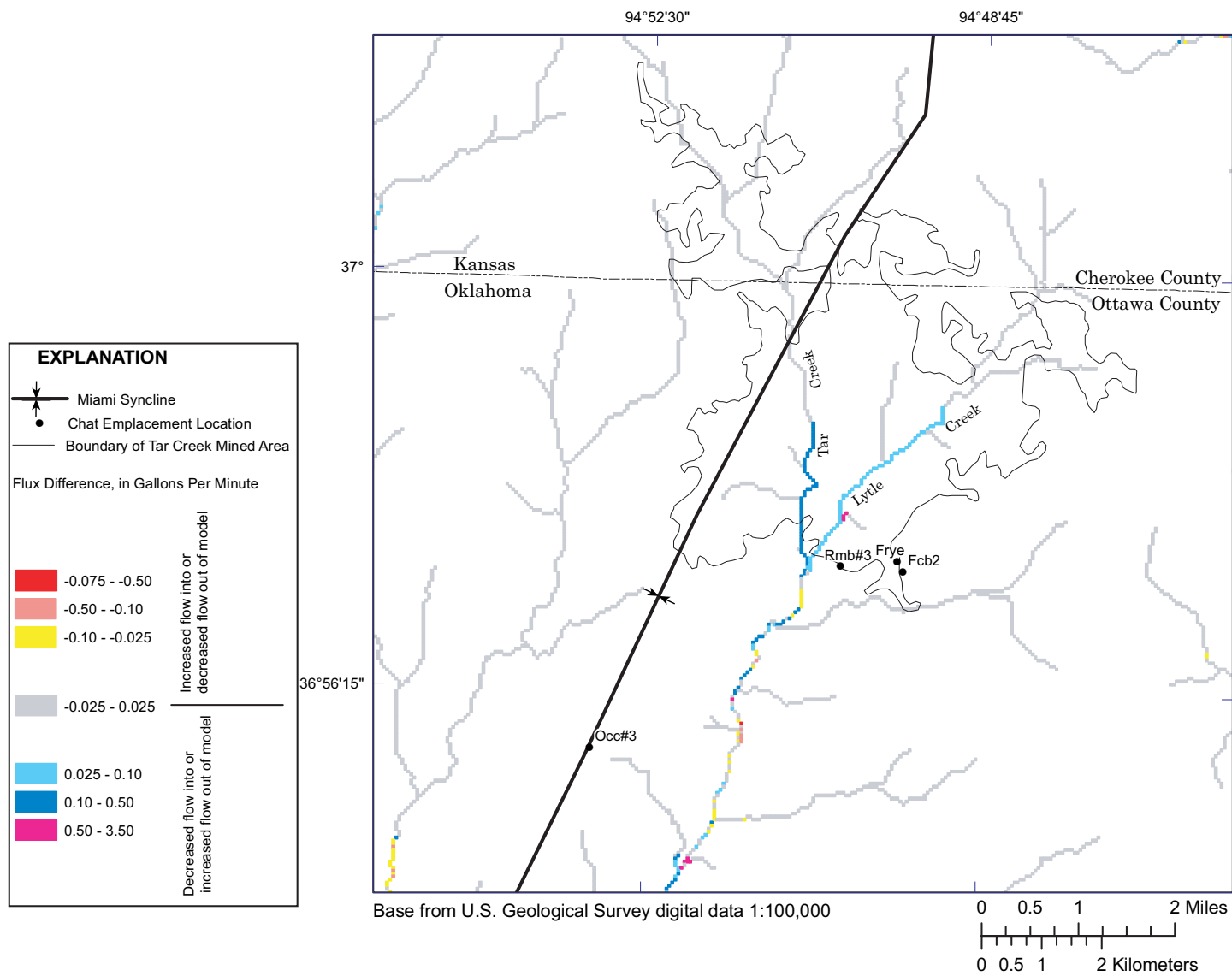


Figure 19. Difference between baseline and scenario 1 drain and stream fluxes.

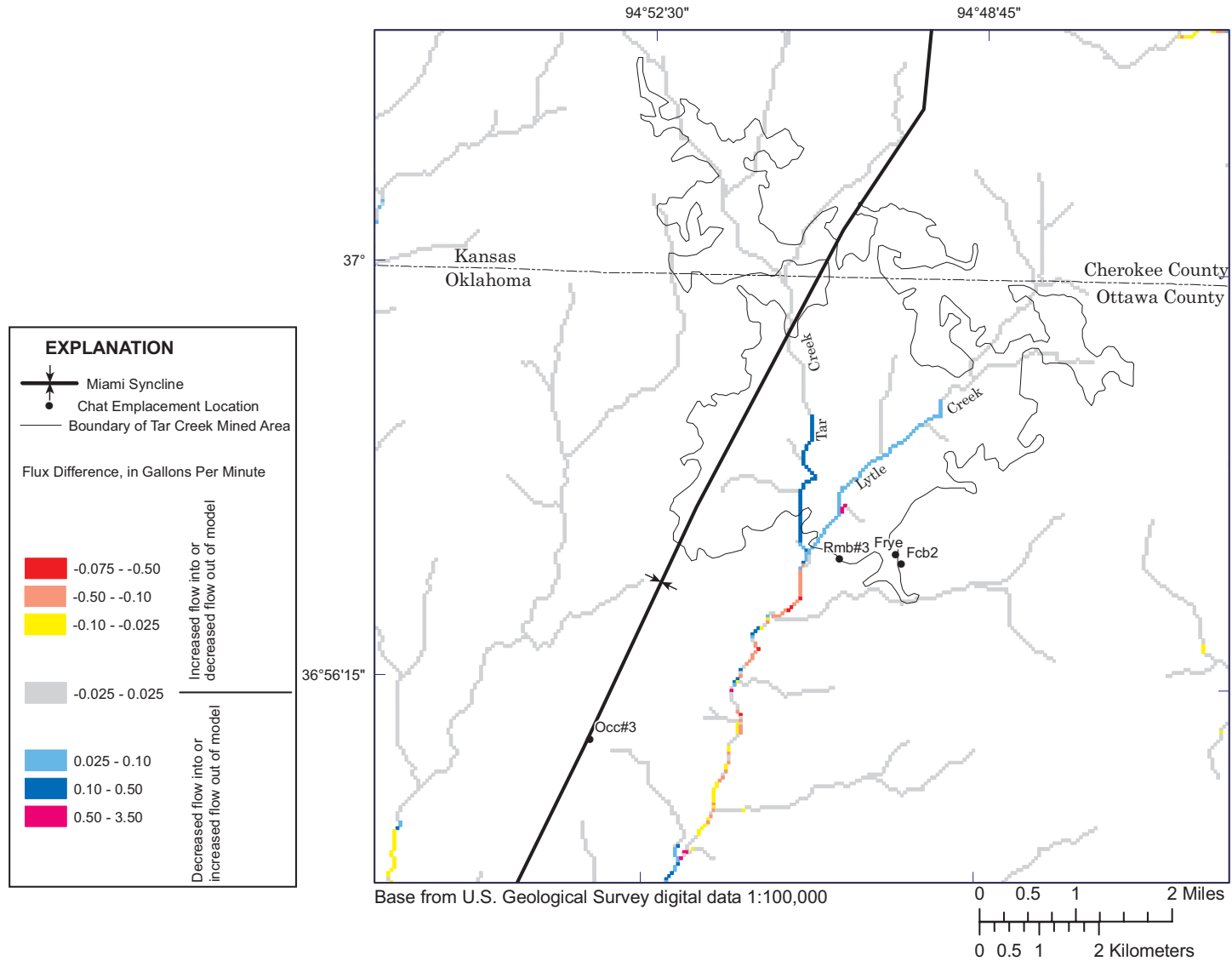


Figure 20. Difference between baseline and scenario 2 drain and stream fluxes.

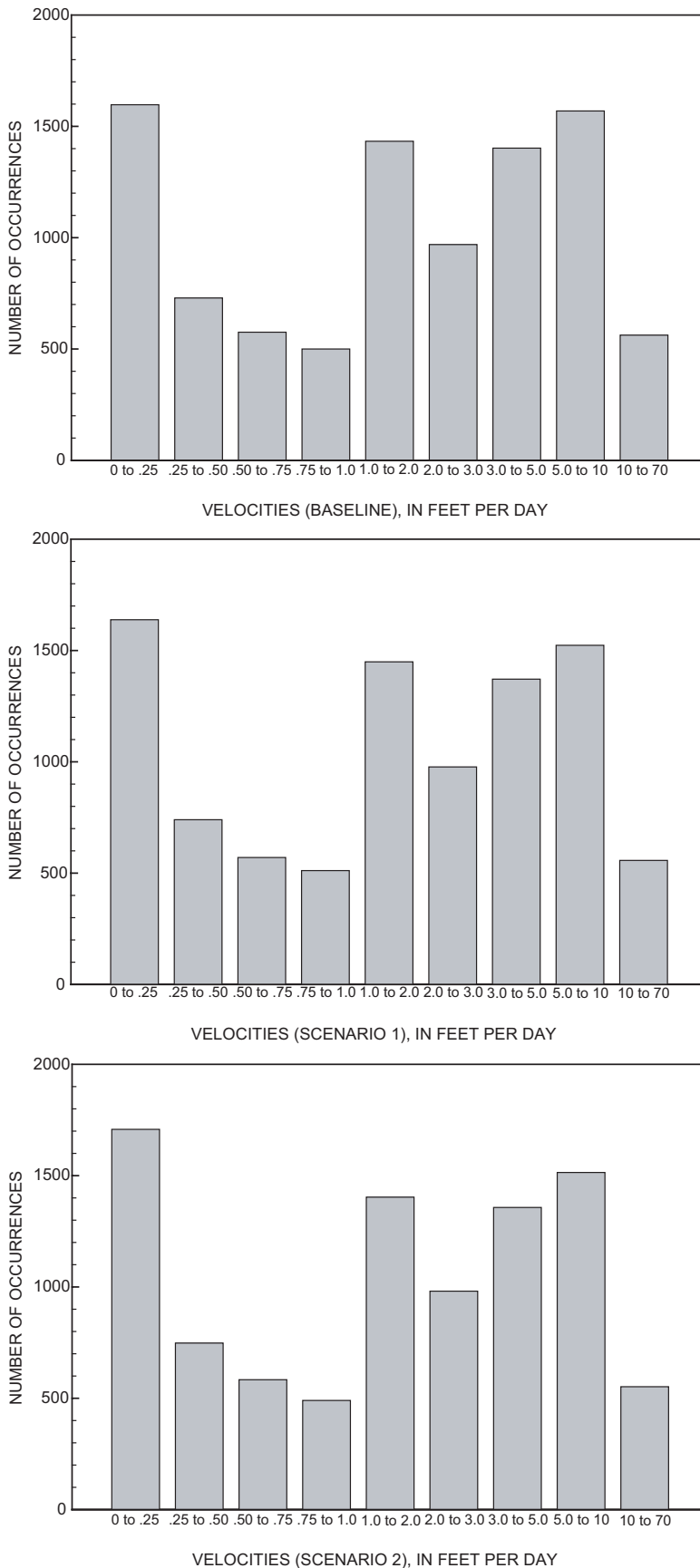


Figure 21. Distribution of simulated ground-water velocities in the mined zone for each scenario.

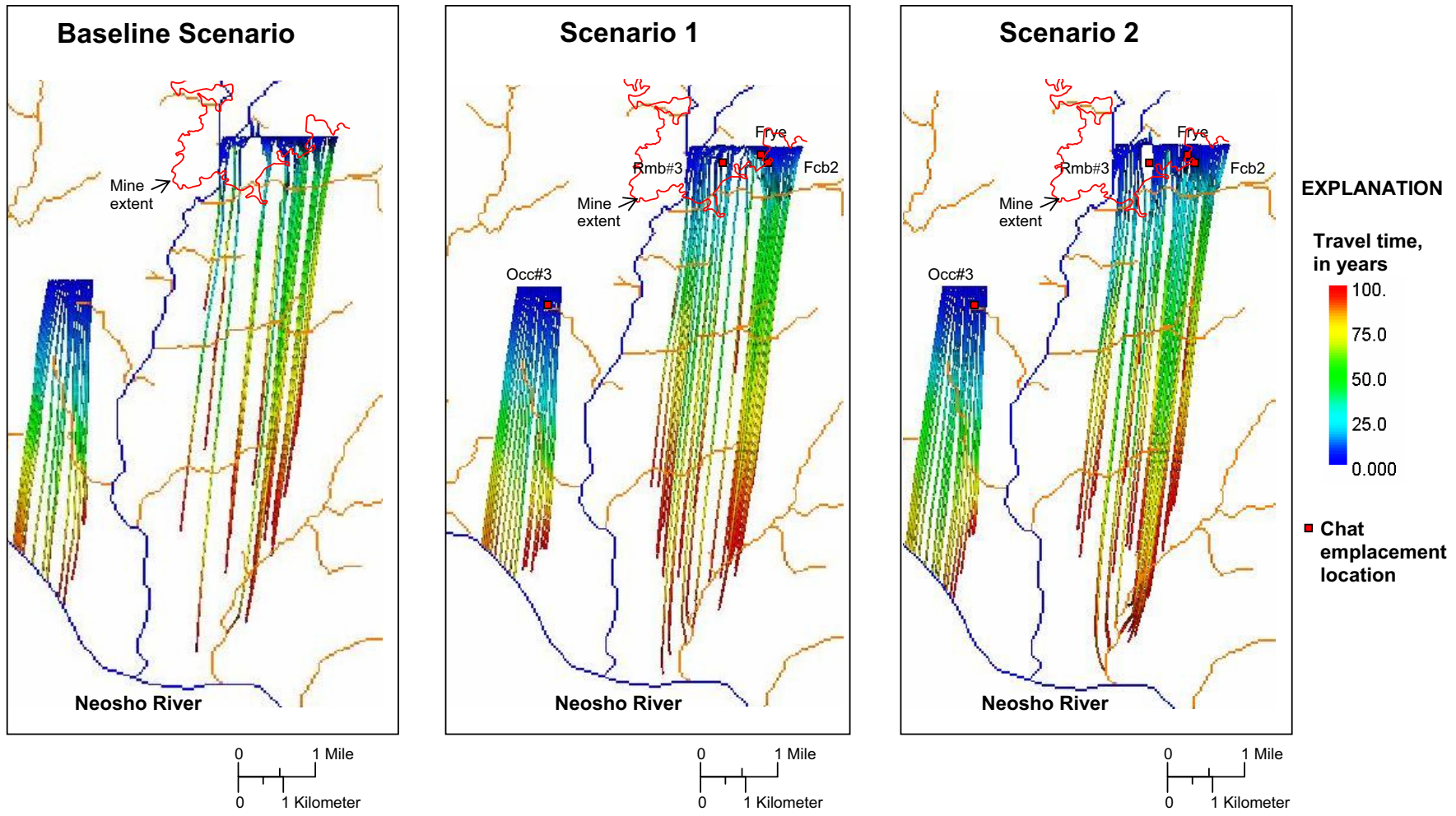


Figure 22. Flow paths for simulated particles for all scenarios.

Summary

The Tar Creek Superfund site is located along the eastern extent of the Oklahoma-Kansas State line. Mining activities at the site in the Picher, Oklahoma, area resulted in large piles of mine waste (chat) and open underground mine workings capable of transmitting ground water; mining activities removed a total of about 6,000,000 tons of lead and zinc by 1949. To evaluate the effect of possible remediation scenarios on the ground-water flow, a MODFLOW-2000 digital model was developed to simulate ground-water flow in the carbonate formations of Mississippian age underlying the Tar Creek Superfund site. The model consists of three layers of variable thickness, and a grid of 580 rows by 680 columns of cells 164 feet on a side. Model flux boundary conditions were specified for rivers along the eastern, southern, and western boundaries and general head boundaries in all layers along the northern boundary of the Boone Formation. Selected cells in layer 1 were simulated as drain cells. Model variable values were adjusted to minimize the difference between simulated and measured water-level altitudes in the Boone Formation. Hydraulic-conductivity values derived during model calibration range from 1.3 to 35 feet per day for the Boone Formation with the larger values occurring along the axis of the Miami Syncline where horizontal anisotropy was specified as 10 to 1. Vertical anisotropy was specified as 2 percent except in the mined zone. Hydraulic conductivity associated with the mine void was set at 50,000 feet per day and a specific yield of 1.0 was specified to represent that the mine void was completely filled with water. Residuals (the difference between observed and simulated ground-water altitudes) had a root-mean-squared value of 8.53 feet and an absolute mean value of 7.29 feet for water levels in the Boone Formation.

The model was used to simulate two scenarios in which 1,800,000 and 6,500,000 tons of chat (mine waste consisting of fines and fragments of chert) were emplaced in the mine. Hydraulic conductivity was reduced from 50,000 feet per day to 35 feet per day in the model cells corresponding to chat emplacement locations. A comparison of the chat emplacement scenarios with the baseline scenario shows little change in head, drainage and stream flux, and simulated ground-water flow velocity when compared to the baseline model.

Particle tracks were simulated for the two chat emplacement scenarios using MODPATH to evaluate the simultaneous movement of particles in water in the vicinity of four potential sites at which various volumes of chat might be emplaced in the underground mine workings as part of remediation efforts at the site. Particle tracks were calculated for a simulated period of 100 years. There is relatively little difference in horizontal flow paths (direction and travel time) between the baseline scenario and the two chat emplacement scenarios. In general, chat emplacement had minimal effect on the direction and rate of ground-water movement when compared to current flow conditions (the baseline scenario). Water-level differences between the baseline scenario and the chat-emplacement scenarios showed declines of as much as 2 to 3 feet in areas immediately

downgradient from the chat emplacement cells. Differences in simulated flux from surface drains and rivers rarely exceed 0.10 gallon per minute and reached a maximum of 3.5 gallons per minute per cell.

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