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Sinkhole Flooding in Murfreesboro, Rutherford County, Tennessee, 2001–02

Scientific Investigations Report 2005–5281

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

Cover photograph. Sinkhole flooding at sinkhole S-01, Shiloh focus area, Murfreesboro, Tennessee, March 19, 2002.

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U.S. Department of the Interior
Gale A. Norton, Secretary

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Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot (ft^3)	28.32	liter (L)
cubic foot (ft^3)	28.320	cubic centimeter (cm^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
inch per hour (in/hr)	0.0254	meter per hour (m/hr)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

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

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Well-numbering system: wells in Tennessee are identified according to the numbering system that is used by the U.S. Geological Survey, Tennessee Water Science Center. The well number consists of three parts: an abbreviation of the name of the county in which the well is located; a letter designating the 7 ½-minute topographic quadrangle on which the well is plotted; quadrangles are lettered from left to right across the county beginning in the southwest corner of the county; and a number generally indicating the numerical order in which the well was inventoried. For example, Ru:J-62 indicates that the well is located in Rutherford County on the “J” quadrangle and identified as well 62 in the numerical sequence.

Sinkhole Flooding in Murfreesboro, Rutherford County, Tennessee, 2001–02

By Michael W. Bradley and Gregg E. Hileman

Abstract

The U.S. Geological Survey, in cooperation with the City of Murfreesboro, Tennessee, conducted an investigation from January 2001 through April 2002 to delineate sinkholes and sinkhole watersheds in the Murfreesboro area and to characterize the hydrologic response of sinkholes to major rainfall events. Terrain analysis was used to define sinkholes and delineate the sinkhole drainage areas. Flooding in 78 sinkholes in three focus areas was identified and tracked using aerial photography following three major storms in February 2001, January 2002, and March 2002. The three focus areas are located to the east, north, and northwest of Murfreesboro and are underlain primarily by the Ridley Limestone with some outcrops of the underlying Pierce Limestone.

The observed sinkhole flooding is controlled by water inflow, water outflow, and the degree of the hydraulic connection (connectivity) to a ground-water conduit system. The observed sinkholes in the focus areas are grouped into three categories based on the sinkhole morphology and the connectivity to the ground-water system as indicated by their response to flooding. The three types of sinkholes described for these focus areas are pan sinkholes with low connectivity, deep sinkholes with high connectivity, and deep sinkholes with low connectivity to the ground-water conduit system.

Shallow, broad pan sinkholes flood as water inflow from a storm inundates the depression at land surface. Water overflow from one pan sinkhole can flow downgradient and become inflow to a sinkhole at a lower altitude. Land-surface modifications that direct more water into a pan sinkhole could increase peak-flood altitudes and extend flood durations. Land-surface modifications that increase the outflow by overland drainage could decrease the flood durations. Road construction or alterations that reduce flow within or between pan sinkholes could result in increased flood durations.

Flood levels and durations in the deeper sinkholes observed in the three focus areas are primarily affected by the connectivity with the ground-water conduit system. Deep sinkholes with a relatively high connectivity to the ground-water system fill quickly after a storm, and drain rapidly after the storm ends, and water levels decline as much as 3 to 5 feet per day in the first 2 to 3 days after a major storm. These sinkholes store the initial floodwater and then rapidly transmit water to the ground-water conduit system (high outflow). Land-surface changes that direct more water into the sinkhole may increase the flood peaks, but may not have a substantial effect on the flood durations.

Deep sinkholes that have low connectivity to the ground-water conduit system may have a delayed peak water level and may drain slowly, only about 2 to 3 feet in 10 days. Outflow from these sinkholes is limited or restricted by low connectivity to the ground-water conduit system. Land-surface alterations that increase the inflow to the sinkholes can result in high flood levels or increased flood durations.

Introduction

The Murfreesboro area of Rutherford County in Middle Tennessee (fig. 1) is typical of many thinly mantled limestone areas where much of the rainfall runoff flows to low areas in sinkholes. Water in a sinkhole may infiltrate to ground water; evaporate to the atmosphere; or, if flood levels are high enough, overflow to adjacent basins. In this type of terrain, some sinkholes never flood[1], some flood then drain quickly, and some flood and remain flooded for long periods. Results of previous U.S. Geological Survey (USGS) investigations in the Murfreesboro area indicate that for some sinkholes, the timing of the rise and recession of floodwater levels correlates closely with the timing of changes in the stage of nearby streams, whereas for other sinkholes, the timing of the rise and recession of floodwater levels is out of sync with nearby streams. Some of these latter sinkholes remain flooded for days after the streams have returned to pre-flood levels. An improved understanding of the patterns and timing of sinkhole flooding and drainage in the Murfreesboro area will provide useful insight into the factors controlling the hydrologic response of the sinkholes to major rainfall events, and indicate the degree of interconnection between the sinkholes and the ground- and surface-water systems.

Land-use planning and infrastructure designs in rapidly urbanizing areas in karst terrains are hampered by insufficient delineation of sinkholes, and by an incomplete knowledge of the hydrologic characteristic of sinkholes and the factors that

[1]Sinkhole flooding in this report refers to the general condition of water inundation (flooding) of a closed topographic depression (sinkhole) and does not necessarily mean damage-causing or hazardous conditions.

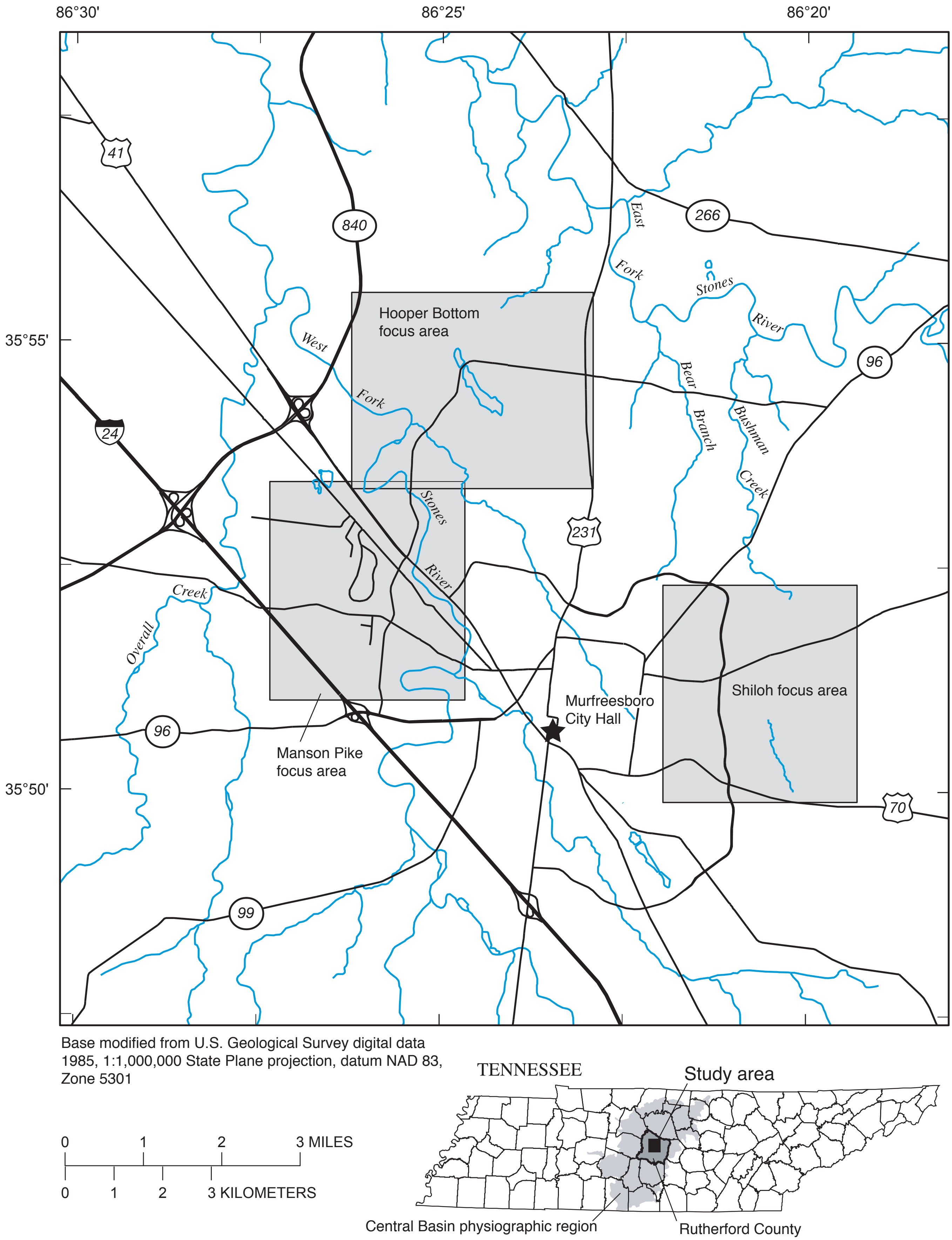


Figure 1. Locations of the study area and three focus areas, Murfreesboro, Tennessee.

control sinkhole flooding. Developers and water-resources managers need to know where sinkholes are located, which sinkholes might present flood hazards, and which sinkholes are well connected to the ground- and surface-water systems.

Purpose and Scope

From January 2001 through April 2002 the USGS, in cooperation with the City of Murfreesboro, conducted an investigation to delineate sinkholes and sinkhole watersheds in the Murfreesboro area and to characterize the hydrologic response of sinkholes to major rainfall events.

The purposes of this report are to describe the delineation of sinkholes and sinkhole watersheds in the Murfreesboro area; to present hydrologic data used to monitor sinkhole flooding; and to characterize the flood response of sinkholes to major precipitation events. Sinkholes deeper than 3 feet (ft) and their associated surface drainage areas (sinkhole watersheds) were delineated from 2-ft contour-interval topographic data of the area. For each of three focus areas within the study area, the hydrologic response of water levels in sinkholes with observable flooding in aerial photographs was evaluated for three major rainfall events during 2001 and 2002. Rainfall and stream stage were measured at a gage on the West Fork Stones River; continuous water-level data were collected at gages in six sinkholes; periodic water levels were measured in nine wells; and peak water levels were recorded at nine sinkhole crest-stage gages.

Study Area

The Murfreesboro area, Rutherford County, is located in the Central Basin physiographic region of Tennessee (Miller, 1974). The terrain of the Murfreesboro area is characterized by gently rolling hills and valleys. Land-surface altitudes in the area generally range between 500 and 600 ft above NAVD 88. Urban, suburban, pasture, glade, and forest areas characterize the land use of the area. Increased development around Murfreesboro has converted forest and pasture land into suburban land use.

The Murfreesboro area has a karstic topography with thin soils and sinkholes developed on the underlying, relatively flat-lying limestone bedrock. Surface outcropping and exposure of flat-lying limestone beds are common in the area. The karst development in the Murfreesboro area includes sinkholes, disappearing streams, numerous springs, and caves.

The Central Basin physiographic region and the Murfreesboro area are characterized by a humid, subtropical climate with mild winters and warm, humid summers. Average daily temperatures are 35 ºF for January and 78 ºF for July (National Climatic Data Center, 1948-2000). Average annual rainfall is about 53.5 inches. Storms that can result in stream and sinkhole flooding are typically the result of large cyclonic storms during the winter and into the spring months (December through March) and high intensity convectional thunderstorm cells during the spring and summer months (April through September).

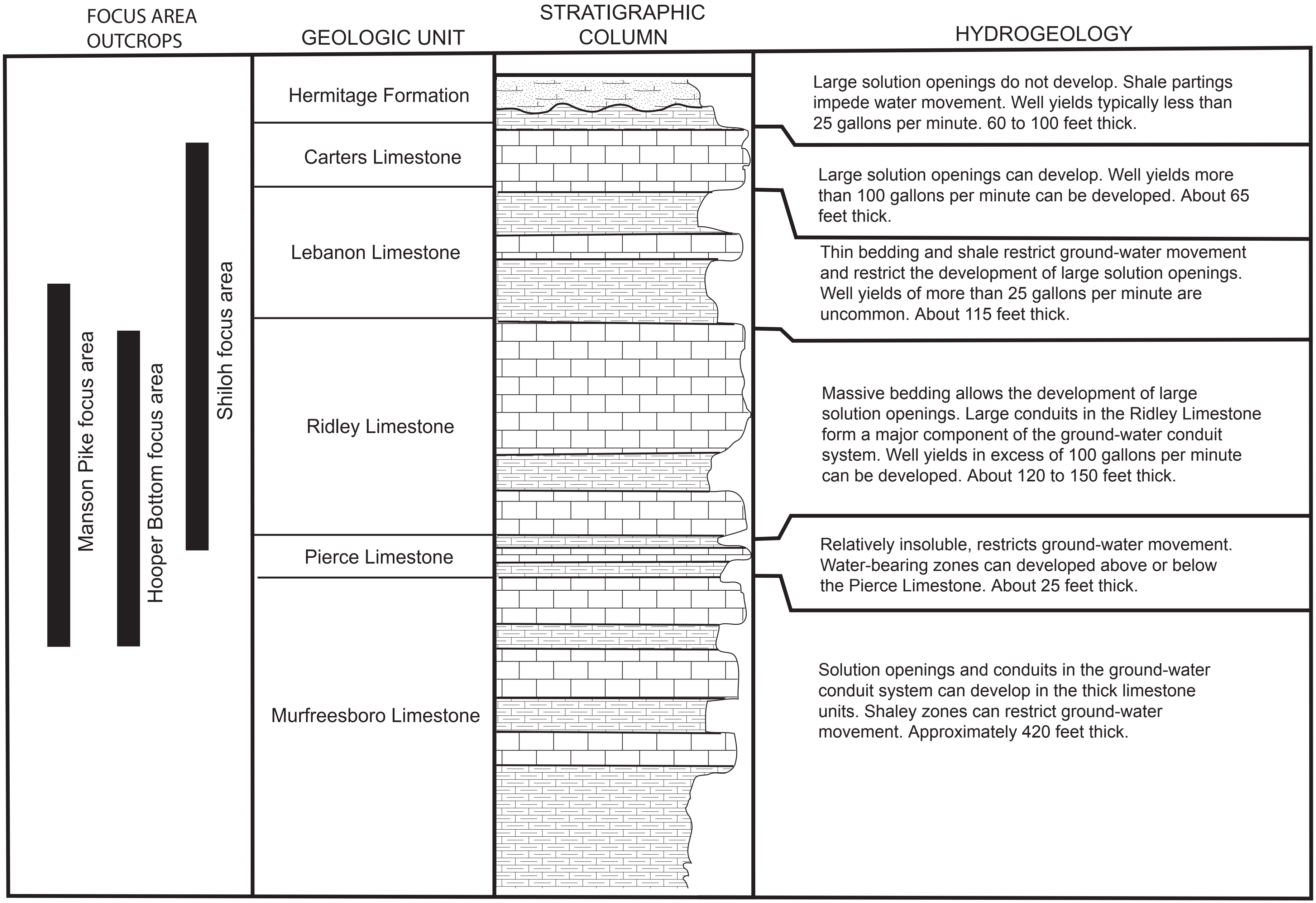
The Murfeesboro study area located in the north central part of Rutherford County, Tennessee, covers approximately 144 square miles (mi^2) roughly centered around the Murfreesboro, Tennessee, City Hall. Three focus areas, each about 7 mi^2, were designated for detailed analysis of sinkhole flooding within the study area (fig. 1). The three focus areas were selected because they contain areas where historically, sinkhole flooding has overtopped roadways or approached buildings. The names of the three focus areas and their locations relative to the Murfreesboro, Tennessee, City Hall are: Shiloh, located about 2.5 miles (mi) east; Hooper Bottom, located about 4 mi north; and Manson Pike, located about 3 mi northwest.

Hydrogeology

The Murfreesboro area is underlain by limestone and shaley limestone of Ordovician age. The formations are relatively flat-lying with some local, low-angle folds (Burchett and Moore, 1971). In the study area, a thin layer of soil or regolith has developed over the predominantly carbonate bedrock. At some locations, the regolith is very thin to nonexistent and accumulates primarily in vertical fractures and joints in the bedrock. All of the limestone units in the Murfreesboro area have some level of karst development. Ground water moving through the joints, bedding planes, and fractures can dissolve and enlarge the openings. Sinkholes are present throughout the study area and range in size from a fraction of an acre to several square miles.

The rock units cropping out in the study area include, in descending order, the Hermitage Formation of the Nashville Group and the Carters Limestone, Lebanon Limestone, Ridley Limestone, Pierce Limestone, and Murfreesboro Limestone of the Stones River Group (fig. 2). The formations exposed at land surface in the three focus areas are the Carters Limestone, Lebanon Limestone, Ridley Limestone, Pierce Limestone, and Murfreesboro Limestone.

The Carters Limestone is a massive-bedded, clean limestone that is about 65 ft thick. Several thin beds of bentonite are present near the top of the Carters Limestone. The Lebanon Limestone is a thin-bedded shaley limestone with a total thickness of about 100 to 120 ft. The Ridley Limestone is a thick- to massive-bedded limestone with a middle shaley part sandwiched between relatively clean limestones in the upper and lower parts of the formation. The Ridley Limestone, as mapped in the study area by Wilson (1964a, b, and c), is about 90 to 100 ft thick; however, in places, this mapped thickness may reflect only the thickness of the upper part of the formation above the top of the middle shaley unit. Farmer and Hollyday (1999) described the full thickness of the Ridley Limestone as 131 to 153 ft. The Pierce Limestone is a thin-bedded, shaley limestone about 20 to 25 ft thick. The Murfreesboro



Geology from Farmer and Hollyday, 1999;
Hydrology modified from Rima and others, 1977

Figure 2. Geologic column and hydrogeology for the Murfreesboro area, Tennessee, and stratigraphic positions of outcrops in the three focus areas.

Limestone is a thick-bedded limestone with interbedded shaley limestone in the upper 75 to 100 ft.

Ground-water conduits are most likely to develop in the thick-bedded, cleaner limestone of the Carters Limestone, the Ridley Limestone, and the Murfreesboro Limestone (fig. 2). Interconnected conduits in these geologic units can form substantial cave systems such as Snail Shell Cave (Barr, 1961) and develop a subsurface drainage system that can move water rapidly from connected sinkholes to wells and springs (Rima and others, 1977). Shaley limestone units such as the Pierce Limestone, Lebanon Limestone, and within the Murfreesboro and Ridley Limestones typically do not develop large, open, solution features. The shale partings and shale layers within these units can restrict ground-water flow (fig. 2).

The ground-water system in the Murfreesboro area is typical of many karst areas with little ground water stored in or transported through the matrix of the limestone bedrock, rather, most of the ground-water resides in and flows through fractures, bedding planes, small solution openings, and large open conduits (White, 2002). Water enters the ground-water system as dispersed recharge from rainfall that infiltrates over wide areas or as concentrated recharge from sinkholes and losing streams that infiltrates to localized parts of the ground-water system. Ground water flows from the recharge areas through fractures and conduits and eventually discharges to springs and gaining streams. Large conduits or interconnected conduit systems may consolidate ground-water flow similar to the way surface water flows from small tributaries to larger streams. These interconnected open conduits (the ground-water conduit system) can transmit water rapidly and can act as important local and regional drains of the ground-water system.

The movement of water into and through the ground-water system has a substantial effect on the occurrence and duration of sinkhole flooding in the Murfreesboro area. For this report, the ground-water system refers to any part of the subsurface capable of containing or transmitting water. The conceptual model of the ground-water system (fig. 3) as used in this report includes three variably interconnected ground-water flow zones: (1) a shallow zone that includes soil, regolith, and near-surface bedrock, this zone may be unsaturated during dry conditions; (2) a bedrock zone with ground-water flow occurring primarily in fractures, along bedding planes, and through small solution openings in bedrock, this zone is primarily beneath the water table; and (3) a ground-water conduit system developed principally in the clean limestone units with ground-water flow occurring in large, open conduits in bedrock, this zone also is primarily beneath the water table. Shaley layers in the subsurface tend to form barriers between the ground-water flow zones. For this report, the degree of connection between the sinkholes and the different zones of the ground-water system is referred to as connectivity.

Previous Investigations

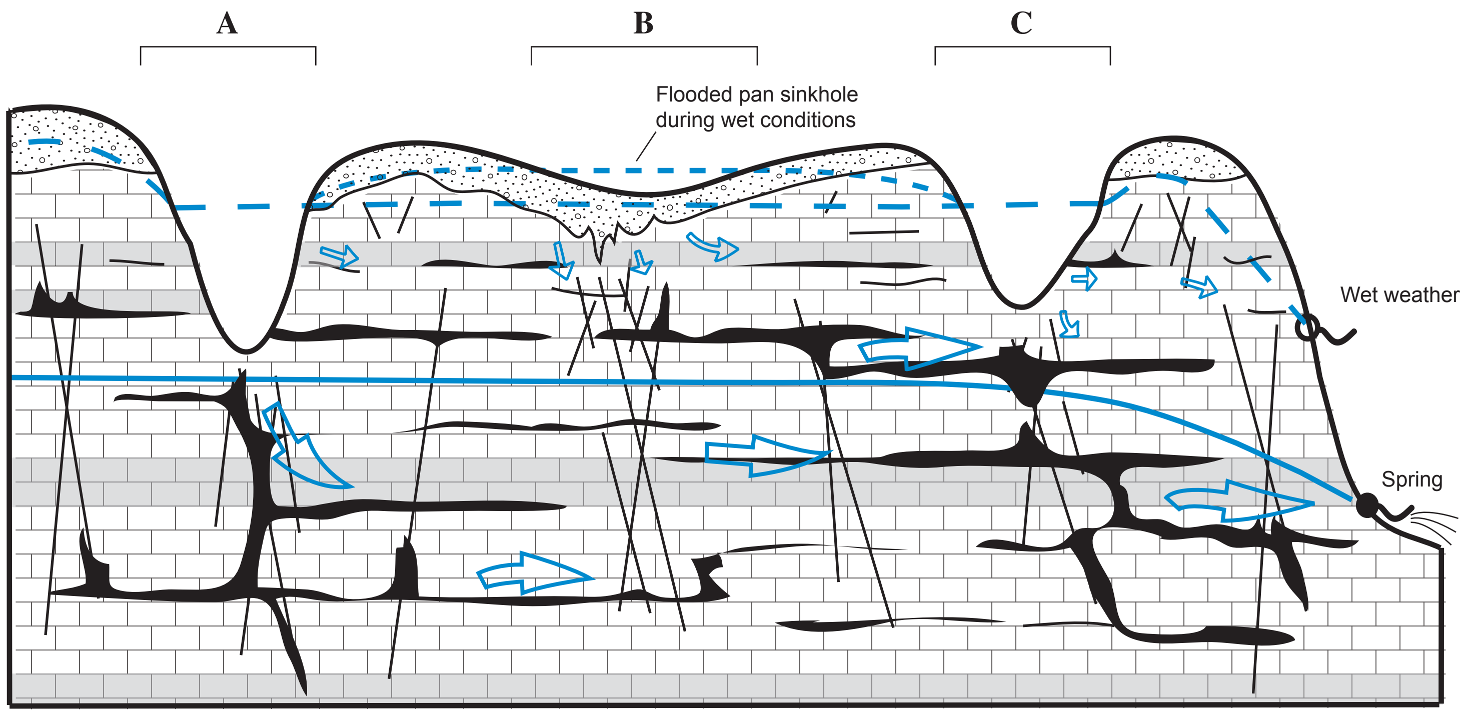
The Murfreesboro area, Rutherford County, has been the focus of several investigations of surface water, ground water, and geology. Studies have been conducted in the area to describe the general water resources, to evaluate the water resources for water supply, and to evaluate flooding and flood frequency.

The water resources and hydrology of the area are described in a number of reports. Information on the hydrology and water budget of the Stones River basin is presented in Burchett and Moore (1971). The results of a ground-water investigation on potential ground-water supplies in the Murfreesboro area are described in Rima and others (1977). A soil survey for Rutherford County contains detailed information on the soils and general information on the landscape and climate (U.S. Department of Agriculture, 1977). The geology of the area has been mapped as part of the Tennessee 1:250,000 scale geologic map (Hardeman, 1966) and at 1:24,000 scale for the Murfreesboro (Wilson, 1964a), Dillton (Wilson, 1964b), Lascassas (Wilson and Miller, 1964), and Walterhill (Wilson, 1964c) quadrangles. Farmer and Hollyday (1999) provide some additional information on the geologic structure of the area. Brahana and Bradley (1986) describe the regional aquifers and confining units in the Central Basin of Tennessee, including the Murfreesboro area. Dye-trace studies have identified recharge areas and ground-water flow directions (Ogden, 1997, 1998, 2000).

Flooding in the Murfreesboro area first was evaluated in a flood-plain study of the West Fork Stones River by the U.S. Army Corps of Engineers (1966), which provides information on major floods in 1902 and 1948. Rainfall, streamflow, and peak-stage data at several gage sites in the Murfreesboro area from March 1989 to July 1992 are documented by Outlaw and others (1992). The flood-frequency and detention-storage characteristics of the Bear Branch watershed in Murfreesboro are described in Outlaw (1996). Periodic flooding of lowlands and sinkholes along the West Fork Stones River and the recurrence of flooding levels independent of surface-water flooding are described in Law (2002).

Acknowledgments

We thank the many landowners in the study area who permitted access to their property for the installation of stream and sinkhole gages or the measurements of ground-water levels. We also thank George S. Law of the USGS for his encouragement throughout the project and his dedication to the collection and preservation of hydrologic data for the Murfreesboro area.



EXPLANATION

SINKHOLE FLOODING MODEL TYPE

A DEEP SINKHOLE WITH HIGH CONNECTIVITY TO GROUND-WATER CONDUIT SYSTEM

B PAN SINKHOLE WITH LOW CONNECTIVITY TO GROUND-WATER CONDUIT SYSTEM

C DEEP SINKHOLE WITH LOW CONNECTIVITY TO GROUND-WATER CONDUIT SYSTEM

WATER TABLE DURING WET OR FLOODED CONDITIONS

WATER TABLE DURING DRY CONDITIONS

FRACTURES AND THIN BEDDING PLANE OPENINGS AND SOLUTION FEATURES

LARGE, INTERCONNECTED CONDUITS AND FRACTURES IN BEDROCK

MINOR GROUND-WATER FLOW COMPONENT

MAJOR GROUND-WATER FLOW COMPONENT

LITHOLOGY

SOIL OR REGOLITH

LIMESTONE

SHALEY LIMESTONE

Figure 3. Conceptual model of the ground-water system, ground-water flow zones, and sinkhole-flooding model types in the Murfreesboro area, Tennessee.

Approach and Methods

The investigation was conducted using terrain analysis to delineate sinkholes and sinkhole watersheds; aerial photography to define the extent and duration of sinkhole flooding; and hydrologic measurements of stream flow and stage, ground-water levels, and flood levels in sinkholes. Hydrologic response of sinkholes to flooding in the Murfreesboro area was accomplished by tracking recession of floodwater in the sinkholes using low-altitude, oblique aerial photographs of the study area, water-level data from six sinkholes, and ground-water level data from nine wells. Major storms were defined as 2 or more inches of precipitation in 24 hours at the rain gage (station number 03428200) near Murfreesboro. The aerial photographs were taken during flights at 1- to 4-day intervals for 8 to 13 days after the three storms.

Terrain Analysis

Delineation of sinkhole locations and drainage areas was accomplished through Geographic Information System (GIS) spatial analysis software working from hypsography data sets (2-ft contour interval land-surface topography, circa 2001) provided by the City of Murfreesboro. The hypsography data were converted to a digital altitude grid with cell dimensions of 10 by 10 ft. Terrain analysis of the altitude grid identified sinkholes and delineated their associated watersheds. Delineation of sinkholes and sinkhole watersheds was conducted for only the part of the study area for which high-resolution hypsography data were available (fig. 4).

A sinkhole, for the purposes of the terrain analysis, is defined as an area of closed, internal drainage with greater than 3 ft of relief, larger than 2,500 ft^2 surface area within the closure, and located more than 200 ft from the nearest stream (blue-line hydrography from 1:24,000-scale USGS maps). A sinkhole watershed is defined as the area based on the altitude grid that would provide overland flow to the sinkhole. The automated terrain analysis process identifies any qualified depression in the topographic data set as a topographic sinkhole (fig. 4) and does not distinguish between naturally formed features and human-created features such as farm ponds or depressions adjacent to raised roadways.

Hydrologic Measurements

Hydrologic data were collected from the West Fork Stones River, sinkholes, and wells in the study area (table 1). Precipitation and stream stage were continuously measured at a USGS stream gage on the West Fork Stones River near Murfreesboro (station number 03428200). Water levels were measured continuously at six sinkholes (fig. 5). Highest floodwater

Table 1. Hydrologic monitoring stations used to evaluate sinkhole flooding near Murfreesboro, Tennessee.

[lsd, land surface altitude in feet above NAVD 88; td, total well depth in feet below land surface; mi^2, square mile]

Map number	Station number	Station name	Data type	Site no. (Law, 2002)	Comments
03428200	03428200	West Fork Stones River	Continuous stage, discharge, and precipitation	--	Drainage area 177 mi^2
M-05	355147086260701	Harding Place lowland (Alexander)	Continuous stage	11	
M-02	355232086263401	Nickens Lane lowland (Dryden)	Continuous stage	12	
H-04D	355420086241001	Siegel Rd Sink (Ru:O-071)	Continuous stage	--	
S-10C	355133086203800	Arnett Sinkhole	Continuous stage	--	
H-04A	355443086244100	Thompson Lane (Hooper Bottom)	Continuous stage	--	
BB-1	03428516	Buckeye Bottom, unnamed spring	Continuous stage	--	
Ru:J-60	355151086254301	Ru:J-060 No. 1	Ground-water level	--	lsd 568.5, td 106
Ru:J-61	355152086254401	Ru:J-061 No. 2	Ground-water level	--	lsd 567.5
Ru:J-62	355146086253601	Ru:J-062 Manson Pike	Ground-water level	5	lsd 571, td 40
Ru:O-62	355257086262601	Ru:O-062 Stoneman quarry	Ground-water level	17	lsd 561, td 150
Ru:O-68	355552086254401	Ru:O-068	Ground-water level	--	lsd 549, td 120
Ru:O-69	355353086240901	Ru:O-069	Ground-water level	--	lsd 579, td 70
Ru:O-70	355359086241501	Ru:O-070	Ground-water level	--	lsd 564, td 50.8
Ru:O-72	355449086240401	Ru:O-072	Ground-water level	--	lsd 571
Ru:O-74	355311086262101	Ru:O-074 Old Nashville Highway	Ground-water level	22	lsd 551, td 61
3 (fig. 18)	355218086254101	National Battlefield lowland	Crest stage	3	
4 (fig. 18)	355154086253901	Thompson Lane at Manson Pike	Crest stage	4	
7 (fig. 18)	355112086255601	Golf range near Thompson Lane	Crest stage	7	
8 (fig. 18)	355113086254801	Thompson Lane at Mall Circle Road	Crest stage	8	
9 (fig. 18)	355133086254901	Thompson Lane karst window	Crest stage	9	
13 (fig. 18)	355243086255401	National Cemetery lowland	Crest stage	13	
14 (fig. 18)	355307086261801	Old Nashville Highway at Asbury Lane	Crest stage	14	
15 (fig. 18)	355310086261701	Old Nashville Highway cave	Crest stage	15	
16 (fig. 18)	03428131	U.S. Hwy 41/70 at Mt. Olive	Crest stage	16	

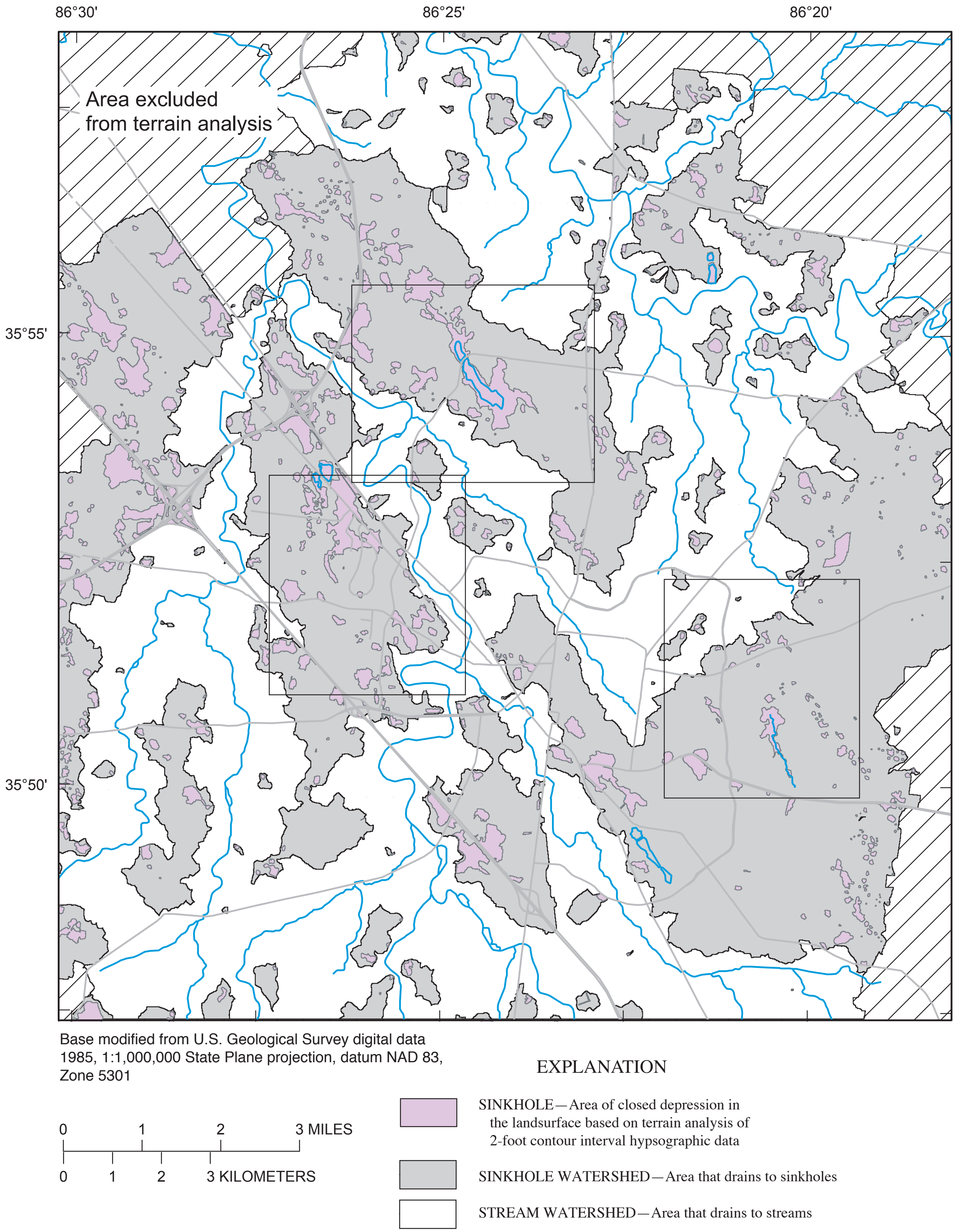
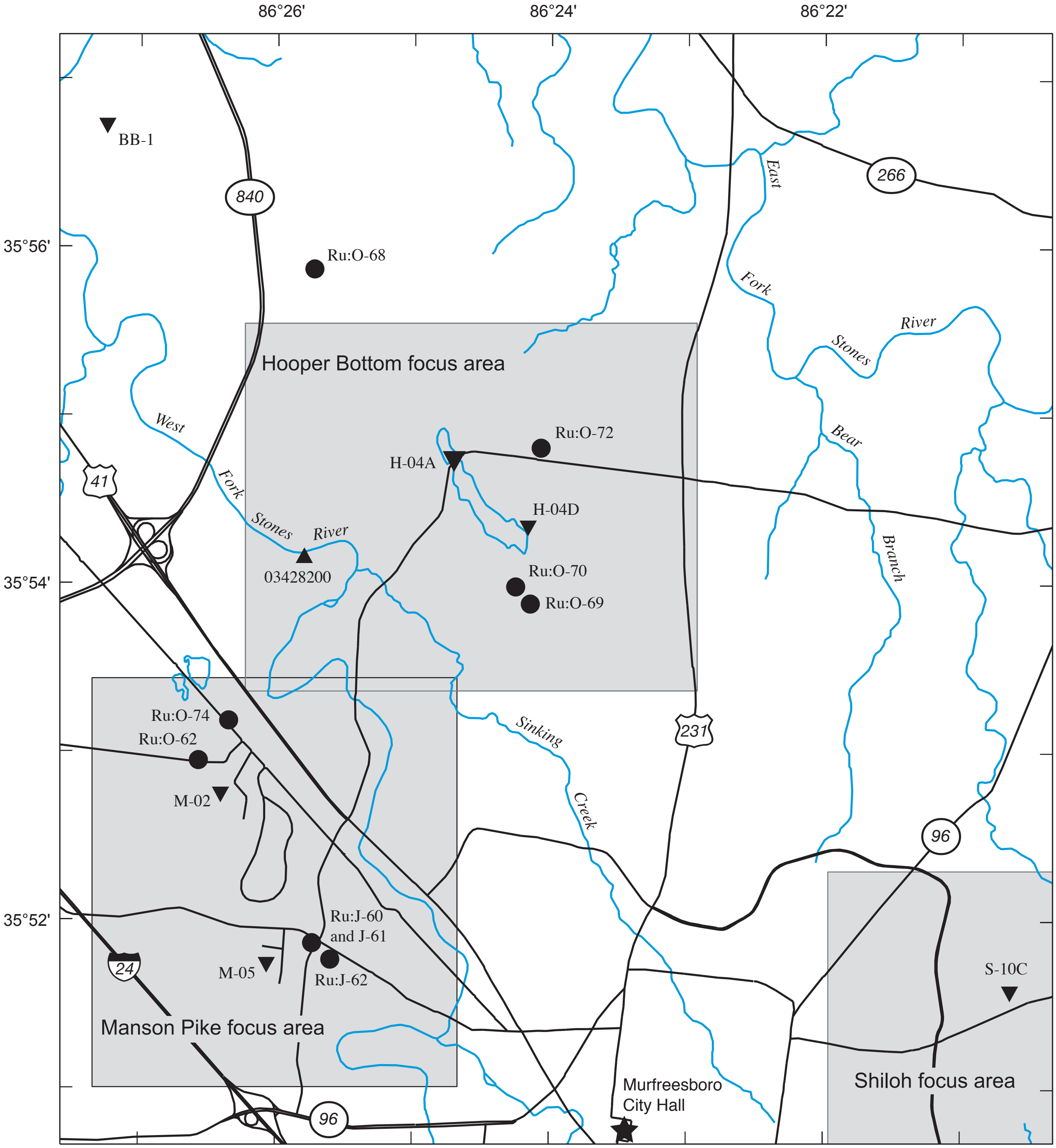


Figure 4. Sinkholes, sinkhole watershed areas, and stream watershed areas as delineated by terrain analysis of 2-foot contour interval hypsographic data, Murfreesboro area, Tennessee.



Base modified from U.S. Geological Survey digital data 1985, 1:1,000,000 State Plane projection, datum NAD 83, Zone 5301

EXPLANATION

MONITORING STATION—Data type in parentheses; number refers to text

03428200 ▲ STREAM GAGE (precipitation; continuous stream flow and stage)

M-05 ▼ SINKHOLE GAGE (continuous water level)

Ru:J-62 ● WELL (periodic water level)

Figure 5. Locations of stream gage, sinkhole gages, and wells used for data collection in the Murfreesboro area, Tennessee.

levels were recorded on crest-stage gages at nine sinkholes (table 2). Ground-water levels were measured periodically at nine wells by using graduated electric tapes (table 3).

Aerial Photography

Low-altitude, oblique aerial photography was used to identify the occurrence and duration of sinkhole flooding following three selected storms in the study area on February 14, 2001, January 23, 2002, and March 17, 2002. Aerial photographs were taken as soon as practical after the end of each selected storm. Additional photographs were taken at varying intervals of 2 to 14 days following the storm. Low-altitude, oblique photographs were taken throughout the Murfreesboro area and the three focus areas (fig. 6).

For each focus area, the aerial photographs were evaluated to identify specific sinkholes that were flooded and to track the level of flooding during the course of the subsequent photography. The locations of flooding visible on the aerial photographs were correlated with locations on 6-inch pixel digital orthophotography and 2-ft contour interval topographic maps provided by the City of Murfreesboro (example shown in fig. 7). The series of photographs for each flooded sinkhole was evaluated to identify and designate the maximum observed flooded level as fully flooded (4/4 full). Aerial photographs taken for several days after each storm were evaluated to track the flooding of individual sinkholes (example shown in fig. 8) and to qualitatively designate the flood level as 3/4, 2/4, or 1/4 full compared to the maximum observed level (Appendix). If no water was visible, the sinkhole was identified as dry. The altitude of the maximum flooded level (Appendix) was determined by translating, with the aid of orthophotography, the locations of shoreline points identified in aerial photographs to the 2-ft contour interval topographic maps. Several narrow, steep-sided sinkholes, shown on topographic maps of the focus area, are located in forested areas, which prevented the observation and tracking of sinkhole-flood response using aerial photography.

The time-series photographs for each flooded sinkhole were used to determine the flooding duration or the number of days from the end of the storm that the sinkhole retained water. The duration of flooding was conservatively chosen as the time interval between the end of the storm and the last day floodwater was observed in aerial photographs. Results of the flooding-duration determinations for the sinkholes in the three focus areas for the three storms are listed in the Appendix.

Sinkhole Flood Response

Sinkhole flooding in the Murfreesboro area occurs when the rate of water flowing into a sinkhole (inflow) exceeds the rate of water flowing out (outflow). Inflow to a sinkhole can include direct precipitation, overland surface run on, or ground-water seepage. Outflow from a sinkhole can include evapotranspiration, surface overflow, and ground-water drainage. The rate at which water in a sinkhole drains to (or seeps from) parts of the ground-water system is controlled by the hydraulic connection between the sinkhole and the ground-water system and by the "head" or potential difference between the water held in storage in the sinkhole and the ground-water system. Where material of relatively low permeability (clay-rich soil or shaley rock) forms the hydraulic connection between water in a sinkhole and the ground-water system, flow through the connection is limited. In general, poor hydraulic connectivity between a sinkhole and ground-water conduit system drains results in low outflow rates from the sinkhole and can result in long flood durations and high flood levels in the sinkhole. High permeability material or open conduits that form the connection between water in a sinkhole and the ground-water conduit system generally results in high outflow rates from the sinkhole and typically results in short sinkhole-flooding durations.

Sinkhole response in the three focus areas was monitored by stage recorders in sinkholes and by aerial photography used to track flooded sinkholes following the three storms. The three storms occurred on February 14-16, 2001, January 22-24, 2002, and March 16-18, 2002. The rainfall volume (inches) and intensity (inches per hour) for all three storms were below the 2-year, 24-hour recurrence values of 3.39 inches and 0.14 inches per hour (in/hr) for the Nashville airport weather station (Camp Dresser & McKee, 2000, fig. 2-1, p. 2-61).

Unlike the West Fork Stones River, which showed short-lived response to intense precipitation, most of the sinkholes tracked for this study showed prolonged retention of storm water. Summaries of precipitation, stream stage, and duration of sinkhole flooding for the three storms tracked for this study are listed in table 4.

For these three storms, the duration of actual stream flooding on the West Fork Stones River (stage greater than 16 ft at station number 03428200) was short-lived, all less than 1 day (table 4, fig. 9). The duration of stream stage greater than a level indicative of nonbase-flow conditions (greater than 5 ft) was less than 4 days. Conversely, more than half of the sinkholes retained floodwater for more than 8 days following the storms.

Rainfall during February 14-16, 2001, was 4.35 inches over 72 hours with 2.4 inches falling on February 16, 2001. Streamflow in the West Fork Stones River increased from an average flow of about 440 cubic feet per second (ft^3/s) on February 13 to about 8,200 ft^3/s on February 16, 2001. The flow of about 8,200 ft^3/s has an approximate 1-year recurrence interval, the annual flood (Law, 2002). The stage of the West Fork Stones River increased from 3.4 ft to about 16 ft during the storm (fig. 9). Analysis of aerial photography, collected during a 13-day period after the storm, determined the duration of sinkhole flooding in 32 sinkholes, primarily in the Manson Pike (12 sites) and the Hooper Bottom (17 sites) focus areas. The 4.35-inch storm only produced flow in the West Fork Stones River about equal to the annual flood, yet

Table 2. Water levels measured at crest-stage gages, Murfreesboro, Tennessee, December 2000 through May 2003.

[water-level altitudes in feet above NAVD 88; <, less than; **Bold** number indicates peak of record; numbers in parentheses are the gage identifier used in this report]

Date of water level	National Battlefield lowland (3)	Thompson Lane at Manson Pike (4)	Golf range near Thompson Lane (7)	Thompson Lane at Mall Circle Road (8)	Thompson Lane karst window (9)	National cemetery lowland (13)	Old Nashville Highway at Asbury Lane (14)	Old Nashville Highway cave (15)	U.S. Highway 41/70 at Mt. Olive (16)
12/16/2000	<561	563.47	568.08	567.66	565.29	550.93	544.82	530.87	<541.8
02/16/2001	561.87	565.52	571.70	567.47	567.34	552.89	544.88	534.07	541.81
03/20/2001	<561	565.59	571.81	567.57	567.28	552.50	544.51	529.87	<541.8
04/13/2001	<561	<562.44	559.27	567.32	563.15	<549	<543.78	<528.93	<541.8
09/13/2001	<561	<562.44	566.55	569.46	565.51	<549	<543.78	532.69	541.93
11/29/2001	<561	<562.44	565.54	568.75	562.98	<549	544.09	<528.93	<541.8
01/24/2002	561.40	565.62	**573.12**	569.06	567.89	553.77	544.95	534.65	545.08
03/17/2002	561.10	564.85	570.99	569.16	566.41	552.00	544.91	531.30	544.51
03/31/2002	<561	<562.44	565.00	569.11	566.44	<549	544.84	<528.93	<541.8
09/26/2002	<561	<562.44	564.00	567.97	564.67	<549	543.78	528.93	541.89
05/07/2003	**562.57**	**566.24**	572.80	**573.20**	**567.97**	**554.90**	546.33	545.60	542.55

Crest-stage data from these sites for December 12, 1998 through September 12, 2000 are published in Law (2002).

Table 3. Altitude of ground water measured in wells near Murfreesboro, Tennessee, February 2001 through March 2002.

[ground water altitudes in feet above NAVD 88; --, no data]

Date	Well Number								
	Ru:O-74	Ru:O-69	Ru:J-60	Ru:J-61	Ru:O-68	Ru:J-62	Ru:O-72	Ru:O-62	Ru:O-70
02-19-2001	--	557.68	--	--	--	--	--	--	--
02-27-2001	--	--	--	--	--	--	--	--	557.38
12-21-2001	--	--	--	--	--	--	563.67	--	--
01-15-2002	--	549.51	--	--	--	--	557.85	--	549.80
01-24-2002	--	559.20	--	--	--	--	568.70	--	559.32
01-25-2002	--	558.64	--	--	--	--	--	--	558.58
01-31-2002	--	555.85	565.35	565.24	--	--	567.77	--	555.49
03-19-2002	523.23	556.12	565.00	564.75	526.33	564.43	567.29	532.93	556.19
03-21-2002	522.80	556.87	565.11	565.10	523.24	--	567.75	532.70	556.73
03-22-2002	522.06	551.58	564.93	564.90	520.96	564.56	567.35	532.17	551.19
03-25-2002	520.32	549.72	564.10	564.06	514.37	563.81	566.18	530.95	549.19
03-27-2002	519.80	549.00	563.58	563.46	513.90	563.44	565.95	530.56	548.34
03-29-2002	518.89	548.25	562.45	562.09	512.37	562.72	565.47	529.77	547.78

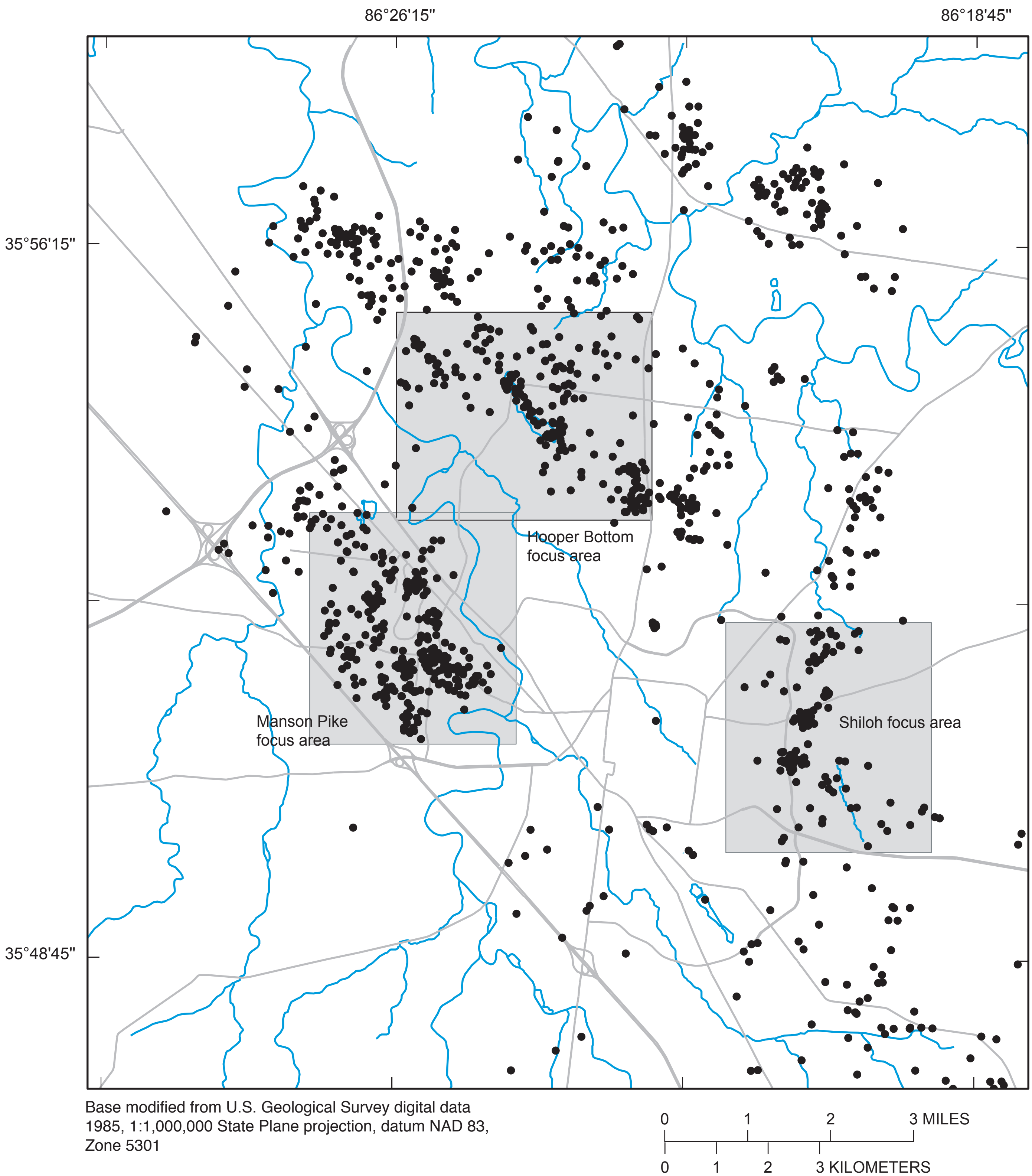
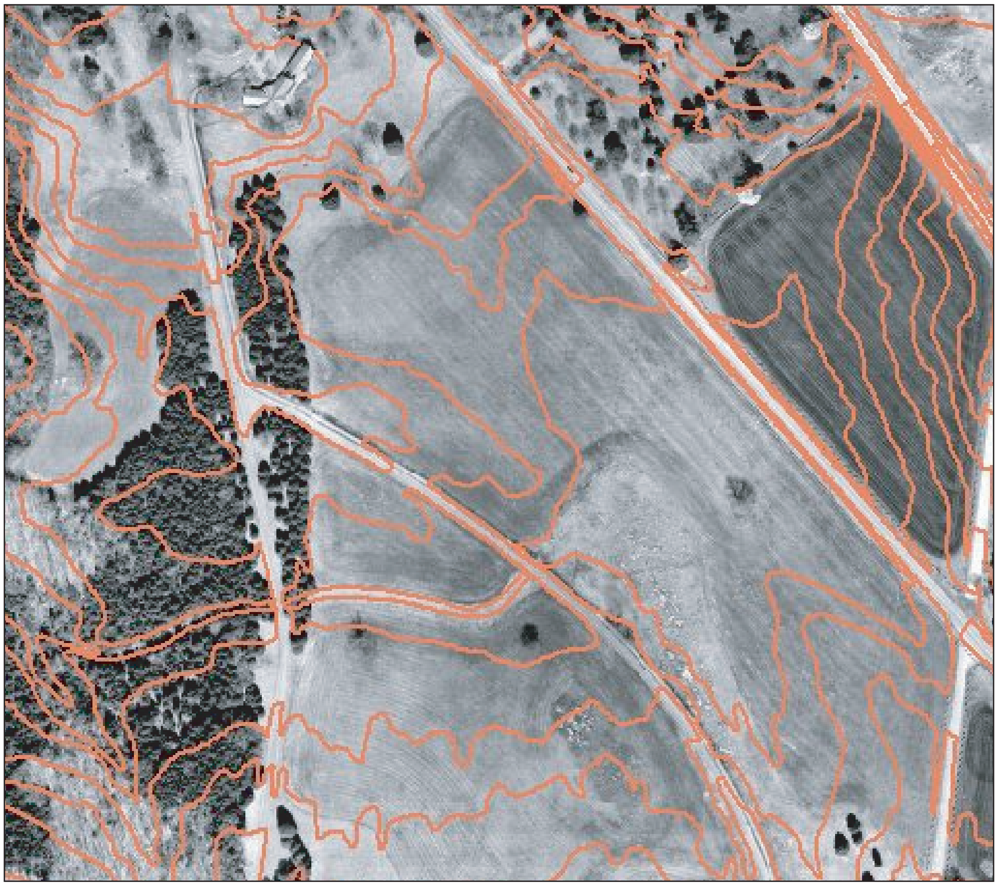


Figure 6. Locations of image center points for low-altitude oblique aerial photographs taken following storms in February 2001, January 2002, and March 2002, Murfreesboro, Tennessee.



A. Digital orthophotograph and 2-foot topographic contour lines.

N

City of Murfreesboro digital data
Orthophoto: 2001, 6-inch pixel
Topography: 2001, 1:4,800

B. Low-altitude, oblique aerial photograph of a partially flooded sinkhole. Photograph has been rotated to align approximately with A above.

Figure 7. (A) Digital orthophotograph and 2-foot topographic contour lines and (B) low-altitude, oblique aerial photograph of a flooded sinkhole at Stones River National Battlefield in the Manson Pike focus area, Murfreesboro, Tennessee.

March 19, 2002, sinkhole flooding at highest level. Flooding level was classified as 4/4 full.

March 25, 2002, sinkhole flooding had declined to a lower level. Flooding level was classified as 2/4 full. The black line shows the approximate 4/4 full level observed on March 19, 2002.

March 29, 2002, sinkhole flooding had declined to the lowest level observed in the March 2002 aerial photography. Flooding level was classified as 1/4 full.

Figure 8. Photographs showing a time-series change in flooding at sinkhole S-01, Shiloh focus area, Murfreesboro, Tennessee, March 19, 25, and 29, 2002.

Table 4. Summary of rainfall, observed sinkhole flooding, and stage on the West Fork Stones River during the February 2001, January 2002, and March 2002 storms.

Description	Dates		
	February 14-16, 2001	**January 22-24, 2002**	**March 16-18, 2002**
72-hr Rainfall, inches	4.35	4.53	2.71
Number of sinkholes tracked with aerial photography	50	77	60
Number of sinkholes with discernable flood duration observed in aerial photography	32	51	60
Duration of aerial photography, days	13	8	12
Number of sinkholes with floodwater at end of aerial photography	28	39	21
Number of days of sinkhole flooding			
Minimum	3	2	<2
Average	12	6.9	8.7
Median	>13	>8	10
Maximum	>13	>8	>12
Number of days West Fork Stones River stage:			
Above base flow, 5 feet	3.7	3.3	2.8
Above flood stage, 16 feet	0.4	0.7	0.5

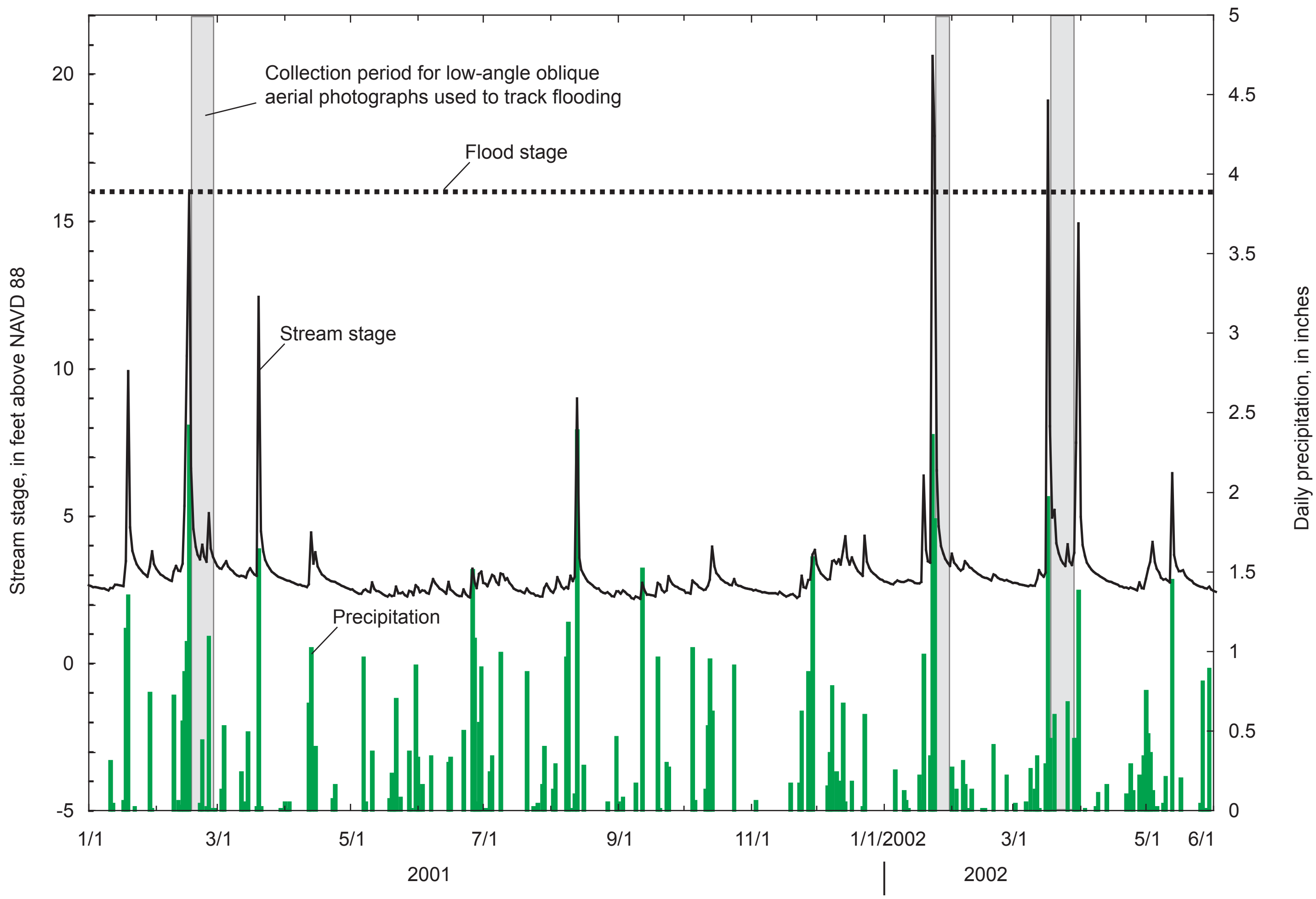


Figure 9. Stream stage and daily precipitation at station number 03428200, West Fork Stones River near Murfreesboro, Tennessee, January 2001 through June 2002 and collection periods for low-altitude, oblique aerial photographs used to monitor sinkhole flooding.

resulted in widespread and extended-duration sinkhole flooding. Eleven of 12 sinkholes tracked in the Manson Pike focus area, 14 of 17 in the Hooper Bottom focus area, and all 3 in the Shiloh focus area retained floodwater for at least 13 days following the storm.

Rainfall during the January 22-24, 2002, storm was 4.53 inches over 72 hours with 2.36 inches of rain falling on January 23, 2002. Streamflow in the West Fork Stones River increased from an average flow of about 390 ft^3/s on January 22 to about 18,100 ft^3/s on January 23, 2002. The flow of about 18,100 ft^3/s has an approximate 3-year recurrence interval (Law, 2002). The stage of the West Fork Stones River increased from 3.4 ft to about 21 ft during the storm (fig. 9). Analysis of aerial photography, collected during an 8-day period after the storm, determined the duration of sinkhole flooding in 51 sinkholes across the three focus areas; 13 sinkholes in the Manson Pike, 10 in the Shiloh, and 28 in the Hooper Bottom focus areas. The rainfall during the January storm exceeded 4.5 inches, and sinkhole flooding again was widespread and extended through the duration of the aerial photography. Only 12 sinkholes with discernible flood durations were noted as dry on or before the eighth day following the storm. Thirty-nine of the 51 sinkholes with discernible flood durations retained floodwater for at least 8 days, and most of these were noted as 3/4 to 4/4 full on day 8 (Appendix).

During the March 16-18, 2002, storm, rainfall was 2.71 inches over 72 hours with 1.97 inch falling on March 17, 2002. Streamflow in the West Fork Stones River increased from an average flow of about 180 ft^3/s on March 15 to about 14,200 ft^3/s on March 17, 2002. The flow of about 14,200 ft^3/s has an approximate 2-year recurrence interval (Law, 2002). The stage of the West Fork Stones River increased from 2.9 ft to about 19 ft during the storm (fig. 9). Analysis of aerial photography, collected during a 12-day period following the storm, determined the duration of sinkhole flooding in 60 sinkholes across the three focus areas; 20 sinkholes in the Manson Pike, 12 in the Shiloh, and 28 in the Hooper Bottom focus areas. The lower rainfall during the March event compared to the other storms evaluated during the study still resulted in widespread sinkhole flooding, but the duration of flooding was shorter and more variable across the three focus areas. Only 21 of the 60 observed sinkholes with discernible flood durations continued to hold floodwater for at least 12 days following the storm. On the 12th day after the storm, 4 of 20 sinkholes held floodwater in the Manson Pike focus area; 5 of 12 held floodwater in the Shiloh focus area, and 12 of 28 held floodwater in the Hooper Bottom focus area (fig. 10, Appendix).

The sinkhole flooding response to the February 2001 and January 2002 storms was characterized by long-duration sinkhole flooding. Because so many of the observed sinkholes retained floodwater for the entire post-storm observation period following the February 2001 and January 2002 storms, the effect of differences in outflow or differences in the hydraulic connection to the ground-water system could not be discerned. The March 2002 storm had only 2.71 inches of rainfall and resulted in a wider range of discernible sinkhole-flooding responses as compared to the other storms. The variation in sinkhole-flooding response associated with the March 2002 storm provided information on the hydrogeologic and man-made controls on sinkhole flooding and the relative hydraulic connection with the regional ground-water system.

Shiloh Focus Area

The Shiloh focus area (fig. 11) is located about 2.5 mi east of the Murfreesboro, Tennessee, City Hall. The area is underlain at land surface primarily by the Ridley Limestone with some occurrence of the Lebanon and Carters Limestones in the northeast (Wilson, 1964b). Much of the focus area has very thin soils overlying upper parts of the Ridley Limestone. Important hydrologic features include Double Springs (located in sinkhole S-18), its outlet stream, Double Springs Branch, which enters a cave system at sinkhole S-15 and reappears at the head of Bushman Creek (Ogden, 1998), and Bushman Creek. A continuous water-level recorder was installed and operated in sinkhole S-10C from January through April 2002.

Numerous sinkholes exist in the Shiloh focus area. Terrain analysis indicated that 80 percent of this 6.9-mi^2 focus area drains to sinkholes. Twenty-four sinkholes in the study area had floodwater observable in the aerial photographs taken following the storms (fig. 9). Surface-water drainage from several parking lots is diverted into and through sinkhole S-12 to the flat, pan sinkhole S-02B.

The flood responses of observable sinkholes in the Shiloh focus area to the March 2002 storm are depicted in figure 12. Observations from the aerial photographs indicate that following the storm, flooding lasted more than a week at most of the sinkholes. Four days after the storm, all of the observable sinkholes retained floodwater except for sinkhole S-10B, which had completely drained. Half (11 of 22) of the sinkholes tracked retained water for at least 8 days after the March 2002 storm. Twelve days after the end of the storm, five sinkholes (S-01, S-02B, S-03, S-06, and S-10C) still retained observable floodwater. The sinkholes in the Shiloh focus area showed similar flood-response patterns following the February 2001 and January 2002 storms. The observed sinkholes were at their highest observed water levels by about 2 days after the storms and tended to drain in a “downhill” sequence. The sinkholes located at the highest altitudes tended to drain first with the sinkholes at lower altitudes draining later.

Continuous data from the water-level gage in sinkhole S-10C compared to altitudes of floodwater in sinkhole S-01, interpolated from oblique, aerial photography and 2-ft interval topographic contours, for the March 2002 storm (fig. 13) show substantial differences in flood response. Sinkhole S-01 is a broad, shallow depression (pan sinkhole) typical of other pan sinkholes in the focus area. The water level in sinkhole S-01 declined by only about 3 ft during the 12 days after the storm and was at an altitude about 10 ft higher than the water level in the nearby sinkhole S-10C on the 12th day after the storm.

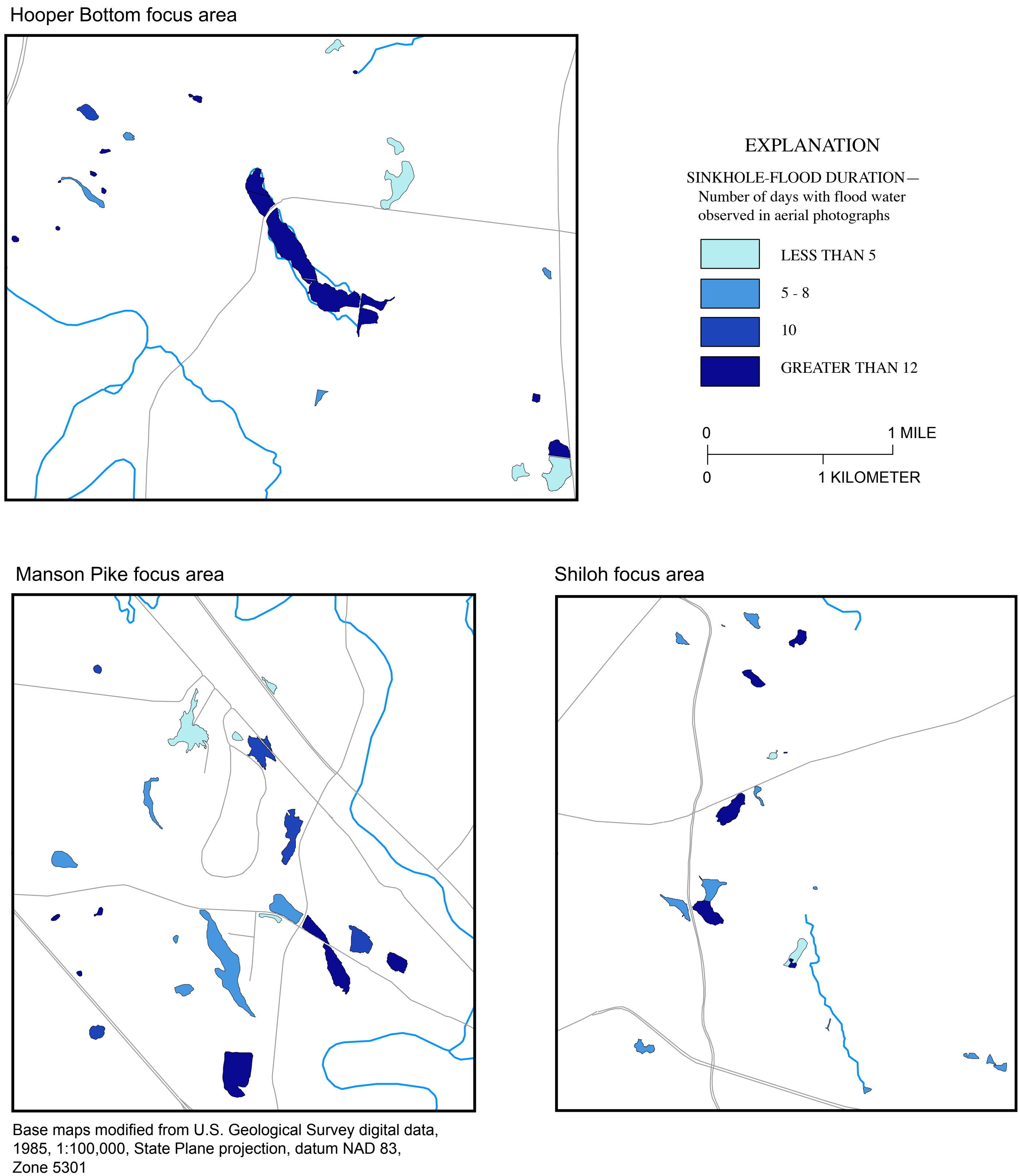


Figure 10. Flood durations of sinkholes observed in aerial photographs following the March 17, 2002 storm, at Hooper Bottom, Manson Pike, and Shiloh focus areas, Murfreesboro, Tennessee.

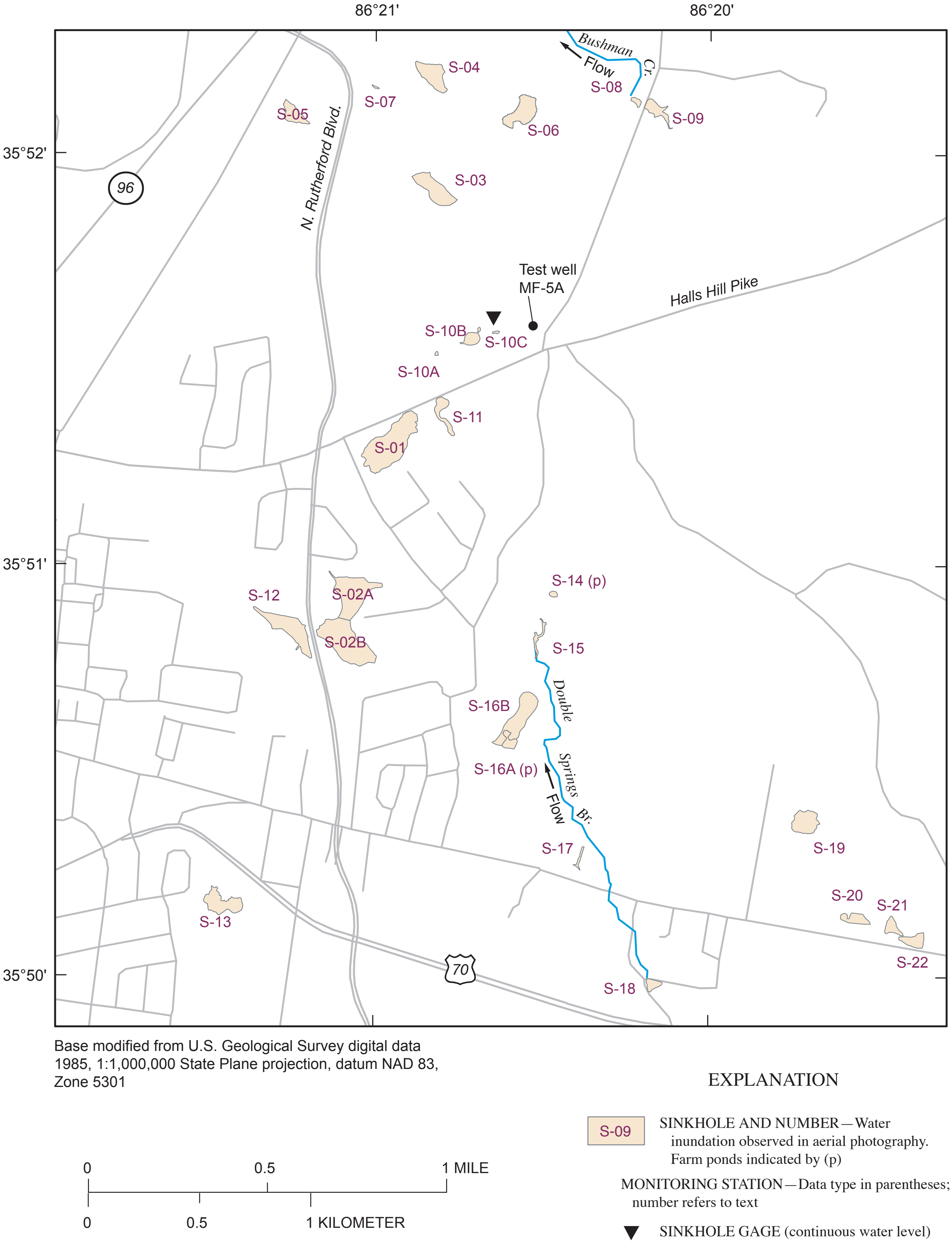
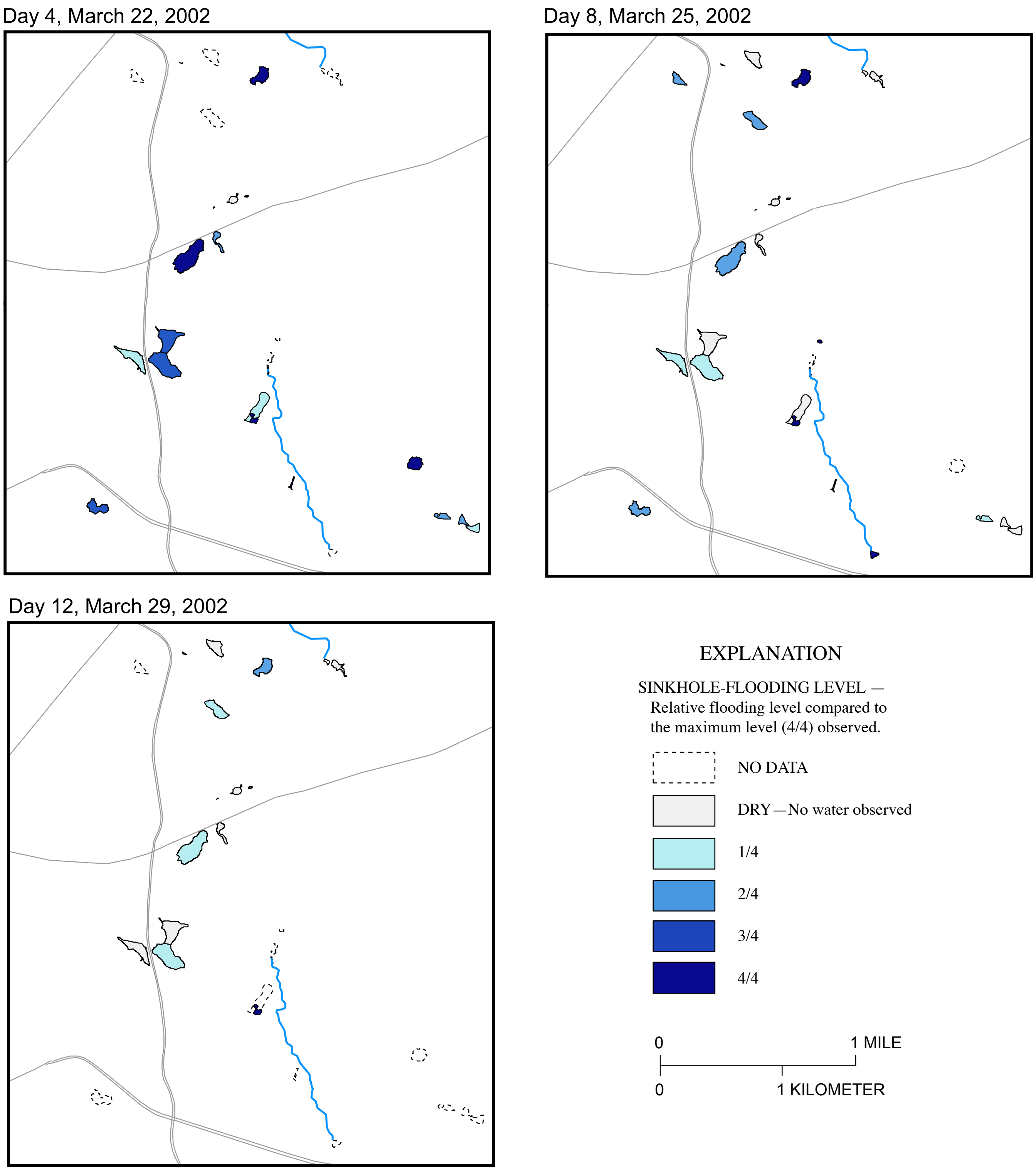


Figure 11. Data-collection points and flooded sinkholes identified in aerial photography, at the Shiloh focus area, Murfreesboro, Tennessee.



Base maps modified from U.S. Geological Survey digital data, 1985, 1:100,000, State Plane projection, datum NAD 83, Zone 5301

Figure 12. Relative sinkhole flooding levels after the March 17, 2002 storm, at the Shiloh focus area, Murfreesboro, Tennessee.

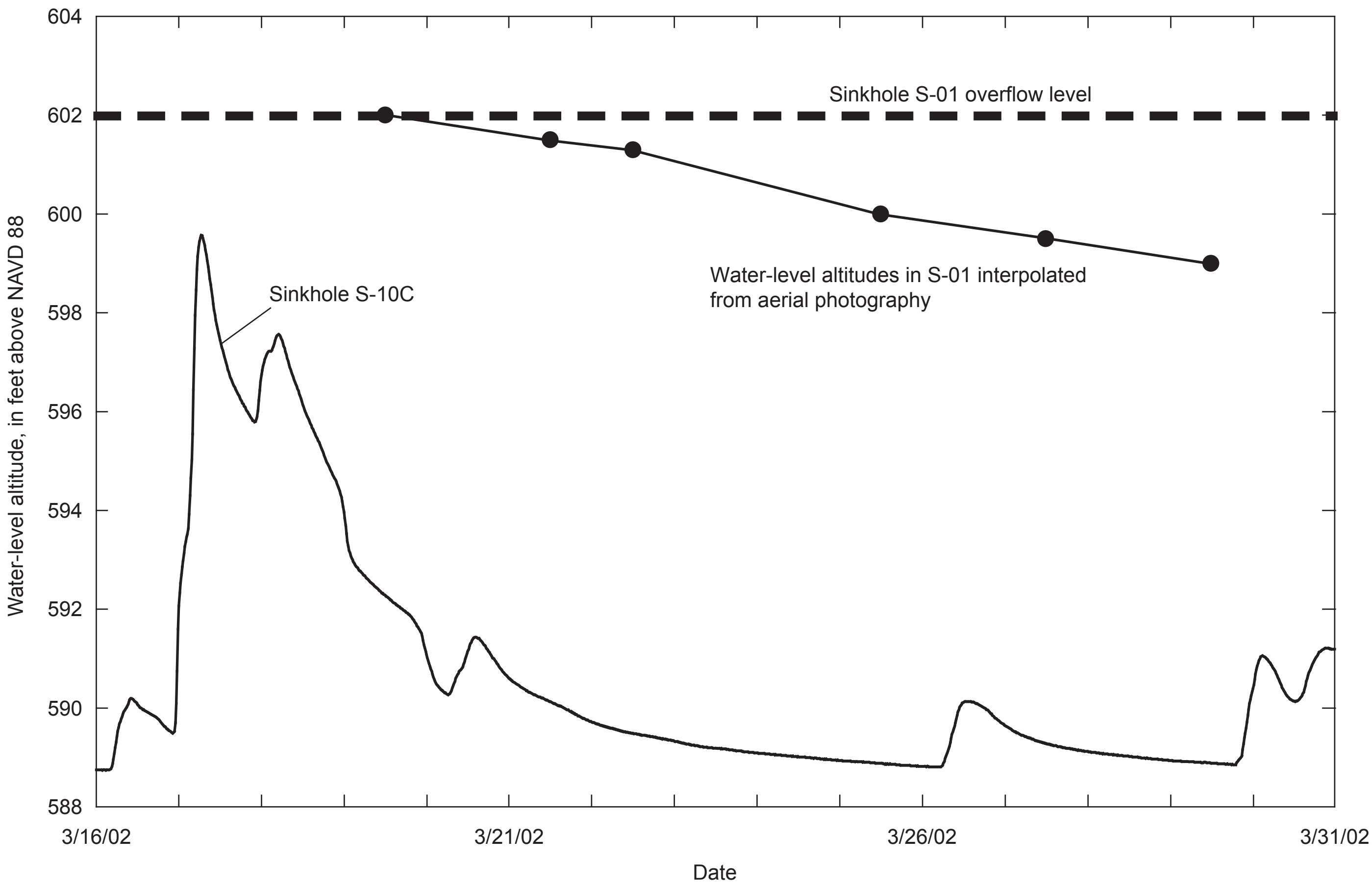


Figure 13. Water-level altitudes in sinkholes S-10C and S-01, at the Shiloh focus area, Murfreesboro, Tennessee, March 16 through March 30, 2002.

Water-level altitudes in S-10C declined rapidly, falling by more than 7 ft during the first 2 days after the storm (fig. 13). The difference in hydraulic response of the two sinkholes reflects differences in the hydraulic connection between each sinkhole and the ground-water conduit system. Sinkhole S-10C shows a rapid hydraulic response that indicates a high connectivity with the ground-water conduit system. The water-level response in S-01 is much more delayed and represents a zone with a much lower connectivity to the ground-water conduit system.

The sinkhole flooding in the Shiloh focus area appears to be associated with both a shallow system and the ground-water conduit system. The upper shallow system is represented by flooding in shallow, broad sinkholes (pan sinkholes) including S-01, S-02A, S-02B, S-05, S-19, S-20, S-21, and S-22. The pan sinkholes appear to be separated from the ground-water conduit system by material (soil or bedrock) with relatively low hydraulic conductivity. The ground-water conduit system is represented by deep, steep-sided sinkholes including S-10C, S-11, S-15, and S-17. Sinkholes associated with this system show rapid water-level rises and declines. The ground-water conduit system is apparently highly developed in this focus area. Test well (MF-5A) drilled in the Shiloh focus area during the 1975 ground-water study of the Murfreesboro area (Rima and others, 1977) intersected water-bearing openings at 53 to 55 and 73 to 74 ft below land surface in upper parts of the Ridley Limestone. During an aquifer test in 1975, while the well was being pumped at 100 to 250 gallons per minute (gal/min), rapid infiltration of rainfall caused water levels in the well to rise and the test to be discontinued. In this focus area, the sinkholes with the longest flood durations appear to have low connectivity with the ground-water conduit system, occur at low altitudes, and may be near ground-water discharge points (such as sinkholes S-03 and S-06), or be affected by surface-water drainage (such as sinkhole S-02B).

Hooper Bottom Focus Area

The Hooper Bottom focus area (fig. 14) is located about 4 mi north of the Murfreesboro, Tennessee, City Hall. Much of the focus area is mapped as being underlain by lower parts of the Ridley Limestone (Wilson, 1964c); thus, numerous shaley layers in the Ridley, Pierce, and Murfreesboro Limestones are present in the shallow subsurface (land surface to 150 ft below land surface). Along the confluence of the West Fork Stones River and Sinking Creek, the contact between the Ridley Limestone and the Pierce Limestone is mapped at an altitude of about 550 ft above NAVD 88. Typical land-surface altitudes

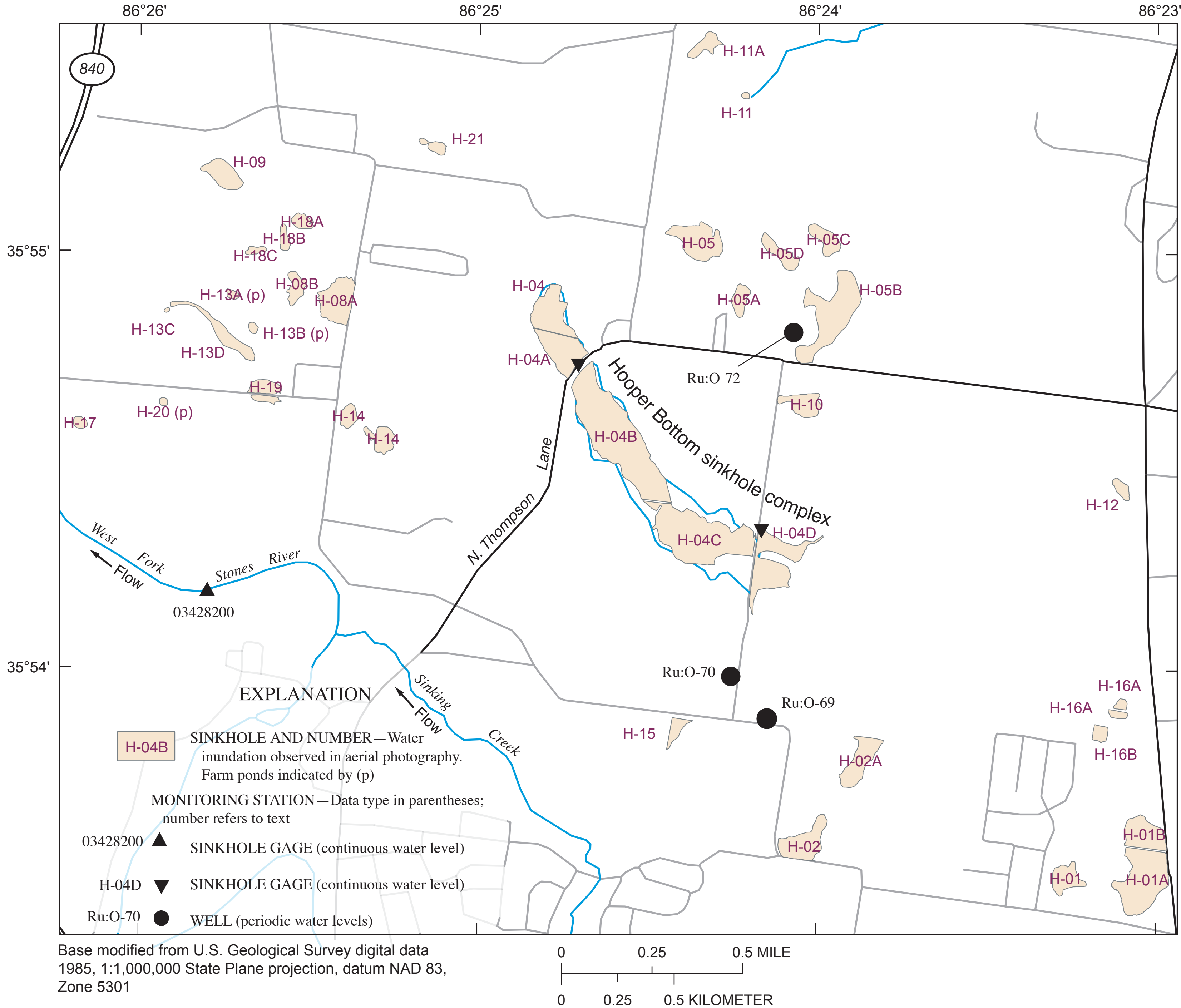


Figure 14. Data-collection points and flooded sinkholes identified in aerial photography at the Hooper Bottom focus area, Murfreesboro, Tennessee.

near the center of the focus area are about 575 ft above NAVD 88. Soils thick enough to support row crops or pasture cover much of the focus area with some areas of very thin soil present in parts of the area.

The major hydrologic features in the focus area are the West Fork Stones River, Sinking Creek, and Hooper Bottom, which consists of a complex of sinkholes (H-04, H-04A, H-04B, H-04C, and H-04D) that are connected by culverts and ditches in an overflow pattern from southeast to northwest. Dye-tracing results from injections into two sinkhole throats in H-04D (Ogden, 1998) confirm a ground-water flow-path connection between this sinkhole and a cave stream at the Buckeye Bottom sinkhole gage (BB-1, in fig. 5) located 4.1 mi northwest of H-04D. The hydrology of the Hooper Bottom focus area was monitored with a stream gage on the West Fork Stones River, two water-level recorders at sinkholes H-04A and H-04D, and with periodic water-level measurements at three wells (Ru:O-69, Ru:O-70, and Ru:O-72; in fig. 14).

Terrain analysis indicated that 65 percent of this 7.8-mi^2 focus area drains to sinkholes. Sinkhole H-04D receives runoff from an approximate 1.2-mi^2 area east of the sinkhole. Thirty-four sinkholes in the focus area (fig. 14) had floodwater observed in the aerial photographs following the three storms. The hydrologic response of sinkholes H-02, H-02A, and H-10 could not be evaluated during the March 2002 storm because the sites had been affected by nearby construction. The sinkholes observed in the aerial photography in this focus area are primarily broad pan sinkholes with deep sinkholes restricted to the Hooper Bottom complex.

The flood response of sinkholes in the Hooper Bottom focus area to the March 2002 storm is shown in figure 15. The flooding levels peaked in most of the sinkholes by about 2 days after the storm. The flooding levels in three of the sinkholes, H-04A, H-04B, and H-04D, continued to rise and reached peak levels 3 to 4 days after the storm. Nearly half (15 of 31) of the sinkholes that were monitored following the March 2002 storm in the Hooper Bottom focus area retained floodwater for at least 8 days, and 13 of 31 of the sinkholes retained water for at least 10 days. The flood response at sinkholes H-13D and H-13C, and at H-18A, B, and C appeared to have some overland flow from one sinkhole to the next lower sinkhole. Following the storms when sinkhole H-13D was observed in the aerial photographs to be fully flooded, overland flow from this sinkhole through a low, grassy swale to sinkhole H-13C (fig. 16) also was observed. Overland flow from H-18A to H-18B and on to H-18C also was observed in some of the aerial photographs.

Hydrologic data depicted in figure 17 show water-level response to the January and March 2002 storms in selected sinkholes and wells near the Hooper Bottom focus area. The water level in sinkhole H-04D increased rapidly following a major storm, peaked shortly after the end of the storm, and maintained a relatively high water level for weeks after the storm. The rise in water levels in the downstream sinkhole, H-04A, lagged several days behind the end of the storms, the timing of peak water levels in upstream sinkholes of the Hooper Bottom complex, and the timing of peak water levels in other observed sinkholes in the focus area. The delay between the end of the storm and peak water levels in H-04A indicates that this sinkhole continued to receive inflow for days following a major rainfall.

Periodic water-level measurements in the wells Ru:O-72, O-70, and O-69 show the ground-water response to the storms (fig. 17). Ground-water levels in all three wells rose about 10 to 12 ft as a result of the January 2002 storm. Water levels in well Ru:O 72, located about 0.5 mi northeast of Hooper Bottom (fig. 14), declined slightly from the peak, but still remained about 10 ft above the pre-storm water levels after 6 days. Ground-water levels in both Ru:O-69 and Ru:O-70 declined from their peak water levels by about 5 ft in 6 days after the January 2002 storm and by about 7 ft in 8 days after the March 2002 storm.

Differences in the water-level altitudes between the wells and the Hooper Bottom sinkhole complex demonstrate the hydraulic gradients that affect sinkhole flooding. The ground-water levels in all three wells were measured at higher altitudes than the flood levels recorded in both of the monitored sinkholes following the January storm and during the beginning of the post-storm measurement period following the March 2002 storm. After about 5 days following the March storm, the ground-water altitudes in wells Ru:O-69 and Ru:O-70 were below water levels in sinkhole H-04D but still above water levels in sinkhole H-04A. Differences in ground-water altitudes and sinkhole water-level altitudes define a gradient that potentially causes water flow from those parts of the system with higher head to the parts of the system with lower head. Deep sinkholes may be connected to multiple zones in the ground-water system and may simultaneously receive inflow from parts of the ground-water system with high head while discharging outflow to parts of the system with low head. Sinkhole H-04D is an example of a sinkhole that connects to multiple ground-water zones. On several occasions, discharge from wet-weather springs on the broad, southern flank of sinkhole H-04D was observed to flow into a throat of the sinkhole with no observable flooding in the throat.

The sinkhole flooding in the Hooper Bottom focus area appears to be associated with ground-water zones having limited connectivity with ground-water conduit system drains. A shallow zone in the ground-water system is reflected by the flooding response in most of the sinkholes observed in the study area. Most of the sinkholes in the Hooper Bottom focus area are shallow (less than 5 ft deep), broad, pan sinkholes that retained floodwater for at least 8 days following the March 2002 storm. Deep sinkholes, such as those in the Hooper Bottom sinkhole complex, may be hydraulically connected to multiple zones in the ground-water system and may simultaneously receive inflow from high-head parts of the ground-water system while discharging outflow to low-head parts of the system. The long delay for the sinkhole flooding to drain in the Hooper Bottom complex is probably a result of the continued inflow from shallow parts of the ground-water system and surface ditches and an apparent low connectivity through

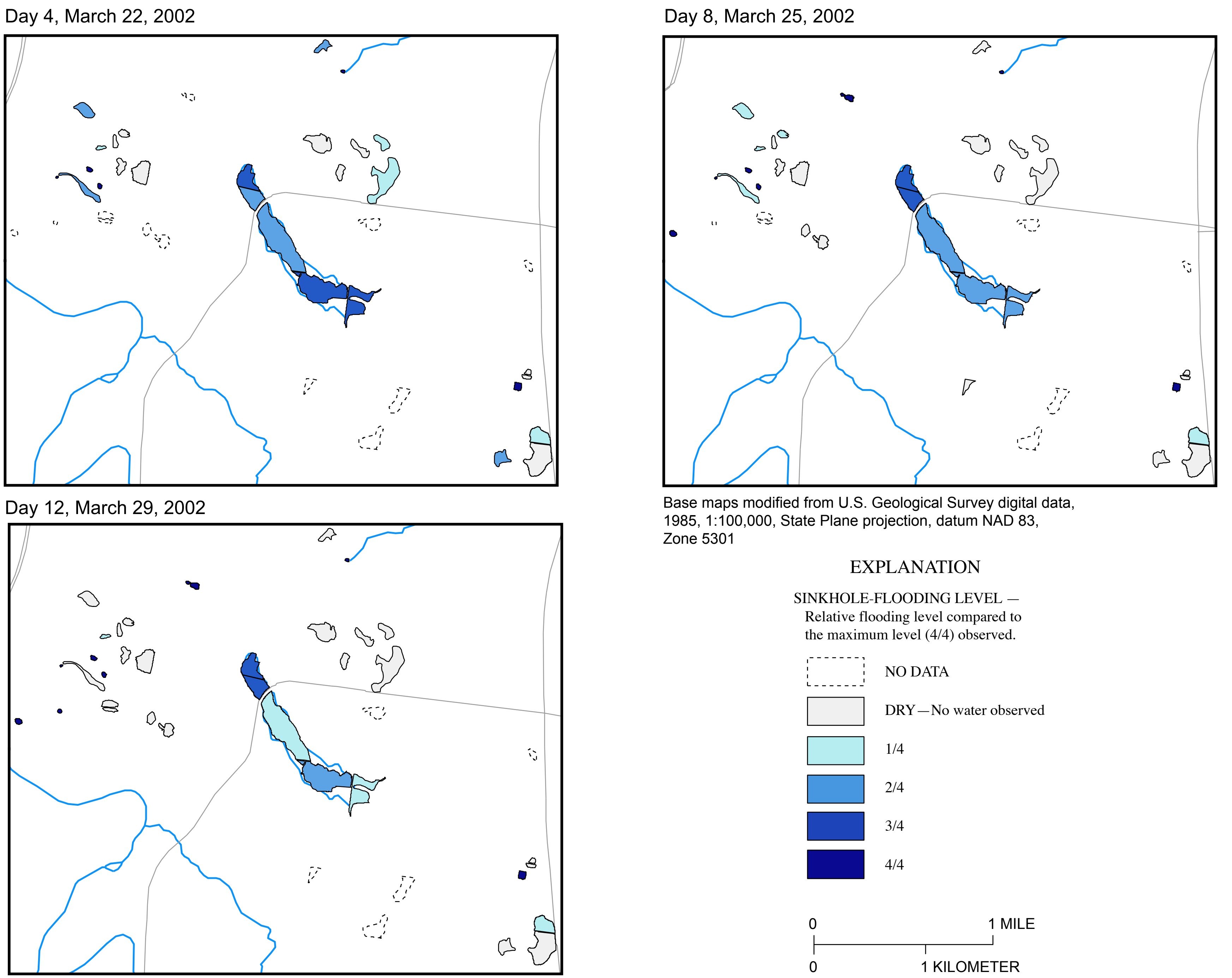


Figure 15. Relative sinkhole-flooding levels after the March 17, 2002 storm, at the Hooper Bottom focus area, Murfreesboro, Tennessee.

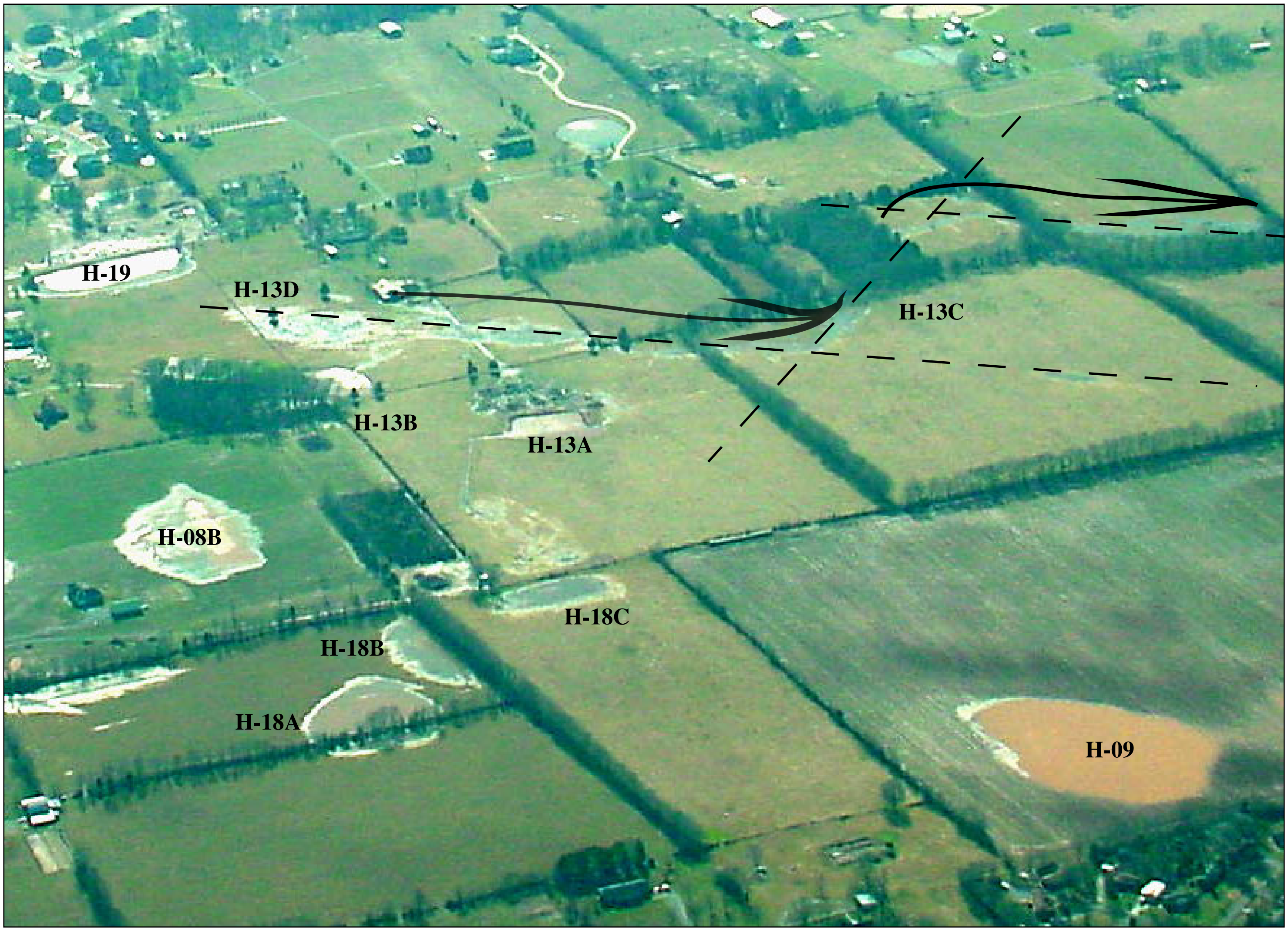


Figure 16. Overland flow between sinkhole H-13D and H-13C in the Hooper Bottom focus area, Murfreesboro, Tennessee, January 25, 2002.

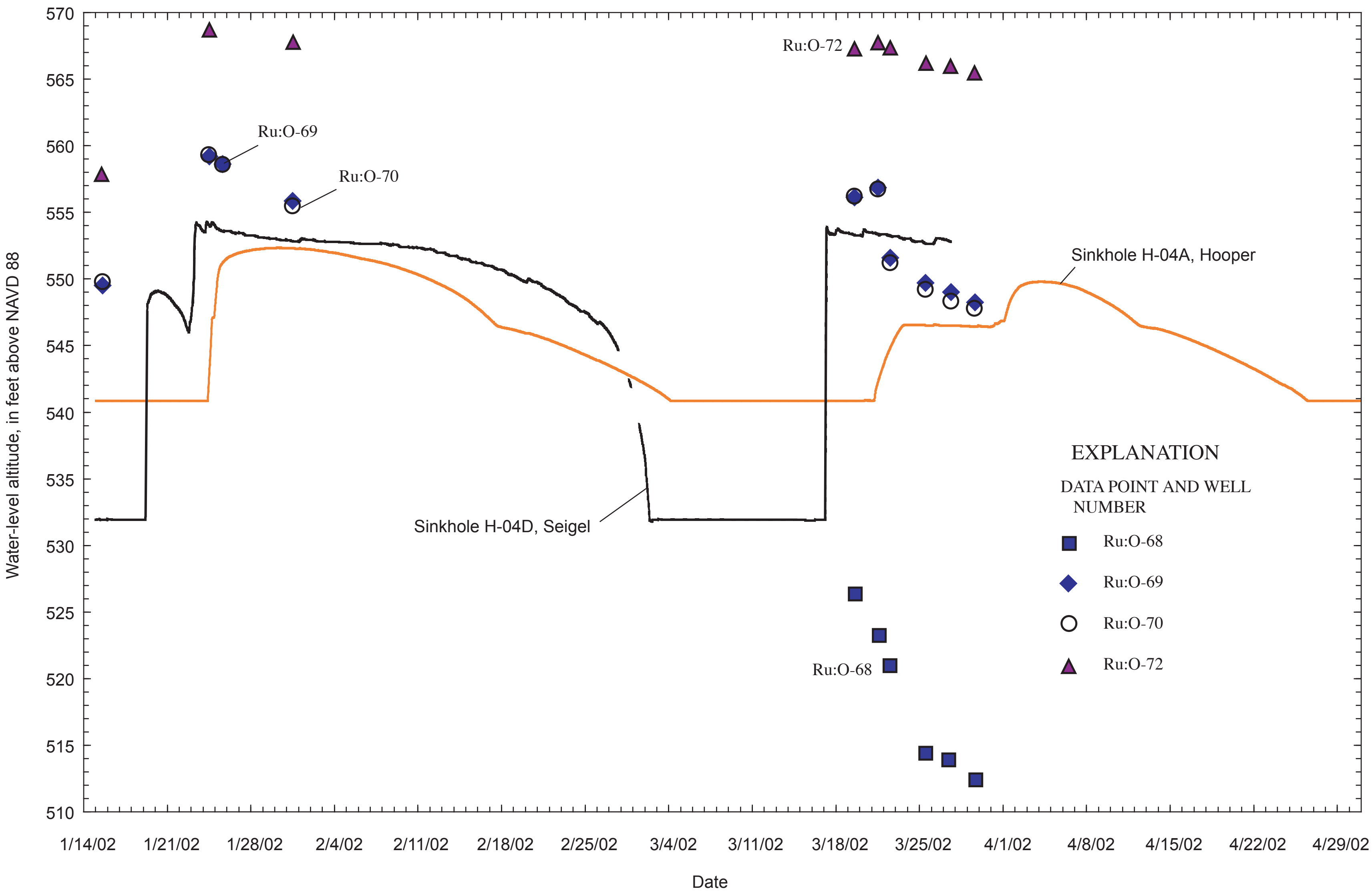


Figure 17. Water-level altitudes in sinkholes H-04A and H-04D; and wells Ru:O-68, Ru:O-69, Ru:O-70, and Ru:O-72 near the Hooper Bottom focus area, Murfreesboro, Tennessee, January through April 2002.

the lower Ridley Limestone and the Pierce Limestone to the regional ground-water conduit system. The Hooper Bottom sinkhole complex provides a connection, although somewhat restricted, with a ground-water conduit system.

Manson Pike Focus Area

The Manson Pike focus area (fig. 18) is located about 3 mi northwest of the Murfreesboro, Tennessee, City Hall. The focus area is primarily underlain by the Ridley Limestone with the Pierce and Murfreesboro Limestones mapped as cropping out along the West Fork Stones River (Wilson, 1964a, c). In the focus area, the top of the Pierce Limestone is mapped at altitudes of about 550 ft to about 570 ft. The top of the Pierce Limestone is mapped at similar altitudes along Overall Creek, located just west of the focus area. Much of the focus area is covered by soils thick enough to support row crops or pasture although some areas with very thin soil occur in glades near the Stones River National Battlefield where the Ridley Limestone crops out.

The major hydrologic feature in the focus area is the West Fork Stones River (fig. 18). Flooding on the river can overflow into some of the sinkholes. Nearly 34 percent of the focus area is within the 100-year flood zone as designated by the Federal Emergency Management Agency (2002).

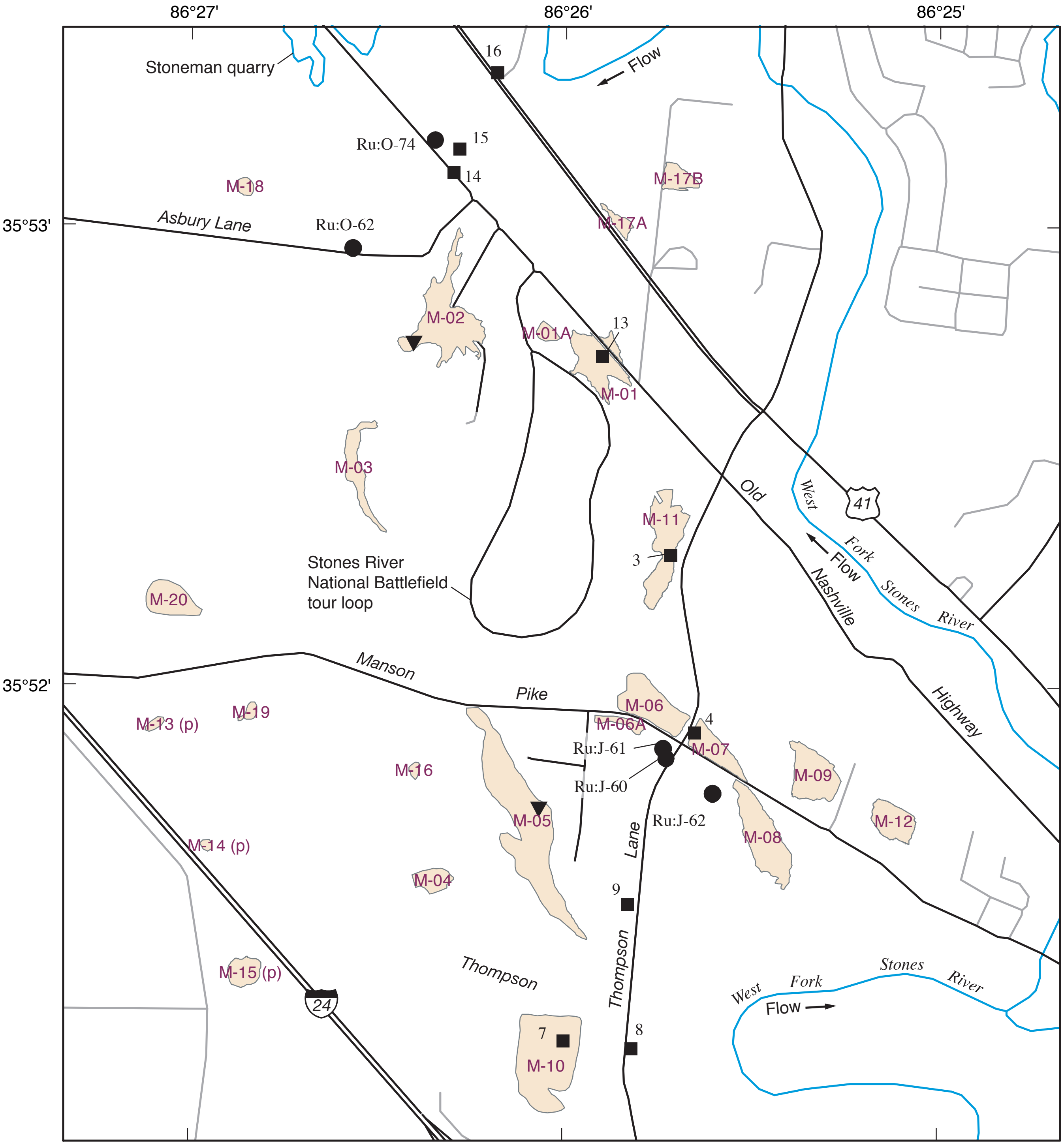
The hydrology in the Manson Pike focus area was monitored at 16 locations (fig. 18). Water-level recorders were installed in two sinkholes, M-02 and M-05. Periodic ground-water levels were measured in five wells, Ru:O-62, O-74, J-60, J-61, and J-62. Crest-stage gages, which record the peak floodwater levels, were installed at nine sinkhole locations in the focus area (fig. 18). The stream gage on the West Fork Stones River is located just north of the Manson Pike focus area (fig. 5).

Terrain analysis indicated that 70 percent of this 7.0-mi^2 focus area drains to sinkholes. Within the focus area, 20 sinkholes had floodwater observable in aerial photographs. Six of the 20 sinkholes were monitored with either water-level recorders or crest-stage gages (fig. 18). Most of the sinkhole flooding observed in the focus area occurs in broad, shallow, natural depressions; although, both M-10 and M-12 coincide with soil ‘borrow pit’ excavations. Two sinkholes, M-02 and M-05, have a broad, shallow surface expression with deep, steep-walled sinkhole throats. The water-level gages in these two sinkholes were installed in the sinkhole throats to monitor the full range of water-level fluctuation.

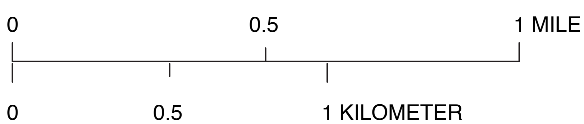
Flood response of sinkholes in the Manson Pike focus area to the March 2002 storm is shown in figure 19. Observations from the aerial photography indicate that floodwaters in the observed sinkholes were at their highest levels within about 2 days after the storm. Four days after the storm, only three sinkholes were observed with dry conditions whereas 14 others retained floodwater. Data from the aerial photographs indicate that flooding lasted longer than a week at most of the sinkholes. By the 12th day after the storm, most of the sinkholes had drained; only sinkholes M-07, M-08, M-10, and M-12 held observable water. Flooding duration in sinkholes M-10 and M-12 probably are affected by construction activities and the use of these sites as borrow pits. Sinkholes M-07 and M-08 are shallow, pan sinkholes with floodwater altitudes (about 565 to 566 ft) that were only slightly above the ground-water altitudes in nearby wells Ru:J-60, J-61, and J-62 (562 to 563 ft). The delayed outflow from these two sinkholes that was observed following the monitored storms could be the result of the small gradient between water levels in the sinkholes and ground-water levels and/or a low connectivity between the sinkholes and the ground-water conduit system drains. Roadways separate the two sinkholes, but after about 8 days, the sinkholes were classified as 1/4 full, the water levels were lower than the roadway culverts, and the culverts did not appear to control the drainage.

In general, sinkholes in the northern and western parts of the focus area drained quicker and sinkholes in the southern and eastern parts retained water longer. In duration analyses of lowland flooding in the Manson Pike area, Law (2002) observed similar patterns and noted that “Land east and south of the battlefield tour loop is slower draining than land west of the battlefield tour loop.”

Water-level responses at sinkholes and in wells in the Manson Pike focus area through the March 2002 storm are shown in figure 20. Ground-water levels measured in the five wells and water levels in the two monitored sinkholes show a decrease in water-level altitudes from the south to the north, toward the West Fork Stones River. Water levels in each of the two monitored sinkholes and in the nearby wells responded differently to the March storm. Water-level altitudes in the southern sinkhole, M-05, peaked about 4 days after the storm and remained at high levels for several days, indicating that inflow to this sinkhole was sustained for days after the storm. Two days after the March 2002 storm, no overland flow to this sinkhole was observed in aerial photographs; the sustained inflow was probably from the ground-water system. Ground-water altitudes measured in wells located west of sinkhole M-05 and near the intersection of Manson Pike and Thompson Lane (wells Ru:J-60, J-61, and J-62) were always above the water-level altitudes in sinkhole M-05. The higher water-level altitudes in the three wells indicate a hydraulic gradient with a potential to cause the continued inflow of water from parts of the ground-water system to the sinkhole. The water-level altitudes in the three wells showed only slight differences between the deepest well (Ru:J-60) and the two shallower wells (Ru:J-61 and J-62). Contrasting with the character of flood response in southern parts of the focus area, water levels in the northern sinkhole, M-02, rose rapidly after the end of the March 2002 storm, peaked quickly, and then declined by greater than 7 ft within 3 days after the storm. Ground-water altitudes in wells Ru:O-62 and O-74 located north of sinkhole M-02 were always at levels below the water-level altitudes of sinkhole M-02. None of the post-storm ground-water level measurements from wells near sinkhole M-02 indicate a gradient with a potential to cause ground-water inflow to the



Base modified from U.S. Geological Survey digital data 1985, 1:1,000,000 State Plane projection, datum NAD 83, Zone 5301



EXPLANATION

M-10 SINKHOLE AND NUMBER—Water inundation observed in aerial photography. Farm ponds indicated by (p)

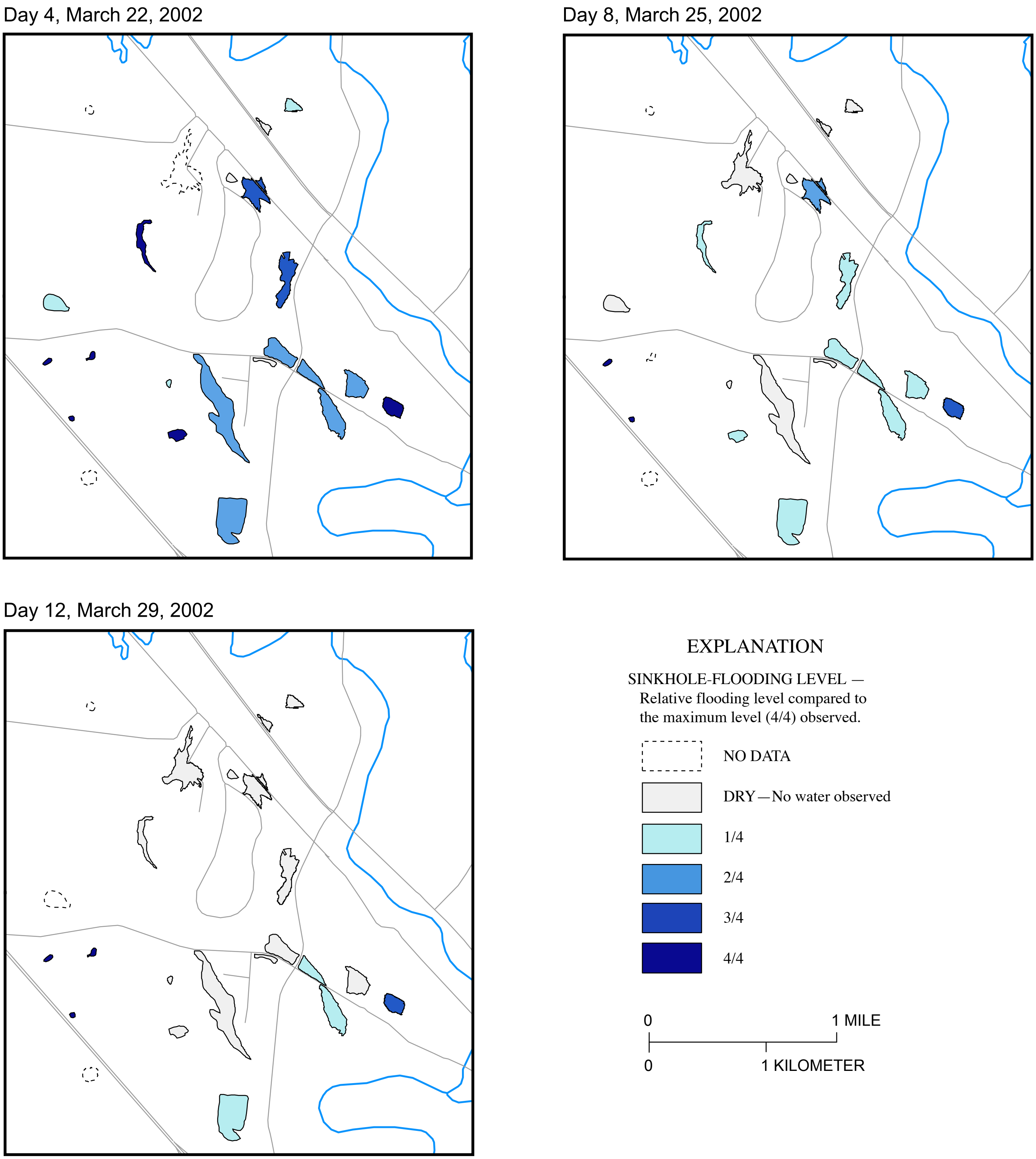
MONITORING STATION—Data type in parentheses; number refers to text

SINKHOLE GAGE (continuous water level)

Ru:J-62 WELL (periodic water level)

8 CREST-STAGE GAGE (peak water level)

Figure 18. Data-collection points and flooded sinkholes identified in aerial photography, at the Manson Pike focus area, Murfreesboro, Tennessee.



Base modified from U.S. Geological Survey digital data 1985, 1:100,000 State Plane projection, datum NAD 83, Zone 5301

Figure 19. Relative sinkhole-flooding levels after the March 17, 2002 storm, at the Manson Pike focus area, Murfreesboro, Tennessee.

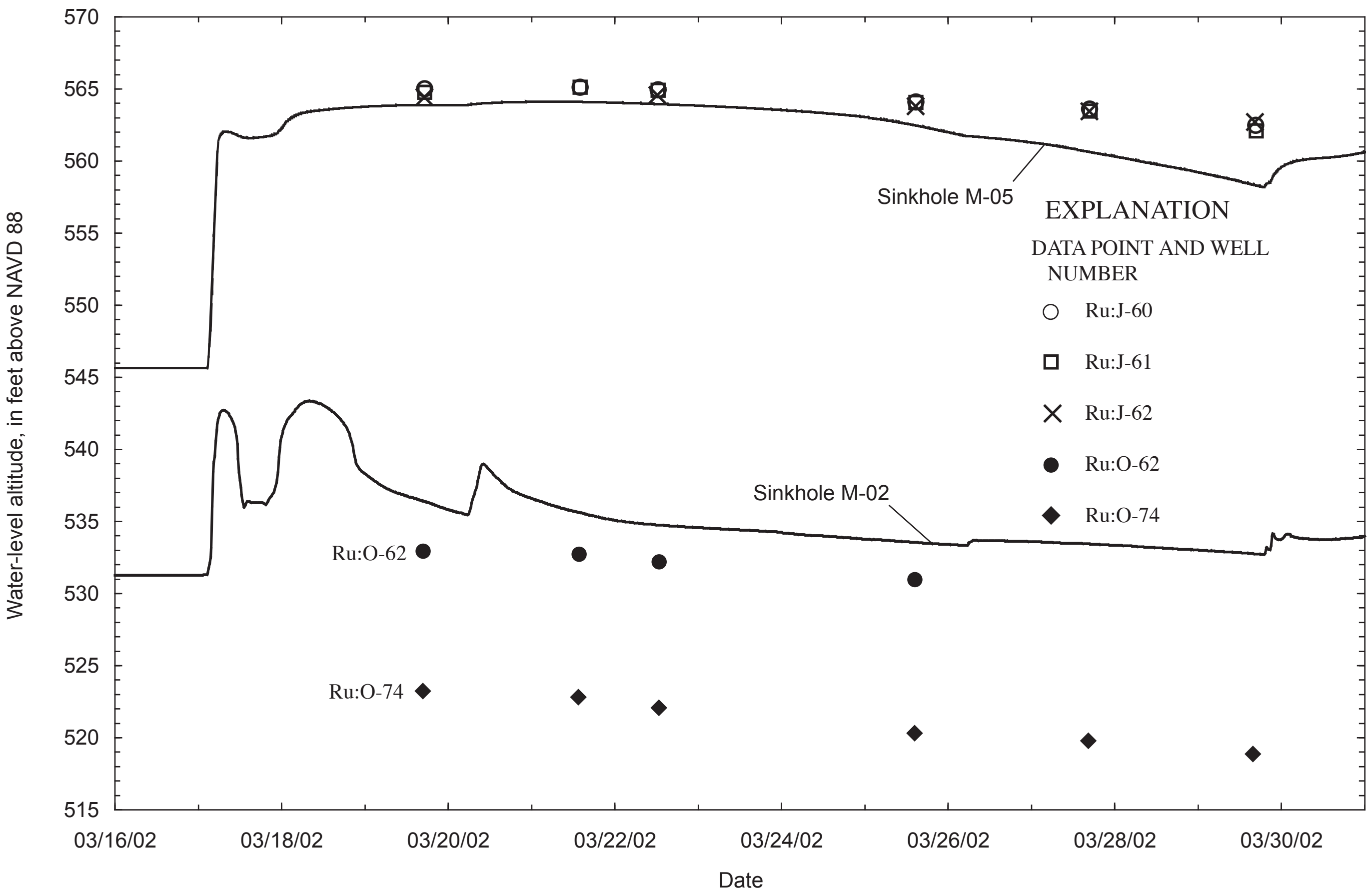


Figure 20. Water-level altitudes in sinkholes M-02 and M-05 and in selected wells in the Manson Pike focus area, Murfreesboro, Tennessee, March 16-31, 2002.

sinkhole. Rather, the water-level data indicate a potential only for outflow from sinkhole M-02 to the ground-water system.

The highest water-level altitudes measured at the water-level gage in sinkhole M-05 (fig. 20) do not always correspond to the relative flooding levels observed in the aerial photographs. In addition to the broad, gently sloping outer areas at altitudes between 564 and 565 ft, sinkhole M-05 has two deep, steep-walled throats, located near its center. The sinkhole water-level gage was installed in one of the deeper sinkhole throats with the water-level sensor at an altitude of about 546 ft (fig. 20). On March 22, 2002, the area observed as flooded had decreased in size and was classified as 1/4 flooded. The water-surface altitude measured at the water-level gage on this date was about 564 ft and was beginning to decline. By March 25, 2002, flooding in sinkhole M-05 was not observed in the aerial photography and the relative flood level was classified as dry (0). The water-level altitudes measured on March 25, 2002 at the water-level gage averaged about 563 ft. The floodwater in the sinkhole had receded into the sinkhole throats and was not visible in the aerial photography.

The differences in hydrologic response among the sinkholes in the Manson Pike focus area show the effect of apparent differences in connectivity with ground-water conduit system drains and, for deep sinkholes, differences in inflow from parts of the ground-water system. Most of the sinkholes in the focus area are pan sinkholes with prolonged flood durations, indicating poor connectivity to drains. Pan sinks near the intersection of Manson Pike and Thompson Lane are located in an area where post-storm ground-water levels in wells also show slow declines; even the 106-ft-deep well (Ru:J-60) may have poor connectivity to ground-water conduit system drains. In this focus area, a deep sinkhole, M-05, receives inflow from parts of the ground-water system for several days following a storm. The sustained, high, post-storm water levels in this sinkhole suggest low connectivity to the ground-water conduit system drain, and similar to deep sinkholes in Hooper Bottom, sinkhole M-05 appears to be connected to multiple zones of the ground-water system. Another deep sinkhole in the Manson Pike focus area, M-02, is located a short distance from the West Fork Stones River, the ultimate drain for the ground-water system. Water levels in M-02 rise and decline quickly, occur at higher altitudes than in nearby wells, and indicate a high connectivity to a ground-water conduit system.

Models of Sinkhole Flooding

Flooding duration and levels in all of the flooded sinkholes observed in the three focus areas are controlled by connectivity to a ground-water conduit system. The ground-water conduit system has high hydraulic transmissivity and tends to develop in the clean-limestone parts of the Ridley and Murfreesboro Limestones. The shaley layers in the Ridley, Pierce, and Murfreesboro Limestones tend to restrict the connectivity between sinkholes and the ground-water conduit system and to restrict the connectivity between zones within the ground-water system. In areas where the Pierce Limestone occurs close to the bottom of a sinkhole, the sinkhole may have a low connectivity to the ground-water conduit system, and thus, may have prolonged flood duration.

The occurrence, intensity, and duration of sinkhole flooding in the study area is controlled by the inflow of water, available storage in the sinkhole, and the outflow of water from the sinkhole. Other than surface overflow, the outflow of water from a sinkhole is largely a function of the degree of connectivity to the ground-water conduit system. Primarily, sinkholes in the study area flood when the rate of water flowing in exceeds the rate of water flowing out to the ground-water conduit system.

The sinkholes that were observed to flood in the three focus areas are represented in one of three models based on the sinkhole morphology and the connectivity to a ground-water conduit system as indicated by the water-level response to flooding. The models of sinkhole flooding are depicted in figure 3 and are described below.

1. Deep sinkholes with a high connectivity (fig. 3, model A)—The sinkholes are more than 10 ft deep and may have steep-sided throats. These sinkholes fill rapidly after a storm and can drain rapidly after a storm ends (3 to 5 feet per day [ft/d] in the first 2 to 3 days). These sinkholes have high connectivity to the ground-water conduit system. Sinkholes S-10C in the Shiloh focus area and M-02 in the Manson Pike focus area are examples of this model of sinkhole flooding.

2. Pan sinkholes with low connectivity (fig. 3, model B)—The sinkholes are broad, shallow depressions formed on the soil and shallow bedrock. Pan sinkholes fill quickly as a result of overland flow and have typical flood durations lasting more than 8 days after the end of a storm. Flooding in the pan sinkholes occurs as part of the shallow zone in the ground-water system; this shallow zone has low connectivity to the ground-water conduit system. Pan sinkholes that receive surface overflow from, or provide surface overflow to, adjacent sinkholes are a subcategory of this model. Sinkholes H-13C and H-13D (fig. 16) are examples of this subcategory where outflow from the upper sinkhole flows across the land surface to the lower altitude sinkhole.

3. Deep sinkholes with low connectivity (fig. 3, model C)—The sinkholes are more than 10 ft deep and may have steep-sided throats. The sinkholes fill with water after a storm and may show a lag between the end of a storm and the timing of peak water levels. Water levels in these sinkholes recede slowly (about 3 ft in 10 days), and the sinkholes remain flooded for several days. These sinkholes continue to receive inflow for several days after the end of a storm and often have post-storm water-level altitudes slightly below local ground-water altitudes. The sinkholes appear to have low connectivity to the ground-water conduit system. Sinkhole M-05 in the Manson Pike focus area and H-04D in the Hooper Bottom focus area are examples of this model of sinkhole flooding.

Alterations in land use and changes to surface-water flow patterns can affect the inflow of water to sinkholes and can change the sinkhole-flooding response to storms. Each of the three categories of sinkholes can be affected in different ways as the result of land-surface changes.

Pan sinkholes with low connectivity—Land-surface modifications that direct more water into a pan sinkhole increase inflow and could result in higher flood-level altitudes and longer flood durations. Conversely, land-surface modifications that increase the outflow by overland drainage (for example, lowering the altitude of the overflow control) could decrease the flood-level altitude and could possibly shorten the duration of flooding. Road construction or alterations that reduce overland flow within or between pan sinkholes could result in longer flood durations if the alterations isolate sinkholes or parts of sinkholes from outflow drains.

Deep sinkholes with high connectivity—These sinkholes store the initial flooding and rapidly transmit water to the ground-water conduit system (high outflow). Land-surface modifications that direct more water into this type of sinkhole may increase the flood peak, depending on the available storage, but may not have a substantial effect on the flood duration. Surface-water inflow that transports large amounts of sediment or debris into these sinkholes could reduce the connectivity to the ground-water conduit system and increase the duration of sinkhole flooding.

Deep sinkholes with low connectivity—Outflow from these sinkholes is limited or restricted by low connectivity to the ground-water conduit system. Land-surface modifications that increase the inflow to these sinkholes could result in higher flood-peak altitudes and longer flood durations.

The classification of the sinkholes in the Murfreesboro area and an understanding of their flood characteristics can be used as a guide for land-use planning such that, with appropriate drainage changes at land surface and development guidelines for sinkhole watersheds, future damage or hazards from sinkhole flooding can be minimized. Classifying a topographic depression into one of the models of sinkhole flooding currently relies on observations of sinkhole morphology and sinkhole water-level response to rainfall.

Summary and Conclusions

Land-use planning and infrastructure design in rapidly urbanizing karst areas are hampered by insufficient delineation of sinkholes and by incomplete knowledge of the hydrologic character of the sinkholes. Developers and water-resources managers need to know where sinkholes are located, which sinkholes might present flood hazards, and which sinkholes act as conduits to the ground-water system.

The Murfreesboro area, Rutherford County, Tennessee, is typical of many areas of thinly mantled karst terrain where much of the rainfall runoff flows to low areas in sinkholes. In this type of terrain, some sinkholes never flood, some flood then drain quickly, and some flood then remain flooded for long periods. The USGS, in cooperation with the City of Murfreesboro, conducted an investigation from January 2001 through April 2002 to delineate sinkholes and sinkhole watersheds in the Murfreesboro area and to characterize the hydrologic response of sinkholes to major rainfall events.

Three focus areas, Shiloh, Hooper Bottom, and Manson Pike, in the Murfreesboro study area were selected to evaluate sinkhole flooding. For each of the three areas, the hydrologic response at sinkholes with observable flooding were tracked and evaluated with aerial photography after three major storms. Hydrologic data collected for the investigation included rainfall and stage measurements of the West Fork Stones River, continuous water-level data from six sinkholes, periodic ground-water levels in nine wells, and peak water levels at nine sinkhole crest-stage gages.

Terrain analysis, the automated processing of 2-ft contour interval hypsography data, was used to delineate sinkholes and sinkhole watersheds in the Murfreesboro area. The terrain analysis indicated that sinkhole watersheds make up most of the topography in each focus area with about 80, 65, and 70 percent of the Shiloh, Hooper Bottom, and Manson Pike focus areas, respectively, draining to sinkholes.

Low altitude, oblique aerial photography was used to track sinkhole flooding following storms on February 14, 2001, January 23, 2002, and March 17, 2002. For each focus area, the aerial photographs were evaluated to identify specific sinkholes that were flooded and to track the flood levels through the course of the subsequent photography taken for several days after the storm.

The Shiloh focus area contains 24 sinkholes with floodwater observable in the aerial photographs taken following the storms. The sinkhole flooding in the Shiloh focus area appears to be associated with both a shallow system and a ground-water conduit system. Sinkholes with high connectivity to the ground-water conduit system show a relatively rapid water-level rise and decline. Sinkholes that remain flooded the longest in the Shiloh focus area have low connectivity with the ground-water conduit system, occur at low altitudes and may be near ground-water discharge points, or are affected by surface-water drainage.

The Hooper Bottom focus area contains 34 sinkholes with floodwater observable in the aerial photographs. The sinkhole flooding in the Hooper Bottom focus area appears to be associated with ground-water zones having limited connectivity with the ground-water conduit system. A shallow zone in the ground-water system is reflected by the flooding response in most of the sinkholes observed in the study area. Most of the sinkholes in the Hooper Bottom focus area are shallow (less than 5 ft deep), broad pan sinkholes that retained floodwater for at least 8 days following the March 2002 storm. Deep sinkholes in the Hooper Bottom sinkhole complex may be connected to multiple zones in the ground-water system and may simultaneously receive inflow from parts of the ground-water system with high head while discharging outflow to parts of the system with low head. The long delay for sinkhole flooding to drain in the Hooper Bottom complex is probably a result of the continued inflow from shallow parts of the ground-water system and surface ditches and an apparent low connectivity through the lower Ridley Limestone and the Pierce Limestone to the regional ground-water conduit system. The Hooper Bottom sinkhole complex provides a connection, although somewhat restricted, with a ground-water conduit system.

The Manson Pike focus area contains 20 sinkholes with floodwater observable in aerial photographs. The differences in hydrologic response among the sinkholes in the Manson Pike focus area show the effect of apparent differences in connectivity with the ground-water conduit system and, for deep sinkholes, differences in inflow from parts of the ground-water system. Most of the sinkholes in the focus area are pan sinkholes with prolonged flood durations indicating poor connectivity to drains. Pan sinkholes near the intersection of Manson Pike and Thompson Lane are located in an area where post-storm ground-water levels in wells also show slow declines. In this focus area, a deep sinkhole, M-05, receives inflow from parts of ground-water system for several days following a storm. The sustained high, post-storm water levels in this sinkhole suggest low connectivity to the ground-water conduit system and, similar to deep sinkholes in Hooper Bottom, sinkhole M-05 appears to be connected to multiple zones of the ground-water system. Water levels in another deep sinkhole in the Manson Pike focus area, M-02, rise and decline quickly, occur at higher altitudes than in nearby wells, and indicate a high connectivity between the sinkhole and the ground-water conduit system.

Flooding duration and levels in all of the flooded sinkholes observed in the three focus areas are controlled by connectivity to the ground-water conduit system. The ground-water conduit system has high hydraulic transmissivity and tends to develop in the clean-limestone parts of the Ridley and Murfreesboro Limestones. The shaley layers in the Ridley, Pierce, and Murfreesboro Limestones tend to restrict the connectivity between sinkholes and the ground-water conduit system and to restrict the connectivity between zones within the ground-water system. In areas where the Pierce Limestone occurs close to the bottom of a sinkhole, the sinkhole may have a low connectivity to the ground-water conduit system, and thus, may have prolonged flood duration.

The sinkholes that were observed to flood in the three focus areas can be classified by one of three models based on the morphology of the sinkhole and the connectivity to a ground-water conduit system as indicated by the water-level response to flooding. The three models are:

1. Pan sinkholes with low connectivity
2. Deep sinkholes with high connectivity
3. Deep sinkholes with low connectivity

Alterations in land use and changes to surface-water flow patterns can affect the inflow of water to sinkholes and, depending on the type of sinkhole, can change the sinkhole-flooding response to storms.

Pan sinkholes with low connectivity—Land-surface modifications that direct more water into a pan sinkhole can result in higher flood-level altitudes and longer flood durations. Land-surface modifications that increase the outflow by overland drainage could decrease the flood-level altitudes. Road construction or alterations that reduce flow within or between pan sinkholes could result in increased flooding duration.

Deep sinkholes with high connectivity—These sinkholes store the initial flooding and then rapidly transmit water to the ground-water conduit system (high outflow). Land-surface modifications that direct more water into the sinkhole may increase the flood-peak altitudes, but may not have a substantial effect on flood durations.

Deep sinkholes with low connectivity—Outflow from these sinkholes is limited or restricted by a low connectivity to the ground-water conduit system. Land-surface changes that increase the inflow to the sinkholes could result in higher peak-flood levels or longer flood durations.

The classification of the sinkholes in the Murfreesboro area along with an understanding of their flood characteristics can guide land-use planning such that, with appropriate drainage changes at land surface and development guidelines for sinkhole watersheds, future damage or hazards can be minimized. Classifying a topographic depression into one of the models of sinkhole flooding requires observations of sinkhole morphology and sinkhole water-level response to rainfall.

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Appendix. Relative flooding levels observed in aerial photography of the Murfreesboro area, February 2001, January 2002, and March 2002.

[Altitude in feet above NAVD 88; ft², square foot; -na-, photography not available or sinkhole not observed; Relative flooding level: 0, dry; 1/4, sinkhole appeared one-quarter full; 2/4, sinkhole appeared about one-half full; 3/4, three-quarters full; 4/4, sinkhole appeared full; nd, flooding duration not determined; >, greater than; <, less than]

Site number	Altitude at 4/4 full (feet)	Area (ft²)	Area (acre)	Relative flooding level February 2001				Flooding duration (days)
				17	19	23	27	
Storm started Feb. 14, 2001; first photos on day 3								
Manson Pike focus area								
M-01	552	339,900	7.80	4/4	4/4	3/4	2/4	>13
M-01A	553	49,580	1.13	4/4	3/4	0	0	5
M-02	546	666,670	15.30	3/4	-na-	-na-	1/4	>13
M-03	553	215,005	4.93	4/4	-na-	-na-	1/4	>13
M-04	581	121,824	2.80	4/4	4/4	-na-	-na-	nd
M-05	565	1,175,296	26.98	4/4	4/4	3/4	2/4	>13
M-06	565	386,349	8.87	-na-	4/4	3/4	3/4	>13
M-07	566	219,237	5.03	-na-	4/4	3/4	3/4	>13
M-08	565	480,764	11.04	-na-	4/4	3/4	3/4	>13
M-09	570	351,400	8.07	-na-	4/4	3/4	3/4	>13
M-10	571	877,332	20.14	4/4	4/4	-na-	4/4	>13
M-11	561	457,785	10.51	-na-	4/4	3/4	3/4	>13
M-12	572	225,445	5.18	-na-	4/4	3/4	3/4	>13
M-16	572	22,323	0.51	4/4	4/4	-na-	-na-	nd
Shiloh focus area								
S-02A	616	238,335	5.47	4/4	4/4	-na-	-na-	nd
S-02B	616	326,262	7.49	4/4	4/4	-na-	-na-	nd
S-04	594	116,961	2.69	4/4	-na-	-na-	-na-	nd
S-07	587	2,274	0.05	4/4	-na-	-na-	-na-	nd
S-12	619	184,007	4.22	4/4	-na-	-na-	-na-	nd
S-13	618	125,202	2.87	-na-	-na-	-na-	1	nd
S-15	596	21,783	0.50	-na-	-na-	-na-	-na-	nd
S-17	607	10,367	0.24	-na-	1/4	-na-	4/4	>13
S-18	617	27,067	0.62	-na-	-na-	-na-	4/4	>13
S-20	633	47,991	1.10	3/4	4/4	-na-	1/4	>13
S-21	634	37,365	0.86	4/4	4/4	-na-	0	nd
S-22	634	51,881	1.19	4/4	1/4	-na-	0	nd
Hooper Bottom focus area								
H-01	602	138,339	3.18	4/4	0	-na-	-na-	3
H-01A	601	518,626	11.91	4/4	3/4	0	-na-	5
H-01B	601	225,677	5.18	-na-	1/4	0	-na-	5
H-02	586	245,483	5.64	-na-	3/4	-na-	-na-	nd
H-02A	586	212,630	4.88	-na-	0	-na-	-na-	nd
H-04	550	283,338	6.50	-na-	-na-	4/4	4/4	>13
H-04A	550	276,404	6.35	-na-	-na-	4/4	4/4	>13
H-04B	552	1,115,036	25.60	-na-	3/4	4/4	4/4	>13
H-04C	552	821,556	18.86	-na-	-na-	4/4	4/4	>13
H-04D	554	416,934	9.57	-na-	-na-	4/4	4/4	>13
H-05	572	285,464	6.55	-na-	4/4	-na-	1/4	>13
H-05A	570	82,167	1.89	-na-	4/4	-na-	1/4	>13
H-05B	572	535,955	12.30	-na-	3/4	-na-	1/4	>13
H-05C	575	114,746	2.63	-na-	4/4	-na-	1/4	>13
H-05D	574	110,241	2.53	-na-	4/4	-na-	2/4	>13
H-08A	566	265,933	6.10	-na-	-na-	3/4	-na-	nd
H-08B	568	86,992	2.00	-na-	-na-	0	-na-	nd
H-09	557	159,515	3.66	-na-	-na-	2/4	-na-	nd
H-10	564	142,865	3.28	-na-	-na-	4/4	2/4	>13
H-11	560	8,823	0.20	-na-	-na-	-na-	4/4	>13
H-11A	565	88,289	2.03	-na-	-na-	-na-	0	nd
H-12	574	46,689	1.07	-na-	-na-	-na-	4/4	>13
H-14	564	172,784	3.97	-na-	-na-	0	-na-	nd
H-15	570	62,833	1.44	-na-	-na-	-na-	2/4	>13

Appendix. Relative flooding levels observed in aerial photography of the Murfreesboro area, February 2001, January 2002, and March 2002.—Continued

[Altitude in feet above NAVD 88; ft², square foot; -na-, photography not available or sinkhole not observed; Relative flooding level: 0, dry; 1/4, sinkhole appeared one-quarter full; 2/4, sinkhole appeared about one-half full; 3/4, three-quarters full; 4/4, sinkhole appeared full; nd, flooding duration not determined; >, greater than; <, less than]

Site number	Altitude at 4/4 full (feet)	Area (ft^2)	Area (acre)	Relative flooding level January 2002				Flooding duration (days)
				24	25	28	31	
Storm started Jan. 23, 2002; first photos on day 1								
Manson Pike focus area								
M-01	552	339,900	7.80	4/4	4/4	4/4	4/4	>8
M-01A	553	49,580	1.14	4/4	4/4	0	0	2
M-02	546	666,670	15.30	-na-	4/4	2/4	0	5
M-03	553	215,005	4.94	-na-	4/4	3/4	1/4	>8
M-04	581	121,824	2.80	-na-	4/4	3/4	-na-	nd
M-05	565	1,175,296	26.98	-na-	4/4	4/4	3/4	>8
M-06	565	386,349	8.87	4/4	4/4	4/4	3/4	>8
M-06A	565	63,700	1.46	4/4	4/4	3/4	0	5
M-07	566	219,237	5.03	4/4	4/4	4/4	3/4	>8
M-08	565	480,764	11.04	4/4	4/4	4/4	3/4	>8
M-09	570	351,400	8.07	4/4	4/4	4/4	3/4	>8
M-10	571	877,332	20.14	4/4	4/4	4/4	-na-	nd
M-11	561	457,785	10.51	4/4	4/4	4/4	3/4	>8
M-12	572	225,445	5.18	4/4	4/4	4/4	4/4	>8
M-15	594	137,625	3.16	-na-	4/4	4/4	-na-	nd
M-16	572	22,323	0.51	-na-	4/4	2/4	-na-	nd
M-17A	562	62,033	1.42	-na-	4/4	2/4	-na-	nd
M-17B	562	118,825	2.73	-na-	4/4	2/4	-na-	nd
M-18	553	42,660	0.98	-na-	-na-	3/4	3/4	>8
M-20	575	245,091	5.63	-na-	4/4	-na-	-na-	nd
Shiloh focus area								
S-01	602	364,233	8.36	-na-	4/4	2/4	1/4	>8
S-02A	616	238,335	5.47	-na-	4/4	3/4	1/4	>8
S-02B	616	326,262	7.49	-na-	4/4	3/4	2/4	>8
S-03	596	144,677	3.32	-na-	-na-	3/4	3/4	>8
S-04	594	116,961	2.69	-na-	4/4	2/4	-na-	nd
S-05	596	65,473	1.50	-na-	-na-	4/4	4/4	>8
S-06	598	133,401	3.06	-na-	4/4	4/4	4/4	>8
S-07	587	2,274	0.05	-na-	4/4	4/4	3/4	>8
S-08	590	11,706	0.27	-na-	-na-	-na-	-na-	nd
S-09	594	55,811	1.28	-na-	-na-	-na-	-na-	nd
S-10A	596	2,247	0.05	-na-	-na-	1/4	-na-	nd
S-10B	598	39,251	0.90	-na-	4/4	0	-na-	2
S-10C	590	2,940	0.07	-na-	4/4	-na-	-na-	nd
S-11	600	56,177	1.29	-na-	4/4	-na-	0	nd
S-12	619	184,007	4.22	-na-	4/4	1/4	1/4	>8
S-15	596	21,783	0.50	-na-	-na-	4/4	-na-	nd
S-16B	606	184,353	4.23	-na-	4/4	0	0	2
S-17	607	10,367	0.24	-na-	-na-	4/4	-na-	nd
S-18	617	27,067	0.62	-na-	-na-	4/4	-na-	nd
S-19	636	107,994	2.48	-na-	4/4	-na-	-na-	nd
S-20	633	47,991	1.10	-na-	4/4	-na-	-na-	nd
S-21	634	37,365	0.86	-na-	4/4	-na-	-na-	nd
S-22	634	51,881	1.19	-na-	4/4	-na-	-na-	nd
Hooper Bottom focus area								
H-01	602	138,339	3.18	-na-	4/4	-na-	0	nd
H-01A	601	518,626	11.91	-na-	4/4	3/4	0	5
H-01B	601	225,677	5.18	-na-	4/4	2/4	0	5
H-02	586	245,483	5.64	-na-	0	-na-	-na-	nd
H-02A	586	212,630	4.88	-na-	2/4	-na-	-na-	nd
H-04	550	283,338	6.50	-na-	4/4	4/4	4/4	>8
H-04A	550	276,404	6.35	2/4	4/4	4/4	4/4	>8
H-04B	552	1,115,036	25.60	-na-	3/4	4/4	4/4	>8
H-04C	552	821,556	18.86	3/4	3/4	4/4	3/4	>8
H-04D	554	416,934	9.57	2/4	3/4	3/4	2/4	>8

Appendix. Relative flooding levels observed in aerial photography of the Murfreesboro area, February 2001, January 2002, and March 2002.—Continued

[Altitude in feet above NAVD 88; ft², square foot; -na-, photography not available or sinkhole not observed; Relative flooding level: 0, dry; 1/4, sinkhole appeared one-quarter full; 2/4, sinkhole appeared about one-half full; 3/4, three-quarters full; 4/4, sinkhole appeared full; nd, flooding duration not determined; >, greater than; <, less than]

Site number	Altitude at 4/4 full (feet)	Area (ft^2)	Area (acre)	Relative flooding level January 2002				Flooding duration (days)
				24	25	28	31	
Storm started Jan. 23, 2002; first photos on day 1								
Hooper Bottom focus area—Continued								
H-05	572	285,464	6.55	4/4	4/4	2/4	0	5
H-05A	570	82,167	1.89	4/4	4/4	2/4	1/4	>8
H-05B	572	535,955	12.30	4/4	3/4	3/4	1/4	>8
H-05C	575	114,746	2.63	4/4	3/4	3/4	-na-	nd
H-05D	574	110,241	2.53	4/4	4/4	3/4	2/4	>8
H-08A	566	265,933	6.10	-na-	4/4	4/4	4/4	>8
H-08B	568	86,992	2.00	-na-	4/4	1/4	1/4	>8
H-09	557	159,515	3.66	-na-	4/4	3/4	3/4	>8
H-10	564	142,865	3.28	-na-	3/4	2/4	1/4	>8
H-11	560	8,823	0.20	-na-	4/4	4/4	4/4	>8
H-11A	565	88,289	2.03	-na-	4/4	2/4	0	5
H-12	574	46,689	1.07	-na-	-na-	4/4	4/4	>8
H-13C	546	4,258	0.10	-na-	4/4	4/4	4/4	>8
H-13D	552	162,738	3.74	-na-	4/4	2/4	1/4	>8
H-14	564	172,784	3.97	-na-	4/4	2/4	0	5
H-15	570	62,833	1.44	-na-	3/4	-na-	-na-	nd
H-16A	592	49,852	1.14	-na-	4/4	3/4	1/4	>8
H-16B	592	45,669	1.05	-na-	4/4	3/4	2/4	>8
H-17	548	27,593	0.63	-na-	4/4	-na-	4/4	>8
H-18A	566	52,967	1.22	-na-	4/4	1/4	0	5
H-18B	566	42,831	0.98	-na-	4/4	1/4	0	5
H-18C	565	26,173	0.60	-na-	4/4	2/4	1/4	>8
H-19	552	113,948	2.62	-na-	4/4	-na-	1/4	>8
H-21	548	46,778	1.07	-na-	3/4	-na-	-na-	nd

Appendix. Relative flooding levels observed in aerial photography of the Murfreesboro area, February 2001, January 2002, and March 2002.—Continued

[Altitude in feet above NAVD 88; ft², square foot; -na-, photography not available or sinkhole not observed; Relative flooding level: 0, dry; 1/4, sinkhole appeared one-quarter full; 2/4, sinkhole appeared about one-half full; 3/4, three-quarters full; 4/4, sinkhole appeared full; nd, flooding duration not determined; >, greater than; <, less than]

Site number	Altitude at 4/4 full (feet)	Area (ft^2)	Area (acre)	Relative flooding level March 2002						Flooding duration (days)
				19	21	22	25	27	29	
Storm started March 17, 2002, first photo taken on day 2										
Manson Pike focus area										
M-01	552	339,900	7.80	4/4	3/4	2/4	2/4	1/4	0	10
M-01A	553	49,580	1.14	1/4	0	0	0	0	0	2
M-02	546	666,670	15.30	1/4	-na-	0	0	0	0	nd
M-03	553	215,005	4.94	4/4	4/4	3/4	1/4	0	0	8
M-04	581	121,824	2.80	4/4	4/4	3/4	1/4	-na-	0	nd
M-05	565	1,175,296	26.98	2/4	2/4	1/4	0	0	0	5
M-06	565	386,349	8.87	3/4	2/4	1/4	1/4	0	0	8
M-06A	565	63,700	1.46	-na-	0	0	0	0	0	nd
M-07	566	219,237	5.03	2/4	2/4	2/4	1/4	1/4	1/4	>12
M-08	565	480,764	11.04	3/4	2/4	2/4	1/4	1/4	1/4	>12
M-09	570	351,400	8.07	2/4	2/4	1/4	1/4	1/4	0	10
M-10	571	877,332	20.14	2/4	2/4	2/4	1/4	1/4	1/4	>12
M-11	561	457,785	10.51	4/4	3/4	-na-	1/4	1/4	0	10
M-12	572	225,445	5.18	-na-	4/4	-na-	3/4	3/4	3/4	>12
M-15	594	137,625	3.16	-na-	-na-	4/4	-na-	3/4	-na-	nd
M-16	572	22,323	0.51	-na-	1/4	1/4	0	0	0	5
M-17A	562	62,033	1.42	-na-	0	-na-	0	0	0	nd
M-17B	562	118,825	2.73	-na-	1/4	-na-	0	-na-	0	nd
M-18	553	42,660	0.98	3/4	-na-	-na-	-na-	1/4	-na-	nd
M-20	575	245,091	5.63	4/4	1/4	1/4	0	0	-na-	5
Shiloh focus area										
S-01	602	364,233	8.36	4/4	4/4	4/4	2/4	1/4	1/4	>12
S-02A	616	238,335	5.47	4/4	3/4	2/4	0	0	0	5
S-02B	616	326,262	7.49	4/4	3/4	3/4	1/4	1/4	1/4	>12
S-03	596	144,677	3.32	3/4	-na-	2/4	2/4	1/4	1/4	>12
S-04	594	116,961	2.69	3/4	-na-	1/4	0	-na-	0	5
S-05	596	65,473	1.50	-na-	-na-	3/4	2/4	-na-	-na-	nd
S-06	598	133,401	3.06	-na-	4/4	4/4	4/4	3/4	2/4	>12
S-07	587	2,274	0.05	-na-	-na-	1/4	0	-na-	0	5
S-08	590	11,706	0.27	2/4	-na-	-na-	0	-na-	0	nd
S-09	594	55,811	1.28	2/4	-na-	-na-	0	-na-	0	nd
S-10B	598	39,251	0.90	4/4	0	0	0	0	0	2
S-10C	590	2,940	0.07	4/4	4/4	3/4	3/4	2/4	2/4	>12
S-11	600	56,177	1.29	2/4	2/4	1/4	0	0	0	5
S-12	619	184,007	4.22	2/4	1/4	1/4	1/4	0	0	8
S-13	618	125,202	2.87	-na-	3/4	-na-	2/4	-na-	-na-	nd
S-16B	606	184,353	4.23	-na-	1/4	0	0	0	-na-	4
S-17	607	10,367	0.24	-na-	4/4	-na-	2/4	-na-	-na-	nd
S-18	617	27,067	0.62	-na-	-na-	-na-	4/4	-na-	-na-	nd
S-19	636	107,994	2.48	-na-	4/4	-na-	-na-	-na-	-na-	nd
S-20	633	47,991	1.10	-na-	2/4	-na-	1/4	-na-	-na-	nd
S-21	634	37,365	0.86	-na-	2/4	-na-	0	-na-	-na-	nd
S-22	634	51,881	1.19	-na-	1/4	-na-	0	-na-	-na-	nd
Hooper Bottom focus area										
H-01	602	138,339	3.18	3/4	2/4	0	0	0	0	4
H-01A	601	518,626	11.91	2/4	0	0	0	0	0	2
H-01B	601	225,677	5.18	1/4	1/4	1/4	1/4	1/4	1/4	>12
H-04	550	283,338	6.50	3/4	3/4	3/4	3/4	3/4	3/4	>12
H-04A	550	276,404	6.35	1/4	2/4	3/4	3/4	3/4	3/4	>12
H-04B	552	1,115,036	25.60	1/4	2/4	2/4	2/4	2/4	1/4	>12
H-04C	552	821,556	18.86	3/4	3/4	3/4	2/4	2/4	2/4	>12
H-04D	554	416,934	9.57	3/4	3/4	3/4	2/4	2/4	1/4	>12
H-05	572	285,464	6.55	0	0	0	0	0	0	<2
H-05A	570	82,167	1.89	0	0	0	0	0	0	<2

Appendix. Relative flooding levels observed in aerial photography of the Murfreesboro area, February 2001, January 2002, and March 2002.—Continued

[Altitude in feet above NAVD 88; ft², square foot; -na-, photography not available or sinkhole not observed; Relative flooding level: 0, dry; 1/4, sinkhole appeared one-quarter full; 2/4, sinkhole appeared about one-half full; 3/4, three-quarters full; 4/4, sinkhole appeared full; nd, flooding duration not determined; >, greater than; <, less than]

Site number	Altitude at 4/4 full (feet)	Area (ft²)	Area (acre)	Relative flooding level March 2002						Flooding duration (days)
				19	21	22	25	27	29	
Storm started March 17, 2002, first photo taken on day 2										
Hooper Bottom focus area—Continued										
H-05B	572	535,955	12.30	1/4	1/4	0	0	0	0	4
H-05C	575	114,746	2.63	1/4	1/4	0	0	0	0	4
H-05D	574	110,241	2.53	0	0	0	0	0	0	<2
H-08A	566	265,933	6.10	0	0	-na-	0	-na-	0	<2
H-08B	568	86,992	2.00	0	0	-na-	0	-na-	0	<2
H-09	557	159,515	3.66	2/4	2/4	-na-	1/4	1/4	0	10
H-11	560	8,823	0.20	-na-	4/4	4/4	4/4	4/4	4/4	>12
H-11A	565	88,289	2.03	-na-	2/4	0	0	0	0	4
H-12	574	46,689	1.07	-na-	-na-	3/4	-na-	-na-	-na-	nd
H-13C	546	4,258	0.10	4/4	4/4	-na-	4/4	4/4	4/4	>12
H-13D	552	162,738	3.74	2/4	2/4	-na-	1/4	0	0	8
H-14	564	172,784	3.97	-na-	-na-	0	0	0	0	nd
H-15	570	62,833	1.44	-na-	-na-	2/4	0	-na-	-na-	5
H-16A	592	49,852	1.14	0	0	0	0	0	0	<2
H-16B	592	45,669	1.05	4/4	4/4	4/4	4/4	4/4	4/4	>12
H-17	548	27,593	0.63	4/4	-na-	-na-	4/4	4/4	4/4	>12
H-18A	566	52,967	1.22	1/4	0	-na-	1/4	-na-	0	8
H-18B	566	42,831	0.98	0	0	-na-	0	-na-	0	<2
H-18C	565	26,173	0.60	1/4	1/4	-na-	1/4	1/4	1/4	>12
H-19	552	113,948	2.62	0	-na-	-na-	-na-	0	0	nd
H-21	548	46,778	1.07	4/4	-na-	4/4	4/4	-na-	4/4	>12