Duration and Frequency Analysis of Lowland Flooding in Western Murfreesboro, Rutherford County, Tennessee, 1998-2000

By George S. Law

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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)
square mile (mi^2)	2.59	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)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = (1.8 X °C) + 32

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 1927.

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ABSTRACT

Periodic flooding occurs at lowlands and sinkholes in and adjacent to the flood plain of the West Fork Stones River in the western part of Murfreesboro, Tennessee. Flooding in this area commonly occurs during the winter months from December through March. The maximum water level that flood waters will reach in a lowland or sinkhole is controlled by the elevation of the land surrounding the site or the overflow outlet.

Maximum water levels, independent of overflow from the river, were estimated to be reached in lowlands and sinkholes in the study area every 1 to 4 years. Minor overflow from the West Fork Stones River (less than 1 foot in depth) into the study area has been estimated to occur every 10 to 20 years. Moderate overflow from the river (1 to 2 feet in depth) occurs on average every 20 to 50 years, while major river overflow (in excess of 2 feet in depth) can be expected every 50 years.

Rainfall information for the area, and streamflow and water-level measurements from the West Fork Stones River, lowlands, sinkholes, caves, and wells in the study area were used to develop a flood-prone area map, independent of overflow from the river, for the study area. Water-level duration and frequency relations, independent of overflow from the river, were estimated for several lowlands, sinkholes, and wells in the study area. These relations are used to characterize flooding in lowland areas of western Murfreesboro, Rutherford County, Tennessee.

INTRODUCTION

City planners and engineers often require estimates of the location, magnitude, and frequency of flooding that occurs on undeveloped land in Tennessee. The design of bridges, culverts, embankments, dams, levees, and buildings near streams, rivers, lowlands, and sinkholes throughout Tennessee depends on accurate estimates of flood depths and frequency of occurrence. The wise management of flood plains to protect the public from flood damages and minimize flood-related costs to government or private enterprise depends on the most accurate available information and techniques for describing floods. Using standardized techniques for the measurement and analysis of hydrologic data, especially through computer simulation of streamflow and water levels, is important when understanding and describing the magnitude and frequency of floods throughout Tennessee.

Murfreesboro, Rutherford County, Tenn., is a rapidly growing city. Between 1990 and 1996, the population of Murfreesboro grew from 45,000 to 54,000 (Tennessee Department of State, 1999), an increase of about 20 percent. Some of the population increase can be attributed to annexation by the city; however, most of the increase is the result of an influx of new residents. The economic growth rate of the Murfreesboro area is among the highest in the State and has increased both property values and the demand for undeveloped land. Much of the undeveloped land in the area is farmland on the western side of the city near Interstate 24 (fig. 1). The proximity to the city and the interstate tends to increase the development potential of the land. The primary deterrent to development in this area is the risk of flooding along the West Fork Stones River and its flood plain and in the many lowlands and sinkholes that are present in the area.

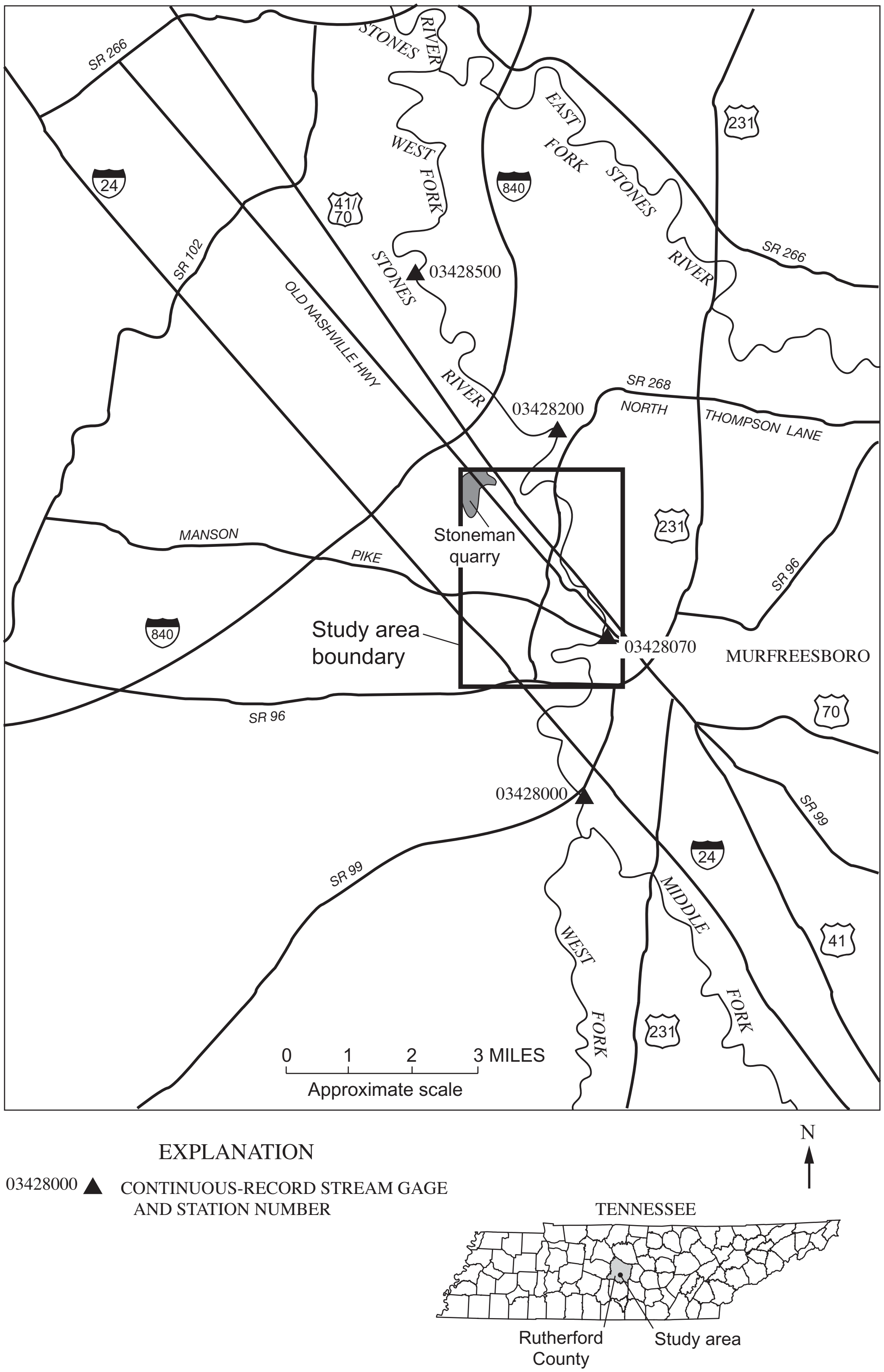

Figure 1. Study area and continuous-record stream-gaging stations on West Fork Stones River, Rutherford County, Tennessee.

Purpose and Scope

From October 1998 through September 2000, the U.S. Geological Survey (USGS), in cooperation with the City of Murfreesboro, conducted a hydrologic study of flood-prone areas in the vicinity of North Thompson Lane and Manson Pike in western Murfreesboro, Rutherford County, Tenn. (fig. 1). The area contains numerous lowlands, sinkholes, and caves, many of which are part of the West Fork Stones River flood plain.

The purpose of this report is to present water-level duration and frequency relations, independent of overflow from the West Fork Stones River, for present-day (2000) conditions at selected off-river lowlands, sinkholes, and wells. The frequency of off-river lowland flooding is compared to flooding along the West Fork Stones River. These relations were used with water levels measured at other lowlands, sinkholes, caves, and wells to develop a flood map of this area that delineates flooding that is independent of direct overflow from the river.

Description Of Study Area

Expanding urban areas such as Murfreesboro, Tenn., often have drainage problems associated with growth and development of the urban landscape. One of the more acute problems commonly found in western Murfreesboro is off-river flooding in sinkholes and low-lying areas in the flood plain of the West Fork Stones River. Western Murfreesboro consists of many interconnected lowlands and sinkholes that are hydraulically connected to the West Fork Stones River or its tributaries. The potential for flooding throughout the area is related to rainfall amount and intensity, ground-water levels, and flow in the West Fork Stones River. The relations among these factors are complex; therefore, characterizing hydrologic responses in off-river lowlands and sinkholes in the area is difficult.

Murfreesboro, Rutherford County, Tenn., is located in the State's Central Basin (Newcome, 1958). The terrain is characterized by gently rolling hills and valleys covered by pasture, glade, and forest. Surface outcropping and exposure of flat-lying limestone beds is common in this area. Typical land elevations throughout the county are between 500 and 600 feet above the North American Vertical Datum of 1988 (NAVD 88). This region of Tennessee has mild winters and warm, humid summers. The temperature rarely falls below 0 ºF or rises above 100 ºF. Average daily temperatures for the months of January and July are 35 ºF and 78 ºF, respectively (National Climatic Data Center, 1948-2000). The average annual rainfall is about 53.5 inches and is evenly distributed throughout the year. Large frontal storms often produce general flooding throughout the area during the winter months (December through March). During the spring and summer months (April through September), high-intensity thunderstorms commonly produce localized flooding in the area.

The topography of the western part of Murfreesboro is typical of karst areas developed on flat-lying, relatively thick layers of carbonate bedrock in areas of low to moderate relief. In the study area, a thin layer of regolith has developed on top of cavernous carbonate bedrock. Subsurface collapse of caves coupled with erosion and transport of soil into subsurface solution channels in the bedrock has created numerous lowlands, sinkholes, and karst windows in the area.

Previous Studies

Several hydrologic investigations have been conducted in the study area. Ogden (1997, 1998) and Wiser (1997) produced investigative reports of ground-water and surface-water hydrology in this area of Rutherford County, Tenn. A recent flood insurance study, published by the Federal Emergency Management Agency in 1999 for the West Fork Stones River, is an authoritative source of information for flooding resulting from overflow from the river. The first flood-plain information study for West Fork Stones River was done by the U.S. Army Corps of Engineers (1966), and provides valuable historical accounts of the major floods of 1902 and 1948 on the West Fork Stones River.

USGS scientists have studied the hydrology, geology, and ground-water resources of this area. Outlaw and others (1992) document the collection of rainfall, streamflow, and peak-stage data at several sites in the Murfreesboro area from March 1989 to July 1992. Outlaw (1996) describes flood-frequency and detention-storage characteristics of the Bear Branch watershed in Murfreesboro. Moore and others (1969), Burchett and Moore (1971), Rima and others (1977), and Farmer and Hollyday (1999) discuss the geologic structure, ground-water resources, and hydrology of the area, respectively. Burchett and Moore (1971) present detailed information on the hydrology and water budget of the Stones River Basin. Rima and others (1977) drilled several observation wells, including one at the Stoneman quarry, which was used for this study, for their report on ground-water supplies in the Murfreesboro area.

A soil survey performed by the Soil Conservation Service (U.S. Department of Agriculture, 1977) also is available for Rutherford County, Tenn. The soil survey contains information on the landscape and climate of the county, as well as detailed information on the soils.

Acknowledgments

The author thanks Mr. Joseph Aydelott, the Murfreesboro City Planner, and Mr. Ken Hays, the Murfreesboro City Engineer, for their assistance during this investigation. The author also thanks Ms. Mary Ann Peckham, Superintendent of the Stones River National Battlefield at the time of this study, for allowing water levels to be measured in wells at the battlefield.

STUDY APPROACH AND DATA DESCRIPTIONS

A data-collection network was installed to measure rainfall and water levels to delineate flood-prone lowlands and sinkholes in the study area. Monitoring stations (fig. 2 and table 1) were selected to provide a uniform coverage of hydrologic information describing rainfall amount and stormwater-drainage rates and to detect areawide differences in the drainage characteristics of lowlands and sinkholes in the study area. Several wells were measured periodically to monitor the depth of the water table in the area.

Data collected from the hydrologic monitoring stations were used to develop a database of daily average rainfall amounts and daily maximum water levels; an estimated long-term daily mean discharge record for West Fork Stones River at old milldam at Manson Pike; flood-frequency estimates for the river; estimated long-term daily maximum water-level records for the continuously monitored lowlands, sinkholes, and wells; and a map delineating flood-prone land, independent of overflow from the West Fork Stones River. Rainfall amounts and water levels measured at monitoring stations during the course of this study are stored in a USGS water-resources database. Hydrologic data measured during the study, along with estimated discharge for the West Fork Stones River at old milldam at Manson Pike, were used to calibrate a nonlinear equation that could be used to simulate water-level response to hydrologic conditions at lowlands, sinkholes, caves, and wells throughout the study area. The calibrated water-level simulation equation was used to produce a 50-year record of daily maximum water levels at selected sites in the study area. Water-level duration and frequency relations could be defined for these sites using the long-term record of simulated water levels from the calibrated equation.

To estimate streamflow characteristics for the West Fork Stones River at the study area, an estimated record of daily mean discharge was developed for the river at the old milldam at Manson Pike (fig. 2). Daily mean discharge estimates were derived from published discharge that was measured at nearby stations that operated on the river at some time during the period from October 1, 1932, to September 30, 2000 (fig. 1 and table 2).

Discharge from a nearby stream-gaging station on the West Fork Stones River was multiplied by the contributing drainage area at the old milldam at Manson Pike and then divided by the contributing drainage area at the nearby gaged site (table 2). This is the drainage-area ratio technique for transferring discharge from a gaged site to an ungaged site (Hirsch, 1979). The technique yields reliable discharge estimates if a high degree of correlation exists between the rates of streamflow at the sites.

Hydrologic Monitoring

Field reconnaissance of the study area was performed during October and November 1998. During a field check of the study area, gage locations were selected and landowners' permissions were obtained for installing monitoring equipment to measure rainfall and water levels. Rain gages were installed and in operation by mid-October 1998, water-level gage construction was completed in early December 1998, and hydrologic data were collected through September 2000.

Monitoring stations installed during the study included two rain gages, one continuous-record river-stage monitor that measured water levels upstream and downstream of the old milldam at Manson Pike, two continuous-record ground-water well monitors, three continuous-record water-level monitors located in lowland areas, and nine partial-record crest-stage

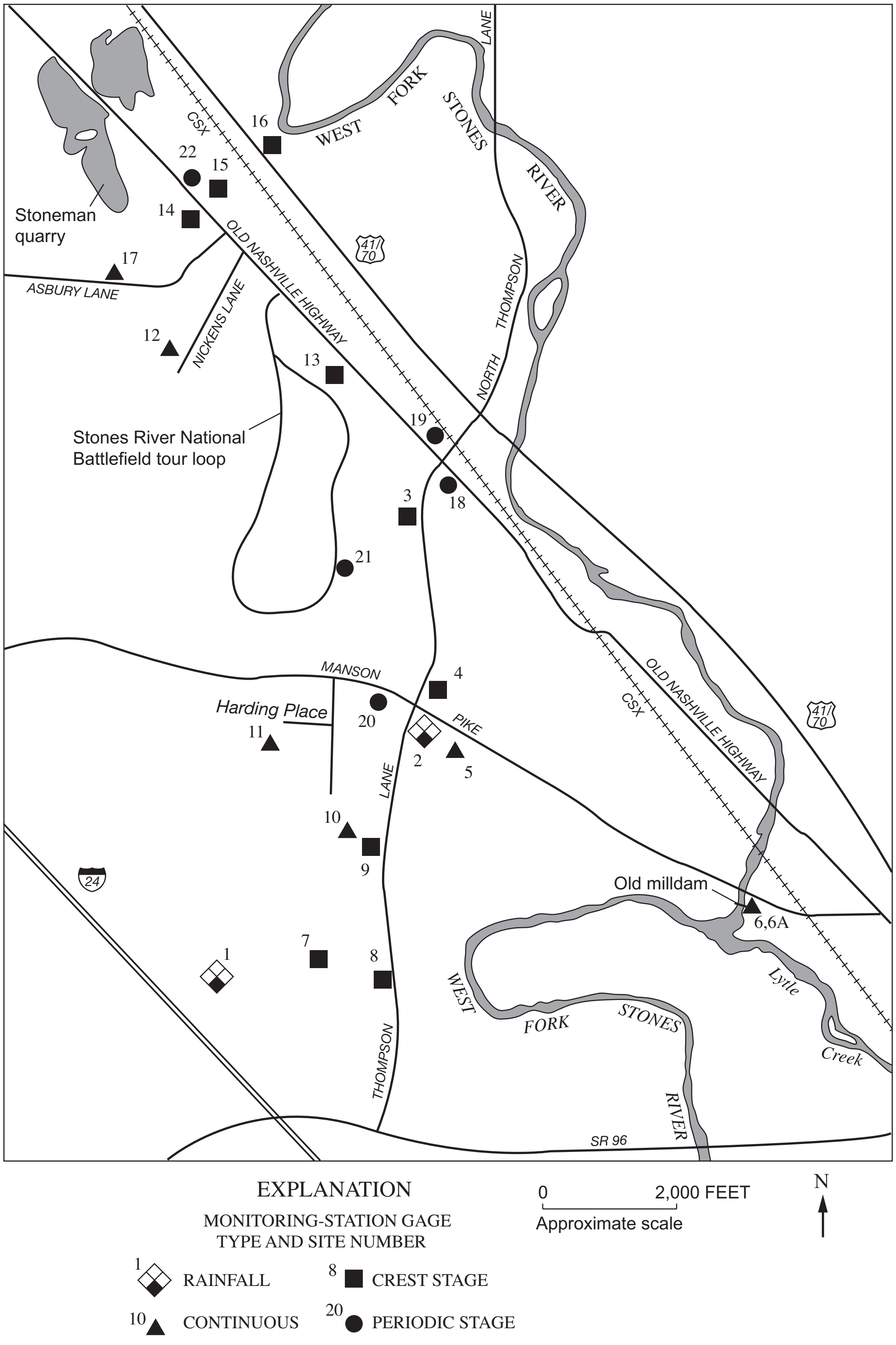

Figure 2. Monitoring-station locations in the Murfreesboro, Tennessee, study area.

Table 1. Hydrologic monitoring stations in the Murfreesboro, Tennessee, study area

Site number (see fig. 2 for site locations)	Station number	Station name	Station type
1	355110086260601	Armory rain gage	Rainfall
2	355150086253901	Manson Pike rain gage	Rainfall
3	355218086254101	National Battlefield lowland	Crest stage
4	355154086253901	Thompson Lane at Manson Pike	Crest stage
5	355146086253601	Manson Pike well	Continuous stage
6, 6A	03428065	West Fork Stones River upstream and downstream of old milldam at Manson Pike	Continuous stage
7	355112086255601	Golf range near Thompson Lane	Crest stage
8	355113086254801	Thompson Lane at Mall Circle Road	Crest stage
9	355133086254901	Thompson Lane karst window	Crest stage
10	355138086255401	Thompson Lane cave	Continuous stage
11	355147086260701	Harding Place lowland	Continuous stage
12	355232086263401	Nickens Lane lowland	Continuous stage
13	355243086255401	National Cemetery lowland	Crest stage
14	355307086261801	Old Nashville Highway at Asbury Lane	Crest stage
15	355310086261701	Old Nashville Highway cave	Crest stage
16	03428131	U.S. Hwy 41/70 at Mt. Olive	Crest stage
17	355257086262601	Stoneman quarry well	Continuous stage
18	355218086252601	College Street well	Periodic stage
19	355233086253601	Abandoned homestead well	Periodic stage
20	355154086254801	Private well at Manson Pike	Periodic stage
21	355216086255301	Rebel Yell well at battlefield	Periodic stage
22	355312086262101	Private well at Old Nashville Highway	Periodic stage

Table 2. Continuous-record stream-gaging stations on West Fork Stones River, Rutherford County, Tennessee

[See fig. 1 for stream-gage locations; DA, total drainage area given in square miles; CDA, contributing drainage area given in square miles; RM, river mile is distance in miles from confluence with East Fork Stones River]

Station number	Station name	DA	CDA	RM	Period of record
03428000	West Fork Stones River near Murfreesboro	128	122	21.0	10-01-32 to 10-07-69
03428070	West Fork Stones River at Manson Pike	165	150	16.1	07-11-73 to 10-08-81
03428200	West Fork Stones River at Murfreesboro	177	160	10.7	07-20-72 to 01-31-82; 01-01-86 to present
03428500	West Fork Stones River near Smyrna	237	194	6.4	10-01-65 to present

recorders located in lowlands and sinkholes. During the study, the water levels measured at Thompson Lane cave (site 10, fig. 2) and Harding Place lowland (site 11, fig. 2) were determined to be similar. In October 1999, the gage located at Thompson Lane cave was discontinued and moved to an observation well near Stoneman quarry (site 17, fig. 2) to provide ground-water-level information for this part of the study area. In addition to the continuous-record monitoring stations, periodic observations of ground-water levels were obtained at five lowlands and private wells in the study area.

Rainfall in the Murfreesboro, Tenn., area was measured by two rain gages located in the study area (sites 1 and 2, fig. 2). Tipping-bucket rain gages were used to record the occurrence and time interval of rainfall in 0.01-inch increments from October 1998 through September 2000. Incremental rainfall amounts, from which daily rainfall totals can be produced, are stored in a USGS water-resources database. A comparison of the rainfall data recorded in the study area with rainfall data for Murfreesboro published by the National Climatic Data Center (NCDC) for the same period shows a strong correlation with a coefficient of determination, R^2, of 0.90.

The average daily rainfall in the study area from October 1998 through September 2000 was determined by calculating the average of the daily rainfall amount measured at the Armory rain gage and the Manson Pike rain gage. During this study, rainfall in the area was substantially below the normal long-term average annual rainfall for Murfreesboro (53.5 in.) (National Climatic Data Center, 1948-2000). During October 1998 through September 1999, rainfall in the study area was about 7 inches below normal. For October 1999 through September 2000, rainfall in the study area was about 5 inches below normal. The wettest months during this study were December 1998 and January 1999 when monthly rainfall amounts in excess of 8 inches above the long-term normal were recorded (fig. 3). Most monthly rainfall totals during the study period were below long-term normal amounts. Dry days during the study period were observed about 60 percent of the time from December through May and about 80 percent of the time from June through November.

Continuously recording water-level monitors were used to measure water levels in selected wells, lowlands and caves, and the West Fork Stones River in the study area. Water levels at seven sites (fig. 2, sites 5, 6, 6A, 10, 11, 12, and 17) were continuously monitored and recorded every 15 minutes at some time during the period of this study (October 1998 through September 2000). These data are stored in a USGS water-resources database and can be used to produce water-level hydrographs and water-surface elevations. Average daily rainfall and daily maximum water levels recorded in the study area during December 1998 through September 2000 (figs. 3, 4, 5, and 6) show a strong correlation between rainfall and river stage, and among one another.

Maximum water levels resulting from ponding in lowlands and sinkholes were measured at the nine crest-stage gages. A crest-stage gage is a device that registers the peak stage that occurred between inspections of the gage. The date of the peak is not always certain but usually can be determined by comparison with records from nearby water-level and rainfall-monitoring stations. Peak elevations and the date of occurrence are given for each water level recorded at the nine sites (table 3). Several other sites located in the study area, including lowlands and wells, were periodically observed and measured during this study (table 4). Water levels measured at these sites were used to supplement information recorded by water-level monitors.

Figure 7 illustrates typical off-river lowland flooding in the study area. Figure 7A shows a water level of 571.2 feet above NAVD 88 on February 2, 1999, at the golf range near Thompson Lane (site 7;

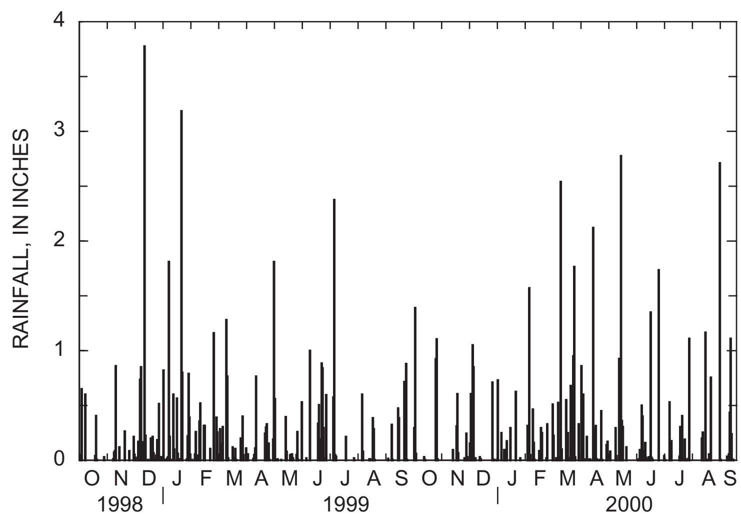

Figure 3. Average daily rainfall for the Murfreesboro, Tennessee, area, October 1998 through September 2000.

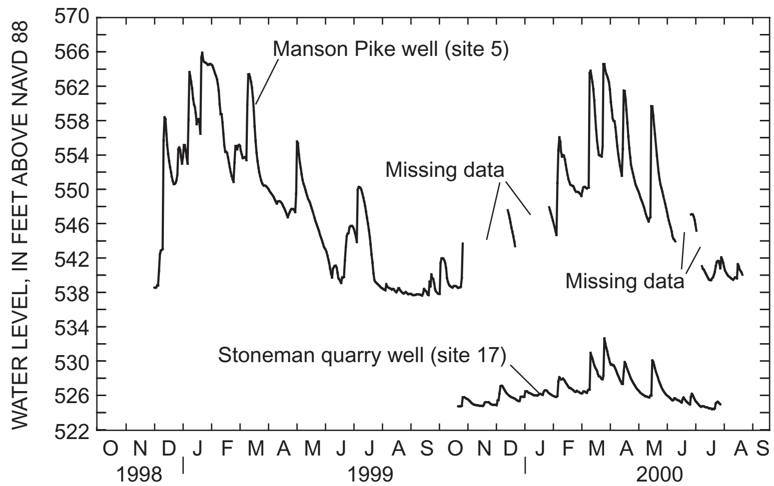

Figure 4. Daily maximum water levels at monitoring wells in the Murfreesboro, Tennessee, study area, December 1998 through September 2000.

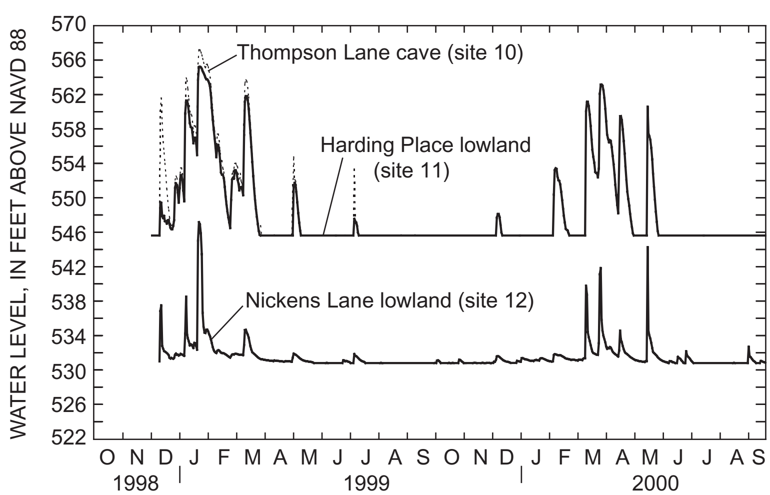

Figure 5. Daily maximum water levels at lowlands and caves in the Murfreesboro, Tennessee, study area, December 1998 through September 2000.

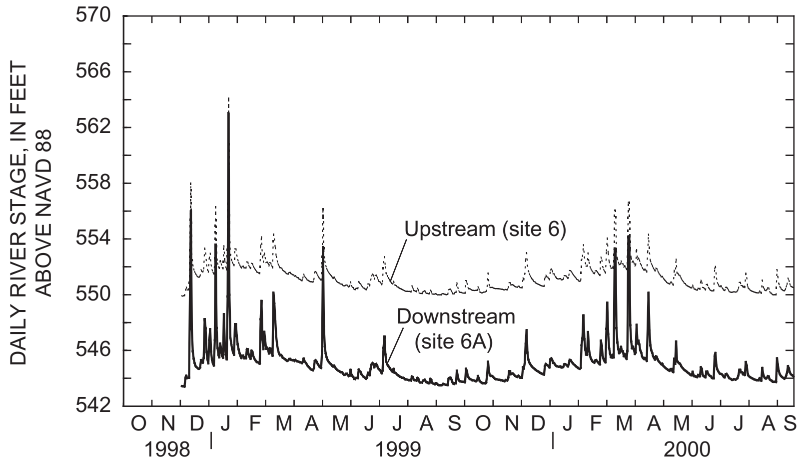

Figure 6. Daily maximum river stage for West Fork Stones River upstream and downstream of the old milldam at Manson Pike, Murfreesboro, Tennessee, December 1998 through September 2000.

Table 3. Water levels measured at crest-stage gages, Murfreesboro, Tennessee, December 1998 through September 2000

[See fig. 2 for gage locations and table 1 for gage descriptions; water levels given in feet above NAVD 88; <, less than, ---, not observed]

Date of water level	National Battlefield lowland (site 3)	Thompson Lane at Manson Pike (site 4)	Golf range near Thompson Lane (site 7)	Thompson Lane at Mall Circle Road (site 8)	Thompson Lane karst window (site 9)	National Cemetary lowland (site 13)	Old Nashville Highway at Asbury Lane (site 14)	Old Nashville Highway cave (site 15)	U.S. Highway 41/70 at Mt. Olive (site 16)
12-12-1998	<561	<562.44	567.32	568.44	565.72	550.77	544.47	<528.93	<541.8
01-01-1999	<561	<562.44	566.91	<567.32	559.94	<548	<543.78	<528.93	<541.8
01-08-1999	<561	562.93	565.75	568.5	564.83	548.9	544.35	<528.93	<541.8
01-23-1999	561.6	565.17	571.62	569.39	567.4	552.67	546.5	546.28	547.11
01-24-1999	561.6	565.17	571.6	---	567.4	552.47	---	541	<541.8
01-25-1999	561.6	565.17	571.45	---	566.95	552.67	---	532.1	<541.8
01-28-1999	561.1	564.77	570.72	---	565.81	552.12	---	<528.93	<541.8
02-02-1999	<561	564.75	570	---	565.32	551	---	<528.93	<541.8
02-11-1999	<561	<562.44	564.13	---	555	<548	---	<528.93	<541.8
02-27-1999	<561	<562.44	564.21	<567.32	562.56	<548	<543.78	<528.93	<541.8
03-13-1999	<561	562.93	566.8	567.43	564.2	<548	<543.78	<528.93	<541.8
05-05-1999	<561	<562.44	565.48	567.93	563.88	<548	<543.78	<528.93	<541.8
07-11-1999	<561	<562.44	563.79	567.85	564.42	<548	544.44	<528.93	<541.8
12-13-1999	<561	<562.44	563.97	567.66	562.56	<548	<543.78	<528.93	<541.8
02-13-2000	<561	<562.44	565.45	568.54	563.04	<548	544	<528.93	<541.8
03-19-2000	<561	562.85	567.26	568.38	563.8	549.33	544.66	<528.93	<541.8
04-03-2000	<561	563.84	568.4	567.93	565.68	550.07	544.38	<528.93	<541.8
04-24-2000	<561	<562.44	567.05	567.9	561.79	<548	544.1	<528.93	<541.8
05-25-2000	<561	563.16	566.73	569.33	565.99	549	544.96	534.57	541.94
07-06-2000	<561	562.62	<563.87	567.81	563.34	<549	543.85	<528.93	<541.8
09-12-2000	<561	562.74	565.16	567.44	563.44	<549	544.54	<528.93	<541.8

Table 4. Water levels measured at lowlands and wells, Murfreesboro, Tennessee, October 1998 through September 2000

[See fig. 2 for site locations and table 1 for site descriptions; land-surface elevations determined from 2-foot contour-interval topographic map; bottom elevations determined from tape downs; ---, not measured]

Site number	Site name	Land-surface elevation, in feet above NAVD 88	Bottom elevation, in feet above NAVD 88
13	National Cemetery lowland	549	540
17	Stoneman quarry well	562	412
18	College Street well	557	530
19	Abandoned homestead well	570	485
20	Private well at Manson Pike	566	525
21	Rebel Yell well at battlefield	568	547
22	Private well at Old Nashville Highway	551	490

Date	Water-level elevation, in feet above NAVD 88 — Site number 13	17	18	19	20	21	22
10-13-1998	---	---	536.25	---	534.34	---	---
10-14-1998	---	---	537.49	---	533.09	---	---
11-05-1998	---	---	---	---	---	---	516.5
01-07-1999	---	527.35	---	---	---	---	---
01-14-1999	543.15	---	---	---	---	556.7	---
01-25-1999	552.67	538.15	---	---	---	---	---
01-28-1999	552.12	532.85	---	---	---	---	---
02-02-1999	551.02	532.12	---	---	---	564	---
03-01-1999	Dry	528	---	---	---	547	---
03-17-1999	---	530.85	---	---	---	---	---
05-06-1999	540.29	527.78	---	---	---	553	---
08-20-1999	---	524.55	535.98	---	534.98	Dry	516.08
02-10-2000	---	525.86	537.78	---	541.78	Dry	516.35
02-16-2000	540.45	527.97	543.56	539.42	552.95	550.5	516.8
03-21-2000	549	530.57	549.69	547.24	561.2	566	518.16
04-10-2000	541.85	529.83	545.62	540.95	558.89	555	517.37
04-28-2000	542	529.34	545.5	541.2	557.05	554	516.5
05-31-2000	540.4	528.43	544.22	539.43	551.74	550	516.84
07-26-2000	Dry	524.53	536.92	531.7	535.6	Dry	516.46
09-22-2000	Dry	525.32	537.96	532.66	536.89	Dry	516.5

(A)

(B)

Figure 7. Golf range near Thompson Lane, Murfreesboro, Tennessee, showing (A) typical off-river lowland flooding in the study area for February 2, 1999, and (B) approximately 1 week later.

fig. 2). Figure 7B shows the same area about a week later after most of the floodwater has receded. This site receives some surface runoff from surrounding land and likely is hydraulically connected to the West Fork Stones River and other lowlands and sinkholes through underground solution channels.

Photographs of the West Fork Stones River at the old milldam at Manson Pike (fig. 2) are shown for three different streamflow conditions (fig. 8). Figure 8a shows the high-water mark caused by a flood that occurred on January 23-24, 1999, at the stream gage, which measures water levels upstream and downstream of the old milldam at Manson Pike. The peak discharge for this storm was 24,800 cubic feet per second and produced stage elevations upstream and downstream of the old milldam of 564.1 and 563.0 feet above NAVD 88, respectively. Figure 8b shows the old milldam during seasonal high-flow conditions; upstream and downstream water levels were 556.2 and 553.4 feet above NAVD 88, respectively, and occurred on May 6, 1999. Figure 8c shows the old milldam during typical summer and fall low-flow conditions on August 20, 1999, when upstream and downstream water levels were 550.1 and 543.7 feet above NAVD 88, respectively.

Water levels were measured on the West Fork Stones River, and in lowlands, sinkholes, and wells throughout the study area during the flooding in late January 1999. In all cases, water levels were the highest during this storm than at any other time during this study (October 1, 1998, through September 30, 2000). Floodwaters on the West Fork Stones River upstream of the old milldam at Manson Pike could reach 575 feet above NAVD 88, or more than 10 feet higher than those observed in January 1999 for floods having recurrence intervals in excess of 100 years (Federal Emergency Management Agency, 1999). A flood of this magnitude would inundate much of the study area with several feet of water.

Streamflow Estimation

Daily mean discharge from gages on the West Fork Stones River was compared for four periods of overlapping record. Comparisons were performed by calculating the value $\log_{10}(Q/CDA)$ for each daily mean discharge. In this calculation, Q is the daily mean discharge in cubic feet per second, and CDA is the contributing drainage area in square miles. The effect of wastewater treatment-plant effluent during low-flow periods was reduced by censoring the daily mean discharge record so that $\log_{10}(Q/CDA)$ is greater than -1. The remaining x-y coordinates were plotted on arithmetic paper, the least-squares regression equation was fitted, and the coefficient of determination (R^2) was calculated for each of the four comparisons (table 5).

Comparisons of $\log_{10}(Q/CDA)$, where Q is the daily mean discharge and CDA is the contributing drainage area, indicate a strong correlation among stream gages on the West Fork Stones River with periods of overlapping discharge record. The comparisons yielded coefficients of determination (R^2) in the range 0.86 to 0.97 (table 5). The high degree of correlation between the sites is not unexpected because the gages are located on the same river in close proximity to one another and measure similar watershed physical characteristics.

To characterize the seasonal variability of flooding on the West Fork Stones River in the study area,

Table 5. Results of comparison of daily mean discharge for continuous-record stream-gaging stations on West Fork Stones River, Rutherford County, Tennessee

[See fig. 1 for station locations and table 2 for station names; x and y, $\log_{10}(Q/CDA)$, where Q is daily mean discharge and CDA is contributing drainage area for given station; data censored such that $\log_{10}(Q/CDA)>-1$; m and b, slope and intercept, respectively, in equation, y=mx+b; R^2, coefficient of determination]

Stations			Regression parameters		
x	y	Dates of comparison	m	b	R^2
03428200	03428070	07-73 to 10-81	1.05	-0.06	0.97
03428500	03428200	07-72 to 01-82; 01-86 to 09-91	1.03	-.13	.97
03428500	03428070	07-73 to 10-81	1.07	-.19	.95
03428500	03428000	10-65 to 10-69	1.06	-.12	.86

(A)

(B)

(C)

Figure 8. West Fork Stones River at old milldam at Manson Pike, Murfreesboro, Tennessee, showing (A) high-water mark for January 23-24, 1999 flood; (B) high flow on May 6, 1999; and (C) low flow on August 20, 1999.

analysis of the estimated long-term daily mean discharge record was conducted (fig. 9). The analysis indicates that average daily flow from the river basin is greatest during December through March (table 6). These are the months when evaporation and vegetative uptake are at a minimum and the ground-water table is highest. During this period of the year, the watershed retains the least amount of water during storms, and so the largest, most damaging floods can occur. Historic floods of March 28, 1902, February 13, 1948, and March 21, 1955, on the West Fork Stones River resulted from heavy rain falling on saturated ground.

Flood-frequency estimates at station 03428000 West Fork Stones River near Murfreesboro (fig. 1) are based on 37 years of published data from October 1, 1932, to September 30, 1969. Information existing about major floods that occurred either before or after the period of systematic data collection can be used to improve estimates of peak discharge. Use of historic data assures that estimates fit community experience and improves the frequency determinations (Interagency Advisory Committee on Water Data, 1982). Annual peak records for station 03428000 include a historic peak for the 1902 flood (U.S. Army Corps of Engineers, 1966). Flood frequency at station 03428500 West Fork Stones River near Smyrna (fig. 1) is based on 33 years of published data from October 1, 1965, to September 30, 1998. No information was available for the historic floods of 1902 and 1948 at this station, and estimates were not made for this study. Flood-frequency calculations were performed using the methodology described in Bulletin 17B of the Interagency Advisory Committee on Water Data (1982). Results of these analyses are provided in table 7.

Flood frequency at West Fork Stones River at old milldam at Manson Pike (fig. 2 and table 7) was estimated using two different approaches that produced similar results. The first approach used linear interpolation, based on contributing drainage area, between flood frequency calculated at stations 03428000 and 03428500. For the second approach, a 67-year record of estimated annual peaks was developed for West Fork Stones River at old milldam at Manson Pike using the contributing drainage-area ratio technique described earlier in this section. An estimate for the 1902 flood peak at this station was derived using the drainage-area ratio method. Flood-frequency calculations were performed for West Fork Stones River at old milldam at Manson Pike using the second approach and the methodology described in Bulletin 17B of the Interagency Advisory Committee on Water Data (1982).

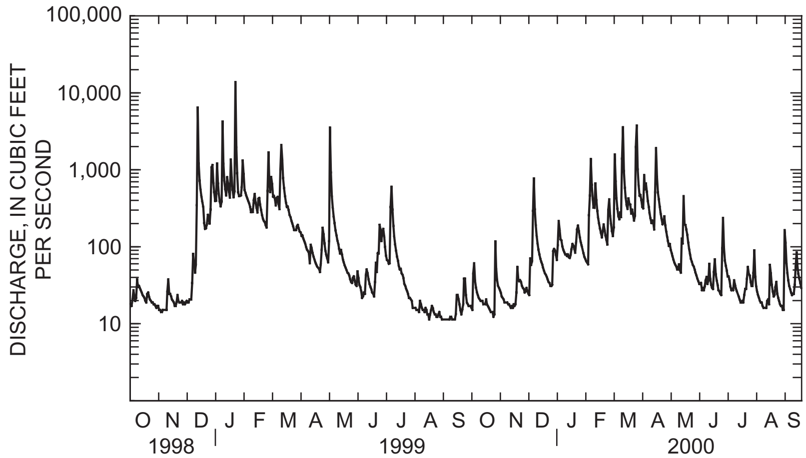

Figure 9. Estimated daily mean discharge for West Fork Stones River at old milldam at Manson Pike, Murfreesboro, Tennessee, October 1998 through September 2000.

HYDROLOGIC SETTING

The hydrology of western Murfreesboro is strongly influenced by the West Fork Stones River and its tributaries. The flood plain consists of a series of lowlands, sinkholes, and caves. Periodic flooding along the river has shaped the land through the years.

Until the late 1990s, the western area of Murfreesboro and Rutherford County was mostly undeveloped, which limited the damage potential for floods. Present-day development in the area is increasing rapidly and is aggravating existing flooding problems. Land development increases the amount of stormwater runoff from paved areas, changes the permeability of the soils in lowlands and sinkholes, and causes crushed rock and soil to fill in parts of the available flood plain and lowland areas.

Streamflow Characteristics

Murfreesboro is located in the Stones River drainage basin. The eastern part of the city is located in the East Fork Stones River Basin and the western part is located in the West Fork Stones River Basin. The volume of flow in the rivers indicates antecedent

Table 6. Streamflow characteristics for West Fork Stones River at old milldam at Manson Pike, Murfreesboro, Tennessee, 1932-99

[Analysis based on estimated daily mean discharge from October 1, 1932, to September 30, 1999; runoff is calculated using the total watershed drainage area; rainfall is from the National Climatic Data Center (1948-2000) using rainfall measured from 1961 through 1990 at Murfreesboro; percent of runoff is calculated by dividing inches of runoff by inches of rainfall]

Month	Characteristic			
	Average daily flow, in cubic feet per second	Runoff from watershed, in inches	Rainfall on watershed, in inches	Percent of runoff
January	547	3.82	4.20	91.0
February	579	3.68	4.02	91.6
March	577	4.03	5.52	73.0
April	329	2.23	4.48	49.7
May	231	1.61	5.36	30.1
June	113	.77	3.87	19.8
July	81.5	.57	4.82	11.8
August	63.1	.44	3.78	11.7
September	78.4	.53	4.25	12.5
October	73.8	.52	3.30	15.6
November	212	1.44	4.51	31.8
December	415	2.90	4.97	58.4

Table 7. Flood-frequency estimates for stream-gaging stations on West Fork Stones River, Rutherford County, Tennessee

[See figs. 1 and 2 for station locations; CDA, contributing drainage area; discharge is in cubic feet per second]

Annual exceedance probability	Recurrence interval, in years	Station and peak discharge for West Fork Stones River		
		Near Murfreesboro (station 03428000) CDA=122 square miles	At old milldam at Manson Pike CDA=150 square miles	Near Smyrna (station 03428500) CDA=194 square miles
0.50	2	12,000	13,000	14,000
.20	5	19,000	21,000	23,000
.10	10	25,000	27,000	30,000
.04	25	33,000	35,000	39,000
.02	50	40,000	43,000	47,000
.01	100	47,000	51,000	56,000

soil-moisture conditions and ground-water levels throughout the area. Flooding in lowlands and sinkholes in the study area is related to flow conditions in the West Fork Stones River. Continuous-record stream gages (fig. 1, table 2) have been used to measure the flow of this river since 1932.

During large floods having recurrence intervals in excess of 10 years, floodwaters overflow the banks of the West Fork Stones River in a 180-degree bend in the channel located south of Manson Pike (fig. 10). Overflow from the river travels overland across the natural flood plain, filling many of the sinkholes and lowlands in the area (Federal Emergency Management Agency, 1999). When floodwaters in the river recede, water remaining in lowlands and sinkholes in the flood plain drains to the river through interconnected underground solution channels in the underlying limestone bedrock.

For the 67-year period from October 1, 1932, through September 30, 1999, most of the annual flood peaks occurred at West Fork Stones River during the 4-month winter period from December through March. Analysis of published annual peaks for the continuous-record stream gages located on West Fork Stones River indicates that 69 percent (46 of 67) of the annual peak discharges occurred during the 4-month winter period from December through March, 7 percent (5 of 67) during the 4-month summer period from June through September, and 24 percent (16 of 67) during the 4-month spring and fall transition periods from April through May and October through November. Recurrence intervals and estimated overflow depths in the study area for the 12 largest floods of the last century for the West Fork Stones River upstream of the old milldam at Manson Pike (fig. 2) are given in table 8. “One of the most intense rainstorms of record in Middle Tennessee occurred on March 28, 1902, and produced disastrous floods throughout the region.” (U.S. Army Corps of Engineers, 1966). Estimated overflow depths for these floods were determined from a recent flood-insurance study for the area (Federal Emergency Management Agency, 1999).

Lowland Flooding

Lowland and sinkhole flooding in the study area occurs through one or a combination of three basic mechanisms—direct storm runoff from surrounding land, a rise in the ground-water level, or overflow from the West Fork Stones River. Direct storm runoff from surrounding land, primarily the result of surface runoff during intense rainfall, occurs when the rate of recharge to the ground-water system through a lowland or sinkhole is less than the rate of surface-water runoff entering the sinkhole. Flooding of lowlands and sinkholes that occurs when ground-water levels rise can be attributed to (1) areawide recharge from storms, (2) an increase in the stage of the West Fork Stones River where river water flows from the river channel through subsurface solution channels that are hydraulically connected to lowlands and sinkholes, and (3) a combination of areawide recharge from storms and rising stage on the West Fork Stones River. Overflow from the West Fork Stones River occurs as a result of flooding when the river overtops its banks. Overflow of the West Fork Stones River into the natural flood plain is an infrequent event but has the potential to cause flooding such as that which occurred in 1902 and 1948 (U.S. Army Corps of Engineers, 1966). Areas subject to flooding from the river are documented in a recent flood insurance study for Murfreesboro and unincorporated areas of Rutherford County (Federal Emergency Management Agency, 1999).

The flood-prone area map (fig. 10) was prepared by using 2-foot contour-interval topographic maps supplied by the City of Murfreesboro Planning and Engineering Department. Flooded areas were determined from information developed during this study. The map in figure 10 illustrates typical off-river

Table 8. Recurrence intervals and overflow depths for the 12 largest floods of the last century for the West Fork Stones River upstream of the old milldam at Manson Pike, Murfreesboro, Tennessee

[See fig. 2 for site location; >, greater than; <, less than]

Date of flood	Recurrence interval, in years	Overflow depth in the study area, in feet
03-28-1902	>100	>2
02-13-1948	75	>2
03-21-1955	50	>2
09-29-1944	30	1 to 2
03-12-1963	20	1 to 2
02-22-1945	15	<1
03-13-1975	10	<1
12-09-1966	10	<1
03-15-1973	10	<1
01-24-1999	<10	none
03-08-1961	<10	none
01-07-1946	<10	none

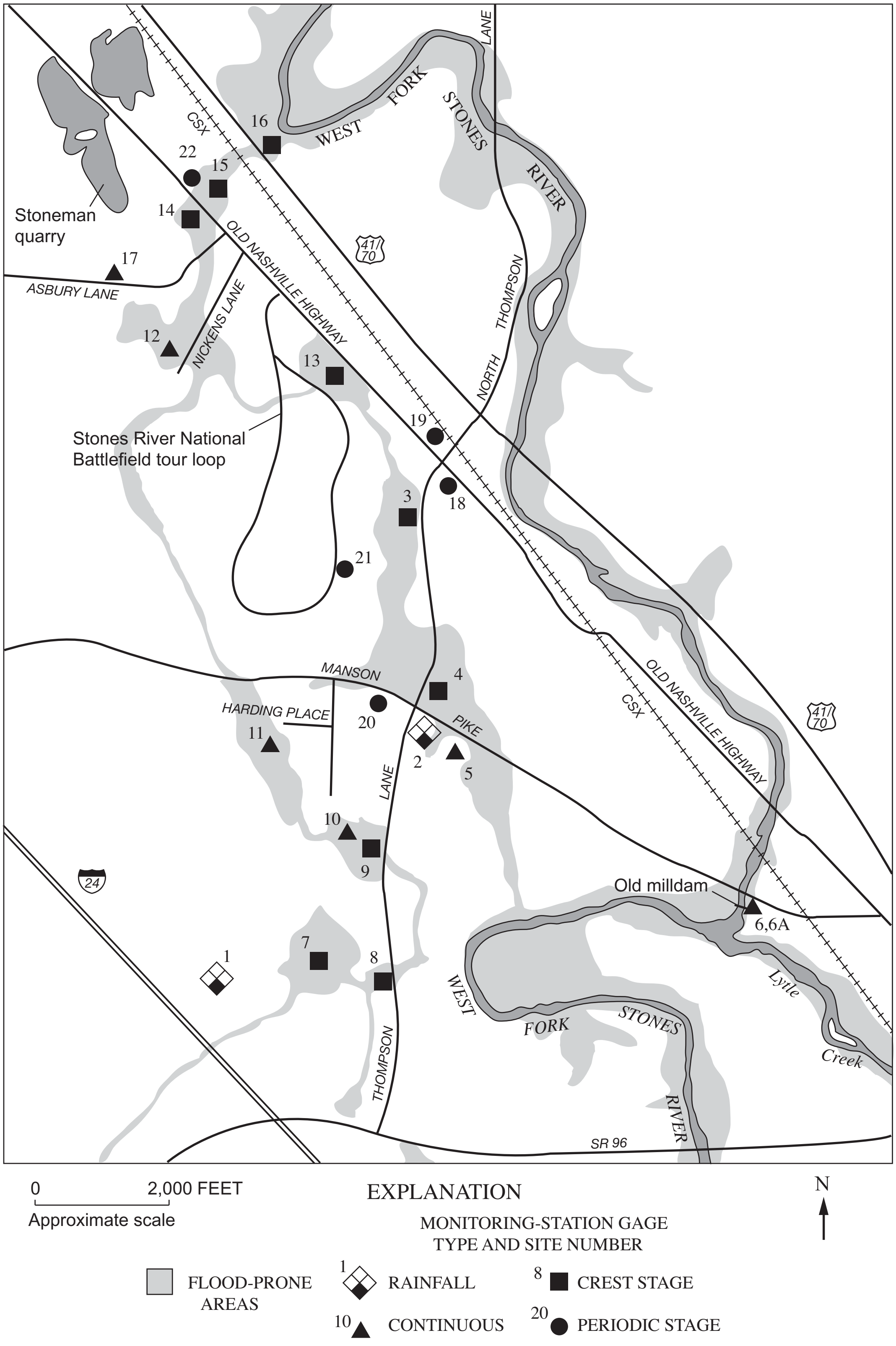

Figure 10. Flood-prone areas, western Murfreesboro, Tennessee.

flooding that is independent of widespread overflow from the West Fork Stones River such as occurred during the flood of January 23-24, 1999. During this storm, overflow from the West Fork Stones River flowed south, through the culvert at U.S. Highway 41/70 at Mt. Olive (site 16, fig. 10) at an elevation of 547.11 feet above NAVD 88 (table 3). The floodwater filled the Old Nashville Highway cave (site 15, fig. 10) and backed through the culvert at Old Nashville Highway and Asbury Lane (site 14, fig. 10) at a water-level elevation of about 546.50 feet above NAVD 88 (table 3). This elevation is slightly less than the water-level elevation of 547.20 feet above NAVD 88 observed at the Nickens Lane lowland during this storm (site 12, fig. 10). Following the January 1999 flood, ponded water remaining at these areas drained rapidly in 2 to 3 days (table 3).

The Federal Emergency Management Agency (1999) in a flood insurance study for Rutherford County, Tenn., documents flooding that could result from widespread overflow from the West Fork Stones River. The flood study is the product of hydrologic and hydraulic analyses performed over the past 40 years by several agencies (U.S. Army Corps of Engineers, 1966). Potential elevations of floodwater overflow from the West Fork Stones River into the study area are analyzed in the flood insurance study. Overflow from the river is nonexistent or minor for the 10-year flood. Floods having recurrence intervals greater than 50 years will produce major flooding in the study area. The most current Federal Emergency Management Agency flood studies and flood insurance rate maps can be used by planners and engineers to analyze flood conditions for storms with recurrence intervals greater than 10 years.

HYDROLOGIC SIMULATION

A nonlinear equation that simulates water-level response to hydrologic conditions in the study area was developed and calibrated to estimate a 50-year record of water levels at five continuously monitored sites in the study area. The period of simulation was from October 1, 1948, to September 30, 1998. The estimated long-term water-level records can be used to develop flood duration and frequency relations at the modeled sites, which can be used to describe flood potential throughout the study area.

Historical rainfall data for Murfreesboro was obtained from the NCDC in Asheville, North Carolina. Daily mean discharge for the West Fork Stones River at the old milldam at Manson Pike was used as streamflow input. The basic form of the simulation equation can be expressed as:

$$\int H_t = 500 + \int h_t = 500 + \int [h_{t-1} - outflow_t + inflow_t], \qquad (1)$$

where

H_t = water level, in feet above NAVD 88, on day t,
500 = a datum adjustment of incremental water levels to NAVD 88,
h_t = incremental water level, in feet, on day t,
$h_{t\text{-}1}$ = incremental water level, in feet, on the previous day,
$outflow_t$ = term to account for system abstractions and drainage, that is, interception and evapotranspiration, and ground-water outflow on day t; and
$inflow_t$ = term to account for surface- and ground-water inflow on day t.

Eliminating the datum adjustment and expanding the outflow and inflow terms in equation 1 to include independent variables and constants, the simulation equation can be expressed in numerical form as:

$$\sum_{t=1}^{n} h_t = \sum_{t=1}^{n} [h_{t-1} + \mathrm{D}(h_{t-1} - \mathrm{A}) + \mathrm{P}(rainfall_t) + \mathrm{Q}(discharge_t)], \qquad (2)$$

where

D = drainage constant,
A = abstraction constant,
P = rainfall response constant,
Q = river response constant,
$rainfall_t$ = rainfall amount, in inches, on day t, and
$discharge_t$ = daily mean river flow, in cubic feet per second, for the West Fork Stones River at old milldam at Manson Pike on day t.

Equation 2 was used to simulate water-level response to hydrologic conditions in the study area. The dependent variable, water level on day t, was predicted using two independent variables: rainfall on day t and daily mean river flow on day t. The simulation equation was solved from day t=1 to day t=n, where n is the last day of water-level simulation at a site. The water level, h_0, was set to an initial water level that is the starting elevation for the simulation equation. The initial water level was set to the minimum water level recorded at a continuously monitored site during the study. The period of continuous water-level monitoring at a site is the equation calibration period for that site. Water-level responses were simulated at Manson Pike well, Thompson Lane cave, Harding Place lowland, Nickens Lane lowland, and Stoneman quarry well (fig. 10, sites 5, 10, 11, 12, and 17, respectively).

Each water-level simulation period was started 2 months prior to the equation calibration period; that is the start of observed water levels at a continuously monitored site. Starting a simulation in advance allows the equation to stabilize prior to the start of the calibration period. For Manson Pike well, Thompson Lane cave, Harding Place lowland, and Nickens Lane lowland, day one (t=1) was set to October 1, 1998. For the Stoneman quarry well, day one was set to September 1, 1999. The initial water level at a site, h_0, was set to the lowest value recorded during the period of operation, minus the 500-foot datum adjustment factor.

Daily water levels at Manson Pike well, Thompson Lane cave, Harding Place lowland, Nickens Lane lowland, and Stoneman quarry well were simulated by using equation 2. The simulation equation was calibrated at each site by comparing simulated water levels with observed water levels. All pairs of simulated and observed water levels were used to calibrate the simulation equation at these monitored sites. The calibrated values for drainage constant, abstraction constant, rainfall response constant, and river response constant (table 9) were determined using an error minimization procedure. The error minimization procedure systematically adjusts the values of the simulation-equation constants to minimize the differences between simulated and observed water levels at the modeled sites.

Average daily rainfall amounts (fig. 3) for the study area and estimated daily mean discharge for the West Fork Stones River at the old milldam at Manson Pike (fig. 9) are the independent variables supplied to the simulation equation. Average daily rainfall for the study period was determined by calculating the average rainfall amounts collected at the National Guard Armory (site 1, fig. 10) and at the intersection of North Thompson Lane and Manson Pike (site 2, fig. 10). Daily mean discharge for the study period at the West Fork Stones River at the old milldam at Manson Pike (fig. 10) was estimated from published discharge data collected at station 03428200 West Fork Stones River at Murfreesboro (fig. 1).

The simulation equation (eq. 2) used for this study results in acceptable estimates of water levels at lowlands, sinkholes, caves, and wells in this area of Murfreesboro, Rutherford County, Tenn. A weakness of this method is the inadequacy of the simulation equation to match the magnitude and timing of water levels that rise or fall rapidly after a heavy rainfall. This is primarily the result of the inadequacy of the simulation equation to precisely duplicate hydrologic responses in this area of complex karst geology. Simulation equation weakness is illustrated by figures 11 and 12, which show the simulated and observed water levels at the continuously monitored sites.

Table 9. Constant values for the calibrated simulation equation for each modeled site

[See fig. 2 for site locations and table 1 for site descriptions; negative value for drainage constant indicates ground-water outflow]

Constant	Manson Pike well (site 5)	Thompson Lane cave (site 10)	Harding Place lowland (site 11)	Nickens Lane lowland (site 12)	Stoneman quarry well (site 17)
Simulation start date	10-01-1998	10-01-1998	10-01-1998	10-01-1998	09-01-1999
Initial condition, h_o	37.60	45.60	45.60	37.60	24.70
Calibration start date	12-03-1998	12-03-1998	12-03-1998	12-11-1998	10-28-1999
Calibration end date	07-17-2000	07-17-2000	07-17-2000	07-17-2000	07-17-2000
Drainage	-.060	-.075	-.060	-.288	-.103
Abstraction	37.60	38.40	38.60	30.29	24.70
Rainfall response	2.29	2.79	2.06	1.26	.67
River response	.0014	.0012	.0010	.0008	.0005

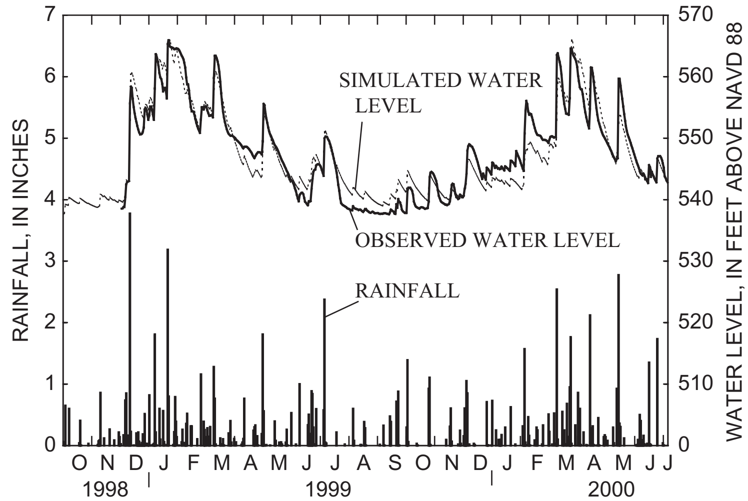

Figure 11. Observed and simulated daily maximum water levels for Manson Pike well, Murfreesboro, Tennessee, October 1998 to July 2000.

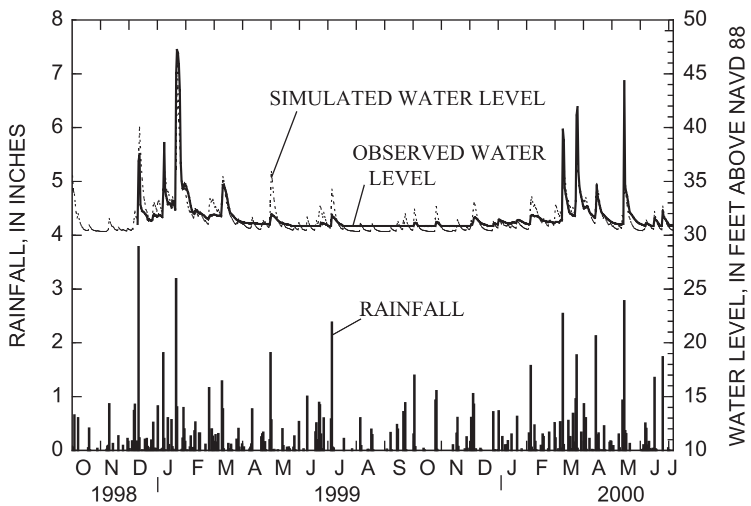

Figure 12. Observed and simulated daily maximum water levels for Nickens Lane lowland, Murfreesboro, Tennessee, October 1998 to July 2000.

A useful indicator of the simulation equation error is the root mean square error (RMSE) of the differences or errors between the simulated water levels and the observed water levels. RMSE is the standard deviation of the simulation equation error. The standard deviation is a measure of the spread of a group of values around the mean value. To illustrate the loss of simulation equation accuracy, mean error and RMSE were calculated for each continuously monitored site for several conditions. Calculations were made by using (1) errors for all observed water levels, (2) errors for the highest 10 percent of the observed water levels, and (3) errors for observed water levels above minimum land-surface elevation. Mean error and RMSE for the monitored sites indicate that the simulated water levels are underestimated, particularly when water levels are above the land surface (table 10).

In general, the simulation equation results were closer to water levels observed for wells than for water levels observed for surface areas of the lowlands,

Table 10. Mean error and root mean square error for the calibrated simulation equation for each modeled site

[See fig. 2 for site locations and table 1 for site descriptions; RMSE, root mean square error; ---, not applicable]

Description	Manson Pike well (site 5)	Thompson Lane cave (site 10)	Harding Place lowland (site 11)	Nickens Lane lowland (site 12)	Stoneman quarry well (site 17)
Errors for all observed water levels					
Lowest elevation for simulation, in feet above NAVD 88	525	545.64	545.64	530.90	412
Highest elevation for simulation, in feet above NAVD 88	566	568	566	548	562
Number of observations	593	214	209	398	264
Mean error, in feet	.03	-.11	-.06	0	0
RMSE, in feet	2.39	2.70	3.15	1.16	.54
Errors for the highest 10 percent of the observed water levels					
Water level threshold, in feet above NAVD 88	558.60	562.99	561.83	533.59	529.03
Number of observations	61	22	20	40	27
Mean error, in feet	-1.19	-2.21	-1.86	-1.18	-.40
RMSE, in feet	2.60	3.00	2.25	2.84	.78
Errors for observed water levels above minimum land-surface elevation (Lowlands and caves only)					
Minimum land surface, in feet above NAVD 88	---	560	558	538	---
Number of observations	---	43	49	11	---
Mean error, in feet	---	-2.63	-2.86	-4.50	---
RMSE, in feet	---	3.34	3.43	5.23	---

sinkholes, and caves. The simulation equation typically underestimates the occurrence of high water at modeled sites in the study area (table 10). Although the equation has a tendency to underestimate water levels, the results indicate that lowlands, sinkholes, and caves in the study area will fill to capacity as a result of storm runoff. The equation used to simulate water levels for this study provides conservative estimates because of a tendency to overpredict the occurrence of high water in the study area while indicating that flooding in the lowlands areas is a common event.

Future research on flooding in lowlands, sinkholes, and caves in the Murfreesboro, Tenn., area could consider developing a water-level simulation equation more sophisticated than the equation developed for this study. Such an equation ideally could be applied throughout Murfreesboro and Rutherford County, Tenn., to more accurately simulate water levels in lowlands, sinkholes, caves, and wells.

DURATION AND FREQUENCY ANALYSIS OF LOWLAND FLOODING IN WESTERN MURFREESBORO, RUTHERFORD COUNTY, TENNESSEE

A 50-year record of daily water levels was simulated for Manson Pike well (site 5, fig. 10), Thompson Lane cave (site 10, fig. 10), Harding Place lowland (site 11, fig. 10), Nickens Lane lowland (site 12, fig. 10), and Stoneman quarry well (site 17, fig. 10). These long-term records were developed using the calibrated simulation equation (eq. 2). Daily rainfall amounts for Murfreesboro published by the National Climatic Data Center (1948-2000) and estimated daily mean discharge for the West Fork Stones River at the old milldam at Manson Pike (fig. 9) were the explanatory variables used in the simulation equation. A record of daily water levels was simulated for the period October 1, 1948, through September 30, 1998, from which water-level duration and frequency relations were developed for the five simulated sites. The duration and frequency relations can be used with water-level data from periodically measured lowlands, sinkholes, caves, and wells to describe flood-prone areas (fig. 10) that are independent of widespread overflow from the West Fork Stones River.

Duration Analysis

Water-level duration curves illustrate the amount of time during a given year that the water level will be equaled or exceeded at a lowland, sinkhole, cave, or well. The relations are defined by ranking the simulated water levels from smallest to largest and determining the percentage of time each water level is equaled or exceeded. Water-level duration data are used for studying drainage characteristics of lowlands, sinkholes, caves, and wells and for comparing hydrologic characteristics of different parts of the study area. Water-level duration data do not represent probabilities and should not be used for prediction.

Water-level duration relations for Manson Pike well, Thompson Lane cave, Harding Place lowland, Nickens Lane lowland, and Stoneman quarry well are constrained by upper and lower water-level limits. The upper limit represents the maximum water level that will occur at a site, independent of overflow from the West Fork Stones River. At a lowland or sinkhole, the upper water-level limit is controlled by the elevation of the surface-water overflow outlet. Overflow outlet elevations in this report were determined from the City of Murfreesboro 2-foot contour-interval topographic map of the study area. The upper water-level limit for wells is defined as either the actual land-surface elevation or an effective land-surface elevation. If a well such as Manson Pike well (site 5, fig. 10) is drilled on high ground surrounded by flood-prone lowlands, an effective land-surface elevation is specified. The effective land-surface elevation at the well is defined as the water level that will occur in the surrounding lowlands if the West Fork Stones River just overflows its banks. The upper limit for Stoneman quarry well is the actual land-surface elevation because lowlands are not in close proximity to the well.

Duration curves for the continuously monitored sites (figs. 13-17) and water levels measured at other sites in the study area (tables 3 and 4) indicate that two areas have distinct stormwater drainage characteristics. Duration curves for Manson Pike well, Thompson Lane cave, and Harding Place lowland have a linear shape, indicating slow, constant drainage rates, whereas the curves for Nickens Lane lowland and Stoneman quarry well have exponential shapes, indicating fast, variable drainage rates. Land east and south of the battlefield tour loop is slower draining than land west of the battlefield tour loop (fig. 10).

Ponded stormwater throughout most of the study area, including the land south of Manson Pike

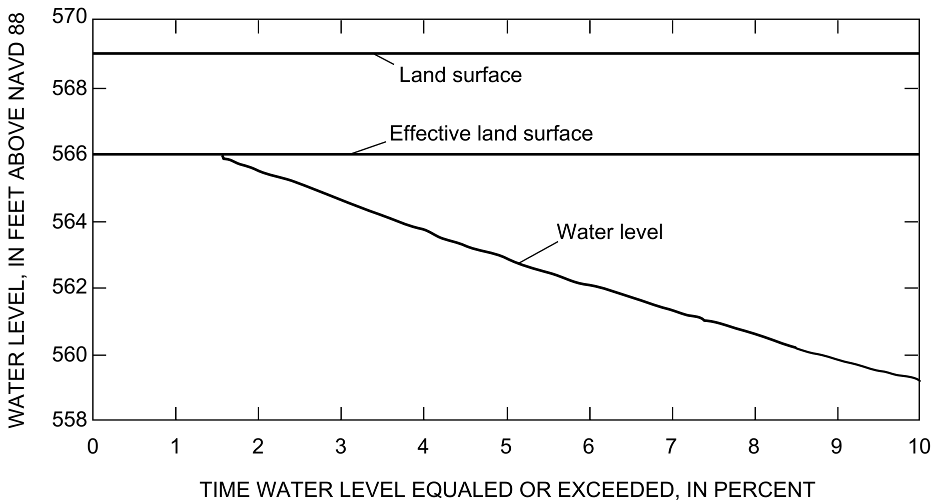

Figure 13. Daily maximum water-level duration curve for Manson Pike well (site 5), Murfreesboro, Tennessee.

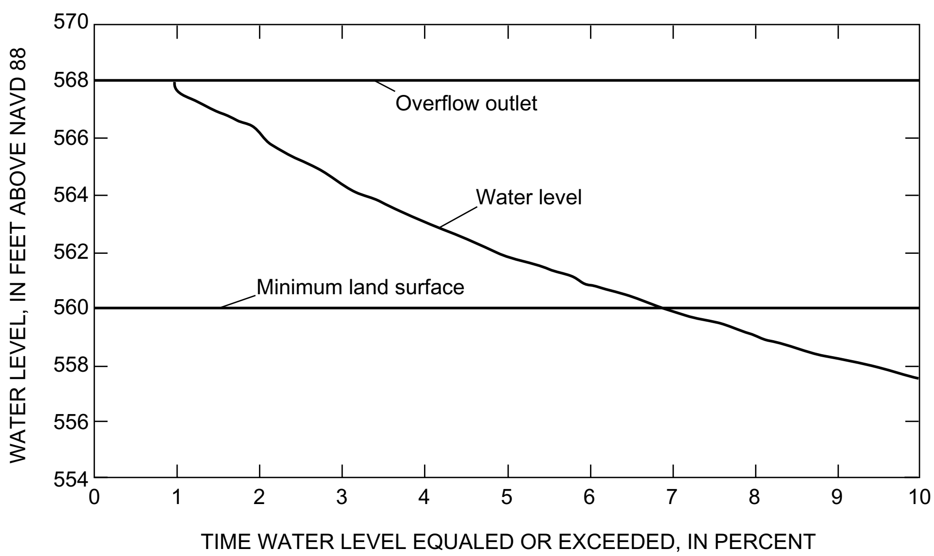

Figure 14. Daily maximum water-level duration curve for Thompson Lane cave (site 10), Murfreesboro, Tennessee.

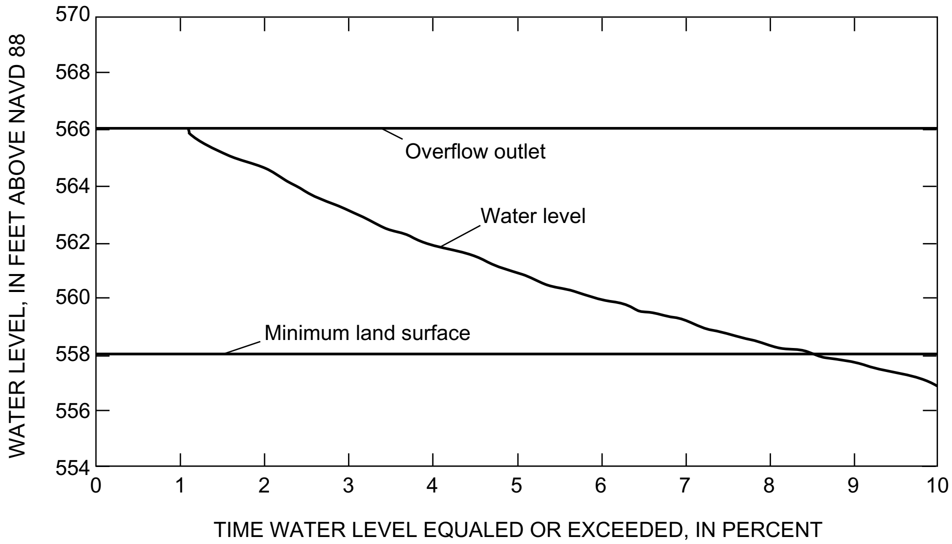

Figure 15. Daily maximum water-level duration curve for Harding Place lowland (site 11), Murfreesboro, Tennessee.

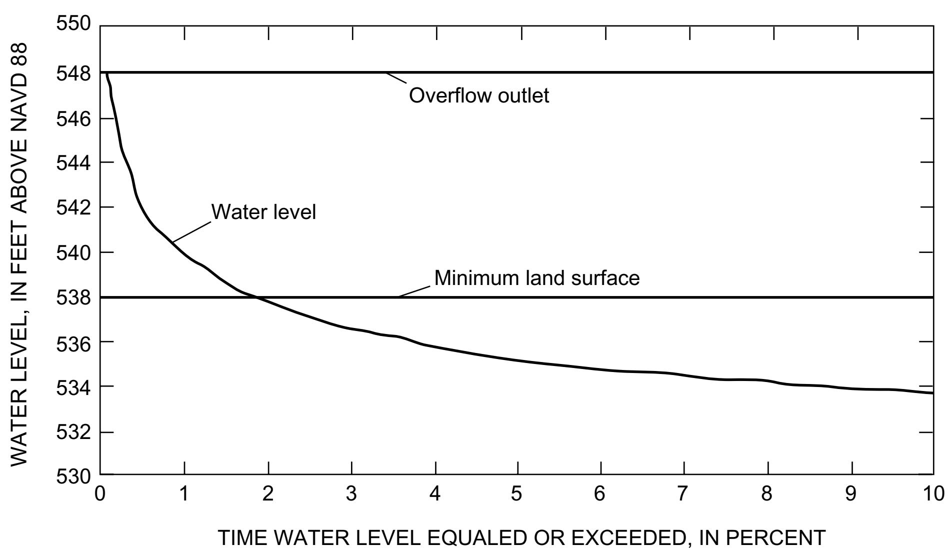

Figure 16. Daily maximum water-level duration curve for Nickens Lane lowland (site 12), Murfreesboro, Tennessee.

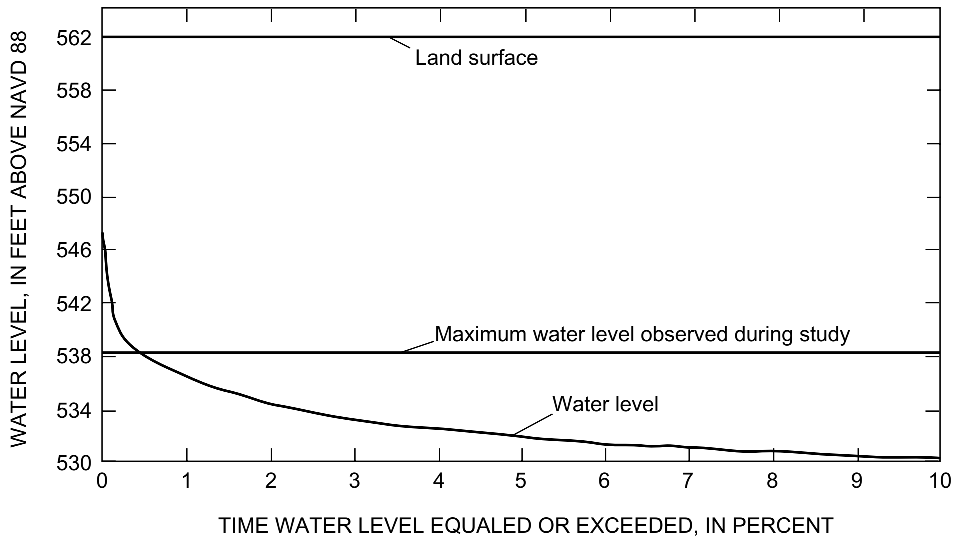

Figure 17. Daily maximum water-level duration curve for Stoneman quarry well (site 17), Murfreesboro, Tennessee.

and east of the Stones River National Battlefield tour loop (fig. 10), exhibits slow, constant drainage characteristics. Manson Pike well, Thompson Lane cave, and Harding Place lowland exhibit water-level duration curves that are typical of drainage characteristics in these areas (figs. 13-15, respectively). Floodwater was observed to drain slowly following the storm that occurred on January 23-24, 1999 (table 3) at the Stones River National Battlefield lowland adjacent to Thompson Lane (site 3, fig. 10), Thompson Lane at Manson Pike (site 4, fig. 10), the golf range near Thompson Lane (site 7, fig. 10), Thompson Lane karst window (site 9, fig. 10), and the Stones River National Cemetery lowland at Old Nashville Highway (site 13, fig. 10).

Floodwater at lowlands, sinkholes, caves, and wells in the area north of Manson Pike and west of the battlefield tour loop (fig. 10) was observed to drain in a rapid, flashy manner. Nickens Lane lowland and Stoneman quarry well exhibit water-level duration curves that are typical of drainage characteristics in this area (figs. 16 and 17, respectively). Floodwater was observed (table 3) to drain rapidly at Old Nashville Highway and Asbury Lane (site 14, fig. 10), Old Nashville Highway cave (site 15, fig. 10), and U.S. Highway 41/70 at Mt. Olive (site 16, fig. 10). In this area, where Nickens Lane lowland and Stoneman quarry well are located, water drains rapidly through solution channels in the underlying bedrock.

Frequency Analysis

Water-level frequency at an off-river flood-prone area is described by a relation of water levels and corresponding recurrence intervals. Water-level frequency relations for the continuously monitored sites were derived using the Weibull plotting position equation described in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). The frequency relations were developed from the 50-year record of simulated annual-peak water levels. The maximum water level that will occur at any site, independent of overflow from the West Fork Stones River, is dependent on the topography at the site. For lowlands and sinkholes, the maximum water level is controlled by the elevation of the surface-water overflow outlet. For wells, the maximum water level is controlled by the proximity of nearby lowlands. Water-level recurrence intervals are determined by ranking the long-term annual-peak water levels from largest to smallest and using the Weibull plotting position equation to compute the recurrence interval for each observation:

$$\text{Recurrence interval (years)} = (n+1) / m. \qquad (3)$$

In equation 3, n is the number of annual peaks and m is the rank of a given peak when ordered from the largest to the smallest. For the highest peak water level, m is equal to 1. For the lowest peak water level, m is equal to n. In this study, n is equal to 50.

Water-level frequency curves for Manson Pike well, Thompson Lane cave, and Harding Place lowland show that the maximum water level, independent of overflow from the West Fork Stones River, usually will occur once a year (figs. 18-20, respectively). Maximum water levels of 566, 568, and 566 feet above NAVD 88 will occur regularly at Manson Pike well, Thompson Lane cave, and Harding Place lowland, respectively. Maximum water-level elevations were determined by identifying the elevation of the surface-water outlet by using the 2-foot contour-interval topographic map of the study area. Overflow from the West Fork Stones River will reach the lowlands near Manson Pike well about once every 10 to 20 years. Overflow from the river can be expected to reach the Thompson Lane cave and Harding Place lowland area about once every 20 to 30 years (Federal Emergency Management Agency, 1999).

Recurrence intervals of 1.30 years, 1.40 years, and 1.60 years were computed for the maximum water levels measured during this study at Manson Pike well, Thompson Lane cave, and Harding Place lowland, respectively. During the storm of January 23-24, 1999, overflow from the West Fork Stones River did not reach any of these sites. During this flood, a peak water level of 564.10 feet above NAVD 88 was observed at the upstream side of the old milldam at Manson Pike (fig. 6). Peak water levels of 565.90, 567.40, and 565.22 feet above NAVD 88 were observed at Manson Pike well (fig. 4), Thompson Lane cave (fig. 5), and Harding Place lowland (fig. 5), respectively, during the January 23-24, 1999 flood. Following the flood, ponded water at these areas drained slowly for 10 to 14 days.

The computed water-level frequency curve for Nickens Lane lowland (site 12, fig. 2) indicates that the maximum water level of 548 feet above NAVD 88, which is independent of overflow from the West Fork Stones River, will occur about once every 4.2 years (fig. 21). A water level of 547.1 feet above NAVD 88 was measured at Nickens Lane lowland following the flood of January 23-24, 1999 (fig. 5). Flood-frequency calculations indicate that overflow from the West Fork Stones River will reach the Nickens Lane lowland about once every 10 to 20 years (Federal Emergency Management Agency, 1999).

The Stoneman quarry well (site 17, fig. 2) provides information about the fluctuation of the area-wide water table in the Nickens Lane lowland and Old Nashville Highway cave areas. The water level in this well was observed at 538.15 feet above NAVD 88 on January 25, 1999, prior to the installation of water-level monitoring equipment (table 4). The recurrence interval of this water level is about 3.5 years (fig. 22). Ground-water levels measured at several locations during this study (table 4) provide supplemental information describing the slope and typical elevation of the water table in the study area.

Water-level frequency curves indicate that maximum water levels in off-river lowlands and sinkholes

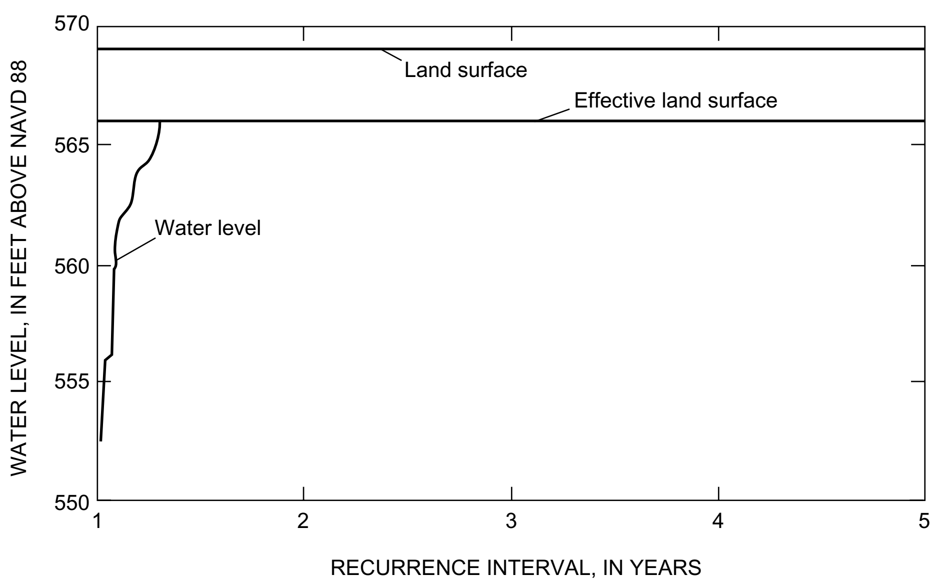

Figure 18. Daily maximum water-level frequency curve for Manson Pike well (site 5), Murfreesboro, Tennessee.

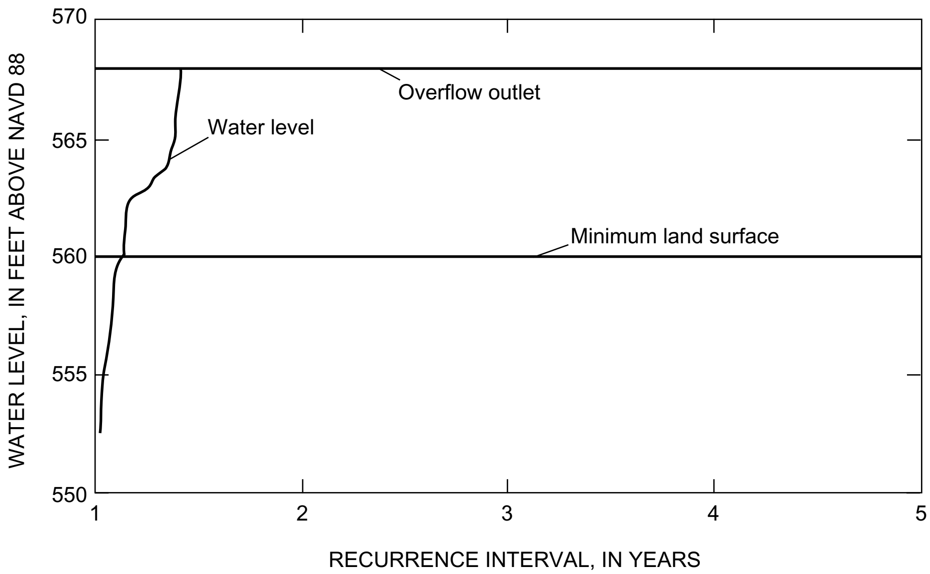

Figure 19. Daily maximum water-level frequency curve for Thompson Lane cave (site 10), Murfreesboro, Tennessee.

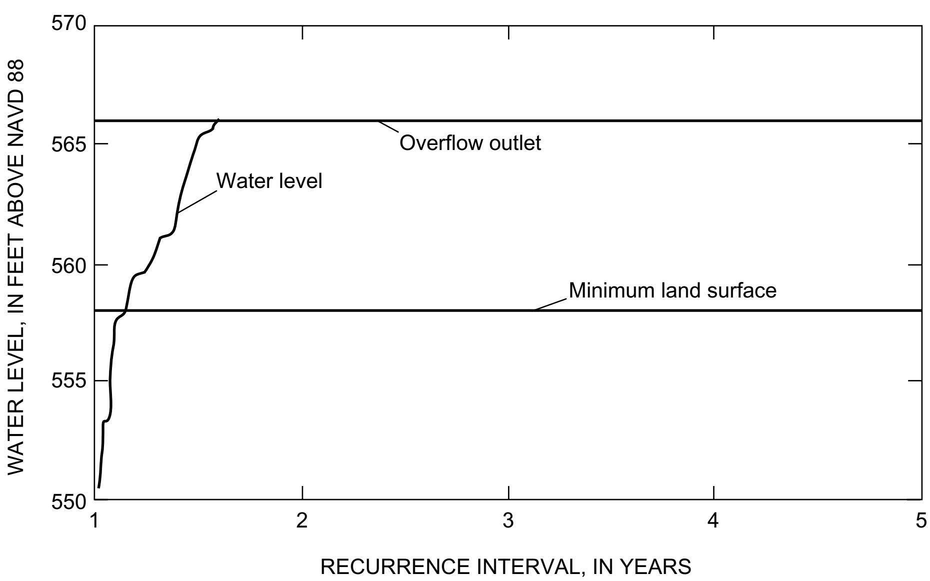

Figure 20. Daily maximum water-level frequency curve for Harding Place lowland (site 11), Murfreesboro, Tennessee.

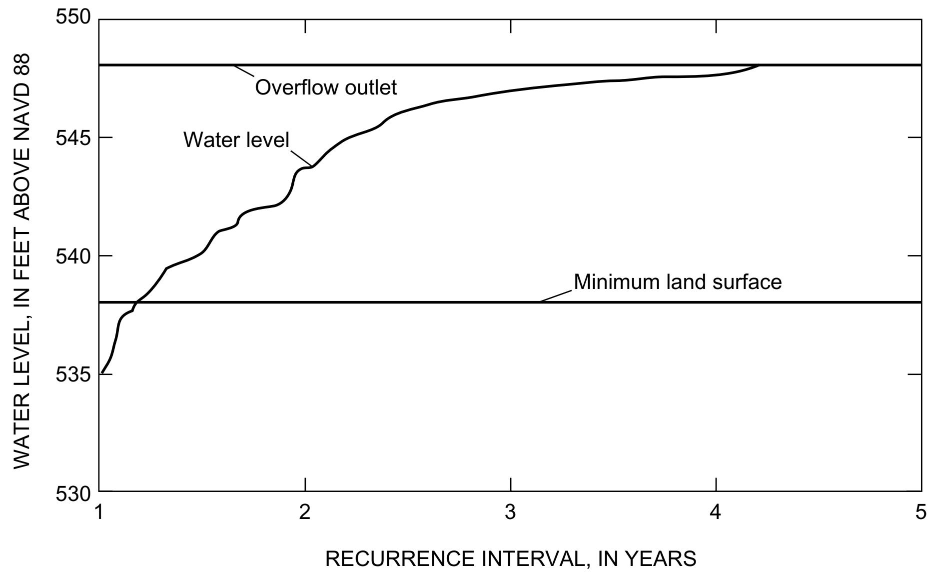

Figure 21. Daily maximum water-level frequency curve for Nickens Lane lowland (site 12), Murfreesboro, Tennessee.

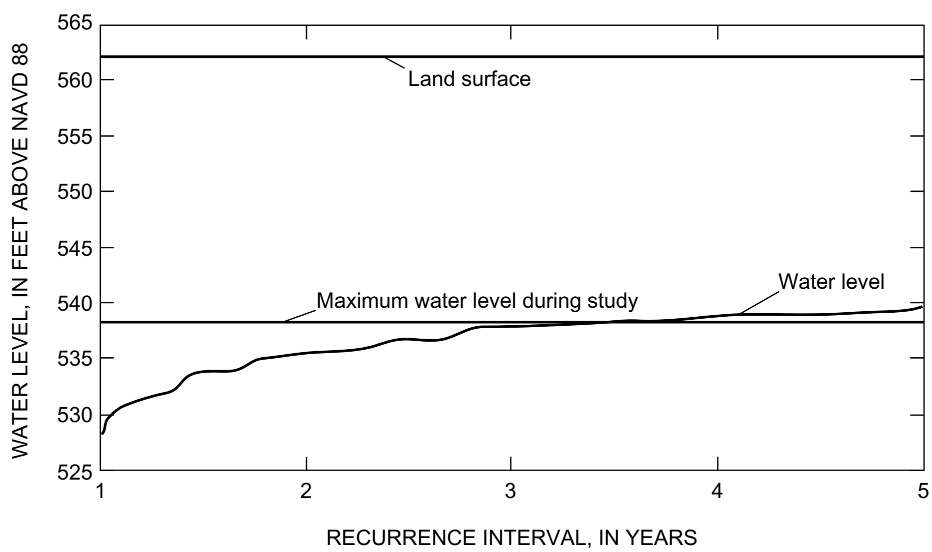

Figure 22. Daily maximum water-level frequency curve for Stoneman quarry well (site 17), Murfreesboro, Tennessee.

in the study area typically occur about every 1 to 4 years. Widespread flooding from the West Fork Stones River could reach off-river flood-prone areas about once every 10 to 20 years. Overland flow travels in a northwesterly direction to the Nickens Lane lowland and Old Nashville Highway cave areas. Water ponded at the Old Nashville Highway cave drains rapidly through underground solution channels.

SUMMARY

The U.S. Geological Survey, in cooperation with the City of Murfreesboro, conducted a hydrologic investigation of off-river flood-prone lowlands and sinkholes near the West Fork Stones River in western Murfreesboro, Tenn., from October 1998 to September 2000. Results of the study include development of a database of rainfall, water-level, and river discharge information for the study area. Water-level duration and frequency relations were developed for selected lowlands, sinkholes, and wells. An off-river flood-prone area map was developed by using a 2-foot contour-interval map of the study area. The flood-prone map delineates areas where frequent flooding occurs independently of overflow from the West Fork Stones River.

Rainfall was measured at two locations and water levels were measured at several lowlands, sinkholes, caves, and wells in the study area. Water levels also were measured on the West Fork Stones River upstream and downstream of the old milldam at Manson Pike. Discharge data for the river were analyzed at points upstream, near, and downstream of the study area. Daily mean and annual-peak discharge were estimated for the river at the old milldam at Manson Pike for the period October 1, 1932, through September 30, 2000. Discharge was estimated by multiplying the discharge recorded at a nearby gaging station on the river by the contributing drainage-area ratio between the old milldam at Manson Pike and a nearby gaged site. Hydrologic data were used to describe off-river lowland flooding in the study area. A flood-prone area map was developed for the study area to illustrate where maximum water levels were expected to occur at off-river lowlands and sinkholes independent of overflow from the West Fork Stones River. The river remains mostly within its banks throughout the study area for floods having a recurrence interval of 10 years or less. Floods on the river having greater than a 10-year recurrence interval produce progressively more widespread flooding as the recurrence interval increases.

Hydrologic data were used to develop and calibrate a water-level simulation equation at lowlands, sinkholes, caves, and wells in the study area. The water-level simulation equation uses daily rainfall recorded at the study area and estimated daily mean discharge for the West Fork Stones River at the old milldam at Manson Pike to estimate the water level at the continuously monitored sites. Simulation equation constants were calibrated by using water levels observed at the continuously monitored sites during the period December 1998 through July 2000. The water-level simulation equation was used to simulate a 50-year record of water levels at these sites.

Water levels for the period October 1, 1948, through September 30, 1998, were calculated by using National Climatic Data Center rainfall records for Murfreesboro and estimated daily mean discharge for the West Fork Stones River at the old milldam at Manson Pike. Water-level duration and frequency relations for the monitored sites were developed from these data. Maximum water levels in lowlands, sinkholes, caves, and wells in the study area, independent of river flooding, can be expected every 1 to 4 years.

A storm occurring during this study on January 23-24, 1999, produced off-river flooding having a recurrence interval of 1 to 4 years. Flooding on the West Fork Stones River had a recurrence interval of almost 10 years for this storm. Conditions similar to these are illustrated on the flood-prone area map included in this report.

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