Report on Sinkhole Flooding and Determination of 100-year Sinkhole Floodplains for the City of Cookeville, TN

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Photos: Herald-Citizen

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Executive summary

The City of Cookeville is situated on the East Highland Rim physiographic province and is underlain by soluble limestone bedrock. Due to its unique geologic setting, Cookeville has one of the highest densities of sinkholes and caves of any city in the region, and perhaps the nation. Cookeville's stormwater drainage system relies on drainage to the subsurface through sinkholes and caves. Sinkhole flooding occurs when the rate of water entering a sinkhole exceeds the rate of water draining from it. In urban areas, impervious surfaces (paved streets, parking lots, etc.) increase runoff rates, elevating the risk of sinkhole flooding.

The objective of this study was to delineate the 100-year floodplains for sinkholes within the Cookeville Urban Growth Boundary (UGB). In order to do this we used detailed topographic data (LiDAR), GIS, and hydrologic modeling software. The results of floodplain prediction were validated by comparing predicted flood heights with those observed during actual storms. Sinkhole floodplain maps are being provided to the city in GIS format (Geodatabase) and in PDF format, for public dissemination or sharing among offices.

Sinkhole drainage areas were determined for 218 major sinkholes within the Cookeville urban growth boundary. The sinkhole drainage area is the land area that contributes runoff to the selected sinkhole. Results show that sinkhole drainage areas cover 14,610 out of the total 32,622 acres of the Cookeville UGB, or 45 percent. Thus land use change and urban development that occurs in almost half of the urban growth boundary directly affects sinkhole flooding. Sinkhole drainage areas average 67 acres in size and, on average, consist of 22 percent impervious surfaces (paved streets, roofs, parking lots, and driveways). These impervious surfaces include over 13,000 structures and 260 miles of roads.

Sinkhole floodplains as defined in this study are those areas around sinkholes that are predicted to flood in the 100-year, 3-hour duration rainfall (4.5 inches for Cookeville, or 1.5 in/hr). The total area predicted to be inundated is 657 acres, or an average area of approximately 3 acres per sinkhole. Flood height elevations range from 938 ft a.m.s.l. to 1276 ft a.m.s.l., depending on which part of the city the sinkhole is located. GIS analysis shows that 225 structures and 7.8 miles of roads are currently built within sinkhole floodplains and would be subject to damage during the 100-year storm event.

Although not the purpose of this study, we offer three recommendations for sinkhole flood mitigation. First, the addition of impervious surfaces should limited by zoning, or offset by properly-functioning detention basins. This will ensure that runoff inputs to sinkholes do not increase dramatically in the future. Second, sinkhole swallets (the point where water enters the ground) should be monitored and periodically cleared of trash and debris. Some swallets may require a filter or trash-rack type structure to prevent large objects from entering the cave/stormwater system. Finally, sinkhole drainage rates should be monitored, perhaps in a longer-term study, to observe changes in rates. Any such changes may signal possible clogging of the subsurface drainage system.

Introduction

Areas with humid climate and underlain by limestone or other soluble rock typically develop terrain called “karst” topography, characterized by caves, sinkholes, and sinking streams. Sinkholes are prone to flood during intense rainfalls, for much of the water may be retained in these basins for hours or even days. Urbanization of sinkhole terrains generally increases the frequency and intensity of flooding.

Despite this hazard, only in the last decade or two have efforts been made to create sinkhole flood-hazard maps analogous to those made for rivers for FEMA (Federal Emergency Management Agency). Kemmerly (1981) was one of the first to recognize this need, and suggested a methodology for determining the 100-year floodline within sinkholes. More recently, FEMA approved a method for sinkhole flood mapping used in the most recent Flood Insurance for Bowling Green, KY (FEMA, 1993). This involved calculating the runoff from the watershed draining directly to the sinkhole. A stage-storage relationship was developed for the sinkhole and used with the volume of runoff to determine the flood elevation. The approved method made the assumption of no leakage from the sinkhole. This method was essentially that used in the study by George and others (1990), except that only spill points were used; there was no use of historic flood levels.

In more detail, the method used by George and others required measuring the stormwater runoff from a measured rainfall event. Hydrograph measurements were obtained from channelized flow locations and pipes at four sites. A survey of the channel cross-section and flow measurements taken with a Marsh McBirney velocity meter were used to determine surface runoff flow into a sinkhole at various times during a rainfall event. A simple staff gauge was used to measure the rise and fall of the water in the channel with time. An observer recorded water level measurements every five minutes during an event. Manning’s equation for open-channel flow was used to develop a flow rating for each location, so that flow rates could be determined at any channel or pipe depth.

The present study follows in the footsteps of the study by George and others (1990). Greater choices in hydrologic models, elevation maps with greater resolution, and more-accurate land-use data, as well as landscape changes that have occurred in the past 19 years, justify a second project along these lines.

Objectives of the Project

1) Delineate significant sinkholes and their catchment boundaries
2) Select a surface runoff model to calculate runoff volume to the sinkhole for rainfall events of given intensity and duration. Such calculations are to be made for each significant sinkhole.
3) Using the hydrologic model of the 100-year rainfall and the volume of water below the sinkhole spill points, predict the area likely to flood for each significant sinkhole
4) Provide a guide to sinkholes likely to have flooding problems.
5) Calibrate the model. Although calibration of models is not a major component of this study, we think that some calibration is necessary in order to support the veracity of the floodplain maps we are producing. As an example of the need for calibration, consider a sinkhole studying in Bowling Green, KY (Campbell, 2005).Flood elevations for four sinkholes were determined using standard methods approved by FEMA. Calculated flood elevations for two of theses sinkholes were much lower than depths actually observed. One possible source of the error was found to be spill-over from uphill sinkholes. Using ArcGIS and 3D Analyst, watersheds were delineated and volumes held by sinkholes up to the lowest spill point were determined. This analysis showed that no significant correlation exists between area draining directly to the sinkholes and volume held. By accounting for spill-over, the watershed of one sinkhole grew from 11 hectares to more than 520 hectares. A calibrated model that accounted for both storage and spillover of upstream sinkholes gave good agreement with observations of a 1998 flood (Campbell, 2005).
6) Data from George and others (1990) also seem to indicate underprediction. Of seven rain events monitored, three showed accurate prediction, and of the remaining four, one showed an overpredicgtion of 34% and the remaining three showed an underprediction of 58%, 16%, and 45%> Hence, summarizing the results for this study and that by Campbell (2005), it appears that prediction is somewhat more likely to underpredict than to overpredict, such that the results of simulation may often be considered minimums. Unlike the Bowling Green area, however, which is low-lying and thus likely to be in a groundwater discharge zone, the Cookeville area is near a divide, and is thus less likely to be subject to such discharge. In any case, the underprediction found in these two studies warrants some attempt at calibration

Physical Setting

The study area lies approximately in the center of the Eastern Highland Rim physiographic province, between the Cumberland Plateau to the east and the Central Basin to the west. Outliers of the Cumberland Plateau occur in the eastern part of the area in the form of tablelands and benches capped by the Hartselle Formation. These tablelands provide the highest elevations, about 435 m. As the lowest point in the study area is about 285 m, the maximum relief is about 150 m, excluding the table-lands, however, however, the relief is only about 50 m, with elevations over much of the area averaging about 335 m. This relatively flat surface has been referred to as the Highland Rim peneplain (Hayes, 1899; Thornbury, 1965). However, this surface is more easily attributed to the highly resistant Fort Payne Formation. Cropping out in the western part of the province, this formation both retards the eastern retreat of the escarpment between the eastern Highland Rim and the topographically lower Central Basin, and also serves as the local base level for streams flowing on the Rim. A great variety of sinkhole shapes and sizes exists in the area. Most would be classified as solution rather than collapse sinks. Most commonly, no swallet is visible, the floor instead being covered with residuum, colluvium, or alluvium. After heavy rains, such sinkholes drain much more slowly than those with swallets.

Geology

The study area lies in parts of four U.S. Geological 7.5-minute quadrangles: Cookeville East, Cookeville West, Burgess Falls, and Dry Valley. Five bedrock formations crop out in this area. All are Upper Mississippian in age, except for the oldest, the Lower-Mississippian Fort Payne Formation. It is a highly siliceous limestone, thin-to-thick bedded, interbedded with calcareous siltstone and argillaceous limestone, containing bands and nodules of dense chert. Thickness is greater than 2 m, Sinkholes in this formation are relatively few, Overlying the Fort Payne is the Warsaw Formation, a sandy, thin- to thick-bedded limestone, interbedded with sandstone and shale, with a thickness ranging from 30 to 35 m. This formation shows a moderate number of sinkholes. Above the Warsaw is the St. Louis Limestone, a fine- to medium-grained, thin- to thick-bedded, fossiliferous limestone. Most beds are somewhat dolomitic, and the formation contains lenses and nodules of chert. Thickness ranges from 25 to 45 m. Overlying the St. Louis is the Monteagle Limestone, a fine- to coarse-grained, medium- to very thick-bedded limestone. Its thickness ranges from 75 to 90 m. Both the St. Louis and Monteagle show numerous sinkholes. Overlying the Monteagle is the Hartselle Formation, a very fine- to fine-grained, thin- to thick-bedded sandstone, locally calcareous, and containing lenses of shale. Thickness ranges from 15 to 25 m. Sinkholes are few (Ferguson, 1968). Of these five formations, the St. Louis and Warsaw underlie most of the study area. Beds are essentially flat-lying, with a very slight eastward dip. Dominant joint sets are oriented about S68^{o}E and N65^{o}E. Sinkholes often follow these joints. The depth of residuum exceeds 10 m at many locations.

Methods used to determine sinkhole floodplains

Because no long term stream flow data exist for the Cookeville area, flood frequency analysis must be done using hydrologic modeling. Hydrologic models of many types have been devised for both rural and urban watersheds. Simply stated, a hydrologic model consists of a basin model (a description of the physical characteristics of the drainage area, i.e., slope, land cover, soils, etc.) and a meteorological model (which estimates the amount and distribution of rainfall). Numerous models have been developed for use in various types of watersheds, including rural and urban areas (Dingman, 2002). While models are not perfect representations of the real world, the do provide a number of advantages in prediction of flood response. For example, Ponce and Hawkins (1996) noted the following about the Soil Conservation Service (SCS, now NRCS) Curve Number method: 1) it is computationally simple; 2) it uses readily available watershed information; 3) it has been packaged in readily available tables graphs, and computer programs; 4) it appears to give reasonable results under many conditions; and 5) in the absence of detailed watershed information, there are few other practicable methodologies for obtaining a priori estimates of runoff that are known to be better. For these reasons, we chose the SCS Curve Number method for predicting runoff to sinkholes in Cookeville.

The SCS curve number method for predicting runoff is widely used for small watersheds. While the method was originally developed for use in agricultural watersheds, modifications have been made to allow its use in urban areas as well. Thus it is well suited for the sinkholes in Cookeville that contain both rural and urban land. The method requires the input of the following variables: watershed area, percentage of impervious area, percentage of forest area, basin lag time, soil infiltration rate, and rainfall rate. Watershed area, percent impervious area, percent forest area were obtained using the GIS coverages described above. Soil types for the urban growth boundary area were determined using the digital Putnam County Soil Survey. The Soil Survey recognizes 4 soil hydrologic groups:

A Low overland flow potential; high minimum infiltration capacity even when thoroughly wetted (> 0.30 in hr-1). Deep, well-to excessively-drained sands and gravels.

B Moderate minimum infiltration capacity when thoroughly wetted (0.15 to 0.30 in hr-1). Moderately deep to deep, moderately well-drained, moderately fine- to moderately coarse-grained (e.g., sandy loam).

C Low minimum infiltration capacity when thoroughly wetted (0.05 to 0.15 in hr-1). Moderately fine- to fine-grained soils or soils with an impeding layer (fragipan).

D High overland-flow potential; very low minimum infiltration capacity when thoroughly wetted (<0.05 in hr-1). Clay soils with high swelling potential, soils with permanent high water tables, soils with a clay layer near the surface, shallow soils over impervious bedrock.

The following combinations of land cover and soil types were used to estimate runoff curve numbers:

1. impervious area—98
2. forest (Soil B)—76
3. forest (Soil C)—87
4. forest (Soil D)—90
5. grass/pasture (Soil B)—76
6. grass/pasture (Soil C)—85
7. grass/pasture (Soil D)—89

No soils of hydrologic soil type A were found within sinkhole drainage areas. Curve numbers used for each land cover category are listed to the right of each type. Curve numbers listed to the right of each land use type above are numbers between 1 and 100 that represent the watershed's capability to infiltrate and store excess rainfall. For example, a curve number of 100 would represent a completely impervious surface, where 100% of rainfall produces direct runoff. A curve number of 0 would produce no runoff. All curve numbers used in this study were selected based on saturated antecedent moisture conditions, which conditions are likely to occur during the 100-year storm. Curve numbers have been developed for various land cover and soil types from previous studies and were selected from data published by the US Soil Conservation Service (1975).

A weighted curve number was calculated for each sinkhole drainage area using the following method. For example, land cover/soil categories are shown in Figure 1 for sinkhole drainage area 153.

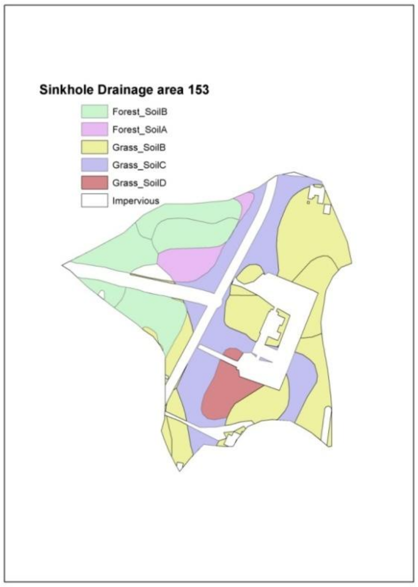


Figure 1. Example sinkhole drainage area map with land cover and soil type data displayed.

Table 1 gives the relative proportions of area for each land cover/soil type category. The percent of total sinkhole area column is multiplied by the curve number for that category, to give a weighted area. The sum of all weighted area values gives the weighted curve number for the drainage area. The curve number is used in the computation of estimated runoff volume as discussed below.

Table 1. Example of how land cover and soil data are used to calculate the weighted curve number (CN).

Land cover/soil type	Curve number (CN)	% of total sinkhole drainage area	Weighted area (CN * % area)
Forest Soil B	76	16	12.2
Forest Soil C	87	5	4.4
Grass Soil B	76	24	18.2
Grass Soil C	85	21	17.9
Grass Soil D	89	5	4.5
Impervious	98	29	28.4
		Weighted CN for sinkhole 153 =	86

Estimating watershed runoff using the SCS method

When rain falls on a land surface a portion of the water volume begins to fill in small depressions on the landscape. Eventually, when these depression storage areas are filled, direct runoff to streams begins. The rate and timing of runoff depend on the infiltration capacity of the land surface. The SCS method offers a way to quantify the rainfall, storage, and runoff processes based on known land use, soils, and rainfall data (United States Soil Conservation Service, 1975).

The following terms are used in runoff estimation under the SCS method (Dingman, 2002):

1) initial abstraction (Vi)—the amount of depression storage that must be filled before event flow can occur
2) retention (VR)—the amount of rain that falls after the initial abstraction is satisfied and is retained in the soil (does not contribute to event flow
3) event flow (Qef)—water that is not retained in the soil and contributes to overland flow and runoff towards streams
4) maximum retention capacity (V_{max})—assumed maximum retention capacity of basin
5) total rainfall volume (W)—the total rainfall volume for a specified storm duration
6) effective rainfall (Weff)—volume of rainfall that is converted to watershed runoff (equal to event flow volume)

These terms are related by the following:

$$\frac{VR}{Vmax} = \frac{Weff}{W - Vi} \qquad (1)$$

where all units are given in length (in or cm) expressed per unit watershed area.

Retention (VR) is found by:

$$VR = W - Vi - Weff \qquad (2)$$

Combining equations (1) and (2) gives:

$$Weff = \frac{(W - Vi)^2}{W - Vi + Vmax} \qquad (3)$$

Data from actual hydrographs shows that Vi = 0.2 Vmax in many cases. Thus, substituting this equation into equation 3 gives:

$$Weff = \frac{(W - 0.2 * Vmax)^2}{W + 0.8 * Vmax} \qquad (4)$$

Vmax is found by:

$$Vmax = \frac{1000}{CN} - 10 \qquad (5)$$

The following is an example of how *Weff* was calculated for sinkhole drainage area 153 in the Cookeville Sinkhole study.

Step 1. Determine rainfall volume for design storm. The design storm for the Cookeville Sinkhole project is the 100-year rainfall of 3-hour duration. The 3-hour duration was chosen because this length of time has been used in other sinkhole flooding studies in settings similar to Cookeville. For example, Crawford (REF) used the 3-hour storm duration in their study of sinkhole flooding in Bowling Green, KY. Operationally, the intensity and duration of a 3-hour storm appears to be provide the maximum potential for sinkhole flooding (i.e., the worst case scenario). Longer storm durations (e.g., 24-hour) are not intense enough to cause major flooding, while shorter duration storms (e.g, 30 min) do not produce enough water volume for major flooding to occur. However, few data have been collected on effective rainfall duration for sinkhole flooding. Furthermore, the effective duration is likely to change depending on several variables including sinkhole drainage area size and sinkhole drainage rate.

Return periods for rainfall were obtained from the National Oceanographic and Oceanic Administration (NOAA) for the Cookeville area (Fig. X). From the intensity-duration-frequency curve below, it is shown that the 3-hour, 100 year storm has an average intensity of 1.5 in per hour. This equates to a 4.5 in total rainfall depth for a 3-hour period. Thus, relating to the terms given above for the SCS method, the term W is set to 4.5 in for all sinkhole drainage areas in Cookeville.

Step 2. Find Vmax. The maximum retention capacity (Vmax) is found by equation 5. The curve number for Sinkhole 153 was calculated above to be 86, thus:

$$\text{Vmax} = \frac{1000}{86} - 10 = 1.63$$

Now solving for Equation 4 we find:

$$Weff = \frac{(4.5-0.2*1.63)^2}{4.5+0.8*1.63} = \frac{17.4}{5.8} = 3.0\ in$$

This is the effective rainfall and is multiplied by basin area to find total runoff volume:
0.25 ft * 940,000 ft^2 = 235,000 ft^3

This result is then entered in to the Area-Volume function in ArcGIS 3D analyst to find the height to which this volume of water would fill the sinkhole (Figure 2). This contour height is then used to create the 100-year floodplain polygon. The process was repeated for each sinkhole drainage area.

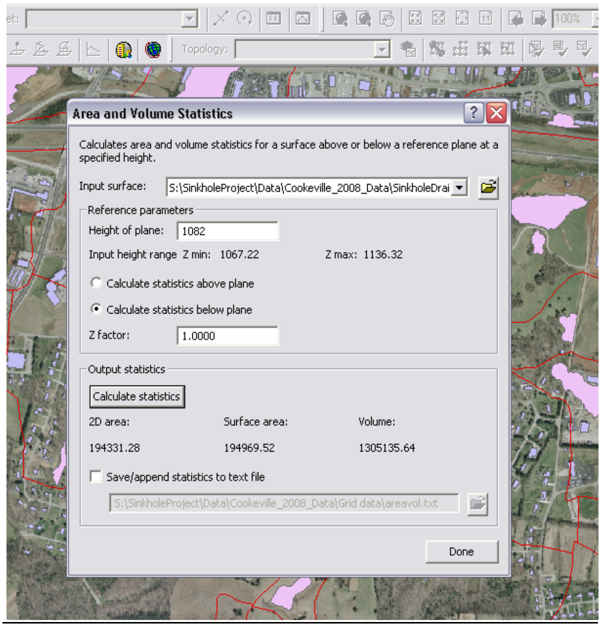


Figure 2. Screen shot of the Area-Volume calculation window. With this GIS function the volume determined from runoff modeling was projected on the grid surface to find the flood elevation.

<u>Calibration of results</u>

Automatic stage recorders and rain gauges were used to calibrate model results obtained from the SCS Curve Number method. Two drainage basins were chosen for calibration, Ensor Sink and Warehouse Sink. These basins were chosen because they have uniform concrete channels. These channels allow for more precise measurements of discharge. In order to calibrate model results the data obtained from GIS analysis, along with actual rainfall and streamflow data, were entered into the HEC-HMS modeling program (U.S. Army Corps of Engineers, 2008).

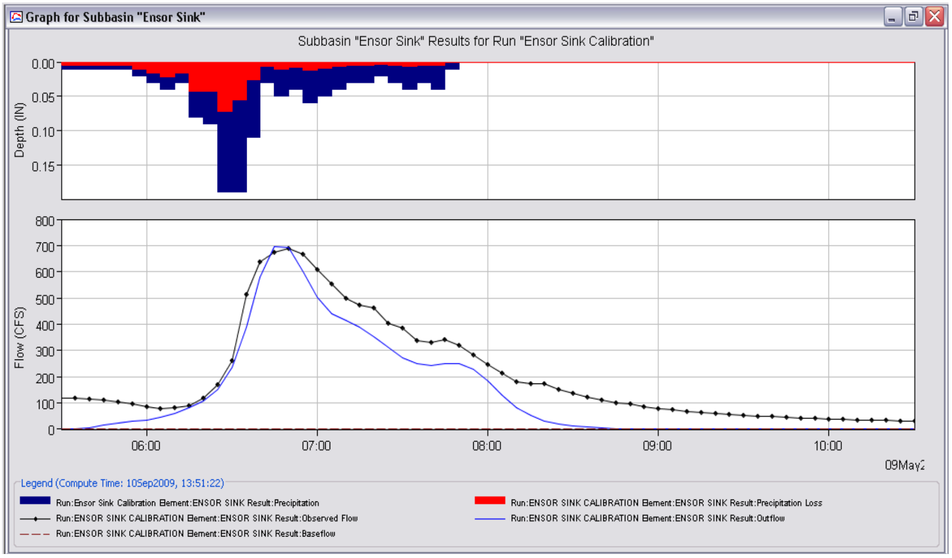


Figure 3. Calibration data for Breedings Mill Branch near bridge on Clover Hill Dr. just upstream from Ensor Sink. Lower panel shows calibration graph with observed (black dotted line) versus predicted (blue line) flow for the 9 May 2009 storm event. Upper panel shows observed rainfall depth (blue bars) and precipitation loss (red bars). Baseflow was not considered to be significant contributor to storm runoff for this basin.

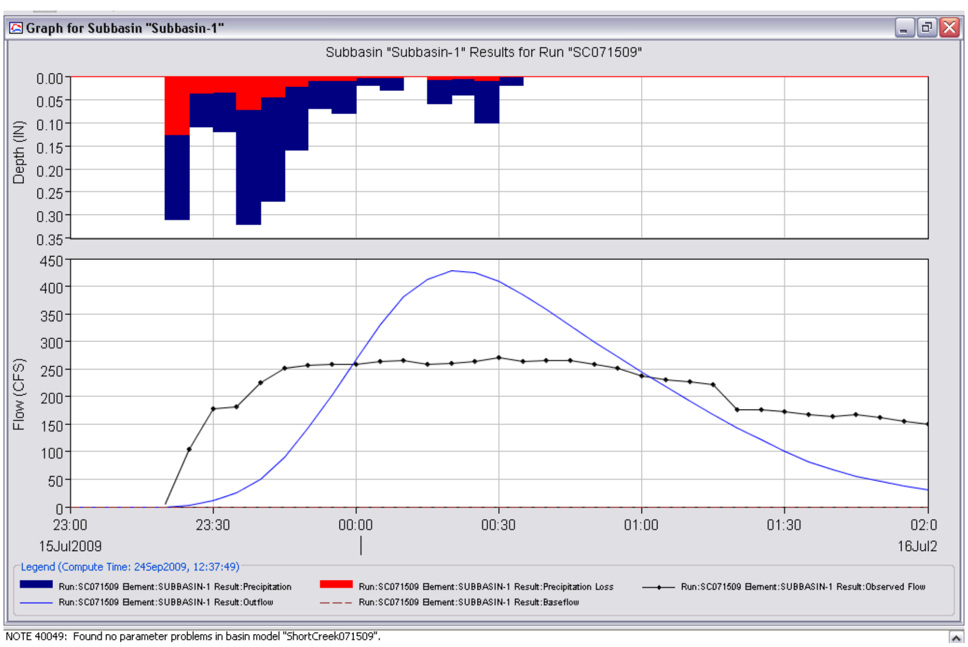


Figure 4. Calibration curve for Short Creek upstream from Warehouse sink for the 15 July 2009 storm. Note that the observed flow does not show a flashy response due to stormwater structures in the basin. However, observed and predicted runoff volumes are similar (i.e., the area under each curve is approximately equivalent), so that sinkhole flood volumes would be similar, if sinkhole drainage rates are assumed to be zero.

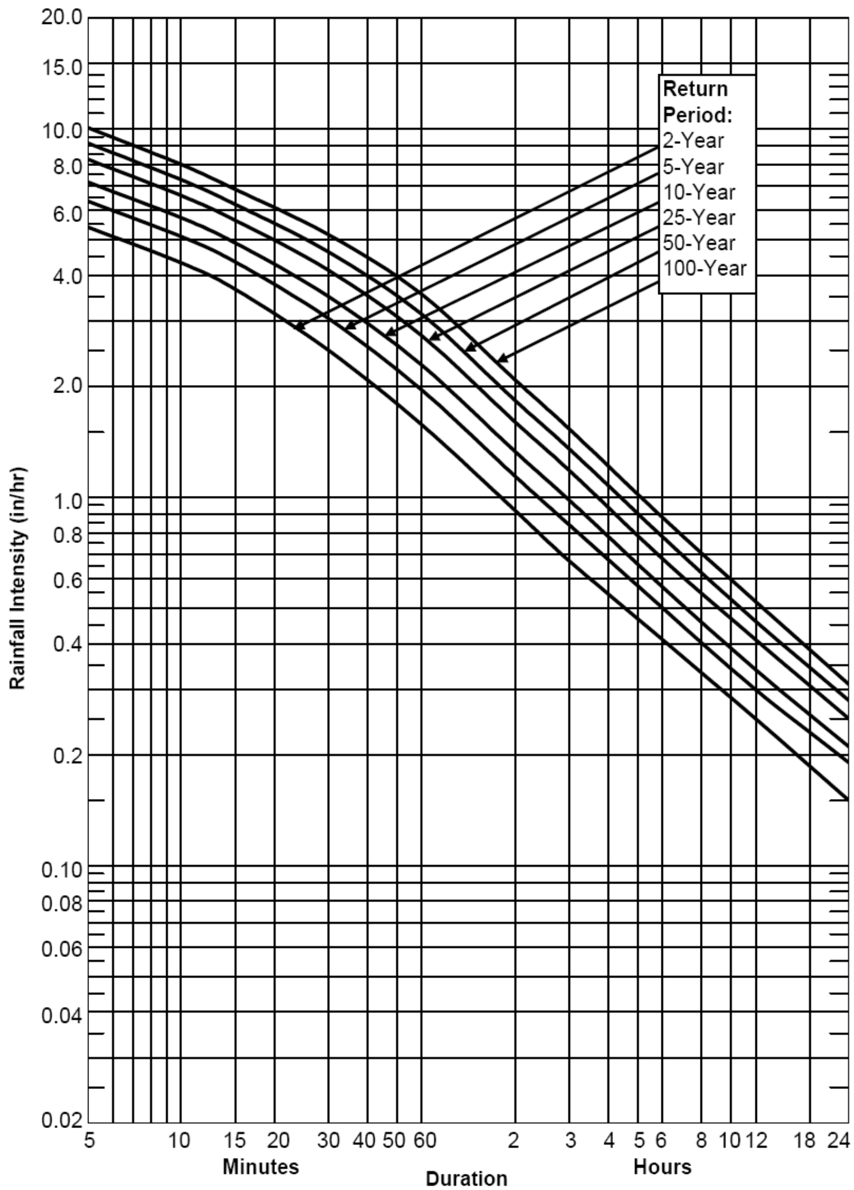


Figure 5. Rainfall Intensity-Duration-Frequency curve for Cookeville. Source: National Weather Service, NOAA Atlas 14, Volume 2 (2004).

The September 16, 2009 100-year flood in Cookeville

On September, 16 2009 several sinkholes in Cookeville flooded during intense rainfall. The Kittrell Hall Rain gauge recorded 5.49 inches of rain between the hours of 8am and 2pm, this exceeded the 100-year rainfall for a 6-hour duration. Floodplain predictions from this study matched closely with the actual flood heights observed in several sinkholes during this storm. For example, in the Byrne Ave. area an apartment complex was flooded and the sinkhole filled to a maximum height of 1092.96 feet (AMSL), as surveyed by city workers on 9-16-2009. The 100-year sinkhole flood height predicted by this study is 1092 feet. In other areas of town, sinkhole flood heights were observed (although not surveyed) and found to be in good agreement with our floodplain map. At Waterfall Sink, water rose near several homes along Hillside Road. Again, the observed flooding was in agreement with the predicted flood level. On Old Walton Road, Ronnie Kelly estimated a flood height of 1027 feet; the predicted 100-year flood height for this sinkhole is 1032. Reasons for the difference in this situation may be that the 9-16-09 storm had a scattered distribution and rainfall may not have been as heavy on this east side of town. However, no rain gauge data exist for that area of town.

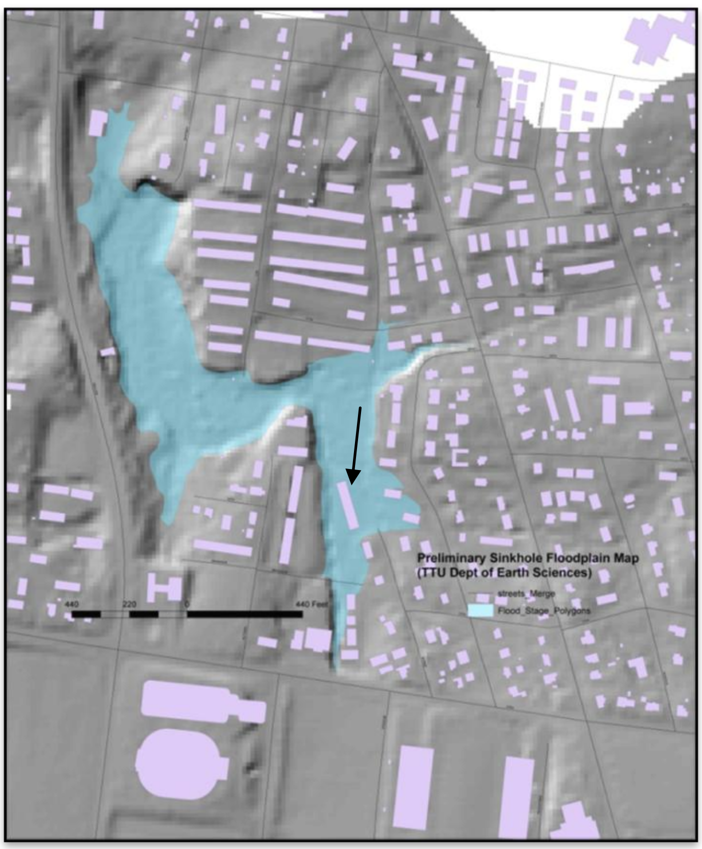


Figure 6. Predicted sinkhole floodplain map showing area around Byrne Ave. expected to flood during 100-year rainfall. Flood height surveyed by city workers on 9-16-09 was within 1 foot of the predicted level. Note arrow pointing out Eagle Creek apartments on Bynre Ave, flooded during the storm. These apartments are show in Figure 7.

Figure 7. Flooded apartments and cars on Byrne Ave on 9-16-09. See Figure 6 for flood prediction map for this area. Photo: Herald-Citizen.

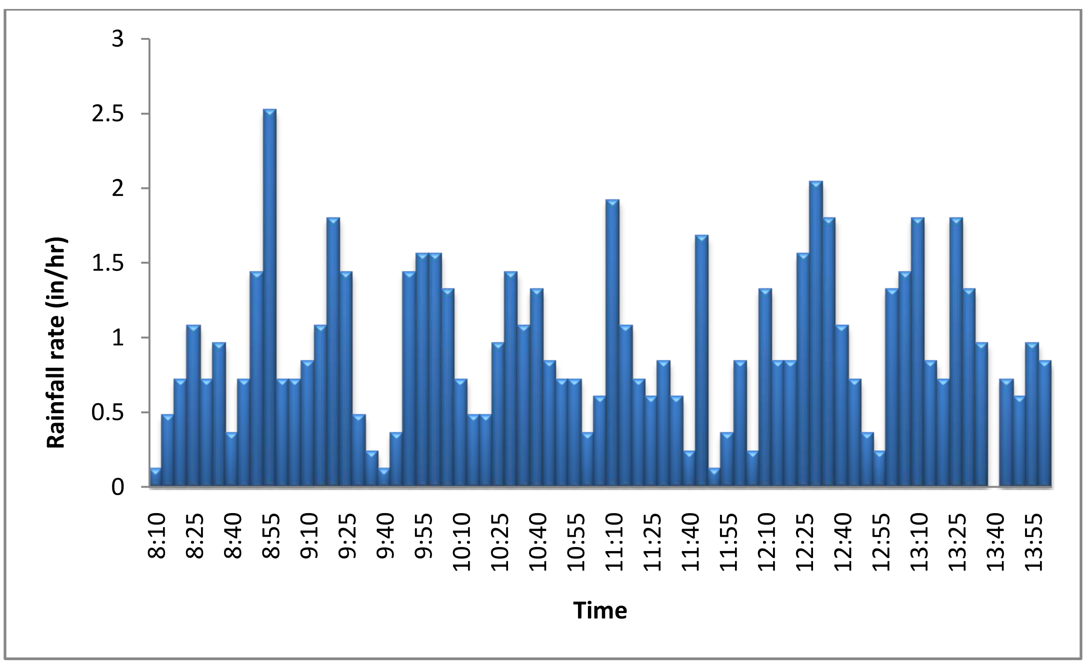


Figure 8. Rainfall hyetograph for the 9-16-09 storm in Cookeville, Kittrell Hall Weather Station. This exceeded the 100-year, 6-hour storm estimated for this area. The most intense 1-hour duration for this storm however had a return interval of <2 yr. Compare with IDF curve on Figure 5.

Figure 9. Hydrogeology students observing flooding along Breedings Mill Branch along Willow Ave. during 9-16-09 storm.

Figure 10. Hydrogeology students making discharge measurement along Short Creek (near intersection of Lowe and Stevens St.) during 9-16-09 storm.

Figure 11. Flooding near the intersection of West 9th St and Hawthorne during 9-16-09 storm.

Table 2. Maximum recorded sinkhole flood heights for two separate sinkholes during the 7-15-09 and 9-16-09 storms. Compare to recorded flood heights in shown in Table 3. Both of these sinkholes have large swallets able to convey water into the cave system below. Because of the relatively high drainage rates for these sinks, the short-duration, intense storms will produce the greatest flood heights. For example, here it is shown that the 7-15-09 storm caused greater flood heights than the 9-16-09 storm. A 100-year, 3-hour or 100-year, 1-hour storm has not been recorded for these sinkholes. (Note: A flood height of 36 feet at the Ensor Sink swallet comes just to the bottom of the bridge on Clover Hill Ave).

	Ensor Sink		Warehouse Sink	
	Recorded flood depth (ft)	Estimated flood elevation (ft)	Recorded flood depth (ft)	Estimated flood elevation (ft)
7-15-09	36	1023	19	1025
9-16-09	35	1022	13	1019

Table 3. Comparison of rainfall rates and totals at different durations for two major storms during the study period. Compare to Table 2.

	<u>1-hour</u> **total (in)** *rate (in/hr)* [return interval--years]	<u>3-hour</u> **total (in)** *rate (in/hr)* [return interval--years]	<u>6-hour</u> **total (in)** *rate (in/hr)* [return interval--years]
7-15-09	**1.92** *1.92* [5]	**2.34** *0.78* [2-5]	**2.35** *0.39* [<2]
9-16-09	**1.2** *1.2* [<2]	**2.92** *0.97* [10]	**5.49** *0.92* [>100]

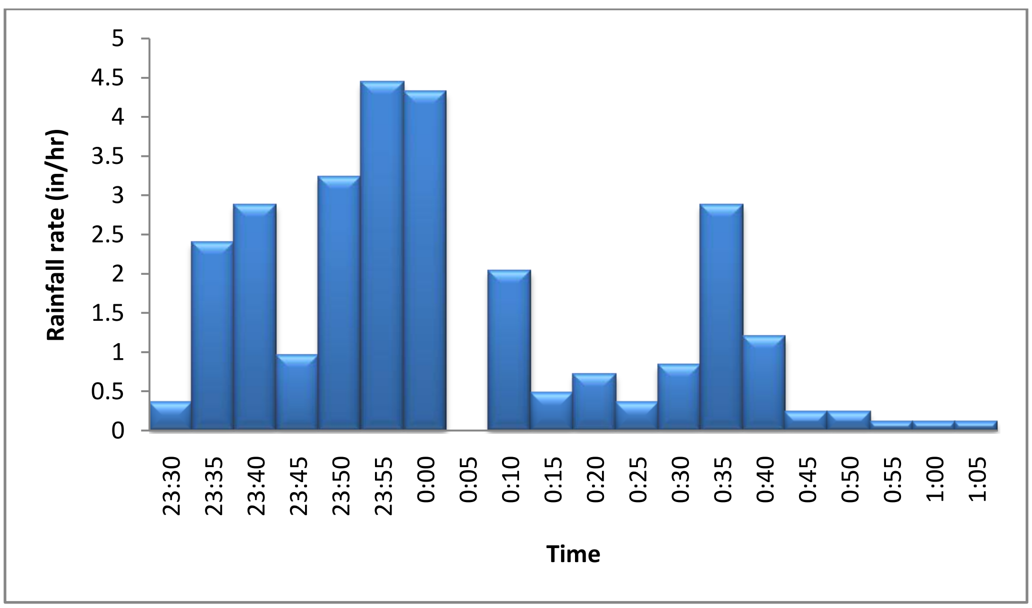


Figure 12. Rainfall hyetograph for the July 15, 2009 storm in Cookeville, Kittrell Hall Weather Station. This is an example of an intense 1-hour storm that has rainfall rates high enough to flood sinkholes with rapid drainage rates like Ensor Sink. For the 1-hour duration, the return interval of this storm was 5 years. Compare with IDF curve in Figure 5. Also compare with Figure 8.

GIS layers provided to the city of Cookeville:

All GIS data provided in this study are spatially referenced in the Tennessee State Plan system NAD 1983 Feet and were processed using ARC GIS Version 9.3. Topographic control was provided by the LIDAR data in possession of the city of Cookeville. All GIS data is stored in a single Geodatabase provided to the city for use in the ArcMap program. The maps are also shown below and are being made available in PDF format. One large-format wall map with sinkhole floodplains is also provided. Other maps can be made using the files in the Geodatabase.

Closed depressions

Closed depressions of several types were recognized from the LIDAR topography data. Farm ponds and culverts crossing under roadways often show up on topographic maps as closed depressions. While these areas may experience flooding during heavy rainfall, they are often designed to mitigate flooding (e.g. culverts, drain pipes, spillways, etc.). Since artificial closed depressions usually have flood mitigation measures in place, they were not considered in the sinkhole floodplain study. However, they are included in the GIS layer of sinkholes. This layer consists of all closed depressions regardless of their origin. All closed contours are included, from the upper to the lower-most. Another layer is provided that shows only those closed contours within the predicted 100-year sinkhole floodplains.

LiDAR Data

LiDAR data used to estimate flood heights in this study. The original LiDAR data provided by the city was in a point coverage and not easily accessible. We contacted the company that produced the LiDAR data for Cookeville, and were able to obtain the LiDAR data in ESRI Grid file format. This format is more easily manipulated and is being provided to the city. We also clipped the LiDAR grid file to the UGB boundary. The LiDAR data have a 15-foot horizontal spacing and 0.5 foot vertical resolution.

Impervious area

Impervious areas include roofs, streets, parking lots, and driveways within the sinkhole drainage areas selected for study. Many additional driveways and parking lots were digitized from the 2007 aerial photographs and added to the city’s existing impervious area layer.

Hydrologic soil groups

Hydrologic soil groups were derived from NRCS County Soil survey data and from TDOT. These soil groups were used in the Curve Number method for predicting runoff volume. Hydrologic soil group types are explained in the text.

Slope map

This is a coverage showing the percent slope of the land within the Urban Growth Boundary. These data were can be used to estimate peak runoff and time of concentration for each sinkhole drainage area. Slope is also needed to do model calibration.

Predicted 100-year floodplains of major sinkholes

This polygon coverage is the final product of the flood study and shows areas likely to be inundated by the 100-year, 3-hour flood. Details on how sinkhole flood heights were predicted are provided in the text. The attribute table for this file contains a field called 'Flood_Elev' that has the contour elevation in feet of the predicted flood surface height. The Hydro-ID field is an identifier showing which sinkhole watershed drains to that sink. Values in the Hydro-ID_2 field indicate that some sinkholes receive drainage from two separate watersheds.

Sinkhole Drainage areas

This layer consists of polygons that are defined by the watershed boundaries for each sinkhole. With this map, one can easily see the areas contributing runoff to each sinkhole in this study. Important parameters such as area, watershed name, and percent impervious area, are included in the attribute table. The field 'Hydro ID' is used to match these polygons with the predicted 100-year floodplains for sinkholes. Overall, 218 sinkhole drainage areas were selected for flood analysis. While most of these drainage areas drained to a single sinkhole, some contained a complex of several sinkholes to which flood waters drain. Sinkhole drainage areas ranged from 2 acres to 1796 acres, with an average area of 68 acres. Total sinkhole drainage area was 14,455 acres, which is approximately 45% of the total area within the Cookeville urban growth boundary.

Structures flooded by the predicted 100-year flood

This map is the same as the sinkhole floodplain map with structures added. 225 structures and 7.8 miles of roads are built within predicted 100-year sinkhole floodplains.

Dye Trace connections

This layer shows the underground connections that are known from dye tracing in Cookeville. From this map, one should be able to trace the path of surface and groundwater in most parts of the city. Not all areas of Cookeville and the UGB have been investigated using dye-tracing, but the major connections are known. However, the accumulated knowledge has never been put together before in a map format like this.

Watershed to which sinkholes drain

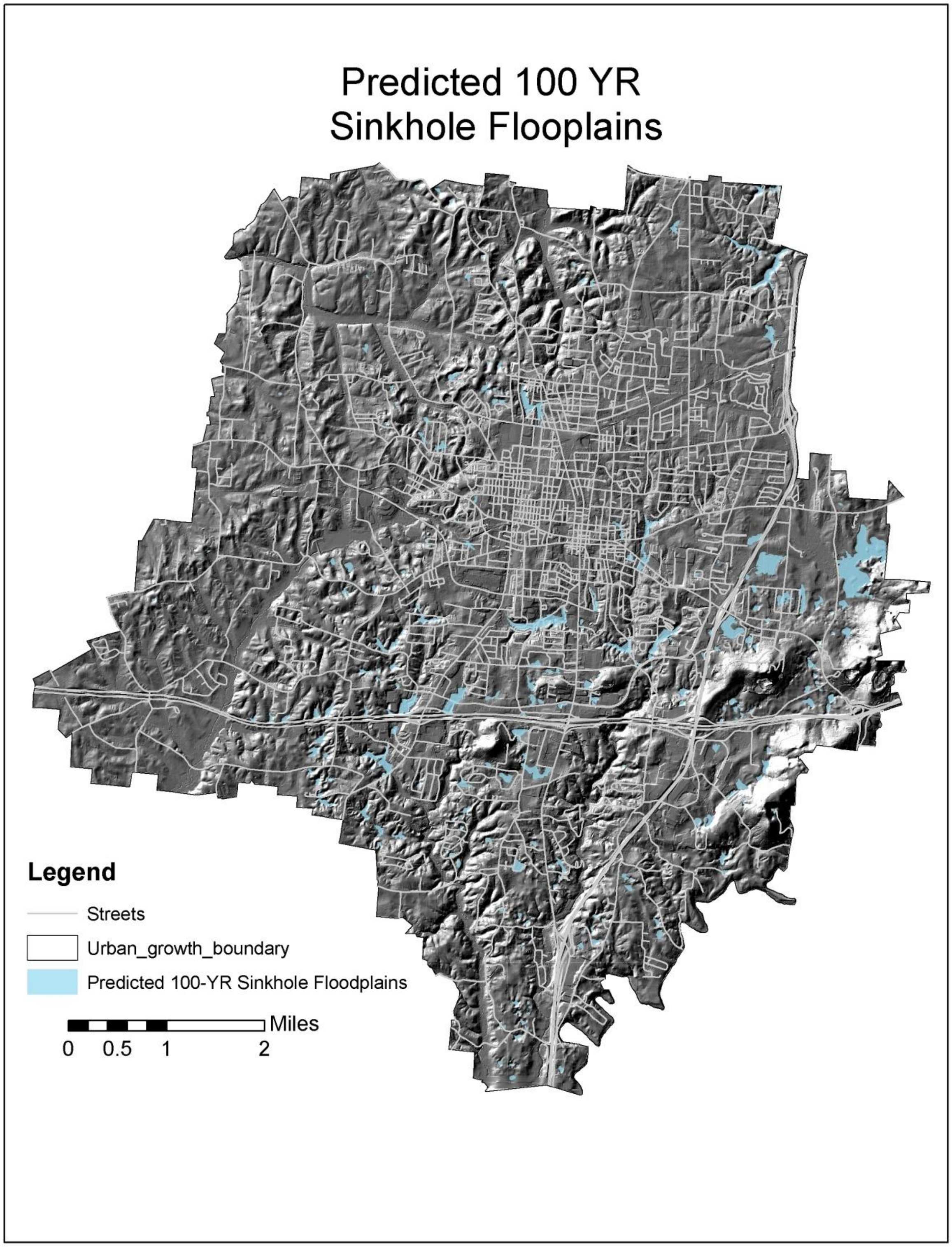
This map indicates the surrounding watershed to which sinkholes drain. Much of this information is known as a result of dye tracing. For some areas, the watershed connection is unknown.

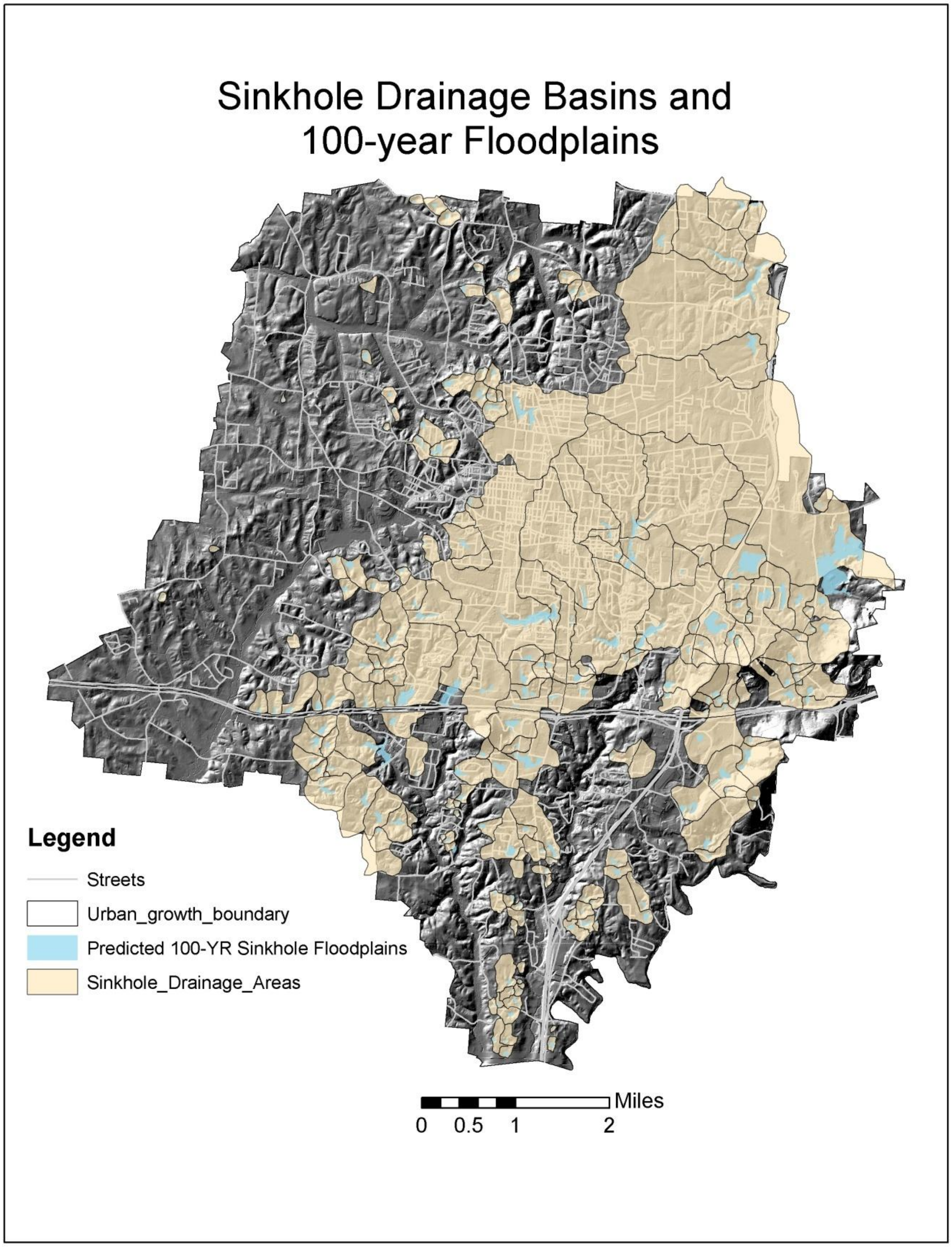
Stream layer

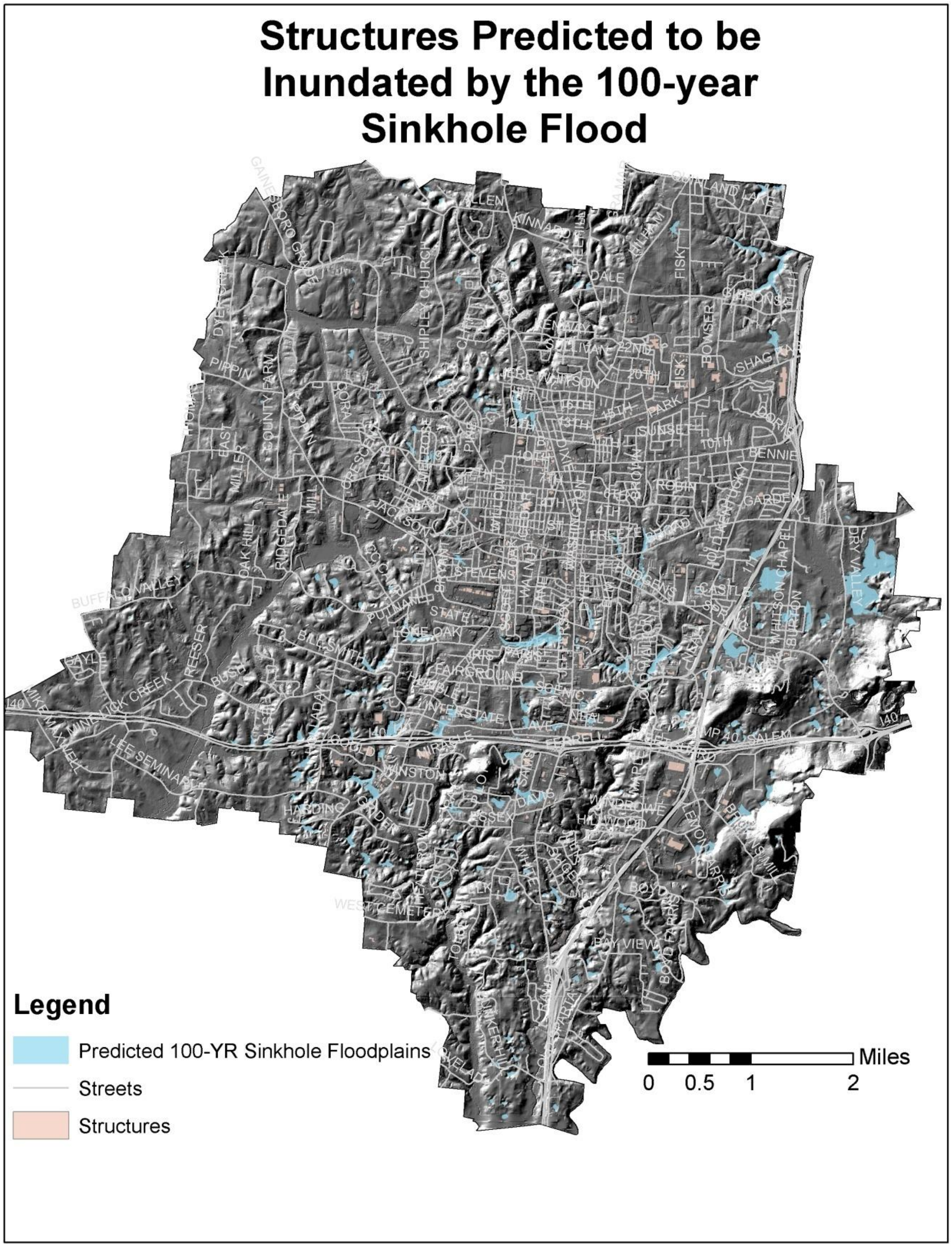
Layer showing flowing water courses, many of which end in sinkholes. The cave system contains underground streams, which are just an extension of the above-ground stream network.

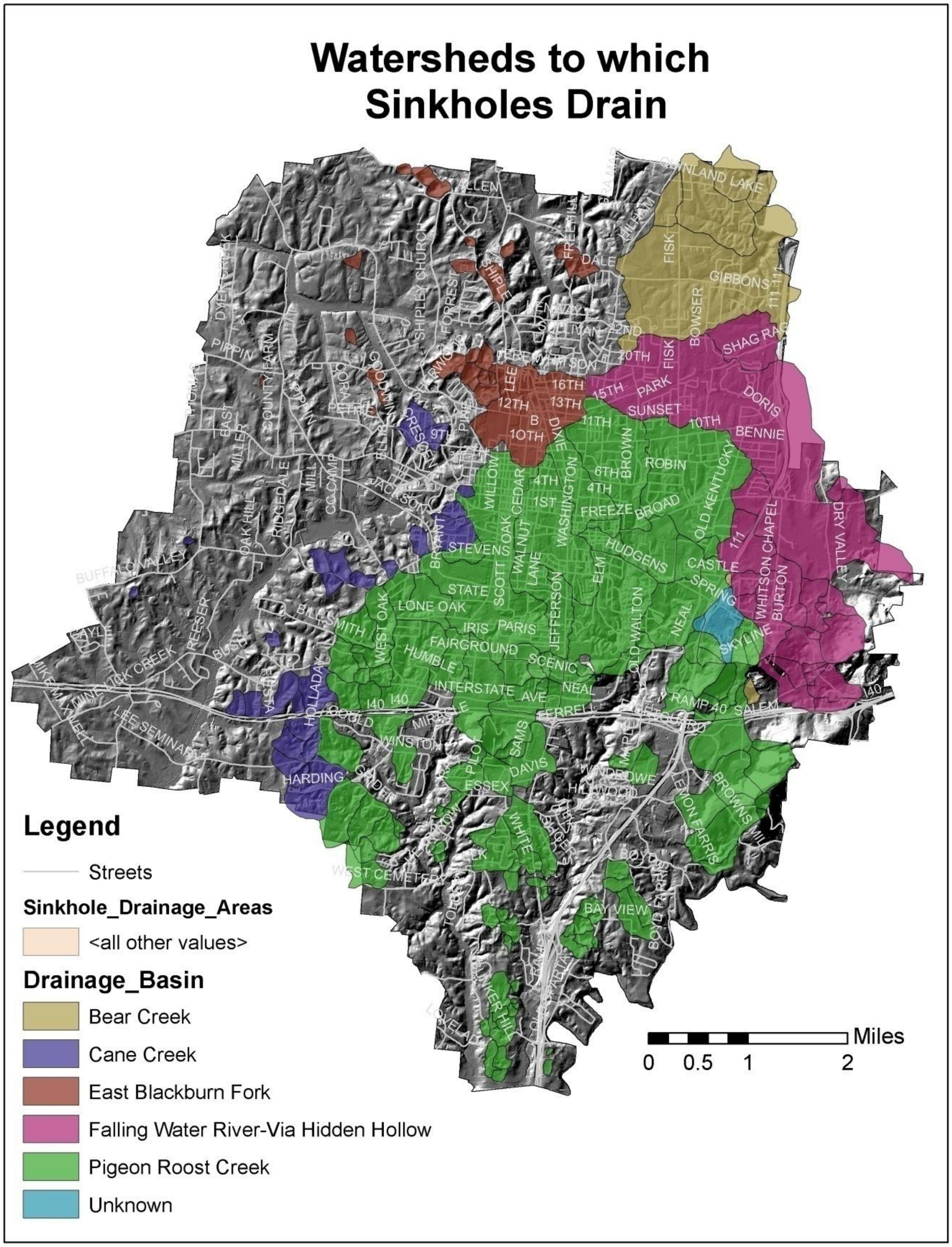
Cave layer

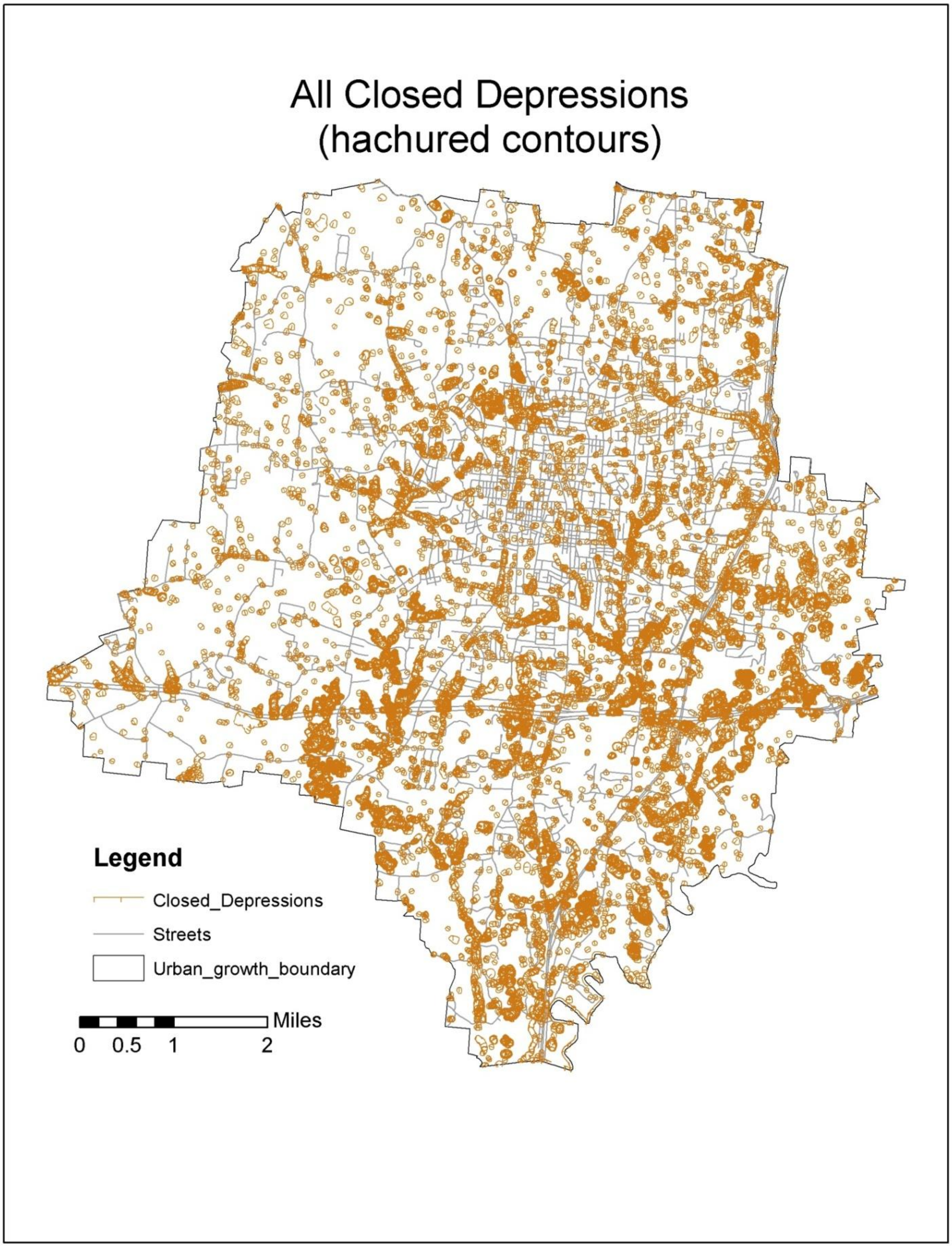
Layer showing cave locations beneath Cookeville. These caves are the stormwater system for the city and their importance in this role cannot be overstated. Changes in flow within these caves, from trash and debris will likely affect flooding in sinkholes that drain to the caves.


Predicted 100 YR
Sinkhole Flooplains
Legend
Streets
Urban_growth_boundary
Predicted 100-YR Sinkhole Floodplains
Miles
0
0.5
1
2

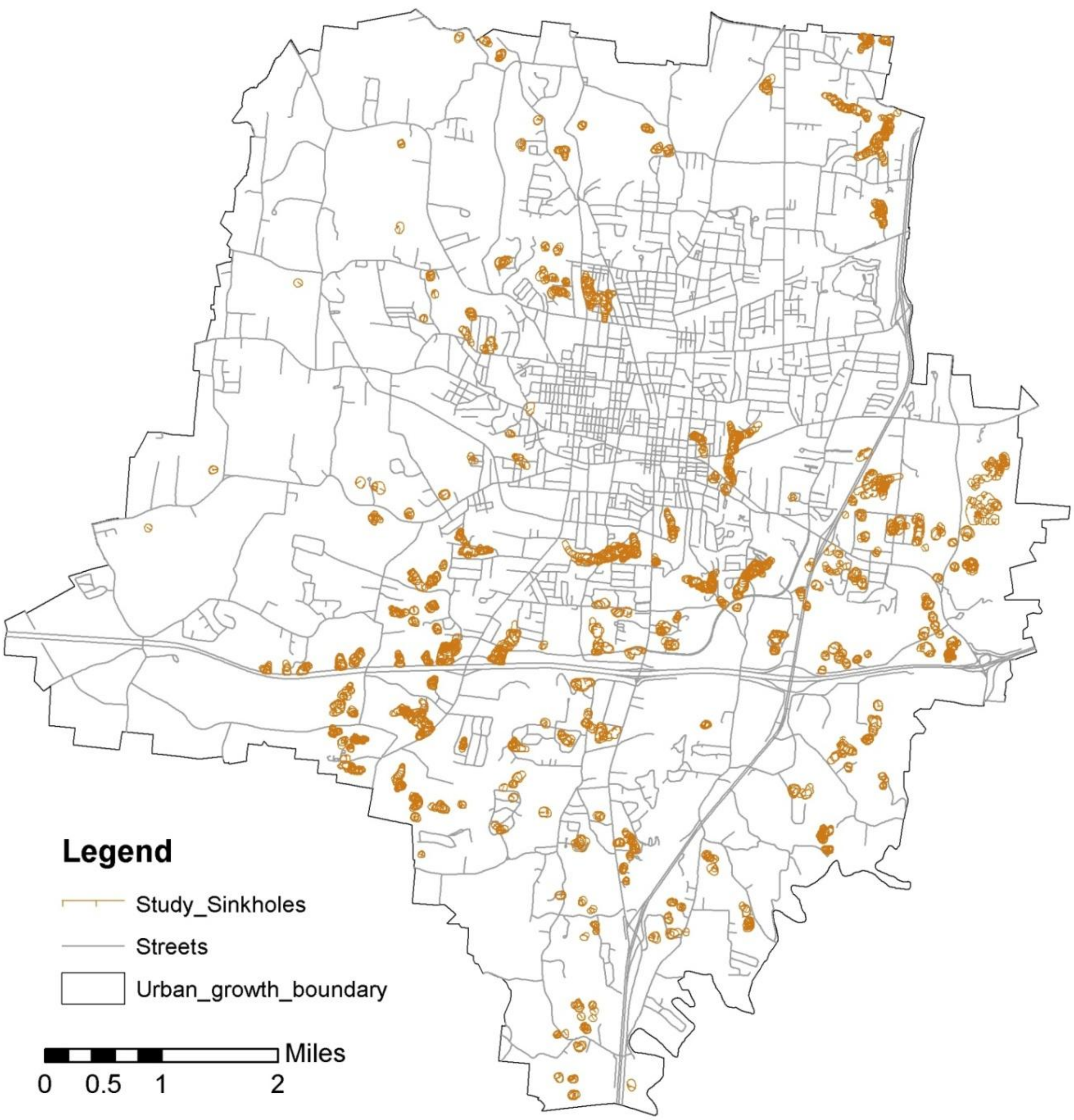

Sinkhole Drainage Basins and
100-year Floodplains
Legend
Streets
Urban_growth_boundary
Predicted 100-YR Sinkhole Floodplains
Sinkhole_Drainage_Areas
Miles
0 0.5 1 2

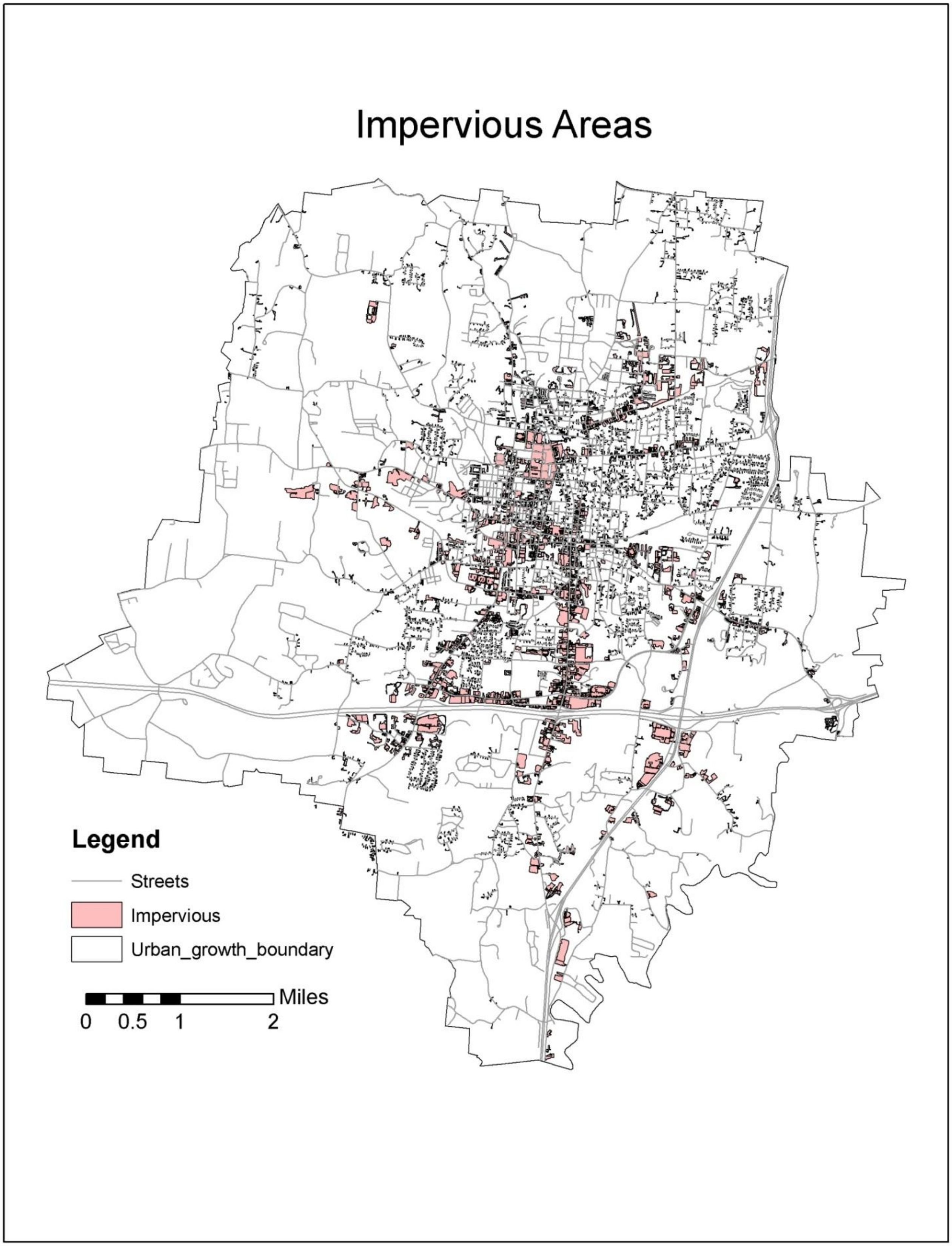

Structures Predicted to be Inundated by the 100-year Sinkhole Flood
Legend
Predicted 100-YR Sinkhole Floodplains
Streets
Structures
Miles
0 0.5 1 2

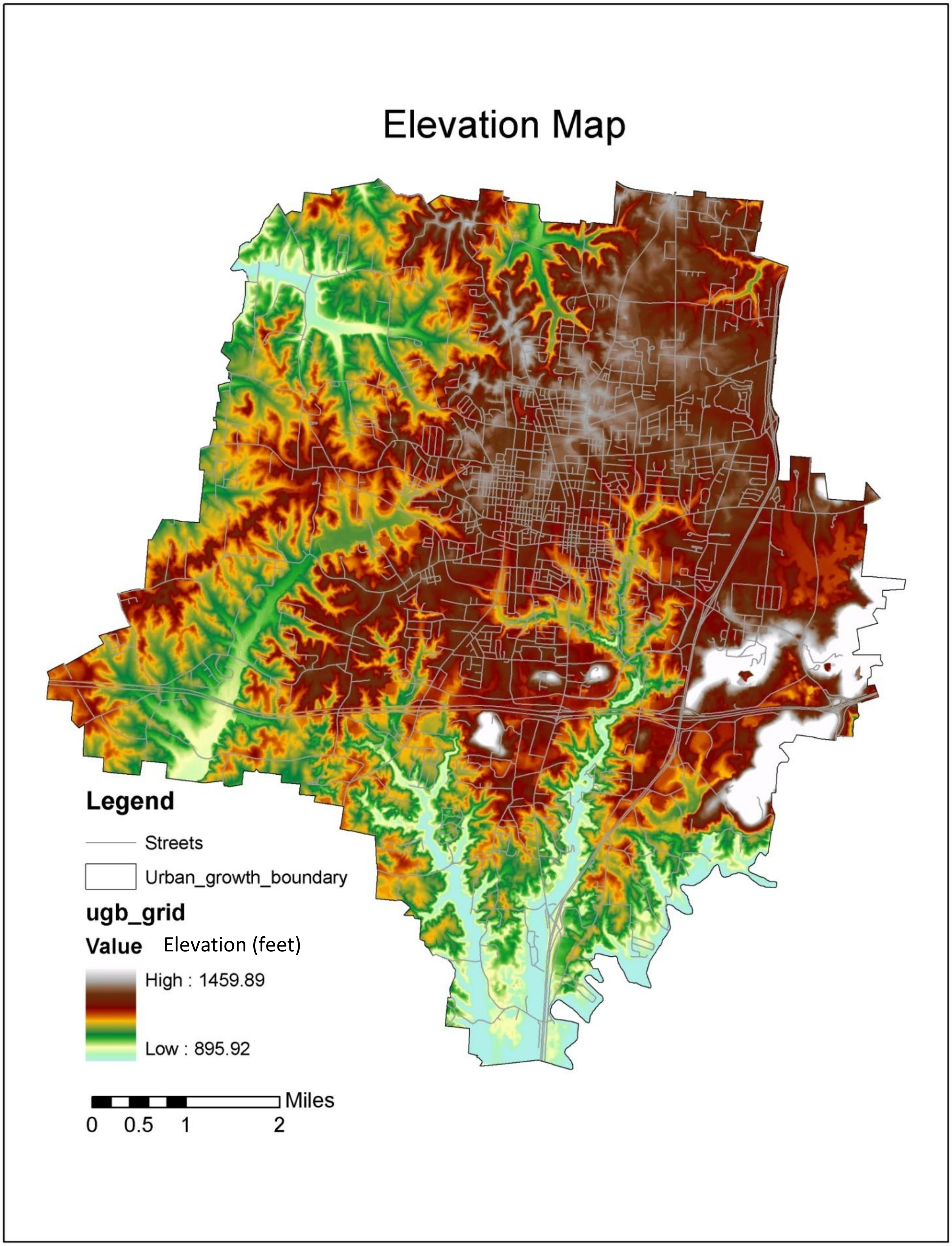

Watersheds to which
Sinkholes Drain
Legend
Streets
Sinkhole_Drainage_Areas
<all other values>
Drainage_Basin
Bear Creek
Cane Creek
East Blackburn Fork
Falling Water River-Via Hidden Hollow
Pigeon Roost Creek
Unknown
Miles
0 0.5 1 2

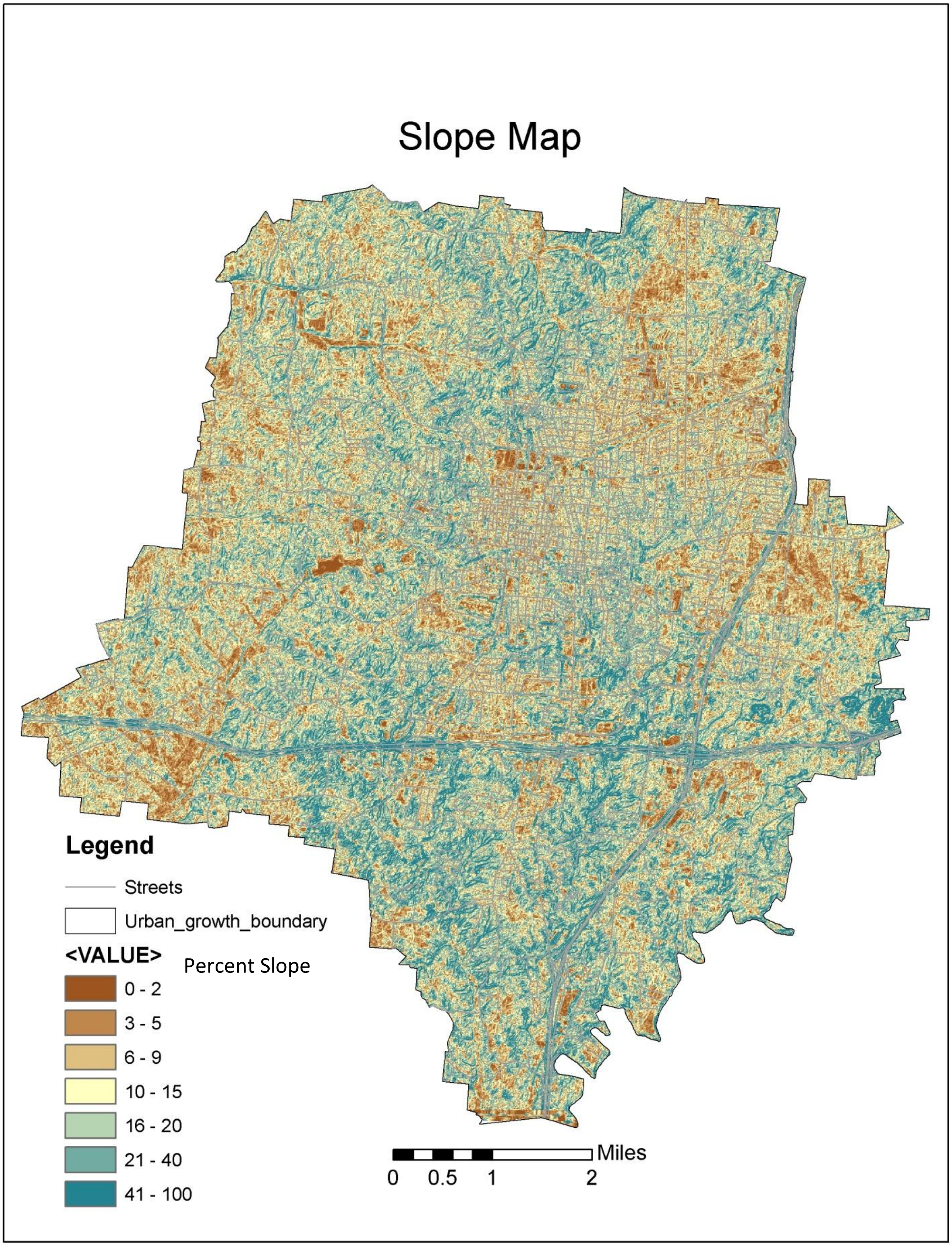

All Closed Depressions
(hachured contours)
Legend
Closed_Depressions
Streets
Urban_growth_boundary
Miles
0
0.5
1
2

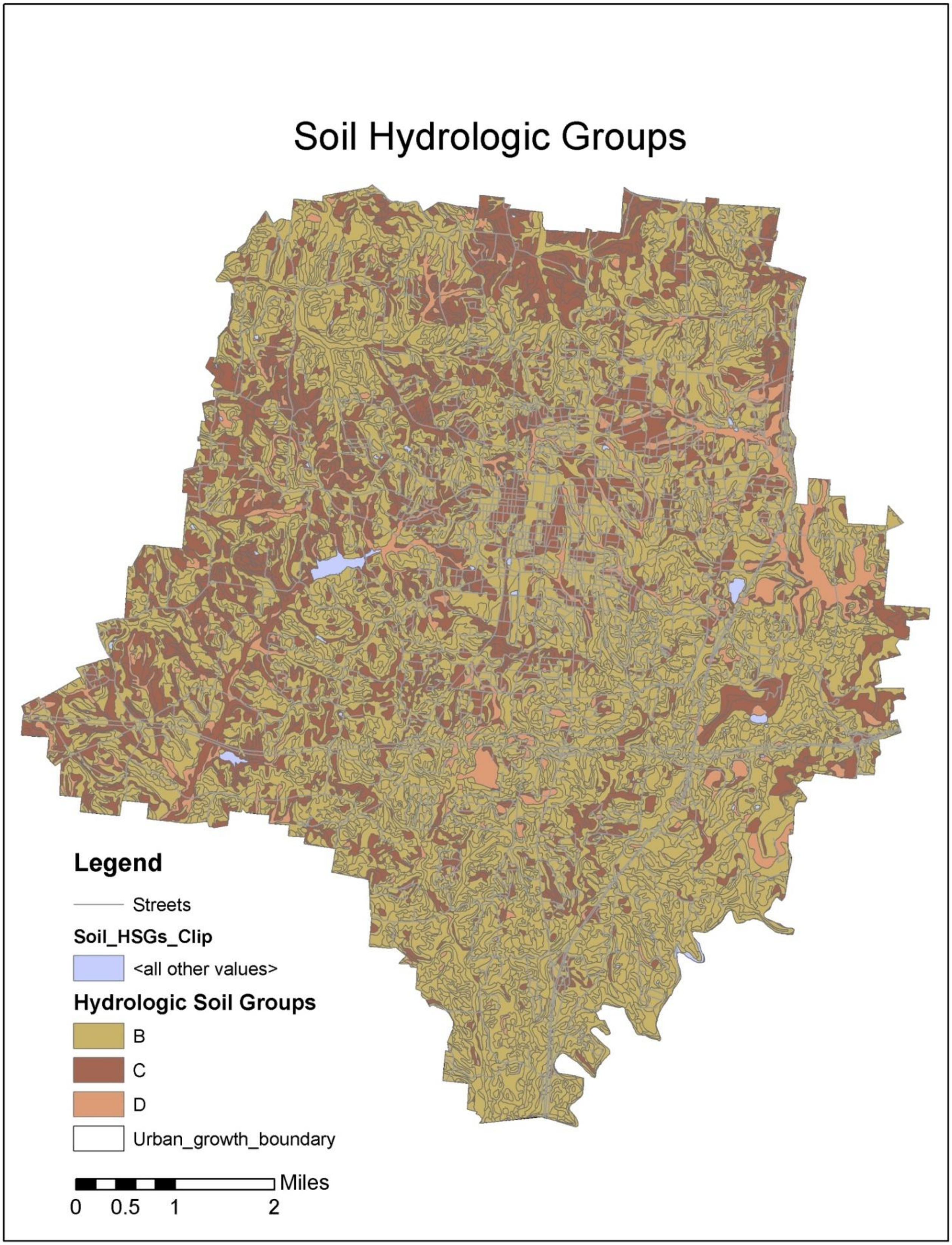
Closed Depressions within Sinkhole Floodplains (hachured contours)

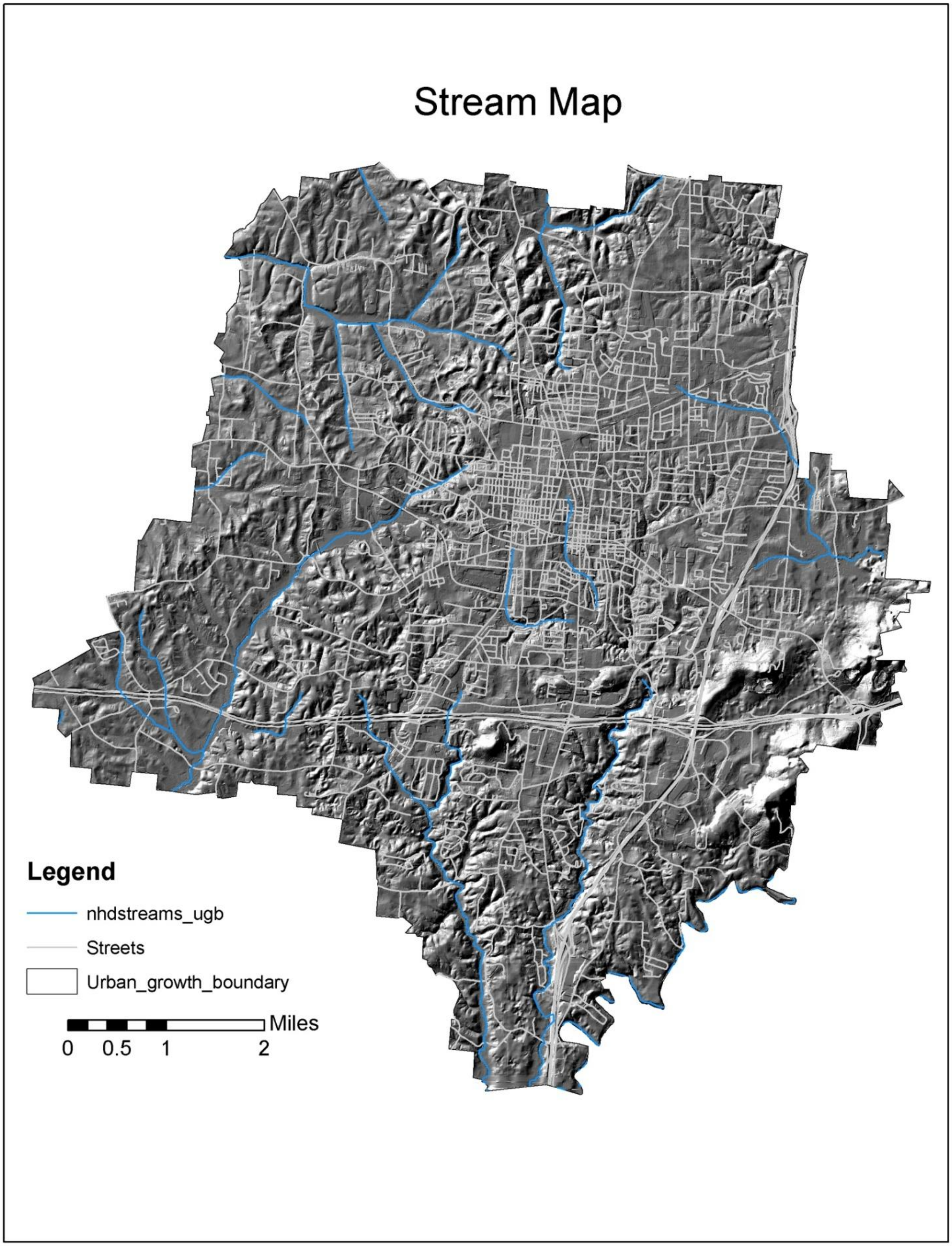


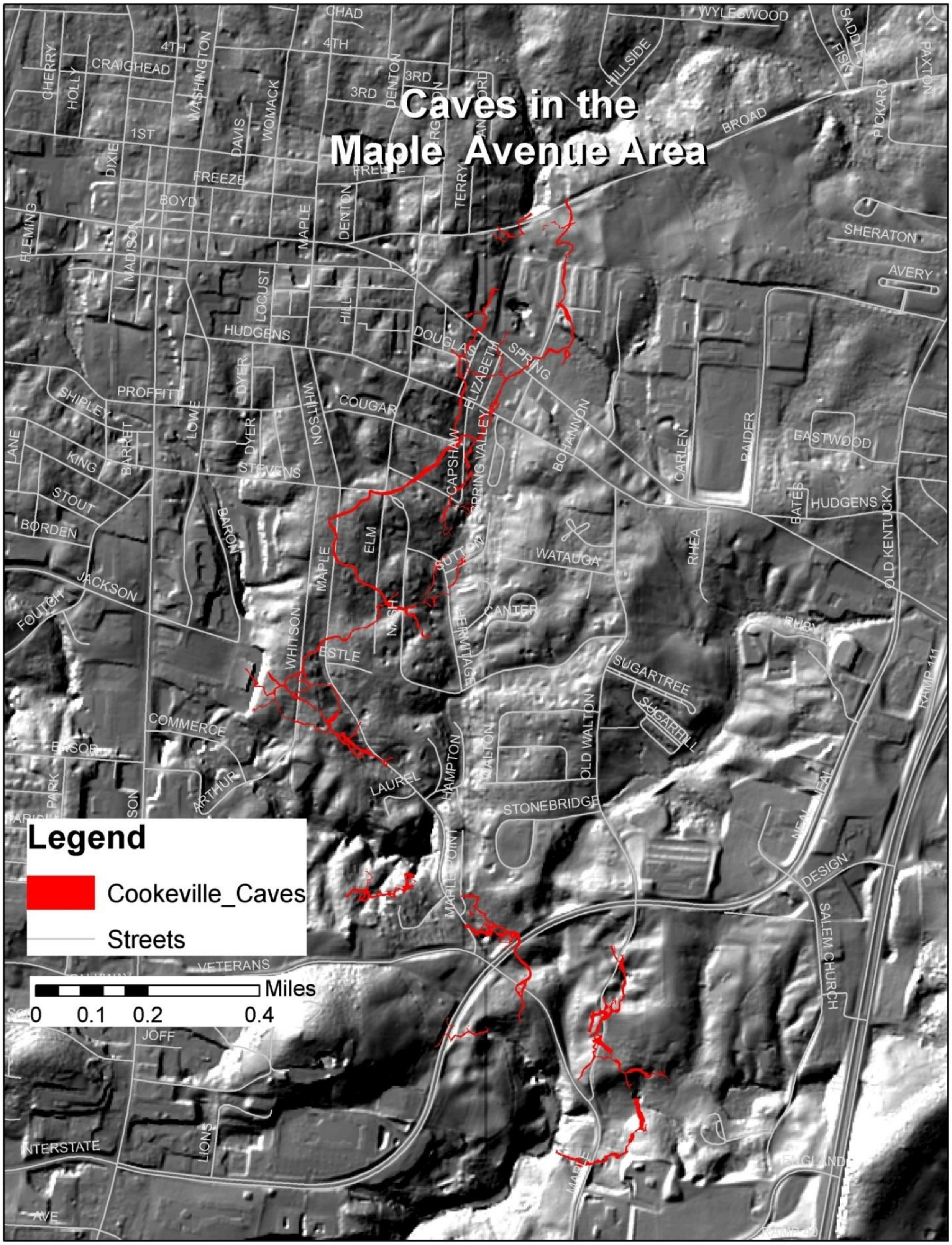

Impervious Areas
Legend
Streets
Impervious
Urban_growth_boundary
Miles
0 0.5 1 2


Elevation Map
Legend
Streets
Urban_growth_boundary
ugb_grid
Value Elevation (feet)
High : 1459.89
Low : 895.92
Miles
0 0.5 1 2


Slope Map
Legend
Streets
Urban_growth_boundary
<VALUE>
Percent Slope
0 - 2
3 - 5
6 - 9
10 - 15
16 - 20
21 - 40
41 - 100
Miles
0
0.5
1
2


Soil Hydrologic Groups
Legend
Streets
Soil_HSGs_Clip
<all other values>
Hydrologic Soil Groups
B
C
D
Urban_growth_boundary
Miles
0
0.5
1
2


Stream Map
Legend
nhdstreams_ugb
Streets
Urban_growth_boundary
Miles
0
0.5
1
2


Caves in the
Maple Avenue Area
Legend
Cookeville_Caves
Streets
Miles
0 0.1 0.2 0.4

Acknowledgements

Special thanks to Department of Earth Science student-workers Derrick Ho and Martin Kimbrell, for the many long hours spent processing and analyzing GIS data and producing maps. Also, we would like to thank Dr. Sid Jones for continuing advice on the project and on sinkhole flooding in general. We thank James Mills and Greg Brown for advice and knowledge on local sinkhole conditions, and for their patience in waiting for this report.

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APPENDIX 1. Sinkhole floodplain polygon HYDRO-IDS, predicted flood elevations, and areas. HYDRO-IDS match sinkhole drainage area HYDRO-IDS in Appendix 2 and 3. If some sinkhole floodplain polygons were associated with more than one HYDRO-ID, then HYDRO-ID-2 or HYDRO-ID-3 were added. For example, sinkhole floodplain polygon HYDRO-ID 28 receives drainage from both sinkhole drainage area HYDRO-ID 28 and HYDRO-ID 29, so '29' is listed in column HYDRO-ID-2. Multiple sinkhole floodplain polygons within the same sinkhole drainage area are given the same HYDRO-ID. For example, there are three polygons labeled HYDRO-ID 170, since they are all located within sinkhole drainage area HYDRO-ID 170.

Hydro_ID	Flood_elevation (feet)	HYDRO_ID_2	HYDRO_ID_3	Area (acres)
1	1062	0	0	3.4
2	1068	0	0	1.8
3	1050	0	0	3.2
4	1044	0	0	3.6
5	1018	0	0	1.1
6	1022	0	0	12.8
6	1030	0	0	5.6
7	1082	0	0	0.6
8	1072	0	0	1.6
9	1084	0	0	3.3
10	1102	0	0	3.0
11	1116	0	0	0.7
12	1112	0	0	2.7
13	1130	0	0	1.2
14	1062	0	0	4.8
15	1062	0	0	1.6
16	1082	0	0	0.9
17	1066	0	0	16.2
18	1082	0	0	2.7
19	1062	0	0	0.5
20	1060	0	0	1.9
21	1076	0	0	0.9
22	1086	0	0	1.4
23	1120	0	0	0.3
24	1092	0	0	15.9
25	1044	0	0	29.8
27	1028	0	0	0.4
27	1028	0	0	0.7
28	1092	29	0	2.6
30	1096	0	0	0.1
31	1086	0	0	3.1
32	1084	0	0	0.9
33	1080	0	0	2.0

Hydro_ID	Flood_elevation (feet)	HYDRO_ID_2	HYDRO_ID_3	Area (acres)
34	1074	0	0	6.0
35	1074	0	0	12.7
36	1100	0	0	1.3
37	1066	0	0	2.0
38	1060	0	0	1.4
39	1044	40	0	8.0
41	1042	0	0	6.1
42	1048	0	0	1.8
43	1038	0	0	2.1
44	1040	0	0	4.3
45	1000	0	0	6.5
45	1002	0	0	0.5
45	1018	0	0	0.2
45	1030	0	0	0.1
45	1018	0	0	0.5
46	1090	0	0	0.5
47	1014	0	0	0.9
48	1074	0	0	0.3
48	1074	0	0	2.6
49	1074	0	0	0.6
50	1032	143	144	14.9
51	1100	0	0	7.7
52	1102	53	0	0.0
53	1096	0	0	2.2
54	1104	0	0	1.6
55	1122	0	0	0.8
56	1094	0	0	2.7
57	1098	0	0	1.2
58	1098	0	0	1.2
59	1096	0	0	1.0
60	1098	0	0	0.3
61	1026	0	0	3.2
62	1102	0	0	2.0
63	1108	0	0	0.6
64	1092	0	0	1.7
65	1102	0	0	0.6
66	1096	0	0	0.2
67	1096	0	0	0.4
68	1088	0	0	1.1
69	1090	0	0	1.1
70	1050	0	0	17.3

Hydro_ID	Flood_elevation (feet)	HYDRO_ID_2	HYDRO_ID_3	Area (acres)
71	1092	0	0	7.6
72	1080	0	0	8.1
73	1070	0	0	3.4
74	1072	0	0	3.4
75	1080	0	0	0.4
76	1132	0	0	0.5
77	1108	0	0	4.1
78	1128	0	0	0.6
79	1070	0	0	0.7
80	1072	0	0	0.8
81	1072	0	0	1.7
82	1072	0	0	0.3
83	1062	0	0	3.5
84	1066	0	0	1.7
85	990	0	0	0.4
86	962	0	0	0.2
87	990	0	0	0.7
88	1018	0	0	0.6
89	990	0	0	0.7
90	1000	0	0	0.8
91	1024	0	0	5.5
92	1040	0	0	1.3
93	1022	0	0	1.6
94	1028	0	0	0.0
95	984	0	0	3.8
96	1000	0	0	0.8
97	1020	0	0	0.2
98	1020	0	0	0.4
99	1020	0	0	0.4
100	1036	0	0	0.3
101	1032	0	0	1.8
102	992	0	0	0.3
103	988	0	0	1.5
104	996	0	0	1.0
105	998	0	0	0.3
106	986	0	0	0.7
107	976	0	0	0.7
108	996	0	0	1.5
109	1040	0	0	2.1
110	1036	0	0	2.1
111	982	0	0	2.6

Hydro_ID	Flood_elevation (feet)	HYDRO_ID_2	HYDRO_ID_3	Area (acres)
112	970	0	0	0.1
113	966	0	0	1.3
114	992	0	0	1.6
115	1008	0	0	0.3
116	1018	0	0	0.2
117	1008	0	0	2.2
118	952	0	0	0.9
119	948	0	0	0.6
120	946	0	0	0.2
121	950	0	0	1.5
122	952	0	0	1.3
123	956	0	0	0.4
124	970	0	0	0.2
125	962	0	0	0.4
126	990	0	0	0.5
127	972	0	0	0.5
128	982	0	0	0.6
129	972	0	0	0.3
130	960	0	0	0.1
131	958	0	0	1.5
132	938	0	0	1.4
133	954	0	0	1.2
134	1150	0	0	0.5
135	1276	0	0	0.5
136	1030	0	0	6.6
136	1034	0	0	3.4
136	1034	0	0	8.6
137	1058	0	0	6.7
138	952	0	0	3.5
139	1058	0	0	2.5
140	1068	0	0	2.6
141	1088	0	0	5.5
142	1050	0	0	1.2
145	1004	0	0	0.6
147	1014	0	0	0.5
148	1090	0	0	1.3
149	1078	0	0	1.0
150	1092	0	0	2.9
151	1082	0	0	3.7
152	1080	0	0	1.2
152	1080	0	0	3.3

Hydro_ID	Flood_elevation (feet)	HYDRO_ID_2	HYDRO_ID_3	Area (acres)
153	1098	0	0	0.1
153	1098	0	0	0.4
154	1098	0	0	5.6
155	1130	0	0	0.6
156	1096	0	0	29.1
157	1080	0	0	104.5
158	1080	0	0	3.2
159	1058	0	0	1.5
160	1070	0	0	2.9
161	1118	0	0	3.7
162	1066	0	0	5.9
162	1066	0	0	1.3
163	1092	0	0	1.3
164	1048	0	0	1.2
165	1074	0	0	1.1
166	1092	0	0	0.7
167	1030	0	0	0.4
168	1052	0	0	0.6
169	1054	0	0	0.9
170	1082	0	0	0.3
170	1082	0	0	0.1
170	1082	0	0	1.8
171	1088	0	0	4.1
172	1066	0	0	1.6
173	1090	0	0	0.4
174	1040	0	0	1.9
175	1072	0	0	0.4
176	1042	0	0	0.5
177	1096	0	0	0.2
178	1084	0	0	2.8
179	1082	0	0	0.3
180	1080	0	0	0.5
181	1074	0	0	1.1
182	1052	0	0	1.6
183	1070	0	0	0.3
184	1042	0	0	3.9
185	1042	0	0	0.9
186	1010	0	0	2.5
187	1056	0	0	0.7
188	1078	0	0	0.8
189	1024	0	0	1.7

Hydro_ID	Flood_elevation (feet)	HYDRO_ID_2	HYDRO_ID_3	Area (acres)
190	1058	0	0	2.2
191	1054	0	0	1.6
192	1056	0	0	2.6
193	1050	0	0	2.2
194	1032	0	0	1.3
195	1034	0	0	1.4
196	1016	0	0	3.9
197	998	0	0	16.0
198	1018	0	0	3.3
199	1018	0	0	1.2
200	1014	0	0	1.4
201	1008	0	0	1.3
202	992	0	0	0.7
203	1008	0	0	4.3
204	1024	0	0	0.2
205	1022	0	0	1.2
206	992	0	0	4.2
207	984	0	0	0.2
208	974	0	0	3.0
209	1020	0	0	0.1
210	1002	0	0	0.9
211	976	0	0	3.4
213	1094	0	0	0.4
214	1270	0	0	0.2
215	1094	0	0	19.0
216	1040	0	0	3.9
217	1068	0	0	5.0
218	1098	0	0	0.9

APPENDIX 2. Sinkhole Drainage Area data. Terms W_{eff} and CN are explained in the text. Sinkhole drainage area HYDRO-IDs match sinkhole floodplain polygon HYDRO-IDs in Appendix 1. There are a total of 217 sinkhole drainage areas listed, HYDRO-ID 26 was combined with HYDRO-ID 25 and so is not used.

Hydro_ID	Predicted Flood Volume (ft^3)	Drainage area (acres)	% Impervious area	Effective rainfall (W_{eff}) (in)	Composite Curve Number (CN)
1	302624	35.9	4.3	2.32	78
2	162003	19.9	4.2	2.25	77
3	722517	80.6	7.5	2.47	80
4	724362	76.4	3.6	2.61	82
5	332357	35.9	21.0	2.55	81
6	2737289	255.4	31.9	2.95	85
7	58823	5.7	16.8	2.85	84
8	191274	18.2	15.2	2.90	85
9	397272	39.0	15.2	2.81	84
10	202609	24.8	1.6	2.25	77
11	72519	9.1	3.7	2.20	77
12	286306	29.5	23.1	2.68	82
13	118623	10.4	43.1	3.13	87
14	1092634	114.7	16.9	2.62	82
15	492222	51.4	17.9	2.64	82
16	105853	12.7	9.6	2.30	78
17	1129951	99.6	37.3	3.13	87
18	2305444	202.3	29.2	3.14	87
19	101828	10.9	0.0	2.56	81
20	374619	42.2	10.6	2.45	80
21	196568	18.2	2.0	2.98	86
22	179161	21.7	0.8	2.27	78
23	42944	5.0	12.6	2.36	79
24	5692204	481.9	45.9	3.25	89
25	10651906	930	42.4	3.1	86.8
27	1240245	92.1	74.0	3.71	93
28	174177	18.1	22.9	2.65	82
29	137061	14.5	23.9	2.61	82

Hydro_ID	Predicted Flood Volume (ft^3)	Drainage area (acres)	% Impervious area	Effective rainfall (W_{eff}) (in)	Composite Curve Number (CN)
30	288660	22.3	64.9	3.56	92
31	274868	22.0	62.5	3.44	90
32	717109	60.1	54.2	3.28	89
33	412839	30.4	74.8	3.74	93
34	1076564	111.7	15.6	2.65	82
35	1198821	105.9	39.4	3.12	87
36	202954	23.3	14.0	2.40	79
37	2355720	201.3	46.0	3.22	88
38	278728	25.4	39.1	3.03	86
39	4487589	418.0	30.3	2.96	86
40	6306905	634.7	22.8	2.74	83
41	1698743	158.4	32.3	2.95	85
42	572561	48.4	50.7	3.26	89
43	181579	16.9	32.4	2.96	86
44	5059029	406.2	57.6	3.43	90
45	4127113	411.1	29.1	2.77	83
46	165307	12.1	65.0	3.76	94
47	200825	23.1	14.3	2.39	79
48	757976	58.8	68.8	3.55	91
49	653358	66.9	22.0	2.69	83
50	2764392	273.6	29.7	2.78	84
51	1953516	187.1	15.0	2.88	85
52	46773	4.0	55.6	3.23	88
53	336693	39.4	12.3	2.35	79
54	251307	28.7	15.7	2.42	79
55	49386	5.2	27.5	2.64	82
56	529117	52.7	22.7	2.77	83
57	223160	22.6	12.2	2.72	83
58	203912	23.2	9.1	2.42	80
59	267108	24.2	47.3	3.04	86
60	160756	18.5	4.8	2.39	79
61	877182	93.4	15.0	2.59	81
62	366020	40.1	0.0	2.51	81
63	100001	11.5	0.5	2.40	79
64	281891	32.1	0.0	2.42	79

Hydro_ID	Predicted Flood Volume (ft^3)	Drainage area (acres)	% Impervious area	Effective rainfall (W_{eff}) (in)	Composite Curve Number (CN)
65	104631	14.5	1.4	1.98	74
66	94113	12.2	0.0	2.13	76
67	119622	11.8	32.6	2.79	84
68	187258	20.3	22.2	2.54	81
69	111243	13.2	0.0	2.33	78
70	9562825	1039.1	11.9	2.54	81
71	1172668	120.9	23.0	2.67	82
72	893477	99.4	5.9	2.48	80
73	477012	58.6	1.2	2.24	77
74	315499	39.0	5.6	2.23	77
75	56836	7.1	4.1	2.20	77
76	59330	7.2	7.4	2.26	78
77	954204	114.2	0.9	2.30	78
78	105829	11.7	14.7	2.50	80
79	84226	9.9	5.5	2.35	79
80	105005	11.2	20.1	2.59	81
81	291465	35.7	2.6	2.25	77
82	16838	2.1	6.4	2.24	77
83	561309	66.4	3.9	2.33	78
84	296508	29.3	28.0	2.79	84
85	50496	5.1	18.1	2.75	83
86	53857	5.9	20.6	2.52	81
87	124234	10.5	43.9	3.27	89
88	173522	20.0	13.1	2.39	79
89	45843	5.7	3.9	2.20	77
90	68223	8.7	1.8	2.16	76
91	841592	88.4	21.1	2.62	82
92	143296	16.0	18.9	2.47	80
93	184623	21.2	6.4	2.40	79
94	57994	7.1	7.0	2.26	78
95	1088124	109.2	20.3	2.74	83
96	305679	28.8	36.3	2.92	85
97	125925	16.1	0.1	2.16	76
98	28256	2.6	17.4	2.95	85
99	48878	5.8	5.6	2.31	78

Hydro_ID	Predicted Flood Volume (ft^3)	Drainage area (acres)	% Impervious area	Effective rainfall (W_{eff}) (in)	Composite Curve Number (CN)
100	28782	3.0	2.4	2.68	83
101	128385	15.4	1.4	2.30	78
102	18056	2.1	13.8	2.38	79
103	47770	5.6	11.8	2.34	79
104	79189	8.2	25.4	2.65	82
105	80990	8.8	17.4	2.53	81
106	199501	23.9	6.2	2.30	78
107	148070	18.5	4.2	2.21	77
108	237482	29.9	8.6	2.19	77
109	231289	25.8	8.2	2.47	80
110	166051	21.0	2.1	2.17	77
111	498900	59.6	5.1	2.31	78
112	17768	2.2	6.1	2.24	77
113	63478	7.8	7.0	2.26	78
114	225435	22.5	21.6	2.77	83
115	63554	6.7	25.6	2.60	82
116	32415	4.1	3.4	2.19	77
117	128574	14.8	14.6	2.39	79
118	175034	22.3	2.1	2.17	76
119	139248	18.0	0.0	2.13	76
120	72817	8.7	9.3	2.30	78
121	182606	21.8	9.7	2.30	78
122	113876	14.5	1.7	2.16	76
123	79580	10.3	0.0	2.13	76
124	15918	2.0	1.2	2.15	76
125	46661	6.0	0.0	2.13	76
126	48973	6.3	0.0	2.13	76
127	125575	15.5	6.0	2.24	77
128	42553	5.4	2.8	2.18	77
129	13603	1.8	0.0	2.13	76
130	43097	5.6	0.0	2.13	76
131	370832	45.3	0.5	2.25	78
132	76279	9.9	0.0	2.13	76
133	210947	26.6	3.1	2.18	77
134	144545	15.0	3.8	2.65	82

Hydro_ID	Predicted Flood Volume (ft^3)	Drainage area (acres)	% Impervious area	Effective rainfall (W_{eff}) (in)	Composite Curve Number (CN)
135	98021	12.5	1.2	2.17	76
136	793674	170.9	15.0	2.45	80
137	892129	105.0	7.2	2.34	79
138	1381903	155.7	4.7	2.45	80
139	647092	75.3	9.3	2.37	79
140	1322738	135.2	13.5	2.69	83
141	838833	102.0	0.1	2.26	78
142	376006	37.9	23.3	2.73	83
143	128935	14.6	12.0	2.43	80
144	48171	5.9	7.0	2.25	78
145	139483	15.1	22.5	2.54	81
146	501620	49.9	25.4	2.77	84
147	245873	26.6	6.0	2.55	81
148	165354	16.2	9.7	2.82	84
149	201001	25.2	3.9	2.20	77
150	331682	30.5	36.5	3.00	86
151	374390	42.7	8.0	2.41	79
152	279026	31.3	16.7	2.46	80
153	253894	21.6	26.9	3.24	88
154	341285	38.1	5.8	2.47	80
155	171811	19.8	2.8	2.38	79
156	1594239	199.5	18.0	2.20	77
157	18845341	1796.4	19.6	2.89	85
158	688417	77.2	10.4	2.46	80
159	481564	47.6	7.0	2.79	84
160	932542	105.1	9.3	2.44	80
161	637398	64.7	13.7	2.71	83
162	2605013	292.6	7.0	2.45	80
163	145353	13.5	2.6	2.96	86
164	184676	20.8	4.3	2.45	80
165	174890	20.4	4.4	2.36	79
166	77629	9.8	0.0	2.19	77
167	114233	12.9	9.8	2.44	80
168	70916	8.5	9.3	2.30	78
169	119501	13.7	15.1	2.41	79

Hydro_ID	Predicted Flood Volume (ft^3)	Drainage area (acres)	% Impervious area	Effective rainfall (W_{eff}) (in)	Composite Curve Number (CN)
170	299422	28.8	29.8	2.87	85
171	283847	28.2	24.1	2.78	84
172	341517	34.4	25.7	2.74	83
173	28290	3.5	5.6	2.23	77
174	67710	8.8	0.0	2.13	76
175	48855	6.2	0.9	2.18	77
176	19902	2.5	0.0	2.18	77
177	463603	39.7	43.5	3.22	88
178	817999	75.0	26.1	3.01	86
179	209788	20.2	29.4	2.86	84
180	272636	27.1	20.0	2.77	83
181	177839	21.7	7.0	2.26	78
182	192691	22.6	6.4	2.35	79
183	36783	4.1	0.1	2.47	80
184	671020	74.7	6.6	2.47	80
185	262844	27.5	11.6	2.63	82
186	585184	54.0	39.9	2.98	86
187	82827	9.5	1.7	2.39	79
188	123630	13.8	0.9	2.46	80
189	385927	40.3	6.6	2.64	82
190	533380	58.7	9.9	2.50	81
191	426431	52.1	5.4	2.26	78
192	121675	12.7	1.9	2.63	82
193	472884	53.6	2.3	2.43	80
194	205417	22.6	1.2	2.51	81
195	250545	26.0	7.3	2.65	82
196	328536	41.4	0.3	2.19	77
197	940628	97.8	12.5	2.65	82
198	304661	37.5	3.0	2.24	77
199	212012	23.4	4.9	2.50	80
200	297545	33.0	4.0	2.48	80
201	134312	17.1	2.2	2.17	77
202	462991	49.2	25.0	2.59	82
203	829224	92.7	6.5	2.46	80
204	14380	1.9	0.0	2.13	76

Hydro_ID	Predicted Flood Volume (ft^3)	Drainage area (acres)	% Impervious area	Effective rainfall (W_{eff}) (in)	Composite Curve Number (CN)
205	410027	47.3	10.7	2.39	79
206	1033677	122.3	5.6	2.33	78
207	76763	9.2	0.0	2.30	78
208	463855	53.0	0.1	2.41	79
209	548188	66.7	5.3	2.26	78
210	257764	26.4	10.4	2.69	83
211	656363	75.1	1.8	2.41	79
212	117046	11.4	19.2	2.82	84
213	40925	5.0	0.0	2.28	78
214	35486	4.5	2.1	2.19	77
215	1098795	102.5	37.9	2.95	85
216	503840	57.8	12.4	2.40	79
217	570651	60.9	15.1	2.58	81
218	91973	9.3	22.4	2.72	83

APPENDIX 3. Sinkhole drainage area land use, soil, and slope data.

Hydro_ID	Grass/ Soil B (acres)	Grass/ Soil D (acres)	Grass/ Soil C (acres)	Impervious area (acres)	Forest/ Soil D (acres)	Forest/ Soil C (acres)	Forest/ Soil B (acres)	Main drainage axis flow length (ft)	Slope along main draianage axis (%)
1	24.4	0.0	4.8	1.6	0.0	0.6	4.5	850	5.9
2	17.9	0.0	1.1	0.8	0.0	0.0	0.0	970	7.2
3	39.6	0.8	13.9	6.1	0.0	5.4	14.7	2870	2.8
4	21.3	0.0	16.9	2.7	0.0	20.5	14.9	2100	3.8
5	4.8	0.0	0.1	7.5	0.0	1.3	22.2	1450	8.3
6	89.9	0.0	42.1	81.5	0.0	13.9	29.3	4200	1.2
7	2.0	0.0	1.5	1.0	0.0	1.2	0.0	420	8.3
8	4.9	0.0	8.5	2.8	0.0	1.8	0.2	1200	4.2
9	7.9	0.1	5.7	5.9	2.0	6.2	11.5	1600	5.0
10	11.8	0.0	2.6	0.4	0.0	0.4	9.7	830	6.0
11	7.2	0.0	0.0	0.3	0.0	0.0	1.5	460	8.7
12	16.3	0.0	4.2	6.8	0.0	0.0	2.1	750	5.3
13	4.4	1.5	0.0	4.5	0.0	0.0	0.0	700	2.9
14	56.1	4.9	15.8	19.4	1.2	1.8	15.6	3300	2.4
15	27.6	0.0	10.2	9.2	0.0	1.1	3.2	1600	5.3
16	11.1	0.0	0.0	1.2	0.0	0.0	0.4	760	7.9
17	27.3	5.8	16.8	37.1	0.1	3.5	9.5	3000	2.0
18	40.1	10.7	18.8	59.1	31.9	12.8	30.4	4900	1.0
19	0.0	0.0	0.0	0.0	0.0	5.2	5.8	600	15.0
20	17.3	0.0	1.9	4.5	1.8	1.7	14.9	1770	6.2
21	1.4	0.0	0.6	0.4	0.0	14.9	0.9	1110	7.2
22	9.6	0.0	0.6	0.2	0.0	2.6	8.7	1000	7.0
23	3.1	0.0	0.0	0.6	0.0	0.0	1.3	560	8.9
24	145.4	30.0	65.8	221.4	4.6	7.7	7.9	5000	1.6
25	306.47	6.40	167.07	415.73	0.08	8.13	25.34	10800	1.0
27	18.9	0.0	4.1	68.1	0.0	1.0	0.1	3000	3.3
28	11.1	0.2	0.0	4.2	0.8	0.0	1.9	910	12.1
29	10.2	0.0	0.0	3.5	0.5	0.0	0.3	740	14.9
30	5.5	0.5	0.0	14.5	1.7	0.0	0.2	1000	9.5
31	4.0	0.0	0.0	13.7	0.0	0.4	3.9	1090	13.8
32	20.9	3.0	0.7	32.6	0.9	0.0	2.1	1390	7.2
33	5.5	1.3	0.7	22.7	0.2	0.0	0.0	1000	12.0
34	64.3	6.0	5.7	17.4	11.0	1.3	6.3	2200	7.7
35	44.9	9.0	2.3	41.7	3.9	0.8	4.2	2700	1.7
36	15.1	0.0	0.3	3.3	0.0	0.3	4.3	920	5.4
37	66.5	15.7	25.5	92.6	0.0	0.0	1.1	5700	1.8
38	12.2	3.2	0.0	9.9	0.0	0.0	0.0	1400	3.6

Hydro_ID	Grass/ Soil B (acres)	Grass/ Soil D (acres)	Grass/ Soil C (acres)	Impervious area (acres)	Forest/ Soil D (acres)	Forest/ Soil C (acres)	Forest/ Soil B (acres)	Main drainage axis flow length (ft)	Slope along main draianage axis (%)
39	151.3	18.6	50.1	126.6	11.6	21.2	40.0	7900	1.8
40	285.3	9.4	68.8	144.9	7.7	27.3	93.7	7600	1.6
41	82.4	8.4	7.6	51.2	0.2	1.6	9.3	3400	2.9
42	17.2	2.6	4.1	24.6	0.0	0.0	0.0	2500	3.6
43	7.0	0.0	4.5	5.5	0.0	0.0	0.0	1000	6.0
44	103.3	12.2	51.2	233.9	0.0	5.5	0.0	8200	1.8
45	197.3	0.0	13.6	119.8	0.0	5.3	78.3	5500	2.5
46	0.7	0.7	0.1	7.9	0.3	1.2	1.5	500	26.0
47	16.5	0.0	0.0	3.3	0.0	0.1	3.2	1800	11.1
48	14.0	0.0	0.9	40.4	0.0	1.2	2.2	1400	11.4
49	26.1	2.1	2.5	14.7	2.8	1.8	17.0	1600	3.8
50	147.1	9.7	17.9	81.3	0.0	1.0	16.6	6200	1.6
51	55.5	30.4	48.6	28.1	1.0	13.9	9.6	4400	1.1
52	1.7	0.0	0.0	2.2	0.0	0.0	0.0	600	5.0
53	34.6	0.0	0.0	4.9	0.0	0.0	0.0	1300	3.8
54	24.1	0.0	0.0	4.5	0.0	0.0	0.0	900	5.6
55	3.7	0.0	0.0	1.4	0.0	0.0	0.0	430	7.0
56	20.3	0.0	2.6	12.0	0.0	7.0	11.2	1700	18.8
57	5.9	0.0	4.0	2.8	0.0	5.0	5.0	1500	22.7
58	17.6	0.0	0.8	2.1	0.0	2.6	0.1	1600	15.0
59	12.7	0.0	0.0	11.4	0.0	0.0	0.0	800	2.5
60	10.1	0.0	0.7	0.9	0.0	3.0	3.9	1600	15.6
61	31.9	0.6	0.9	14.0	1.5	12.4	32.5	3400	9.7
62	16.7	0.0	3.8	0.0	0.0	15.9	3.4	2000	12.5
63	7.5	0.0	3.4	0.1	0.0	0.5	0.0	900	14.4
64	16.3	0.1	0.6	0.0	0.5	10.9	3.4	2100	15.7
65	13.3	0.0	0.0	0.2	0.0	0.0	0.6	1200	9.2
66	11.9	0.0	0.0	0.0	0.0	0.0	0.3	1000	8.0
67	4.2	0.0	0.3	3.9	0.0	0.2	3.3	1100	7.3
68	14.1	0.0	0.0	4.5	0.0	0.0	1.7	700	2.9
69	8.5	0.0	0.5	0.0	0.0	2.5	1.7	1300	23.8
70	531.3	6.8	157.3	124.0	8.9	60.1	151.1	9400	1.3
71	75.4	0.8	6.2	27.8	0.0	8.4	2.4	4000	7.8
72	64.6	4.7	11.7	5.9	6.9	1.7	4.0	2100	4.8
73	50.9	1.1	1.7	0.7	1.9	0.8	1.5	2100	4.3
74	34.2	0.0	0.0	2.2	0.0	0.0	2.6	1500	11.3
75	6.8	0.0	0.0	0.3	0.0	0.0	0.0	500	10.0
76	6.7	0.0	0.0	0.5	0.0	0.0	0.0	430	9.3
77	50.8	0.0	4.5	1.1	0.0	16.1	41.8	2500	10.4

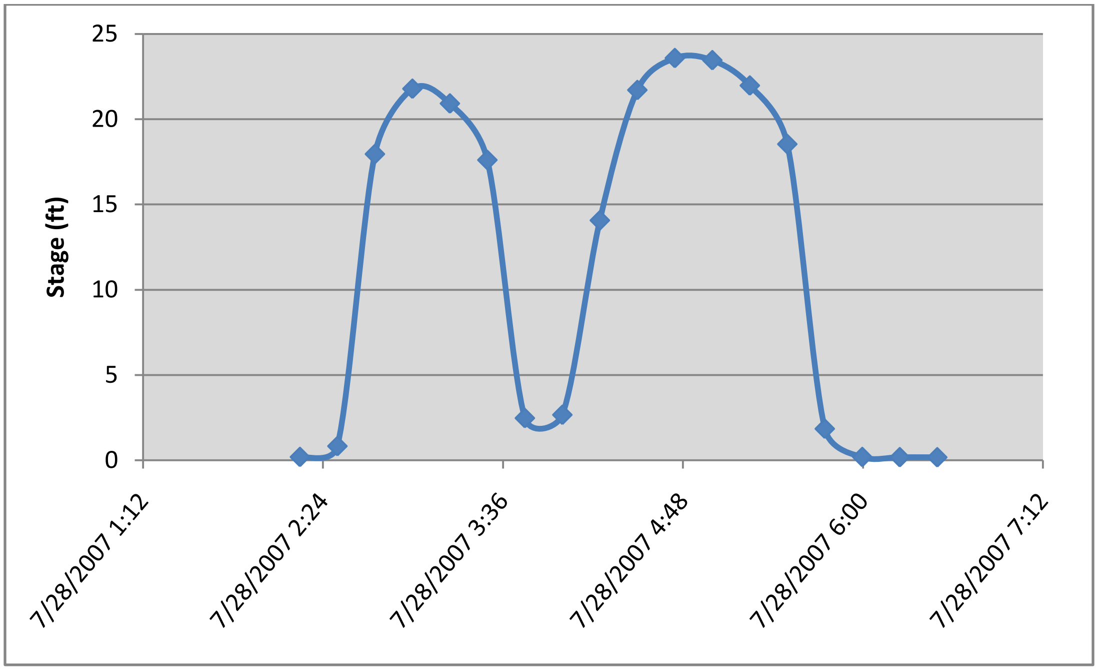
Hydro_ID	Grass/ Soil B (acres)	Grass/ Soil D (acres)	Grass/ Soil C (acres)	Impervious area (acres)	Forest/ Soil D (acres)	Forest/ Soil C (acres)	Forest/ Soil B (acres)	Main drainage axis flow length (ft)	Slope along main draianage axis (%)
78	7.4	0.0	1.2	1.7	0.0	0.0	1.5	600	11.7
79	5.9	0.0	0.2	0.5	0.0	0.8	2.5	1200	15.0
80	4.9	0.0	0.7	2.2	0.0	0.5	2.9	1300	13.8
81	30.8	0.0	2.2	0.9	0.0	1.0	0.8	2500	10.4
82	1.9	0.0	0.0	0.1	0.0	0.0	0.0	250	10.0
83	52.5	0.0	2.3	2.6	0.0	7.4	1.6	3300	10.9
84	13.0	0.0	4.0	8.2	0.0	0.6	3.5	1700	7.6
85	1.8	0.0	1.5	0.9	0.0	0.3	0.5	400	10.0
86	1.4	0.0	0.0	1.2	0.0	0.0	3.3	600	11.7
87	2.9	0.0	0.8	4.6	0.0	1.5	0.8	800	6.3
88	13.7	0.5	0.0	2.6	0.0	0.0	3.1	1200	4.2
89	5.5	0.0	0.0	0.2	0.0	0.0	0.0	500	12.0
90	2.7	0.0	0.0	0.2	0.0	0.0	5.8	600	11.7
91	55.5	0.1	8.9	18.6	0.0	0.5	5.0	2400	3.8
92	12.9	0.0	0.0	3.0	0.0	0.0	0.0	700	7.1
93	14.5	0.0	3.0	1.4	0.0	1.1	1.2	1200	6.7
94	3.0	0.0	0.0	0.5	0.0	0.0	3.6	300	13.3
95	49.4	1.8	15.4	22.2	0.0	9.5	11.2	3900	3.6
96	15.0	0.0	1.0	10.5	0.0	2.1	0.3	1300	6.9
97	15.2	0.4	0.0	0.0	0.0	0.0	0.5	500	10.0
98	0.5	0.0	1.6	0.5	0.0	0.0	0.0	230	17.4
99	3.0	0.0	0.6	0.3	0.0	0.0	1.8	500	8.0
100	0.9	0.0	1.5	0.1	0.0	0.4	0.1	220	9.1
101	12.2	0.0	3.0	0.2	0.0	0.0	0.0	1200	5.8
102	1.8	0.0	0.0	0.3	0.0	0.0	0.0	250	16.0
103	3.9	0.0	0.0	0.7	0.0	0.0	1.1	440	9.1
104	5.7	0.4	0.0	2.1	0.0	0.0	0.0	680	8.8
105	3.8	0.0	0.0	1.5	0.0	0.0	3.6	760	6.6
106	2.7	0.0	0.0	1.5	0.0	0.0	20.0	1200	7.5
107	11.7	0.0	0.0	0.8	0.0	0.0	6.0	760	7.9
108	20.5	0.0	0.0	2.6	0.0	0.0	6.4	2200	3.2
109	13.8	0.0	5.4	2.1	0.0	0.7	3.9	890	5.6
110	18.8	0.0	0.1	0.4	0.0	0.0	1.6	780	5.1
111	39.4	0.6	2.5	3.0	2.4	0.2	11.4	3000	2.3
112	2.1	0.0	0.0	0.1	0.0	0.0	0.0	260	3.8
113	7.2	0.0	0.0	0.5	0.0	0.0	0.0	450	4.4
114	10.9	0.0	6.7	4.8	0.0	0.0	0.0	1000	6.0
115	5.0	0.0	0.0	1.7	0.0	0.0	0.0	540	3.7
116	3.9	0.0	0.0	0.1	0.0	0.0	0.0	500	8.0

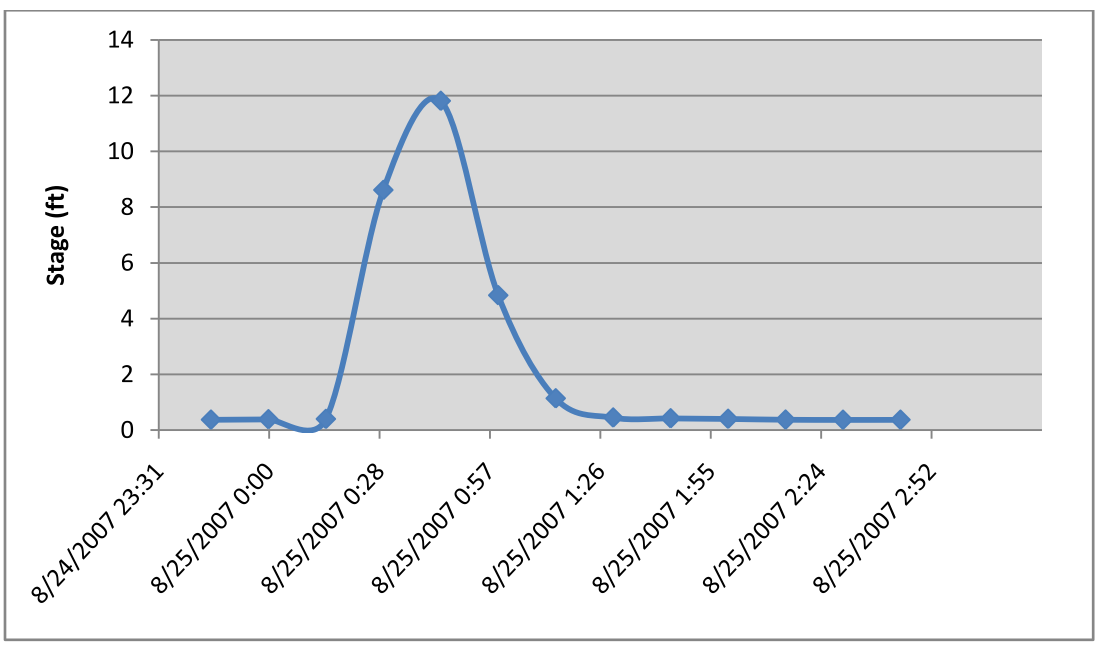
Hydro_ID	Grass/ Soil B (acres)	Grass/ Soil D (acres)	Grass/ Soil C (acres)	Impervious area (acres)	Forest/ Soil D (acres)	Forest/ Soil C (acres)	Forest/ Soil B (acres)	Main drainage axis flow length (ft)	Slope along main draianage axis (%)
117	12.6	0.0	0.0	2.2	0.0	0.0	0.0	750	6.7
118	20.7	0.0	0.0	0.5	0.0	0.0	1.1	1200	3.3
119	10.0	0.0	0.0	0.0	0.0	0.0	8.0	1100	4.1
120	7.9	0.0	0.0	0.8	0.0	0.0	0.0	590	6.8
121	19.7	0.0	0.0	2.1	0.0	0.0	0.0	850	4.1
122	14.3	0.0	0.0	0.2	0.0	0.0	0.0	1100	3.6
123	7.1	0.0	0.0	0.0	0.0	0.0	3.2	680	5.9
124	2.0	0.0	0.0	0.0	0.0	0.0	0.0	310	6.5
125	6.0	0.0	0.0	0.0	0.0	0.0	0.0	590	6.8
126	6.3	0.0	0.0	0.0	0.0	0.0	0.0	620	4.8
127	6.2	0.0	0.0	0.9	0.0	0.0	8.3	1100	10.0
128	5.2	0.0	0.0	0.2	0.0	0.0	0.0	700	3.6
129	1.8	0.0	0.0	0.0	0.0	0.0	0.0	250	12.0
130	4.1	0.0	0.0	0.0	0.0	0.0	1.5	490	4.1
131	30.2	0.8	0.0	0.2	3.4	0.0	10.9	1800	3.9
132	8.4	0.0	0.0	0.0	0.0	0.0	1.4	660	6.1
133	25.8	0.0	0.0	0.8	0.0	0.0	0.0	1800	5.0
134	2.7	1.4	0.3	0.6	1.5	3.4	5.3	1100	24.5
135	4.3	0.0	0.0	0.1	0.0	0.3	7.8	560	26.8
136	28.6	0.1	6.7	5.1	2.9	11.5	34.4	2500	2.4
137	72.1	2.9	3.1	7.5	2.6	5.9	10.0	2100	17.6
138	64.2	0.4	2.1	7.4	11.2	10.9	61.3	3800	12.4
139	57.1	0.2	6.3	7.0	0.1	2.7	1.6	1700	11.8
140	66.4	30.9	13.0	18.3	1.6	0.0	4.4	2600	2.7
141	32.4	0.0	3.8	0.1	0.0	18.8	46.0	2000	17.5
142	18.2	0.9	1.0	8.8	0.8	2.4	6.1	1100	13.6
143	11.1	0.0	1.6	1.8	0.0	0.0	0.1	730	11.0
144	1.3	0.0	0.0	0.4	0.0	0.0	4.1	390	15.4
145	9.0	0.0	0.0	3.4	0.0	0.0	2.7	940	9.6
146	22.6	0.0	8.6	12.7	0.0	1.6	4.3	1400	7.1
147	14.1	0.0	10.8	1.6	0.0	0.0	0.0	1900	4.7
148	5.1	0.3	0.1	1.6	6.3	0.2	2.7	990	25.3
149	17.6	0.0	0.0	1.0	0.0	0.0	6.7	650	13.8
150	14.4	2.3	2.6	11.1	0.0	0.0	0.0	970	4.1
151	21.8	0.4	2.1	3.4	2.0	0.5	12.7	1600	3.1
152	20.0	0.1	0.6	5.2	0.0	0.0	5.3	1400	6.8
153	6.5	0.9	4.3	5.8	0.0	0.9	4.3	1000	2.0
154	18.4	4.9	2.6	2.2	1.1	0.4	8.6	1100	3.6
155	9.0	0.0	0.0	0.6	0.0	4.5	5.8	1100	11.8

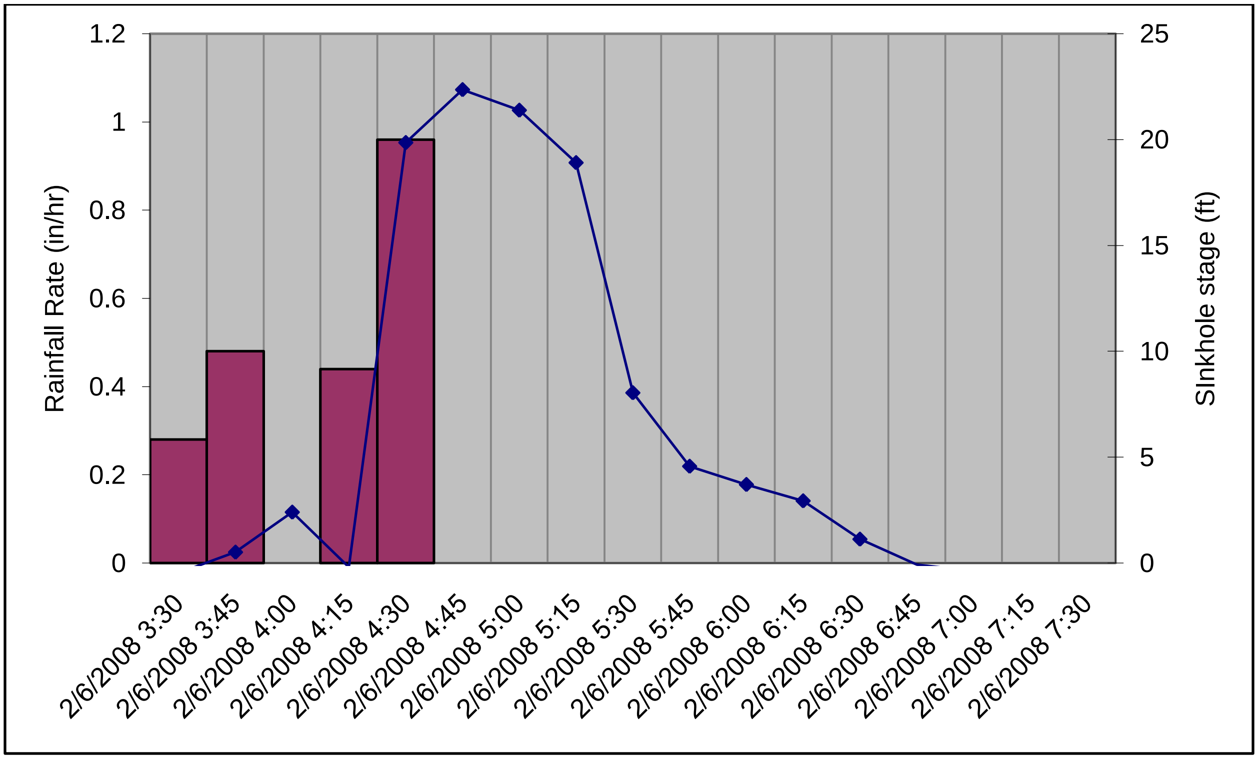
Hydro_ID	Grass/ Soil B (acres)	Grass/ Soil D (acres)	Grass/ Soil C (acres)	Impervious area (acres)	Forest/ Soil D (acres)	Forest/ Soil C (acres)	Forest/ Soil B (acres)	Main drainage axis flow length (ft)	Slope along main draianage axis (%)
156	79.6	15.2	16.4	35.8	24.4	1.5	9.2	1900	2.1
157	623.4	213.7	276.0	351.7	168.2	56.0	105.2	12000	0.6
158	48.7	0.0	11.5	8.1	0.0	0.2	9.0	1900	12.1
159	10.6	0.0	23.9	3.3	0.0	6.6	3.1	1000	6.0
160	44.3	0.0	14.3	9.7	0.0	4.4	32.5	1600	5.6
161	22.4	0.0	23.7	8.9	0.0	3.2	6.6	2500	2.0
162	146.3	0.0	38.2	20.6	0.0	30.6	56.9	4700	2.1
163	0.6	0.0	0.3	0.3	0.0	10.8	1.4	790	7.6
164	10.7	0.0	6.5	0.9	0.0	0.1	2.7	600	18.3
165	10.5	0.0	3.9	0.9	0.0	0.1	5.0	650	13.8
166	2.9	0.0	0.0	0.0	0.0	0.7	6.2	740	12.2
167	4.0	0.0	2.0	1.3	0.0	0.3	5.4	890	4.5
168	3.0	0.0	0.0	0.8	0.0	0.0	4.7	580	10.3
169	11.5	0.0	0.1	2.1	0.0	0.0	0.0	540	11.1
170	12.2	0.0	5.4	8.6	0.0	0.5	2.1	1700	2.9
171	10.7	0.0	3.8	6.8	0.0	2.0	4.9	1250	4.8
172	16.1	0.0	5.0	8.8	0.0	0.5	3.9	1330	2.6
173	3.3	0.0	0.0	0.2	0.0	0.0	0.0	370	13.5
174	8.8	0.0	0.0	0.0	0.0	0.0	0.0	570	5.3
175	3.5	0.0	0.3	0.1	0.0	0.0	2.3	840	8.3
176	1.6	0.0	0.1	0.0	0.0	0.1	0.7	540	5.6
177	10.8	0.0	11.6	17.3	0.0	0.0	0.0	1500	2.0
178	14.7	2.4	22.1	19.6	2.8	12.3	0.0	2400	1.7
179	8.6	0.0	2.6	5.9	0.0	1.6	1.4	1300	4.6
180	9.2	1.2	5.2	5.4	0.1	1.2	4.8	1400	4.6
181	8.0	0.0	0.2	1.5	0.0	0.0	12.0	810	7.4
182	13.9	0.0	3.0	1.4	0.0	0.2	4.0	1260	6.3
183	2.2	0.0	1.9	0.0	0.0	0.0	0.0	390	12.8
184	30.9	0.0	11.8	4.9	0.0	8.4	18.8	2000	4.5
185	14.0	0.0	6.8	3.2	0.0	2.9	0.6	840	9.5
186	20.9	0.3	5.6	21.6	0.0	0.0	5.6	1200	7.5
187	5.5	0.0	2.9	0.2	0.0	0.1	0.9	740	8.1
188	2.0	0.0	0.4	0.1	0.0	4.4	6.9	780	5.8
189	14.8	0.0	16.0	2.7	0.0	3.0	3.9	1600	6.9
190	22.8	0.0	6.4	5.8	0.0	7.1	16.5	1700	4.7
191	23.9	0.4	5.2	2.8	0.0	2.6	16.4	2100	3.6
192	2.7	0.0	0.2	0.2	0.0	6.2	3.4	990	9.1
193	24.2	1.3	3.8	1.2	1.5	8.0	13.8	2500	3.6
194	12.1	0.0	5.0	0.3	0.0	4.5	0.8	1270	4.7

Hydro_ID	Grass/ Soil B (acres)	Grass/ Soil D (acres)	Grass/ Soil C (acres)	Impervious area (acres)	Forest/ Soil D (acres)	Forest/ Soil C (acres)	Forest/ Soil B (acres)	Main drainage axis flow length (ft)	Slope along main draianage axis (%)
195	11.4	0.0	7.0	1.9	0.0	4.6	1.3	1320	2.3
196	33.4	0.0	2.7	0.1	0.0	0.1	5.0	1600	2.5
197	31.5	0.0	19.0	12.2	0.0	14.7	20.5	3000	3.3
198	33.1	0.0	2.7	1.1	0.0	0.0	0.6	1190	4.2
199	8.2	0.0	3.1	1.1	0.0	4.6	6.3	1520	5.3
200	19.3	0.3	11.9	1.3	0.0	0.0	0.3	1460	3.4
201	12.0	0.0	0.0	0.4	0.0	0.0	4.6	900	6.7
202	29.4	0.0	0.0	12.3	0.0	0.0	7.5	2100	4.3
203	52.5	0.8	14.1	6.0	0.8	8.5	10.0	1850	3.8
204	0.9	0.0	0.0	0.0	0.0	0.0	0.9	200	22.5
205	34.8	0.0	4.0	5.1	0.0	0.0	3.4	1740	4.0
206	59.6	1.8	2.3	6.9	0.1	8.9	42.8	2200	4.5
207	1.7	0.0	0.0	0.0	0.0	1.7	5.8	970	5.7
208	14.2	0.0	1.9	0.0	1.6	12.7	22.6	1740	5.7
209	51.8	0.0	3.6	3.5	0.0	0.0	7.7	1300	6.5
210	10.6	0.0	4.4	2.8	0.0	6.8	1.9	1360	5.1
211	28.1	0.0	5.9	1.4	0.0	15.4	24.2	2200	5.5
212	4.2	1.2	2.7	2.2	0.0	0.0	1.1	670	9.0
213	2.3	0.0	0.8	0.0	0.0	0.2	1.7	290	10.3
214	0.7	0.0	0.0	0.1	0.0	0.1	3.6	500	29.0
215	52.7	0.7	4.0	38.9	0.0	6.3	0.0	2300	3.9
216	30.9	0.0	3.7	7.2	0.0	0.0	16.0	2000	3.0
217	34.4	5.5	6.0	9.2	0.0	0.0	5.9	1600	1.9
218	5.5	0.8	1.0	2.1	0.0	0.0	0.0	600	2.5

APPENDIX 4. Stage heights for selected floods in Ensor Sink, 2007-2009. Measurements of stage are in feet above mouth of Ensor Sink swallet. To find estimate for the elevation of sinkhole stage add stage values to the elevation of the swallet (986 feet).







Rainfall Rate (in/hr)
SInkhole stage (ft)
1.2
1
0.8
0.6
0.4
0.2
0
25
20
15
10
5
0
2/6/2008 3:30
2/6/2008 3:45
2/6/2008 4:00
2/6/2008 4:15
2/6/2008 4:30
2/6/2008 4:45
2/6/2008 5:00
2/6/2008 5:15
2/6/2008 5:30
2/6/2008 5:45
2/6/2008 6:00
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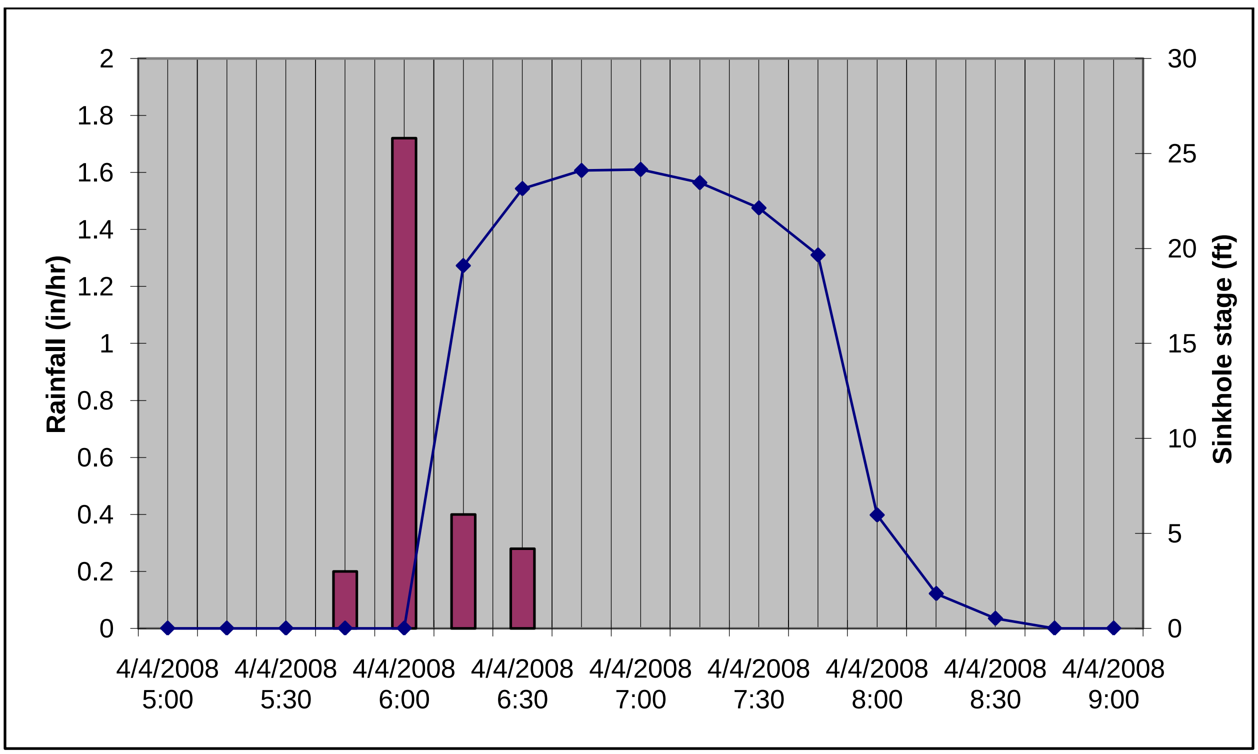
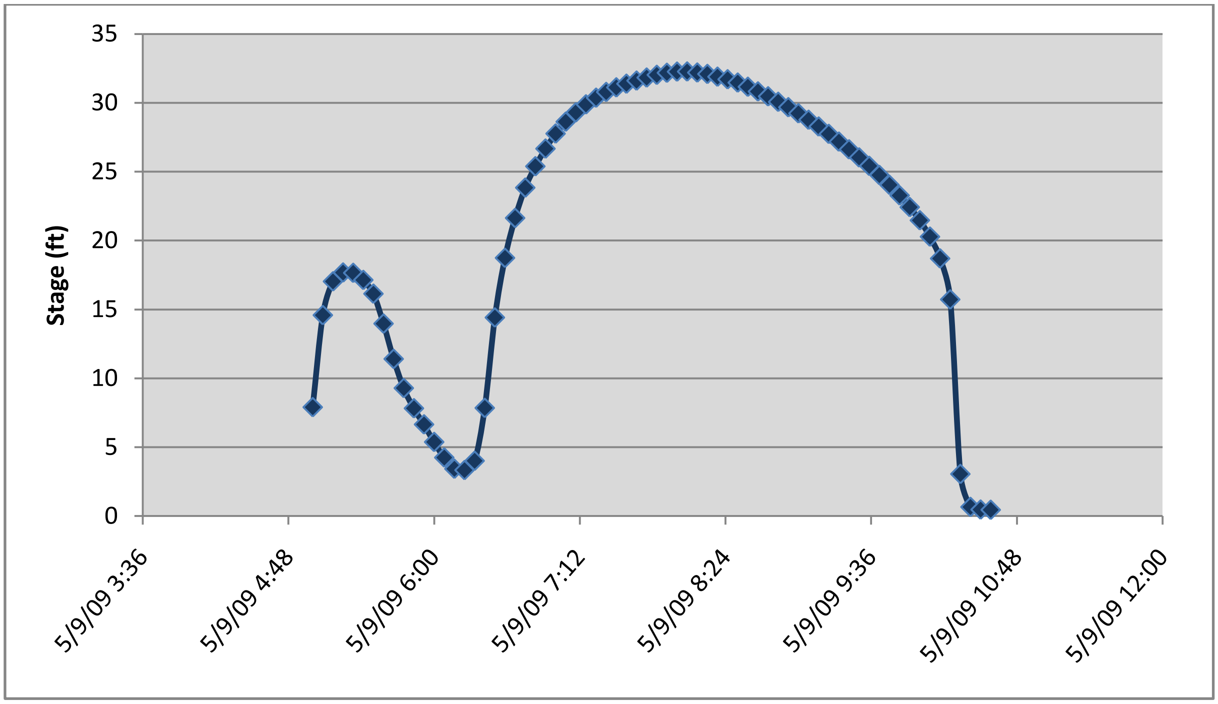
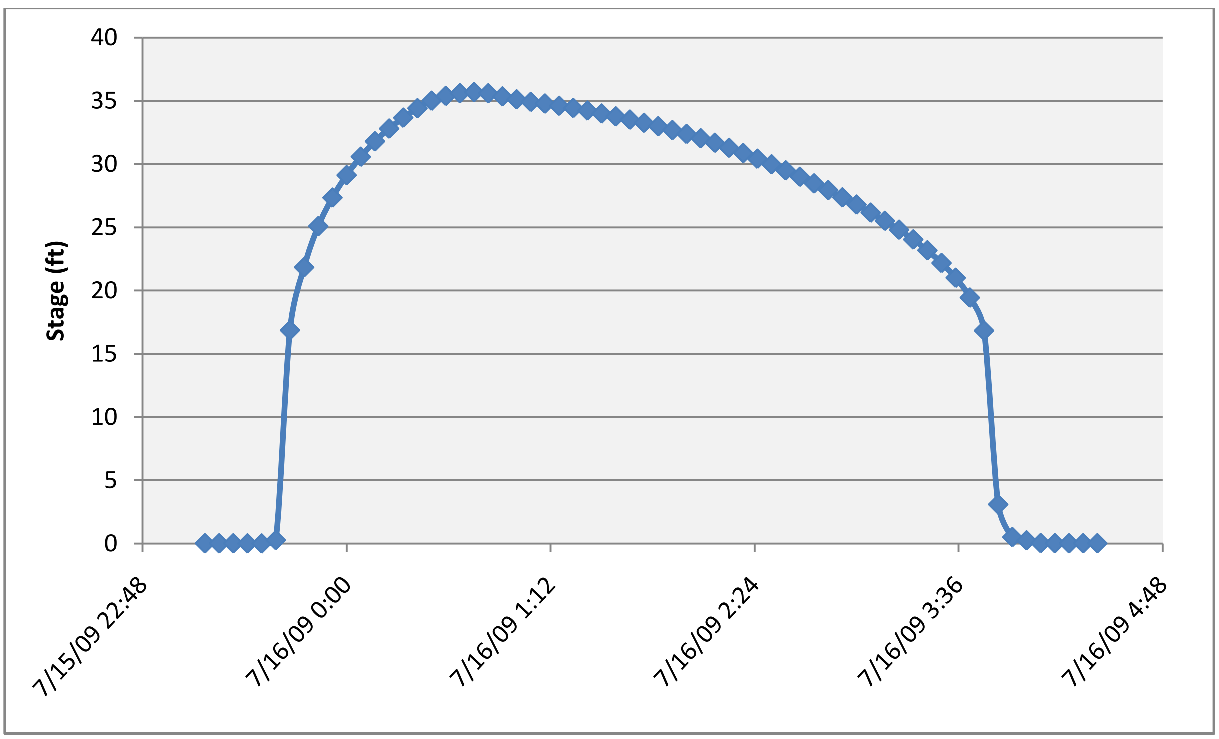
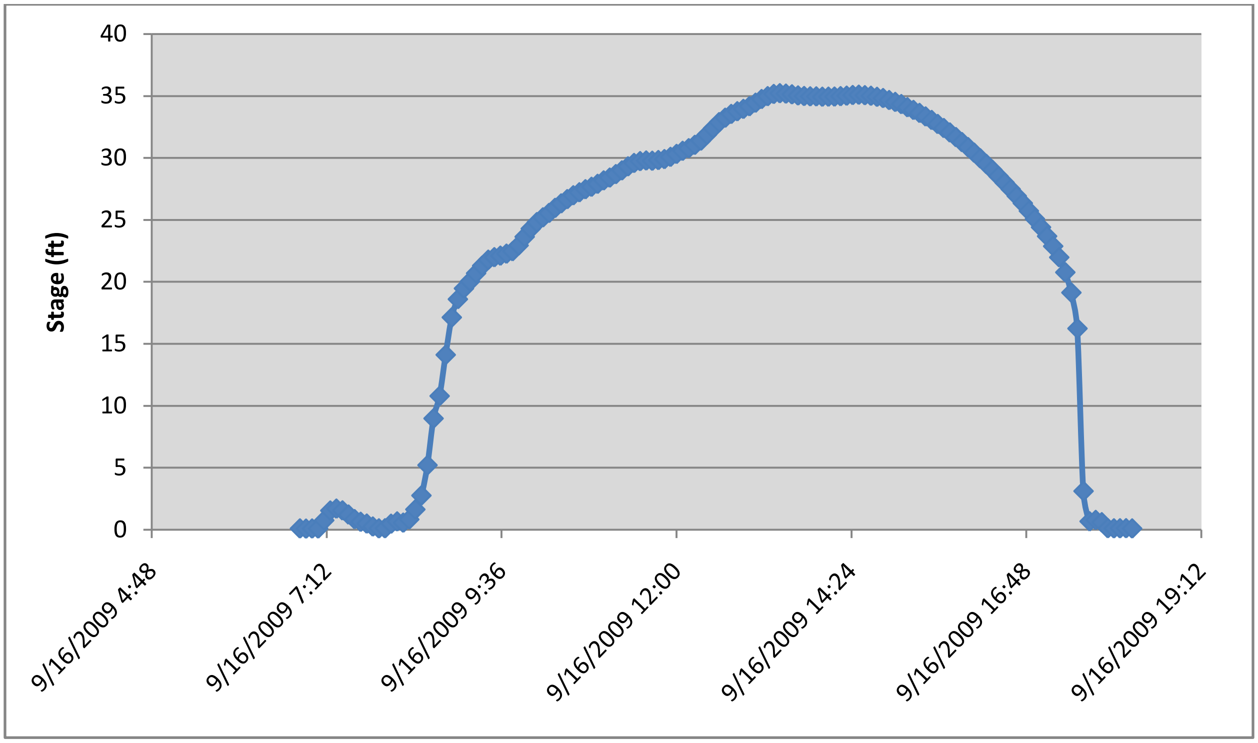
2/6/2008 7:00
2/6/2008 7:15
2/6/2008 7:30



Rainfall (in/hr)
Sinkhole stage (ft)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
30
25
20
15
10
5
0
4/4/2008 5:00
4/4/2008 5:30
4/4/2008 6:00
4/4/2008 6:30
4/4/2008 7:00
4/4/2008 7:30
4/4/2008 8:00
4/4/2008 8:30
4/4/2008 9:00

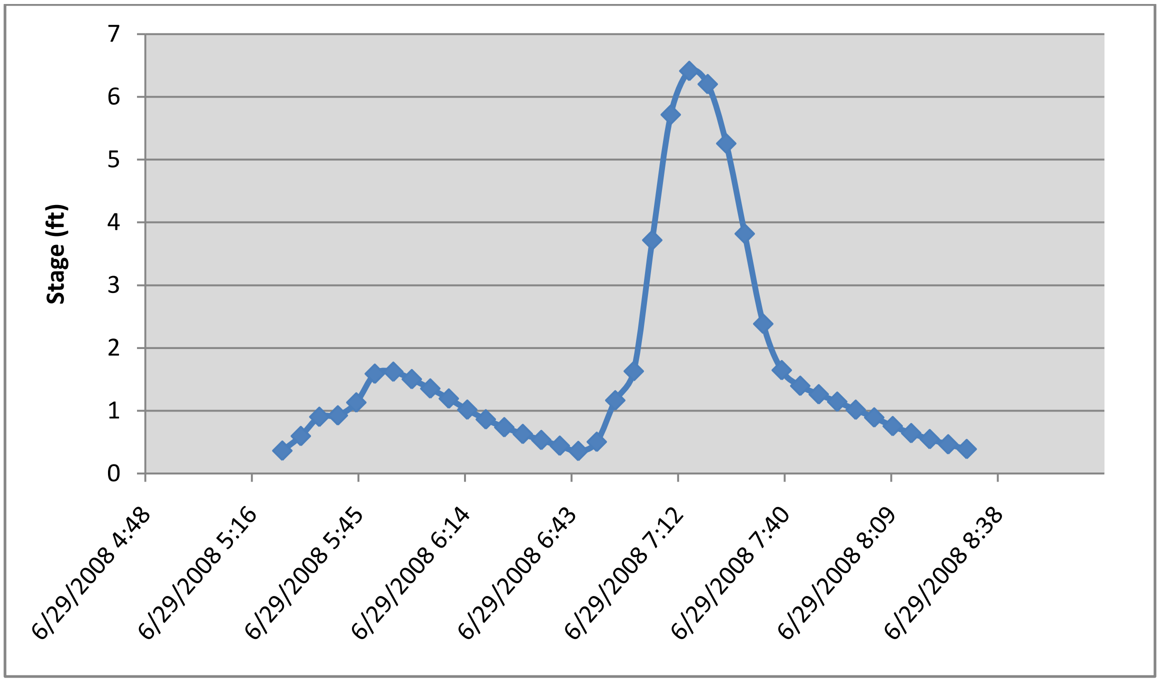

Stage (ft)
35
30
25
20
15
10
5
0
5/9/09 3:36
5/9/09 4:48
5/9/09 6:00
5/9/09 7:12
5/9/09 8:24
5/9/09 9:36
5/9/09 10:48
5/9/09 12:00

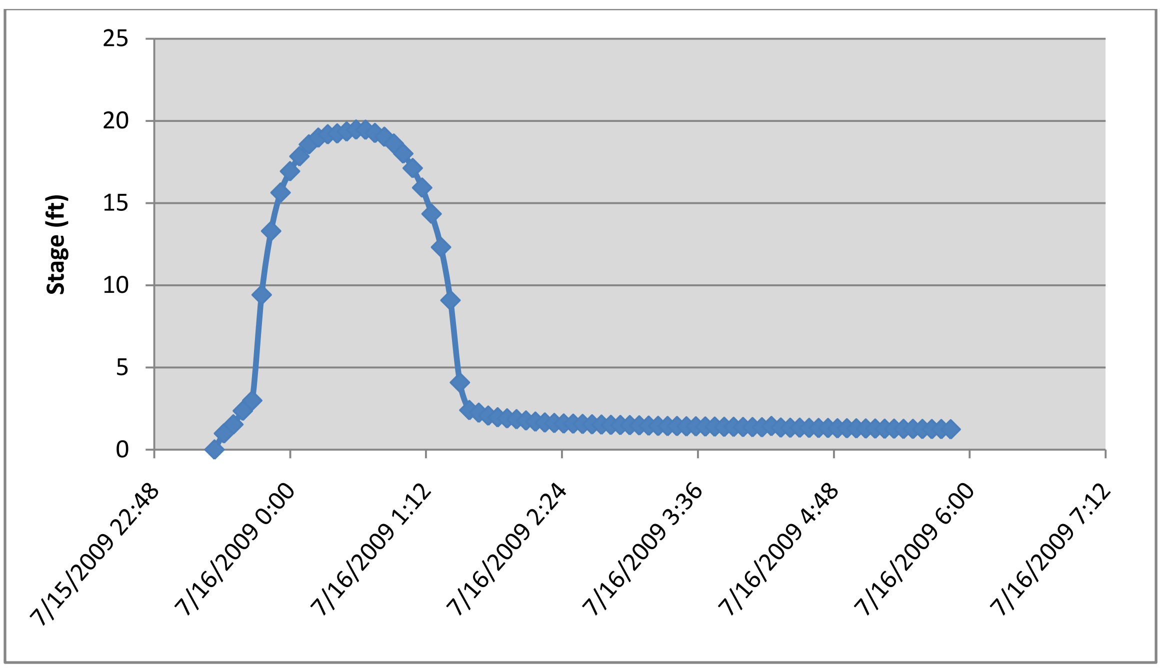

Stage (ft)
40
35
30
25
20
15
10
5
0
7/15/09 22:48
7/16/09 0:00
7/16/09 1:12
7/16/09 2:24
7/16/09 3:36
7/16/09 4:48

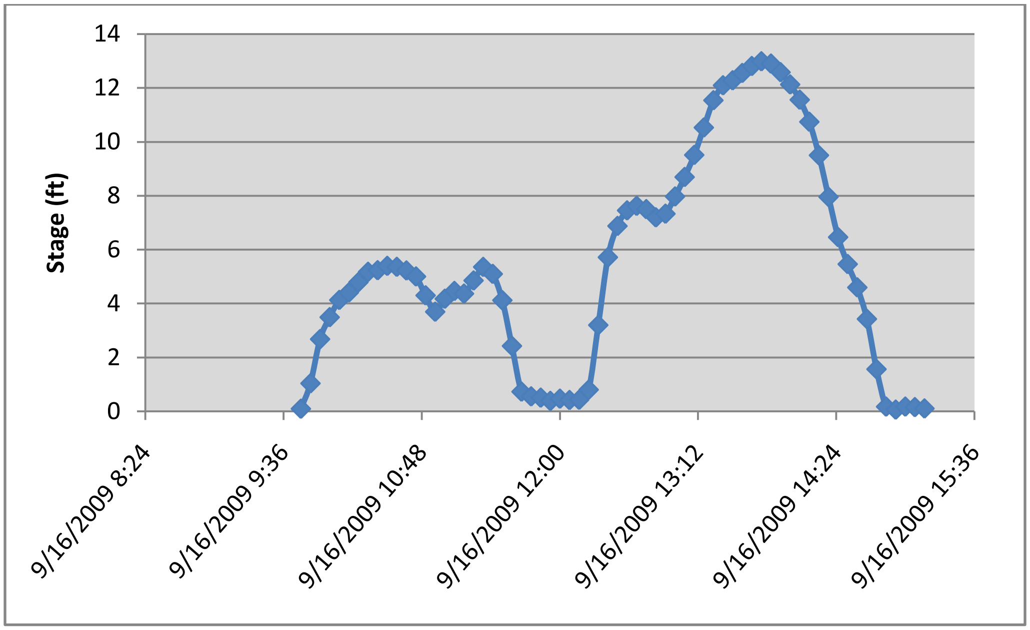


Stage (ft)
40
35
30
25
20
15
10
5
0
9/16/2009 4:48
9/16/2009 7:12
9/16/2009 9:36
9/16/2009 12:00
9/16/2009 14:24
9/16/2009 16:48
9/16/2009 19:12

APPENDIX 5. Stage heights for selected floods in Warehouse Sink (Hydro-ID 44), 2008-2009. Measurements of stage are in feet above mouth of Warehouse Sink swallet. To find estimate for the elevation of sinkhole stage add stage values to the elevation of the swallet (1006 feet).

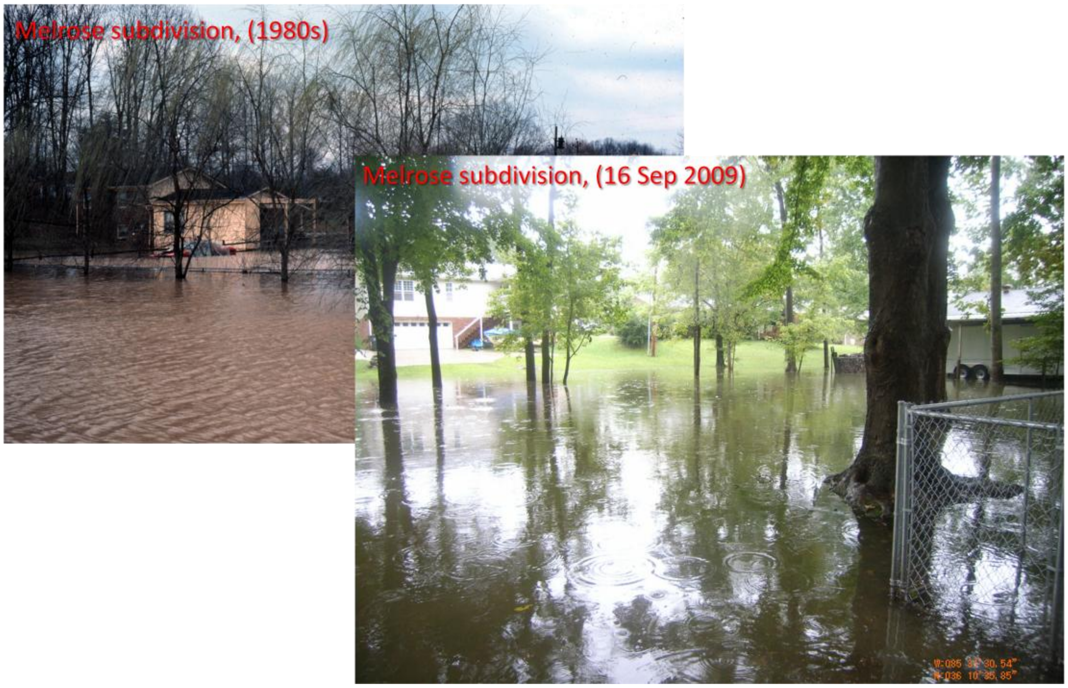





Stage (ft)
14
12
10
8
6
4
2
0
9/16/2009 8:24
9/16/2009 9:36
9/16/2009 10:48
9/16/2009 12:00
9/16/2009 13:12
9/16/2009 14:24
9/16/2009 15:36

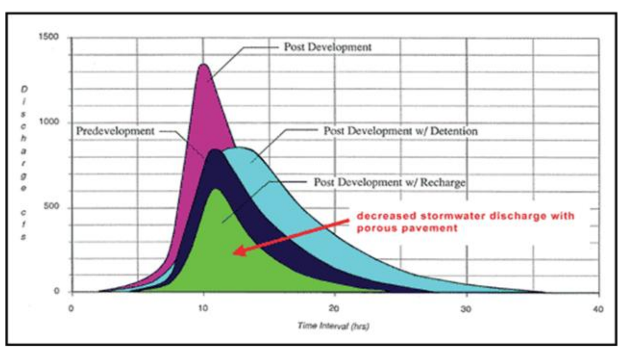
APPENDIX 6. Recommendations.

1. Prohibit or limit building permits within 100-year sinkhole floodplains



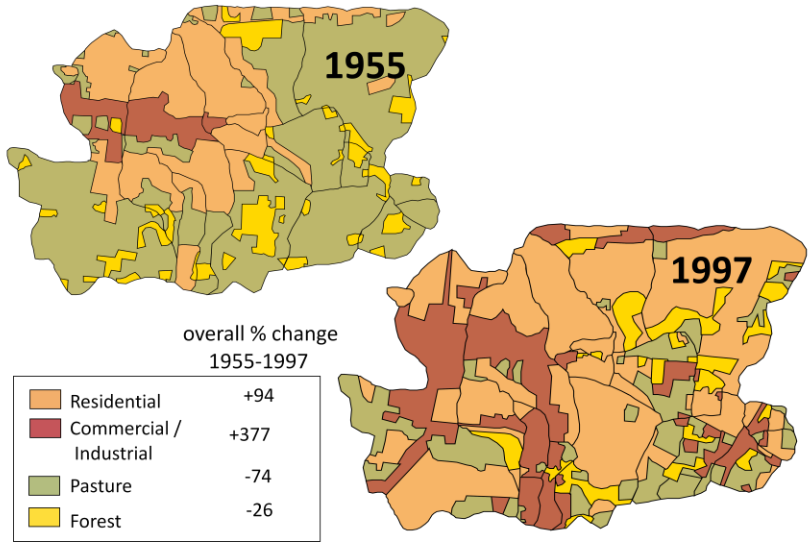
2. Reduce impervious surfaces in sinkhole watersheds

- Require porous asphalt surfaces
- Restrict development of sinkhole watersheds

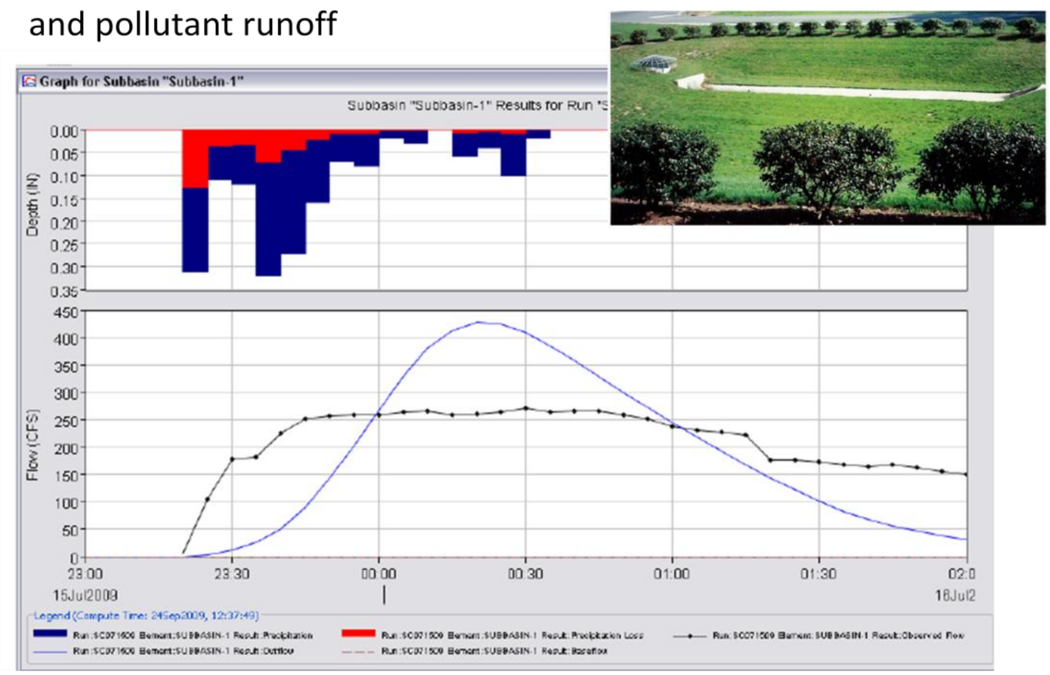


Images from Cahill Assoc.

Land use change within sinkholes, Cookeville, TN



3. Require greater use of detention ponds to reduce water and pollutant runoff



4. Reduce trash entering sinkholes
   - Use of trash-rack filters
   - Clean-up efforts

5. Invest in ‘Greenways’ or parks around sinkholes