GIS Applied to Flood Mapping in Sinkhole Areas

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Abstract:

Most of the flooding problems in Bowling Green, Kentucky are associated with sinkholes. Flood elevations for four sinkholes were determined using standard methods approved by FEMA. However, calculated flood elevations for two of these sinkholes were much lower than those commonly 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. Also, most of the sinkholes studied have spill-over during the 100-yr flood. 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 spill-over of upstream sinkholes gave good agreement with observations of a 1998 flood.

Introduction:

Bowling Green in Warren County, Kentucky sits in one of the best-known karst (cave and limestone) areas in the world. Most storm water runoff drains into subterranean passages, and many flood problems are associated with sinkholes. Constructing stormwater drainage systems for this area is much more complicated than in non-karst and even some karst areas. In a non-karst area, most storm water from development is routed into surface streams. In Bowling Green, it is usually routed either into cave entrances or into storm water drainage wells. The city has more than a thousand of these wells. They usually consist of a standpipe which may be made of corrugated metal or smooth metal pipe. The standpipe may have orifices cut in the side of the pipe. The well is drilled down into bedrock until a cavity is encountered.

One of the problems with these natural drainage systems is that only the entrance can be maintained. Debris can wash into the natural cavity and block it so that the well no longer functions as intended. Even if not plugged, the natural conduit may feed into a cave system that floods so that water may come out of the “drainage” well rather than draining water from the surface. These facts make development of reliable flood maps very difficult. The Flood Insurance Study for Warren County (FEMA, 1993) explains that seven of the sinkhole flood zones in the county had flood elevations set based on historic floods rather than on detailed analysis of runoff from the sinkhole catchments because the calculations gave flood elevations that were much lower than those observed.

The twenty flood map panels covering Warren County have at least 110 flood zones associated with ponds or sinkholes. Of these 110, only 59 have been studied in detail to determine flood elevations. These sinkholes are designated as AE or 100-yr flood zones. The other sinkholes are classified as approximate A zones. This means that the flood zone is based on historic floods. Sometimes, these flood zones do not conform to surface topography. Originally, this study began as a student project to improve flood maps for four sinkholes. For two of the sinkholes, standard methods gave results consistent with observations. For the other two sinkholes, calculated 100-yr flood elevations were much below those commonly observed. A more involved approach was required for these.

The 110 sinkhole or pond flood zones in Warren County are only the tip of the iceberg as many other sinkholes flood but were not included in the flood maps. Some of these do flood buildings. For example, in a 1998 flood one house in a sinkhole flooded to a depth of more than one meter even though the sinkhole was not listed as a flood zone.

Inadequacy of the Standard Method for Mapping Sinkhole Flood Zones

The Federal Emergency Management Agency (FEMA) approved a method for sinkhole flood mapping used in the most recent Flood Insurance Study for Bowling Green (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. Historic floods were used to estimate 100-yr flood elevations for seven of the sinkholes and spill points were used for nine others. The use of historic floods was necessary because of high water tables, that is, by back flooding from subterranean cavities.

Runoff calculations gave reasonable results for two of the four sinkholes in the study. However, when applied to the other two, Nashville Road North and Nashville Road South, the calculated 100-yr flood elevations were well below the high water mark for the mean annual flood. A study of the complex of sinkholes nearby indicated that the direct catchment area had very little correlation with the volume held to the spill point. This information was developed using ArcGIS and 3D Analyst. The actual correlation coefficient was approximately 0.11. Spill-over from uphill sinkholes was strongly indicated. Residents who lived around the sinkholes during a major flood that occurred during April 1998 described the flow across a road (separating Nashville Road North from uphill sinkholes) as a river. Another resident said that there were standing waves in the road, the flow was at least knee deep, and it was difficult to stand up. He added that you could have gone white water canoeing. For this group of sinkholes, use of spill points would give flood elevations at least 30 cm too low.

Clearly, spill-over was a major issue. Determining which sinkholes spilled into which others presented a major difficulty because of the complexity of the terrain. A method to determine sinkhole spill-over was needed. A very simple approach was taken with the aid of GIS. A TIN of the terrain was made from the topography shape file. Only two display colors were used on the map. All elevations below a given elevation were painted blue, and the elevations above were not painted. The dividing elevation was adjusted until two sinkholes were just connected by a strip of blue. This method is very crude, but surprisingly, more and more sinkholes were found with potential contributions to the Nashville Road North complex. This is illustrated in Figure 1 with elevations below 145 colored blue. The connection between Nashville Road North and the sinkholes to the south was unexpected.

If two sinkholes are connected, it is not clear which sinkhole spills into which. The general approach taken was to assume that the largest and deepest sinkholes were on the downstream end of the spillover. The actual direction of spill-over depends physically on the watershed draining to each sinkhole, and on the response time of the catchments to rainfall. It is quite possible that one sinkhole would overflow into a second one, and later the second could overflow into the first. Modeling should be general enough to account for these effects.

Watershed Modeling, Calibration, and Uncertainty

Based on the previous analysis and interviews with residents, a model was constructed using EPA's Storm Water Management Model (SWMM 5.0). From the Introduction, it is apparent that the depth of flow over spill points can be at least 0.5 m. In flood mapping, this difference in elevation is significant. Consequently, a dynamic simulation was done rather than just a static determination of water elevations from runoff into the sinkhole. Because the direction of spill-over was unclear, a dynamic wave modeling approach was taken to account for back-water effects.

In all, flow between 69 sinkholes was modeled. Each sinkhole was modeled as a storage node with the stage-storage relationship obtained with 3D Analyst as described below. A detailed topographic map for two sinkholes was obtained by survey. These were Nashville Road North and Nahm-McElroy. The survey points were processed to obtain a TIN and stage storage data. These were inserted into the SWMM model.

The only soil maps available were paper so these were scanned and georeferenced with ArcGIS. No reliable land use maps were available, so these were obtained from interpretation from ortho-photos and limited field investigation. Land use and hydrologic soil groups were used to obtain initial estimates of runoff curve numbers. During calibration, curve numbers were adjusted downward to account for significant tree cover in the older neighborhoods.

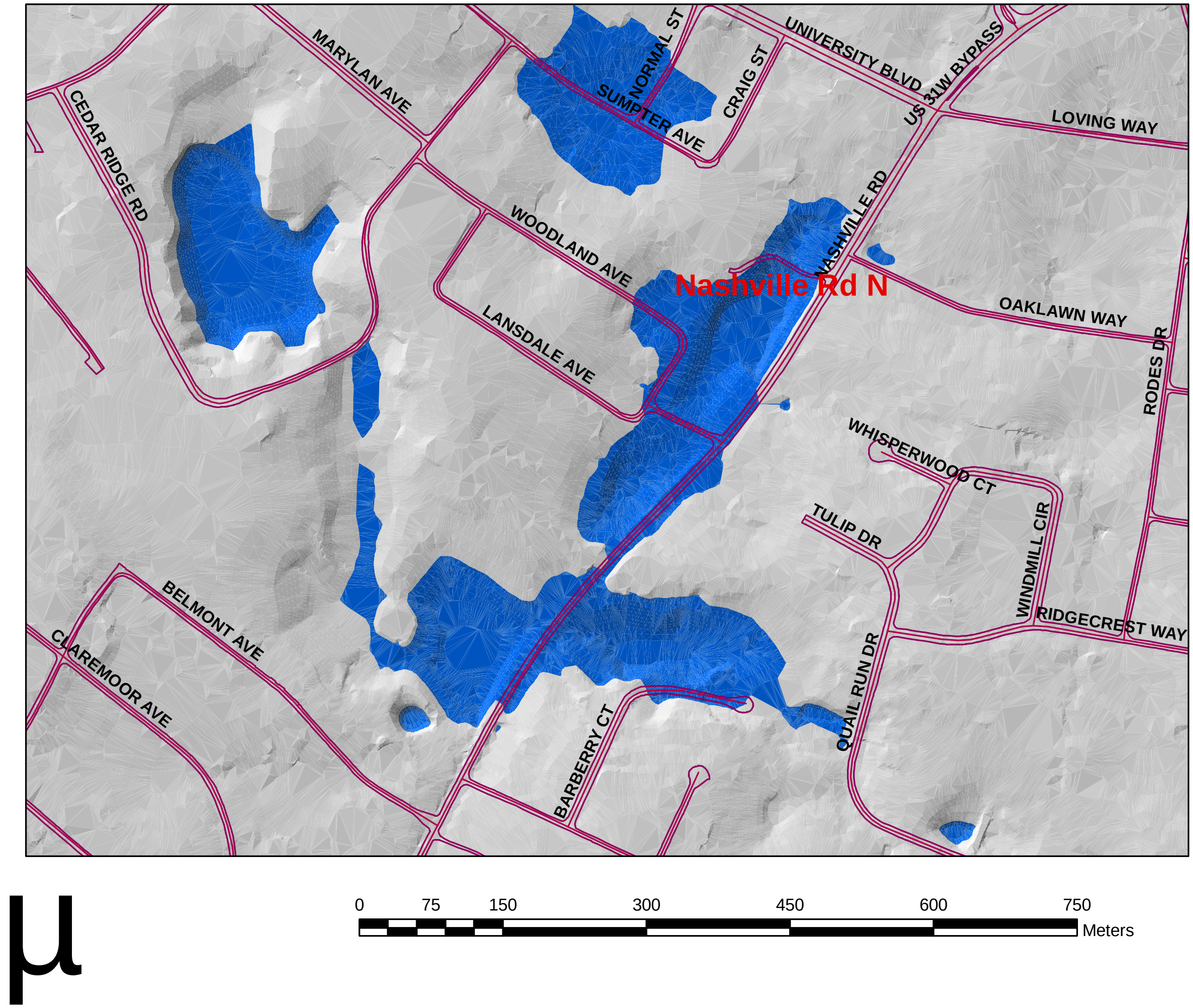

Figure 1. Nashville Road North with elevations below 145 m colored blue

A single TIN was made for the whole area from a topographic shape file. The 69sinkhole sub-basins were delineated and separated into single shape files. These files were used to clip the TIN. The clipped TINs were processed to obtain stage-storage (actually stage-area) relationships.

SWMM requires a parameter known as sub-basin width. An initial guess for this was obtained by drawing several flow lines in each sub-basin and finding the mean length of the lines. The area of the sub-basin is divided by this average length to obtain the width. SWMM also requires the mean slope of the sub-basin. 3D Analyst was used to obtain this value. Overflow from sinkhole to sinkhole was modeled as a broad-crested weir. The crest elevation of the weir was obtained from the process shown in Figure 1.

With the data inserted into the model, calibration was achieved using a storm that occurred on April 16, 1998. The rainfall came in three separate events that day. Between 4:00 AM and 7:00 AM, 34 mm (1.35 in) fell. Between 10:00 AM and 11:00 AM, 14 mm (0.52 in) fell. Then in the afternoon between 3:00 PM and 8:00 PM, 87 mm (3.4 in) fell accompanied by baseball-sized hail. The total rainfall for the day was 135 mm (5.31 in), but the maximum 3-hour total was only 76 mm (3.0 in). The 100-yr, 3-hr storm for Bowling Green is 100 mm (4.0 in). The question arose as to whether the entire total rainfall of 135 mm should be used for calibration or only a part of the total. On May 20, 2005, the Bowling Green area received 52 mm (2.1 in) of rainfall, most occurring in heavy thunderstorms just after midnight. During this storm, Nashville Road North experienced no ponding. Nearby uphill sinkholes also had little or no ponding. Based on these observations and the rainfall totals before noon on April 16, 1998, the decision was made to use only the afternoon rainfall for the calibration storm.

The calibration was completed by modifying two SWMM parameters governing depression storage. Depression storage is specified for both pervious and impervious areas. For forested areas, the SWMM manual recommended 1 mm (0.05 in) for impervious areas and 8 mm (0.3 in) maximum for forested areas. The values used to achieve calibration were 3 mm (0.1 in) and 13 mm (0.5 in), respectively. The higher values are justified because of the presence of numerous drainage wells in the area.

With these changes, excellent calibration was achieved when compared to a high water mark indicated by one of the residents. The elevation of this high water mark was obtained during the topographic survey of Nashville Road North. Unfortunately, the rainfall measurement was made for a site approximately 2.6 km away from the center of the watershed. Based on procedures suggested by the Natural Resources Conservation Service (NRCS 1993), the afternoon rainfall total for the calibration storm would with a 90 percent probability lie within the interval of 69-120 mm (2.7-4.8 in). Assuming that the calibrated model is accurate, and that the rainfall is known no better than this, then the uncertainty in the location of the inundation boundary would lie somewhere in the colored band shown in Figure 2. This translates into uncertainty in the location of the edge of the floodplain. If the April 1998 storm were the 100-yr storm, then either zero or fourteen buildings would lie within the floodplain. This is a large uncertainty and it does not account for inaccuracies in the model.

The purpose of the preceding discussion was not to destroy confidence in the watershed model. Rather, it was to illustrate the uncertainties that are commonly ignored in determination of flood insurance rates. These uncertainties are ignored with some justification. It is not feasible to ask that an insurance agent have a degree in engineering or geography to be able to set flood insurance rates for a house.

The model provided flood elevations as a function of time. The method of Figure 1 was applied for water surface elevations at 1 hour intervals during the storm. Using layout and adjusting the elevations appropriately, a sequence of water elevations were created using the map export capability in ArcGIS. Once created, the images were assembled into a looping GIS to produce an animation of the flood inundation.

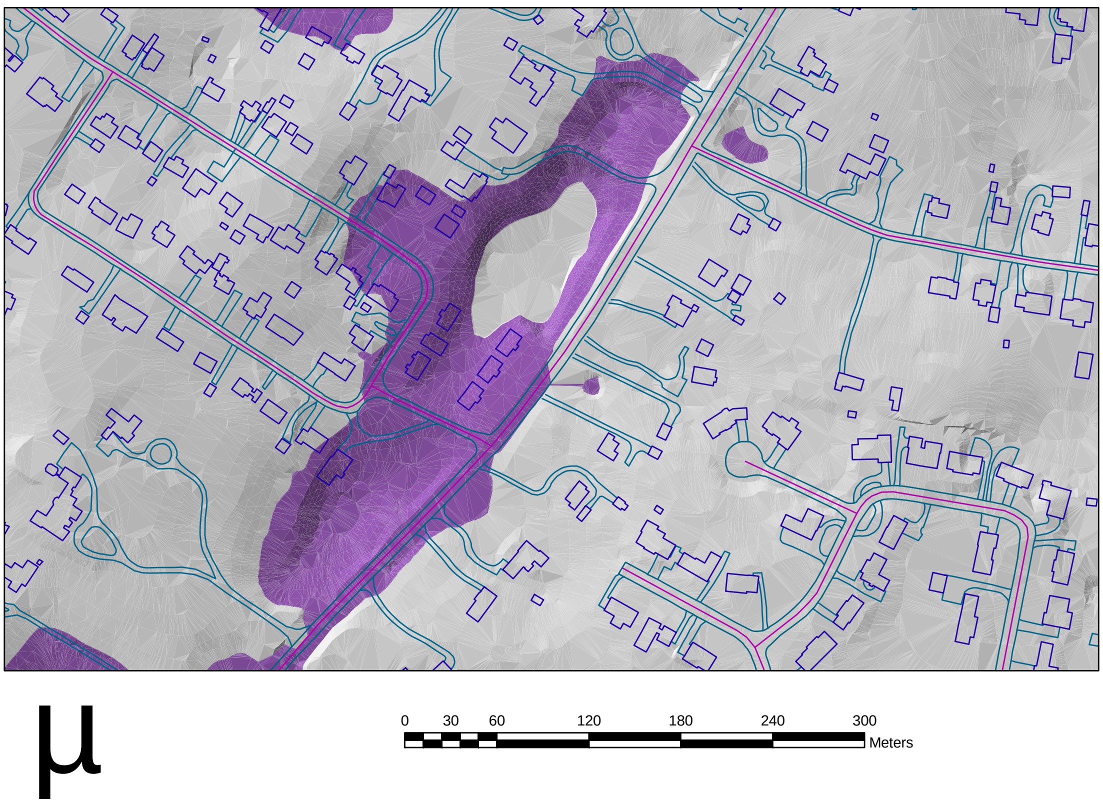

Figure 2. Uncertainty in the inundation boundary for the April 1998 storm

Summary

Flood mapping for complexes of sinkholes is complicated by spill-over from one sinkhole to the next. GIS was indispensable for the development of a watershed model of the site in Bowling Green, Kentucky. GIS was applied to obtain parameters and stage-storage relations for sinkholes and to develop runoff curve numbers for sinkhole catchments. Excellent model results were obtained for the calibration storm. However, the rainfall measurement for the storm came from a gage approximately 2.6 km from the center of the watershed. This introduces significant uncertainty in the calibration of the model and in the determination of flood zones. These uncertainties are, by necessity, always ignored in rating a building for flood insurance.

GIS provided many solutions in the development of the model. It was used to develop parameters for the model such as curve numbers, sub-basin areas, slopes, and stage-storage relations for sinkholes. It also provided a simple method to determine spill-over elevations. EPA's Storm Water Management Model (SWMM 5.0) was used to develop the model. The schematic of watersheds, sinkholes, weirs, and pipes was wired together based on GIS determination of hydraulic connections between sinkholes.

References

Federal Emergency Management Agency (1993). "Flood Insurance Study for Warren County, Kentucky and Incorporated Areas," 47pp.

Natural Resources Conservation Service (1993). *National Engineering Handbook, Part 630 Hydrology*, http://www.info.usda.gov/CED/ftp/CED/neh630-ch04.pdf (downloaded May 24, 2005), pp. 4- 6.