Using LiDAR Data to Map Depressions and Sinkholes in Mammoth Cave National Park

Makiko Shukunobe
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Introduction

Leveraging recent technology developments in remote sensing instruments and improved data handling capabilities of computer software, Light Detection and Ranging (LiDAR) data has become known for its accuracy, representing the state of the art in remote sensing data. Digital Elevation Models (DEM) derived from LiDAR data are now accurate up to 15 cm RMSE on open, flat, and hard surfaces (Hodgson and Bresnahan, 2004; Pereira and Janssen, 1999). Yet LiDAR data collection is still in its relative infancy, as only some States have entire or partial LiDAR data coverage, meaning the benefits of using LiDAR data is not yet widely available for research.

Recently, Mammoth Cave National Park obtained LiDAR data covering the entire park boundaries for the project “Joint Fire Science Program project 10-1-06-1, Fire and Foraging Habitat Quality for Endangered Bats in Kentucky’s Mammoth Cave National Park”. The primary purpose of collecting LiDAR data for Mammoth Cave National Park is to assist in protection for endangered bats. However, in addition, the resulting DEM derived from such LiDAR data also provides information potentially useful in identifying depressions and sinkholes commonly found in the park’s karst landscape (but not always visible to the naked eye). Mammoth Cave National Park generously shared LiDAR data for selected sections of the park, and this study created a high resolution DEM based on such data and then focused on identifying potential depressions and sinkholes on the ground surface.

Study site

Mammoth Cave National Park is located in Kentucky and has an area of approximately 52,830 acres (21,380 ha). The park is primarily located in Edmonson County, with small areas extending into Hart County and Barren County. The Nolin River flows from the northwest corner of the park and feeds into the Green River, which in turn flows towards the center of the park and then heads to the park’s north east corner (Figure 1). The Green River is recognized as having most biological diversity in the Ohio River system (USDA/FSA, 2010). However, such diverse fish and wildlife habitats are in danger because of harmful anthropogenic activities, such as altering natural flows by creating dams in order to control flooding and create recreation sites (The Nature Conservancy, 2012). Mammoth Cave National Park was established on July 1, 1941, designated a World Heritage Site on October 27, 1981, and on September 26, 1990 was established as an international Biosphere Reserve for purposes of conserving and protecting unique geological and hydrologic systems, fish, wildlife and archeological sites.

Figure 1 shows the three park study sites for which sample LiDAR data was provided by Mammoth Cave National Park: (a) Indian Hill, (b) Boardcut Island, and (c) near Mammoth Cave Rd.
Karst geomorphology

Mammoth Cave National Park is famous for being the longest cave network in the world, having more than 360 miles of surveyed underground passageways (National Park Service). The area’s karst landscape is a key element in the cave system’s creation, and understanding karst morphology, both ground level and subsurface, is necessary to, in turn, understand how the caves were formed (De Waele, Plan, and Audra, 2009). Karst landforms are developed on carbonate rocks, including limestone, dolostone, and marble (De Waele, Plan, and Audra, 2009). Indeed, about half of Kentucky geomorphology is limestone karst aquifers created from dissolution of soluble bedrocks, which also results in Kentucky being famous for its large number of caves with underground rivers and springs (Croskrey and Groves, 2008). Geology and karst maps for Mammoth Cave National Park are included in Appendix I and II, respectively. Currently, about 25 percent of Kentucky is defined as well-developed karst topology, in which type of topology caves can still potentially be developed over prolonged time periods (Currens, 2002). Mammoth Cave National Park includes just such a living karst landscape. Many scientists point out the critical importance of karst aquifers, noting their vulnerabilities associated with anthropologic activities. For instance, the ground water in karst areas is highly susceptible to contamination due to karst aquifers’ high permeability with minimal attenuation (Croskrey and Groves, 2008). Anthropogenic activities such as construction, agriculture, water collection, waste disposal and more alter both surface and subsurface karst morphology (De Waele, Plan, and Audra, 2009).

Biodiversity and Archaeological sites

Mammoth Cave National Park is also known for its diverse biodiversity, both underground and ground surface. There are over 200 species living in the park’s cave ecosystem, the majority of them being invertebrates indigenous to the park’s cave network (UNESCO). 42 cave species are adapted to live in total darkness (UNESCO). The surface features of Mammoth Cave National Park include the temperate deciduous forest known as Big
Woods, which is a relic of the ancient oak and hickory forests that once blanketed the region (UNESCO). Archaeological sites in the park identify four distinct pre-Columbian Indian cultures: palaeo-Indian, Archaic, Woodland and Mississippian (UNESCO). Notably, Early Woodland culture (2,200 to 3,000 years ago) marked the beginnings of organized agriculture in the Western Hemisphere and the start of organized mining of minerals in Mammoth Cave (UNESCO). Surface archaeological sites, which constitute the focus of the present inquiry, include Indian burial mounds (UNESCO).

Data

Relevant Mammoth Cave National Park LiDAR and DOQQ datasets were created in connection with the Mammoth Cave National Park project entitled “Joint Fire Science Program project 10-1-06-1, Fire and Foraging Habitat Quality for Endangered Bats in Kentucky’s Mammoth Cave National Park”. In connection with such project, LiDAR data was taken for the entire park, and such data was separated into 500 m × 500 m grid cells, resulting in a total 1,355 LiDAR data tiles. Sample data locations provided for the current depression and sinkhole analysis included Indian Hill (2 × 3 tiles), Boardcut Island (2 × 2 tiles) and an area near Mammoth Cave Road (1 × 3 tiles; for the near Mammoth Cave Road data). Other data used for the analysis were geology, known sinkhole and park boundary ESRI ArcGIS shapefiles that were obtained from the National Park Service website. The coordinate system used for the data was NAD 1983 UTM 16N unit in meters, and vertical datum was NAVD 1988.

Methods

Preprocessing LiDAR data

The LAS-formatted LiDAR data included a header file containing information such as the date on which the data was collected, projections, number of points/point density, classifications (such as ground, high vegetation and unclassified), and more. To obtain information for the LiDAR data, the open source software LAStools was used in order to extract the header file information, as well as for merging, filtering bare earth classified points and converting LAS-formatted data to an ASCII file format in order to import the data for each location into the GRASS GIS application. After merging the LiDAR data for each location, bare earth point density was observed in order to determine resolution for the DEM (Table 1), from which analysis it was concluded that creating a 1 meter resolution DEM would be sufficient for this initial observation.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Point density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Hill</td>
<td>15.09</td>
</tr>
<tr>
<td>Boardcut Island</td>
<td>14.82</td>
</tr>
<tr>
<td>Near Mammoth Cave Rd</td>
<td>15.09</td>
</tr>
</tbody>
</table>
DEM, depression filling and flow routing

First, a DEM needed to be created from provided point cloud LiDAR data. The ASCII formatted point cloud data for each location was imported to GRASS as 1 meter resolution raster data applying mean value to be a raster value (points falling within each 1 m × 1 m cell are averaged and assigned an average value to be the cell value). It is important to note is that when there is no point within a cell, a NULL value is assigned as a cell value. LiDAR point cloud data is not equally distributed so there are locations where no point exists in the data; therefore, an interpolation method need to be applied in order to assign appropriate values to NULL cells. This method is critical if locations requiring accurate information do not have any point data. Thus, where locations such as a sinkhole require accuracy, the data resolution must again be considered. For this analysis, spline with high tension parameter was selected in order to create a smooth surfaced DEM and to make landscape details visible with 3D visualization (Figure 2).

**Figure 2.** 1-m resolution DEM shown in 3D

![3D DEM](image)

a. Indian Hill  
b. Boardcut Island  
c. Near Mammoth Cave Rd

The second step was identifying depressions in the created DEM by applying a filling algorithm. For this analysis, near Mammoth Cave Rd (0.75 km²) was selected since the location displays more highly developed karst terrain than the other two locations. The algorithm
identifies depressions and then fills such depressions in the DEM; thereafter, the resulting filled DEM data must be subtracted from the original DEM so as to only show depressions. The resulting raster data was converted to polygon vector data and overlaid to DOQQ to examine sinkholes that can be identified from the DOQQ image. Finally, flow routing was tested applying the multiple flow direction (MFD) method. MFD uses all neighboring cells to compute flow direction instead of the steepest single downslope cell. Therefore, more natural accumulation of water flow can be observed rather than single accumulated flow.

Results

The resulting data for depressions and sinkholes identified using DEM-derived from LiDAR data are shown in red and National Park Service (NPS) sinkholes data is shown in blue (Figure 3). Since detailed metadata for the NPS sinkhole data was not available, the method used by NPS to identify sinkholes in 2007 is unknown. Therefore, the reason for differences between newly created depressions and sinkholes and NPS known sinkholes data cannot be explained. It could be that the karst landscape has further developed in past 5 years or that NPS used a different approach for delineating sinkholes.

Figure 3. a. DEM, and b. Depressions and Sinkholes (200% vertical exaggeration)
The 200 percent vertically exaggerated DEM (Figure 3a) displays flat floors with elongated or circle-shaped depressions surrounded by steeper slopes, which feature vessel like shapes, while some of depressions have black dotted sinkholes within the depressions. Such features can be also observed in the slope map in Figure 4. The slope map is not as exaggerated as the DEM shown in Figure 3, yet the magnitude of slope (steeper the slope colored magenta to red), clearly displays depressions and sinkholes in the same manner. Figure 4 shows an orthophoto with depressions and sinkholes data derived from the DEM overlaid for comparison purposes to see if such depressed features can be identified from the aerial photograph. It may be possible to recognize closed depressions; however, the aerial photograph was insufficient for this specific location since the study sought detailed information for depressions and sinkholes that the photo simply cannot provide. Sinkholes have the potential to be an entrance for contaminated surface water into the underground aquifer; therefore, the water flow direction modeling is advantageous in order to recognize any water contamination factors. The water flow direction can be intuitively observed in the aspect map shown in Figure 4 (north: yellow to green, west: cyan, south: red, east: orange).

**Figure 4.** Slope and aspect maps derived from DEM
Figure 5. Orthophoto with depressions and sinkholes data overlay

For the hydrologic model, the resulting data of the multiple flow direction (MFD) is shown in Figure 6a. As can be seen in red in Figure 6a, the watershed shown does not conform to what one would expect based on experience. This is due to the complex karst ground surface, especially its discontinuous and highly varied ground surface features, with numerous subsurface openings of various sizes that complicate the analysis and prevent the GIS application from adequately performing watershed delineation (La Valle, 1968). An analogy to this watershed delineation problem is also often observed on flow accumulation analyses performed using GIS applications. The Figure 6b bounding box shows connected flow accumulation which does not occur in nature since the flow accumulation on the centered ridge is supposed to flow opposite directions, but GIS application attempts to connect the flow accumulation. Such difficulty is not only observed in the watershed, but also water flow directions. Considering both the karst landscape and GIS operations, hydrologic analysis unfortunately cannot in this case accurately represent hydrologic modeling including watershed delineation, flow direction and flow accumulation.
Figure 6.
Flow accumulation computed using MFD method (DEM is 200 percent exaggerated vertically).

a. MFD showing in blue and created watershed in red color
b. Zoomed view of ‘a’ (1 and 2 are sinkholes).
c. The elevation profile for the largest sinkhole found in the site (left) and sinkhole (right).
However, it still is useful for observing a small depression or sinkhole as a unit. For example, circled locations 1 and 2 in Figure 6b display clear water flow directions downslope in a depression and ground water eventually reaches to the sinkholes. This is valuable to measure the area that contributes to water contamination and thus a potential connection to underground water. Figure 6c displays the largest sinkhole in the study site. The elevation profile indicates a sinkhole width of about 10 meters and a depth of about 7 meters. Of course, conclusively identifying this feature requires field investigation to examine whether the DEM created from LiDAR data truly represents what is in fact a sinkhole on the ground.

By using both depressions and sinkholes and flow accumulation data, potential water flow (Figure 7a) and alignment of sinkholes (Figure 7b) can be determined. Most of the Mammoth Cave National Park surface area is forested, so in order to observe terrain features in the field, high resolution DEM works well. Potential water flows (Figure 7a) that pass through under the Mammoth Cave Rd could not observed on Google Earth, yet if ground-truthing prove their existence, this will help ensure the accuracy and usability of DEM. Figure 7b shows aligned sinkholes. This may indicate actual ground water flow, but as Lindsey and et al note, the complex karst surface topography ensures it commonly does not reflect the direction of groundwater flow (2010). Nevertheless, the potential water flow shown may remain accurate.

**Figure 7.**
Flow accumulation computed using MFD method with depressions and sinkholes data overlay (DEM is 200 percent exaggerated vertically).

a. Potential water flow under the road
b. Aligned sinkholes

- **Depressions and sinkholes**
Conclusion

This study conducted usability of LiDAR data to map depressions and sinkholes with hydrologic examination to observe surface water flow in large scale. Despite having a highly accurate DEM, it may still contain errors associated with vertical measurement, as well as classification or labeling errors (Hodgson and Bresnahan, 2004). The vertical error concern is often associated with steep slopes and irregular shapes, both of which features are indicative of depressions and sinkholes and, along with can canopy cover can cause inaccurate measurement. In addition, there could be not enough LiDAR data point coverage around a depression or sinkhole area to properly identify such feature. In this case, interpolation errors will be concern. Therefore, to verify the accuracy of a created DEM, field reconnaissance is required. According to Hubbard, sinkholes and depressions are easy to recognize with the digitized 1:24,000 scale topographic maps and also 6-m contour maps, yet with field reconnaissance, ten times more sinkholes and depressions potentially be found (2003). However, with recent technology improvements, LiDAR data can potentially provide more detailed information than field reconnaissance data; in fact, Lindsey and et al state that LiDAR data may be useful to define sinkholes with detail (2010).

There are many studies conducted relating to water contamination in karst geomorphology – such as sinkholes and depressions density, land use, wells, nonpoint source pollutions, and chemical dissolution of bedrock. It is because karst morphology is sensitive and vulnerable to any changes such as chemicals in the water, surface water flow volume, flow speed and air pollution, any of these could easily affect water quality in karst regions. Especially given Mammoth Cave National Park's unique biodiversity and ecosystem, it is very important to ensure water quality. Identifying density, orientations, size, depth, opened or closed depressions and sinkholes with surface water flow direction will be useful to trace source of water contaminants in order to formulate an optimal ground water protection plan. Ensuring a healthy habitat for park wildlife is one of the most important duties imposed upon Mammoth Cave National Park. Efficient use of LiDAR data will be able to assist in providing productive management of the park by increasing knowledge of park geology and other matters.
References

http://www.nps.gov/maca/naturescience/cave.htm


Currens, J. (2002). Kentucky is karst country! What you should know about sinkholes and springs. Should Know about Sinkholes and Springs Kentucky.


http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/kentucky/placesw eprotect/green-river.xml


http://whc.unesco.org/en/list/150
Appendix

I. NPS Geology map with study sites overlay

Source: National Park Service
II. 30 m resolution DEM with karst and sinkholes overlay

Data and software

National Park Service: http://www.nps.gov/gis/
LAStools: http://www.cs.unc.edu/~isenburg/lastools/
GRASS GIS
ESRI ArcGIS