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Potential Sinkhole Identification with Light Detection and Ranging (LiDAR) Data at Fort Leonard Wood, MO

Scott A. Tweddale

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Potential Sinkhole Identification with Light Detection and Ranging (LiDAR) Data at Fort Leonard Wood, MO

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Abstract

This work used a bare-earth Digital Elevation Model (DEM) derived from airborne Light Detection and Ranging (LiDAR) data to identify potential sinkholes at Fort Leonard Wood, MO using Geographic Information Systems (GIS) algorithms. Potential sinkholes identified in the DEM were compared with known sinkhole locations to evaluate the utility of the 60cm spatial resolution bare-earth DEM as a tool for identifying potential sinkholes. Initially, 30 of 34 known sinkholes were correctly identified using the 60cm LiDAR-derived DEM with no size limit on the sinkholes and no depth threshold. With this size and depth threshold, a total of total of 973,875 potential sinkholes were identified in the study area ($\sim 32\text{km}^2$). Minimum size and depth thresholds for detected sinkholes were incrementally adjusted to become more restrictive while not sacrificing accuracy, resulting in the detection of fewer sinkholes, which in turn, reduced the likelihood of false positives. A final sinkhole size threshold of 27m^2 and depth threshold of 23cm were determined to be optimal. Using these thresholds, the tool identified 29 of 34 known sinkholes and 2,694 potential sinkholes. The same procedures were tested using 5m and 10m spatial resolution DEMs as input, but detection accuracies were significantly lower.

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Preface

This study was conducted for the U.S. Army Garrison Fort Leonard Wood, Plans, Analysis, and Integration Office (PAIO) under Project F57BBJ, “Potential Sinkhole Identification.” The technical monitor was Bryan Parker, Director, Fort Leonard Wood PAIO.

The work was performed by the Ecological Processes Branch (CNN) of the Installations Division (CN), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). Special acknowledgement is owed to James Westervelt, Susan Bevelheimer, and Annette Stumpf for their help in the formulation and execution of this project. Lester Trigg, of Fort Leonard Wood, provided a GIS layer of known sinkholes that was used for accuracy assessment. At the time of publication, Chris Rewerts was Chief, CEERD-CNN; Michelle Hanson was Chief, CEERD-CN; and Alan Anderson, CEERD-CZT was the Technical Director for Military Lands. The Deputy Director of ERDC-CERL was Dr. Kiran-kumar V. Topudurti and the Director was Dr. Lance D. Hansen.

COL Bryan S. Green was the Commander of ERDC, and Dr. David Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
feet	0.3048	meters
inches	2.54	centimeters
square feet	0.09290304	square meters

Acronyms and Abbreviations

Term	Definition
AGC	U.S. Army Geospatial Center
AGU	American Geophysical Union
ALSM	Airborne Laser Swath Mapping
ANSI	American National Standards Institute
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (Global Digital Elevation Model)
CAC	Common Access Card
CERL	Construction Engineering Research Laboratory
CON	Conditional
DEM	Digital Elevation Model
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
ESRI	Environmental Systems Research Institute, Inc.
FIU	Florida International University
GIS	Geographic Information System
GPR	Ground-Penetrating Radar
IFSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
LIDAR	Light Detection and Ranging
MSDIS	Missouri Spatial Data Information Service
NAIP	National Agriculture Imagery Program
NCKRI	National Cave and Karst Research Institute (NCKRI)
NHD	National Hydrography Dataset
NSN	National Supply Number
OMB	Office of Management and Budget
PAIO	Plans, Analysis, and Integration Office
PLOS	Public Library of Science
RTV	Rapid Terrain Visualization
SAR	Same As Report
SF	Standard Form
SRTM	Shuttle Radar Topography Mission
TR	Technical Report
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984

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1 Introduction

1.1 Background

Sinkholes are depressed or collapsed areas formed when rainwater slowly dissolves carbonate bedrock, forming underlying caves that cause surface material to sink or collapse. Sinkholes are part of what is known as “karst topography” (Ford and Williams 1989).

Much of the state of Missouri, particularly in the southern half of the state, is underlain with carbonate bedrock, which makes the region highly susceptible to sinkholes. The Missouri Department of Natural Resources Geological survey program has verified 15,981 sinkholes in Missouri (Missouri Dept. of Natural Resources 2017). Fort Leonard Wood, MO has many sinkholes, and it is suspected that many more exist that have not been identified or reported. Newly developing sinkholes may be especially difficult to identify because the depression, which may have just recently started to subside, would not be obvious to a casual observer. This is especially true if the depression is large enough in circumference that an observer on the ground cannot see the entire extent of the sinkhole.

This work was undertaken to evaluate the use of Light Detection and Ranging (LiDAR) data and Geographic Information Systems (GIS) algorithms in identifying sinkholes at Fort Leonard Wood. This is an important mission, since sinkholes comprise a potential safety hazard and can cause major damage to infrastructure if they collapse. In addition, they can serve as conduits for surface water to rapidly infiltrate into the underlying groundwater aquifer, and pollute drinking water supplies (Mukherjee and Zachos 2012, Miao et al. 2013).

1.2 Objective

The objective of this project was to evaluate the utility of LiDAR data and Geographic Information Systems (GIS) algorithms for delineating potential sinkholes at Fort Leonard Wood, MO.

1.3 Approach

An existing bare-earth Digital Elevation Model (DEM) (60cm spatial resolution) derived from airborne LiDAR data collected in 2010 were acquired for

Fort Leonard Wood. Potential sinkholes, or depressions in the DEM that drain rainwater inward, were identified using GIS algorithms. Potential sinkholes identified in the DEM were compared with known sinkhole locations to evaluate the utility of LiDAR-derived bare-earth DEMs as a tool for identifying potential sinkholes. DEMs at 5m and 10m spatial resolution were also acquired for Fort Leonard Wood and processed with the same algorithms to compare their utility with the 60cm DEM derived from LiDAR data.

2 Sinkhole Identification Methods

Traditional mapping of depressions or potential sinkholes has been done using a GIS to digitize closed depressions on topographic maps with contours (Angel et al. 2004, Seale et al. 2007). These methods are tedious and labor intensive, and the process typically misses shallow and small sinkholes. Moreover, some topographic maps used in this method are 40 to 50 years old. Alternative methods have included manual, visual interpretation of aerial photographs and satellite imagery (Wilson 2004, Ernst et al. 2010, Dinger et al. 2007). These methods are also tedious and labor intensive, and typically miss shallow and small sinkholes. Once LiDAR data became more commonly available, high resolution LiDAR-derived DEMs have been manually and visually evaluated to delineate potential sinkholes (Montane 2001, Doctor and Young 2013). Although these methods were more time efficient than manually digitizing closed depressions on contour maps, they were prone to subjective errors by the analyst.

Several different automated methods have attempted to use LiDAR-derived DEMs for automated sinkhole identification. A combination of an adaptive Wiener filter, a hierarchical watershed segmentation and hole-filling process, followed by a random forest classifier were applied to LiDAR data to successfully identify potential sinkholes in the Nixa Karst Plain in Southwest Missouri (Miao et al. 2013). Image processing techniques, including a morphological operation and depth filter, were used to automate a sinkhole identification process in Winona County, MN (Rahimi and Alexander 2013). An automated approach to sinkhole identification under forest canopy highlighted the ability of LiDAR to penetrate vegetation canopies and detect forested karst sinkholes in Slovenia (Kobal et al. 2015). Filan et al. (2011) used LiDAR-derived DEMs to identify small, embryonic sinkholes near the Dead Sea.

The most commonly implemented automated approach for identifying potential sinkholes has been to use a “fill” algorithm in a GIS to fill depressions in a DEM to their pour point. The original DEM is then subtracted from the “filled” DEM to identify potential sinkholes and characterize their depth (Antonic et al. 2001, Siart et al. 2009, Anders et al. 2011, Doctor and Young 2013, Mukherjee and Zachos 2012, Zhu et al. 2014). This final method was adopted for use in this study.

3 Methods

3.1 Data acquisition

Airborne LiDAR data were collected for Fort Leonard Wood in April 2010 by the U.S. Army Geospatial Center (AGC) as part of the Rapid Terrain Visualization (RTV) project. Using proprietary LiDAR processing algorithms in TerraScan software, a bare-earth DEM was created from the LiDAR point cloud by AGC for Fort Leonard Wood, MO at 60cm spatial resolution. The data were developed using Universal Transverse Mercator (UTM) projection and World Geodetic System 1984 (WGS84) G1150 ellipsoid for both the horizontal and vertical datums. Accuracies were approximately 0.5m CE90 absolute horizontal and 0.3m LE90 absolute vertical. The data were acquired by CERL from AGC's Common Access Card (CAC)-enabled Data Doors online data library (<http://agc.datadoors.net/dd3/>).

In the process of searching for and acquiring a LiDAR-derived bare-earth DEM for Fort Leonard Wood, a 5m spatial resolution bare-earth DEM derived from Interferometric Synthetic Aperture Radar (IFSAR) data by Intermap (www.intermap.com) was discovered for Fort Leonard Wood in the Data Doors online data library. A 10m spatial resolution bare-earth DEM derived from softcopy photogrammetry as part of the National Elevation Dataset was also discovered for Fort Leonard Wood on the Missouri Spatial Data Information Service (MSDIS) Geoportal: <http://msdis.missouri.edu/data/10mDEM/springfielde-37092.html>

These additional DEMs were downloaded from the AGC Data Doors online data library and the MSDIS Geoportal for comparison purposes with the LiDAR-derived DEM.

A GIS data layer that delineated known depressions at Fort Leonard Wood was provided by Fort Leonard Wood staff and used as ground truth for assessing GIS algorithms for identifying potential sinkholes. The known sinkholes database was validated in the field by Fort Leonard Wood staff.

A GIS data layer delineating hydrographic features (streams and lakes) on Fort Leonard Wood was downloaded from the National Hydrography Dataset (<https://nhd.usgs.gov/data.html>).

3.2 Study area

CERL digitized an approximately 4x8km study area, centered on the Fort Leonard Wood cantonment area, that had been verbally described by the Fort Leonard Wood project sponsor. The 34 known depressions/sinkholes in the study area were used as ground truth (Figure 1).

Figure 1. Fort Leonard Wood study area outlined in red with known sinkholes identified with green points.

3.3 Data preprocessing

All data preprocessing and analysis were done using Environmental Systems Research Institute (ESRI) ArcGIS version 10.4.1 for desktop. There were a total of four bare-earth DEM individual tiles derived from LiDAR data (60cm) that covered the study area. The four individual tiles were mosaicked into a single file and were georeferenced to a NAD_1983_UTM_Zone_15N projection/coordinate system using a bilinear resampling technique in ArcGIS. The mosaicked and georeferenced bare-earth DEM was then clipped to the study area.

Similarly, there were four bare-earth DEM individual tiles derived from IFSAR data (5m) that were mosaicked, georeferenced, and clipped to the study area. Likewise, there were four bare-earth DEM individual tiles derived from softcopy photogrammetry (10m) that were also mosaicked, georeferenced, and clipped to the study area.

For comparison purposes, Figure 2 shows a bare-earth DEM from each of the spatial resolutions (60cm, 5m, 10m) displayed for a known depression/sinkhole.

Figure 2. Bare-earth DEM for a known sinkhole at 60cm (left), 5m (center) and 10m (right).

3.4 Data analysis

3.4.1 Fill algorithm

A “Fill” algorithm in the ArcGIS Spatial Analyst/Hydrology toolbox was run on the bare-earth DEMs for each of the spatial resolutions. The ArcGIS “Fill” algorithm uses the equivalent of several geoprocessing tools, such as Focal Flow, Flow Direction, Sink, Watershed, and Zonal Fill to locate and fill sinks in a DEM (<http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/fill.htm>). A sink is a cell in a DEM that does not drain to a neighboring cell. In other words, it is a depression in the DEM surface where no cells surrounding a sink cell are lower. The “Fill” algorithm fills sinks up to their pour point. The pour point is the point where water would pour out of the sink if it were filled with water. The “Fill” algorithm has a “z-limit” setting which determines which sinks will be filled. The “z-limit” is the maximum difference between the depth of the sink and the pour point. In this analysis, a “z-limit” of 10m was specified.

3.4.2 Identification of potential sinkholes

A multi-step process in ArcGIS was executed to identify potential sinkholes and estimate their size and depth. First, the bare-earth DEM was subtracted from the output DEM derived from the Fill algorithm described in Section 3.4.1. This resulted in a raster map in which all values > 0 represented a depth of a depression in meters. All values ≤ 0 were set to Null or No Data in the map using the Setnull function in the Raster Calculator tool in the Map Algebra toolbox under Spatial Analyst Tools.

Since the output from the DEM subtraction process and Setnull process resulted in floating point values for the individual pixels, the Int function in the Raster Calculator tool was used to convert the floating point values to integers. The Int function truncates pixel values when converting to integers. Therefore, the output from the Int function was evaluated using a conditional or CON function in the Raster Calculator tool to assign any pixel value ≥ 0 to a pixel value = 1, resulting in a binary, integer raster map where pixel values for depressions were equal to 1, and non-depressions were assigned to Null or No Data category. The output raster layer from the CON function was then input to the Raster to Feature tool, resulting in a vector feature class delineating all potential sinkholes. The same process was repeated for each of the spatial resolutions of DEMs (60cm, 5m, 10m) that were available

3.4.3 Area and depth filtering

To eliminate some of the small depressions identified from the 60cm LiDAR data that were not likely to be sinkholes, a size and depth threshold was used as a filter. Based on input from the Fort Leonard Wood project sponsor, a size of 50 ft in diameter (approx. 182m²) and 50cm depth were established as thresholds, meaning that any depression identified by the fill algorithm that was less than this size or depth was eliminated. In addition to unfiltered data and filters of 182m² in size and 50cm in depth, depth filters of 10cm and 25cm were also tested. Every unique combination of size and depth filter was tested for each different spatial resolution of DEM.

It was necessary to filter for size first, followed by depth. To implement a size threshold of 182m², an “Area” field was added to the vector map of potential sinkholes that was created from the Raster to Feature tool described in Section 3.4.2. The “Calculate Geometry” function was used to calculate the area of each potential sinkhole. Those potential sinkholes > 182m² in size were selected and exported to a new vector feature class.

A “MAX_DEPTH” field was added to both the unfiltered potential sinkholes feature class and the potential sinkholes > 182m² feature class. Using these feature classes as “feature zone data” and the raster created from the Setnull process described in Section 3.4.2 as the “input value raster” and selecting “Maximum” as the “Statistics type” in the “Zonal Statistics as Table” function, an output table was created with a record for each potential sinkhole along with their maximum depth. This table was joined to the unfiltered potential sinkholes feature class and the potential sinkholes

>182m² feature class and the “MAX_DEPTH” field was populated. In summary, a total of eight feature classes was created for each of the three spatial resolutions of DEMs that were tested (Table 1).

Table 1. Eight different size and depth filter combinations originally tested for each spatial resolution of DEMs.

Size Filter	Depth Filter
None	None
None	10cm
None	25cm
None	50cm
182m ²	None
182m ²	10cm
182m ²	25cm
182m ²	50cm

3.4.4 Accuracy assessment

A GIS data layer that delineated known sinkholes from Fort Leonard Wood was used as ground truth for assessing the accuracy of the GIS algorithms described above for identifying potential sinkholes. For each unique combination of size filter, depth filter, and DEM spatial resolution, the feature class delineating potential sinkholes was overlaid on the ground truth layer of known sinkholes. The number of known sinkholes (34 total) that were correctly identified by the potential sinkhole feature class were visually examined and tabulated for each unique combination of size filter, depth filter, and DEM spatial resolution. Due to the differences in spatial resolution among the three different DEMs that were tested, there was not a perfect co-registration between the potential sinkholes and known sinkholes. In addition, the known sinkhole GIS layer provided by Fort Leonard Wood was a point file rather than a polygon file. Therefore, a correct sinkhole identification was defined as any instance in which an estimated sinkhole overlapped a 2-ft contour indicating a depression associated with the sinkhole. Figure 3 shows an example of this assessment.

Figure 3. Example of visual comparison between known and potential sinkholes. In this example, the known sinkhole would be labeled as correctly identified.

4 Results

Tables 2 to 4 summarize the accuracy assessment results for all unique size filter, depth filter, and spatial resolution combinations originally tested. Using the LiDAR-derived bare-earth DEM (60cm) without any size or depth filters, 973,875 potential sinkholes were identified in the study area, and 30 of the 34 known sinkholes were correctly identified (Table 2). The high number of potential sinkholes identified with the LiDAR-derived DEM was not unexpected and emphasizes the need to establish minimum area and depth filters when attempting to identify potential sinkholes.

Adding a depth threshold of 10cm still resulted in the correct identification of 30 of 34 known sinkholes while significantly reducing the total number of potential sinkholes from 973,875 to 51,897. Increasing the depth threshold to 25cm and 50cm resulted in fewer potential sinkholes, but also reduced the number of correctly identified sinkholes (27). Once a size threshold of 182m² was applied, only 20 of 34 known sinkholes were correctly identified across the entire range of depth thresholds that were tested, including the 182m² size and 50cm depth threshold suggested by the project sponsor.

Using the 5m spatial resolution DEM without any size or depth filters resulted in the identification of significantly fewer potential sinkholes (815), but also the identification of only nine of 34 known sinkholes (Table 3). Only nine of 34 known sinkholes were correctly identified for most of the size and depth filter combinations, with the exception of the 50cm depth threshold, in which the number of correctly identified sinkholes fell to seven.

Using the 10m spatial resolution DEM without any size or depth filters resulted in the identification of 406 potential sinkholes, and the correct identification of only 11 of 34 known sinkholes (Table 4). Increasing the depth threshold resulted in the correct identification of fewer known sinkholes. Using the size and depth thresholds suggested by the project sponsor (182m² and 50cm) resulted in the correct identification of only five of 34 known sinkholes.

Based on the accuracy assessment results for all unique size filter, depth filter, and spatial resolution combinations, it was clear that results derived from the 60cm LiDAR-derived DEM were significantly better than those derived from the 5m and 10m DEMs. Using the 60cm DEM, accuracies

ranged from 88 to 79% accurate with no size threshold and varying depth thresholds. However, once a size threshold was implemented, accuracies dropped off to 59% for all depth thresholds.

Table 2. Sinkhole identification accuracy using 60cm DEM with size thresholds of none and 182m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No size or depth filter	30	4	88	973875
No size and 10cm depth filter	30	4	88	51897
No size and 25cm depth filter	27	7	79	7031
No size and 50cm depth filter	27	7	79	1017
No depth filter and >182m ²	20	14	59	709
10cm depth filter and >182m ²	20	14	59	703
25cm depth filter and >182m ²	20	14	59	629
50cm depth filter and >182m ²	20	14	59	441

Table 3. Sinkhole identification accuracy using 5m DEM with size thresholds of none and 182m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No size or depth filter	9	25	26	815
No size and 10cm depth filter	9	25	26	350
No size and 25cm depth filter	9	25	26	193
No size and 50cm depth filter	7	27	21	88
No depth filter and >182m ²	9	25	26	400
10cm depth filter and >182m ²	9	25	26	315
25cm depth filter and >182m ²	9	25	26	191
50cm depth filter and >182m ²	7	27	21	88

Table 4. Sinkhole identification accuracy using 10m DEM with size thresholds of none and 182m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No size or depth filter	11	23	32	406
No size and 10cm depth filter	10	24	29	169
No size and 25cm depth filter	9	25	26	74
No size and 50cm depth filter	5	29	15	34

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No depth filter and >182m ²	10	24	29	237
10cm depth filter and >182m ²	10	24	29	146
25cm depth filter and >182m ²	9	25	26	72
50cm depth filter and >182m ²	5	29	15	34

As the results indicate, as size and depth thresholds become more restrictive, the accuracy decreases. However, as size and depth thresholds become more restrictive, the total number of potential sinkholes also decreases, which decreases the likelihood of false positives. Therefore, there is a trade-off between increased accuracy and the likelihood of false positives.

Since there was a significant decrease in accuracy when using no size threshold vs. implementing a 182m² size threshold, additional size thresholds were tested. The GIS layer of known sinkholes provided by Fort Leonard Wood included a size attribute for each known sinkhole. Sizes ranged from 0.003 acres (approx. 12m²) to 21.14 acres (approx. 85,550m²). Only four of the known sinkholes in the study area were greater than 1 acre in size. Therefore, a size threshold of 12m² was tested and increased by 12m² increments to identify an optimal combination of size and depth threshold that was accurate and that also resulted in the least number of potential sinkholes. Tables 5 to 7 summarize the accuracy assessment results for size thresholds of 12m², 24m², and 36m², each with depth thresholds on none, 10cm, 25cm, and 50cm.

Table 5. Sinkhole identification accuracy using 60cm DEM with a size threshold of 12m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No depth filter and >12m ²	29	5	85	15,647
10cm depth filter and >12m ²	29	5	85	10,990
25cm depth filter and >12m ²	29	5	85	4248
50cm depth filter and >12m ²	27	7	79	988

Table 6. Sinkhole identification accuracy using 60cm DEM with a size threshold of 24m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No depth filter and >24m ²	29	5	85	6,030
10cm depth filter and >24m ²	29	5	85	4,969
25cm depth filter and >24m ²	28	6	82	2,691
50cm depth filter and >24m ²	27	7	79	920

Table 7. Sinkhole identification accuracy using 60cm DEM with a size threshold of 36m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No depth filter and >36m ²	27	7	79	3,620
10cm depth filter and >36m ²	27	7	79	3,201
25cm depth filter and >36m ²	27	7	79	2,007
50cm depth filter and >36m ²	26	8	76	850

Using 12m² as a size threshold, 29 of 34 known sinkholes were identified with depth thresholds of none, 10cm, and 25cm. Only 27 of 34 known sinkholes were identified when the depth threshold was increased to 50cm (Table 5). The size threshold was increased another 12m² to 24m². At this size threshold, 29 of 34 known sinkholes were still identified with depth thresholds of none and 10cm (Table 6). Therefore, the size threshold was increased another 12m² to 36m². At this size threshold, only 27 of 34 known sinkholes were identified with depth thresholds of none, 10cm and 25cm (Table 7).

Since the accuracy dropped when increasing the size threshold to 36m², the size threshold was decreased to 30m². At this size threshold, only 27 of 34 known sinkholes were identified (Table 8). Finally, the size threshold was decreased to 27m². At this size threshold, the accuracy remained high, with 29 of 34 known sinkholes identified with depth thresholds of none and 10cm. At the 10cm depth threshold, a total of 4,374 potential sinkholes were identified (Table 9). When the depth threshold was increased to 25cm, the accuracy went down slightly, but the number of potential sinkholes fell to 2,498. Therefore, while holding the size threshold constant at 27m², depth thresholds of 18cm, 20cm, and 23cm were evaluated (Table 10). The sinkhole detection accuracy remained the same for all three of

these depth filters. Since the accuracy decreased when the depth filter was set to 25cm, a final size filter of 27m² and a final depth filter of 23cm was identified as the optimal combination for identifying sinkholes at Fort Leonard Wood. A total of 2,694 potential sinkholes were identified in the study area using this combination.

Table 8. Sinkhole identification accuracy using 60cm DEM with a size threshold of 30m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No depth filter and >30m ²	27	7	79	6,030
10cm depth filter and >30m ²	27	7	79	4,969
25cm depth filter and >30m ²	27	7	79	2,691
50cm depth filter and >30m ²	26	8	76	920

Table 9. Sinkhole identification accuracy using 60cm DEM with a size threshold of 27m² and depth thresholds of none, 10cm, 25cm, and 50cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
No depth filter and >27m ²	29	5	85	5,203
10cm depth filter and >27m ²	29	5	85	4,374
25cm depth filter and >27m ²	28	6	82	2,498
50cm depth filter and >27m ²	27	7	79	907

Table 10. Sinkhole identification accuracy using 60cm DEM with a size threshold of 27m² and depth thresholds of 18cm, 20cm, and 23cm.

	Known Sinkholes Correctly Identified with DEM	Known Sinkholes Not Identified with DEM	% Accuracy	Number of Potential Sinkholes Identified
18cm depth filter and >27m ²	29	5	85	3,309
20cm depth filter and >27m ²	29	5	85	3,058
23cm depth filter and >27m ²	29	5	85	2,694

As requested by the Fort Leonard Wood project sponsor, potential sinkholes associated with drainage features (i.e., streams and lakes) were identified separately from potential sinkholes not associated with drainage features. Using the National Hydrography Datasets, the “NHD_Flowline” GIS data layer was used to identify streams and the “NHD_Waterbody” GIS data layer was used to identify lakes. To identify those potential sinkholes

associated with drainage features, the “select by location” tool was used to identify all potential sinkholes identified with a size threshold of 27m² and a depth threshold of 23cm that intersected drainage features (streams and lakes) or were within 5m of drainage features. Of the 2,694 potential sinkholes identified, 190 intersected drainage features and an additional 128 were within 5m of drainage features. All of the remaining potential sinkholes were visually assessed and those that were obvious false positives (e.g., on building rooftops) were removed. A total of 291 false positives were removed, resulting in 2085 potential sinkholes and 318 potential sinkholes in drainages. There are likely many more false positives that were not removed as part of the manual editing process. For example, many of the potential sinkholes appear to be road side ditches. These were left in the final potential sinkhole feature class intentionally so that they could be evaluated by Fort Leonard Wood staff. For reference, Figure 4 shows a final map showing potential sinkholes and potential sinkholes intersecting drainage overlaid on 2-ft resolution aerial photography collected 02 April 2007.

Figure 4. Potential sinkholes (red) and potential sinkholes intersecting drainage (blue) as identified using a 60cm DEM.

5 Conclusion

A high spatial resolution (60cm), LiDAR-derived DEM can be used to accurately identify potential sinkholes using the GIS algorithms described in this study. Twenty-nine of 34 known sinkholes were correctly identified when analyzing a 60cm LiDAR-derived DEM. The same process was applied to 5m and 10m spatial resolution DEMs, but at this resolution, accuracy was significantly lower, with only nine of 34 known sinkholes correctly identified in the 5m DEM and 11 of 34 known sinkholes in the 10m DEM.

There are several explanations for why the detection accuracy differed significantly between the different spatial resolutions:

- The source data used to create the DEMs were collected at different time periods, and although one would not expect bare-earth elevation to change significantly over time, it could on an active military base where there are construction projects and training impacts.
- The bare-earth DEMs were created using different source data and using different analysis workflows. The LiDAR-derived DEM was created by classifying bare-earth LiDAR returns from a LiDAR point cloud and using those returns to interpolate a bare-earth surface. The 5m DEM was created from Radar data processing routines. The 10m DEM was created using softcopy photogrammetry from older aerial photography.
- Some of the known sinkholes are located in forested, closed canopy areas. Some LiDAR returns are able to penetrate the canopy and therefore, the bare-earth surface derived from LiDAR may be more accurate than the bare-earth surface derived from Radar or softcopy photogrammetry in these forested areas.

A total of 2,694 potential sinkholes were identified in the study area using a LiDAR-derived DEM and GIS processing routines. Clearly, not all of the potential sinkholes, or depressions, are actually sinkholes. Subject matter experts must make that determination after visiting potential sites in the field. A total of 190 potential sinkholes intersect a lake or stream, and are not likely sinkholes. An additional 128 were within 5m of a drainage. Visual inspection of the potential sinkhole map reveals that many more potential sinkholes are in close proximity to streams. In addition, there are many potential sinkholes that intersect building footprints. These depressions in the DEM are likely an artifact of the LiDAR point cloud data pro-

cessing routines implemented to remove man-made structures when creating a bare-earth DEM. A total of 291 false positives that intersect building footprints were manually removed from the final potential sinkhole feature class. However, there are many potential sinkholes that do have the size and shape that would suggest that they are good candidates for field verification.

References

- Anders, N. S., A. C. Seijmonsbergen, and W. Bouten. 2011. Segmentation optimization and stratified object-based analysis for semi-automated geomorphological mapping. *Remote Sensing of Environment* 115 (12):2976–2985.
- Angel, J. C., D. O. Nelson, and S. V. Panno. 2004. Comparison of a new GIS-based technique and a manual method for determining sinkhole density: An example from Illinois' sinkhole plain. *Journal of Cave and Karst Studies* 66(1):9-17.
- Antonic, O., D. Hatic, and R. Pernar. 2001. DEM-based depth in sink as an environmental estimator. *Ecological Modelling* 138:247-254.
- Dinger, J. S., D. P. Zourarakis, and J. C. Currens. 2007. Spectral enhancement and automated extraction of potential sinkhole features from NAIP imagery – initial investigations. *Journal of Environmental Informatics* 10(1):22-29, doi:10.3808/jei.200700096.
- Doctor, D. H., and J. A. Young. 2013. An evaluation of automated GIS tools for delineating karst sinkholes and closed depressions from 1-meter LIDAR-derived digital elevation data. 13th sinkhole conference, *National Cave and Karst Research Institute (NCKRI) Symposium 2*, pp 449–458.
- Ernst, C., J. Hadizadeh and J. L. McCarty. 2010. A remote sensing study of regional variation in sinkhole morphology – Florida karst vs. Minnesota karst, *Proceedings of the AGU Fall Meeting*, 13-17 December, San Francisco, CA.
- Filin, S., A. Baruch, Y. Avni, and S. Marco. 2011. Sinkhole characterization in the Dead Sea area using airborne laser scanning. *Natural Hazards* 58:1135-1154, doi:[10.1007/s11069-011-9718-7](https://doi.org/10.1007/s11069-011-9718-7)
- Ford, D. C., and P. Williams. 1989. *Karst Geomorphology and Hydrology*. London: Unwin-Hyman.
- Kobal, M., I. Bertoneclj, F. Pirotti, I. Dakskobler, and L. Kutnar. 2015. Using Lidar To Analyze Sinkhole Characteristics Relevant for Understory Vegetation under Forest Cover – Case Study of a High Karst Area in the Dinaric Mountains. *PLOS One* 10(3):e0122070, doi:10.1371/journal.pone.0122070
- Miao, X., X Qiu, S. Wu, J. Luo, D. Gouzie, and H. Xie. 2013. Developing efficient procedures for automated sinkhole extraction from Lidar DEMs. *Photogrammetric Engineering and Remote Sensing* 79(6):545-554.
- Missouri Department of Natural Resources. 2017. *Sinkholes in Missouri*. Web page, <https://dnr.mo.gov/geology/geosrv/envgeo/sinkholes.htm>
- Montane, J. M. 2001. Geophysical analysis of a central Florida karst terrain using light detection and ranging (LIDAR) and ground penetrating radar (GPR) derived surfaces. *FIU Electronic Theses and Dissertations*. 42, <http://digitalcommons.fiu.edu/etd/42>

- Mukherjee, A., and L. G. Zachos. 2012. GIS analysis of sinkhole distribution in Nixa, Missouri. *Geological Society of America Abstracts with Programs* 44(7):549.
- Rahimi, M., and E. C. Alexander Jr. 2013. Locating sinkholes in LiDAR coverage of a glacio-fluvial karst. *13th Sinkhole Conference, NCKRI Symposium 2, Winona County, MN*, pp 469–481.
- Seale, L. D., L. J. Florea, H. L. Vacher, and R. Brinkmann. 2007. Using ALSM to map sinkholes in the urbanized covered karst of Pinellas County, Florida – 1. methodological considerations. *Environmental Geology* 54(5):995-1005.
- Siart, C., O. Bubenzer, and B. Eitel. 2009. Combining digital elevation data (SRTM/ASTER), high resolution satellite imagery (Quickbird) and GIS for geomorphological mapping: A multi-component case study on Mediterranean karst in Central Crete. *Geomorphology* 112(1-2):106–121.
- Vacher, H. L., L. D. Seale, L. J. Florea, and R. Brinkmann. 2007. Using ALSM to map sinkholes in the urbanized covered karst of Pinellas County, Florida - 2. accuracy statistics. *Environmental Geology* 54(5):1007-1015.
- Wilson, K. V., 2004. *Modification of Karst Depressions by Urbanization in Pinellas County, Florida*, MS dissertation. Tampa, FL: University of South Florida.
- Zhu, J., T. P. Tayler, J. C. Currens, and M. M. Crawford. 2014. Improved karst sinkhole mapping in Kentucky using LiDAR techniques: A pilot study in Floyds Fork Watershed. *Journal of Cave and Karst Studies* 76(3):207-216, doi:10.4311/2013ES0135.
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<p>This work used a bare-earth Digital Elevation Model (DEM) derived from airborne Light Detection and Ranging (LiDAR) data to identify potential sinkholes at Fort Leonard Wood, MO using Geographic Information Systems (GIS) algorithms. Potential sinkholes identified in the DEM were compared with known sinkhole locations to evaluate the utility of the 60cm spatial resolution bare-earth DEM as a tool for identifying potential sinkholes. Initially, 30 of 34 known sinkholes were correctly identified using the 60cm LiDAR-derived DEM with no size limit on the sinkholes and no depth threshold. With this size and depth threshold, a total of total of 973,875 potential sinkholes were identified in the study area (~32km²). Minimum size and depth thresholds for detected sinkholes were incrementally adjusted to become more restrictive while not sacrificing accuracy, resulting in the detection of fewer sinkholes, which in turn, reduced the likelihood of false positives. A final sinkhole size threshold of 27m² and depth threshold of 23cm were determined to be optimal. Using these thresholds, the tool identified 29 of 34 known sinkholes and 2,694 potential sinkholes. The same procedures were tested using 5m and 10m spatial resolution DEMs as input, but detection accuracies were significantly lower.</p>					
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