Lidar-derived karst feature inventory of Huntingdon County, Pennsylvania: Challenges to remote identification of closed depressions in the Valley and Ridge Province

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Abstract

Karst feature density mapping is vital for geohazard assessment, risk mitigation, and groundwater protection. Closed depressions were identified in Huntingdon County using a modified, semi-automated method described by Doctor and Wall (2018). The study area, located in central Pennsylvania, is in an unglaciated part of the Appalachian Mountain section of the Valley and Ridge Province. Twenty percent of the area is underlain by Cambrian, Ordovician, and Devonian carbonate rocks. Closed depressions greater than nine square meters and over 0.2 meters deep were identified using the one-meter digital elevation model and individually examined using slope shade, hillshade, and aerial imagery. The depressions were categorized as karst, anthropogenic, alluvial, or natural non-karst features. Karst features were subdivided into closed depressions, springs, or swallets.

This project encountered challenges not faced in the pilot project in neighboring Mifflin County. The greatest challenge was the mantled Cambrian and Ordovician carbonates where residuum and colluvium created enigmatic closed depressions. Many of these features may be actual karst depressions, groundwater sapping structures, snow dune relics, periglacial patterned ground, or solifluction landforms. An additional challenge was historical human impact. The population density is nearly half of Mifflin County, but there is greater evidence of historical human impact, including iron mines, exploration pits, ore wash pits, and charcoal hearths. The third challenge was removing false sinks caused by natural phenomena such as landslides, breaks in slope, and solifluction. The lower resolution of geologic mapping, only 25% mapped at 1:24k, as opposed to 75% in the pilot study area, and increased structural complexity did not hamper analysis due to the 1000-meter buffer applied in the analysis.

Though Huntingdon County is currently less developed, two valleys have nearly twice the karst feature density as the pilot study. Future development, including pipeline and infrastructure work, land stability evaluation, and groundwater protection efforts need to be aware of risks associated with karst.

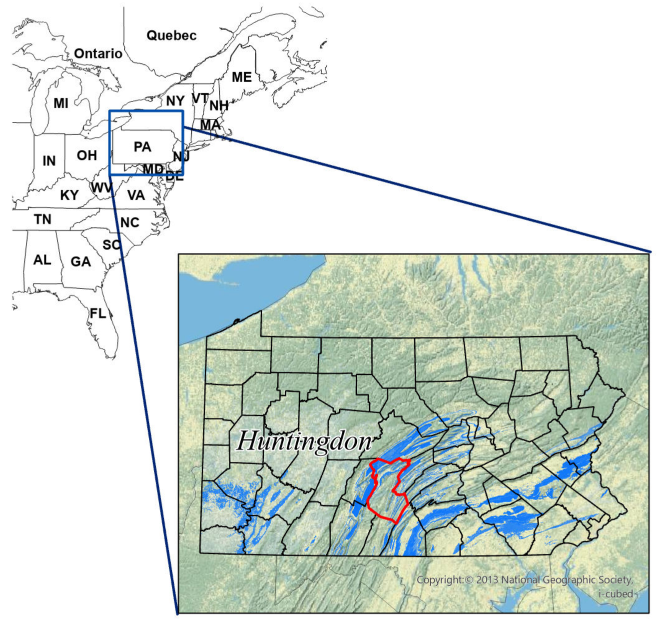

Figure 1- Map showing the location of Huntingdon County (red) within Pennsylvania. The light blue regions are underlain by carbonates.

Location

Huntingdon County is located in the Valley and Ridge Province in central Pennsylvania (Figure 1). Twenty percent of the county is underlain by carbonate bedrock such as limestone and dolomite. This bedrock is more easily eroded and tends to form the valleys or low ridges in broad valleys. Cambrian- to Ordovician-age carbonates floor the Nittany Valley including a region called The Barrens. Ordovician carbonates from Blacklog Valley and the southern terminus of Kishacoquillas Valley. Silurian to Devonian carbonates form Woodcock Valley, Hares Valley, Germany Valley, Shade Valley, and Warrior Ridge, Chestnut Ridge, and Rocky Ridge. These rocks form a karst landscape marked by sinkholes, closed depressions, disappearing streams, dry valleys, caves, and springs (Figures 2, 3, 4, and 5). Huntingdon County was selected for follow up study because it is largely rural and the karst is not mantled by glacial deposits, two factors that complicate sinkhole identification. It is located directly west of the pilot study area in Mifflin County (Behr, 2023). There are currently no karst hazard potential maps for this county.

Why is karst hazard mapping important?

It is important to know and understand risks on karst landscape. Sinkholes pose a geologic hazard that is a risk to lives, transportation, and buildings (Figure 4). The broken, weathered carbonate rocks have open fractures, cavities, and solutional pipes, resulting from millennia of slow dissolution. These may be completely clogged by soil, clay, sand, and gravel and have no surface expression. Sinkholes form when soil collapses after deeper soils and sediments wash in to these caverns and subsurface voids. New sinks may form suddenly following storms, droughts, high well pumping rates, or changes in land use. Increased rainfall and storm intensity due to climate change, combined with development of communities in areas especially vulnerable to sinkhole development, will result in a rise of sinkhole formation incidents.

In karst areas there are often no surface streams. Rainfall drains through a system of underground passages. The hollow nature of karst means transport from the surface to the water table is rapid, so contamination can happen more easily and travel farther faster, impacting wells and springs. Streams and run-off often bypass the natural filtration provided by vegetation and soil. Water may move thousands of feet a day so contaminants can quickly reach wells and springs. Karst areas are also known for caves which provide unique habitats for species of concern who depend on crevices in limestone and dolomite and clean groundwater.

Karst density mapping is vital for geohazard assessment, mitigation, and groundwater protection. This map can help to guide decisions to avoid areas of high risk or increase awareness of, and preparedness for, the risks. Sound management on karst land requires conscientious citizens, farmers, home owners, planners, developers, government officials, and land-use decision makers. These maps will be useful for project planning and siting, emergency management, soil and water conservation, and public awareness.

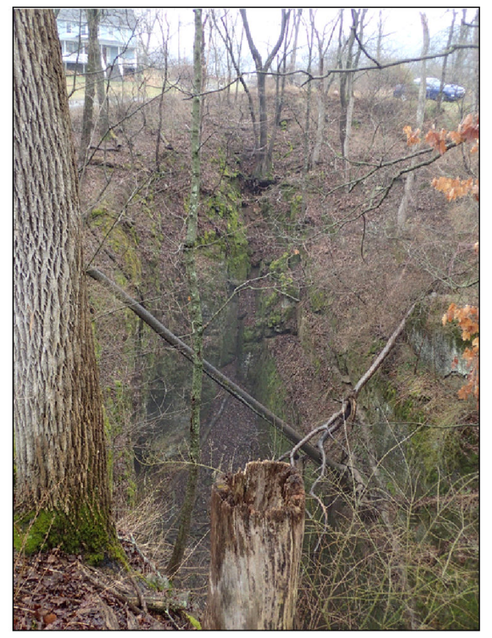

Figure 4- Karst landscapes are marked by sinkholes. This steep-sided sinkhole in the Ordovician carbonates is 75 feet wide, 125 feet long, and 59 feet deep. It hosts Tippery #1 cave which is hydrologically connected to Tippery Spring.

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Figure 2- The largest closed depression in the study area is the 100-acre Warrior Ridge Depression found in the Silurian to Devonian limestones. White dotted line marks the edge of the depression. Photo taken from the spillover point.

Figure 3- Near Tippery Spring showing high water flow versus normal flow with Dr. Will White for scale. Photographs used by permission from Dr. Ellen Herman.

Figure 5- Caves provide unique habitat for species of concern. Kooken Cave is the longest and deepest cave in Huntingdon County with over 9,400 feet of mapped passage, and 239 feet of relief. Photograph used by permission from Derek Von Nieda.

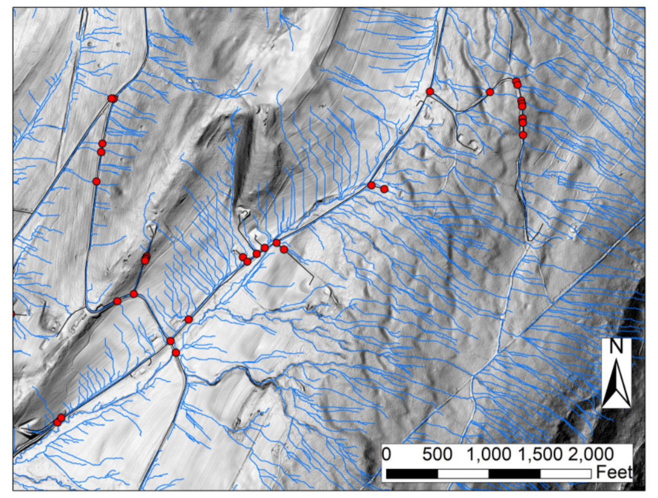

Figure 6- The third and final iteration of the Cutter and Hydro scripts at a scale of 1:2,000 create a drainage pathway for each point in the landscape. Red dots mark places where streams cross roads, and the model will "burn" a drainage through the artificial dam created by the road to remove potential false sinks.

Methodology

The process utilized to create the dataset is a series of automated algorithms outlined by Doctor and Wall (2018) which condition the digital elevation model (DEM) to reduce artificial digital dams that form at road and stream crossings. It was processed in ArcMap 10.8.1 with minor modifications. Bare-earth, 1-meter digital elevation models derived from QL2 Lidar collected in 2019 with sub one-meter horizontal accuracy and better than ten-centimeter vertical accuracy were processed with the NHDHighRes flowlines from the National Hydrography Dataset and TNM_Roads from the USGS National Map. The Hydrocutterv1_1 custom ArcGIS toolbox created by Wall et al (2015) contains models and scripts used in the process. The Cutter model and Hydro script were run three times, with increasing scale (1:400,000, 1:10,000, and 1:2,000) to drain further into the headwaters. Each time the new flow paths were "burned" into the DEM. This "burned" DEM better represents how streams flow through culverts or bridges not previously processed out of the bare-earth model (Figure 6). Finally, the custom model Sinker_v2 was run. This fill-difference method was used to locate closed depressions by "filling" closed depressions to their spill point. This filled DEM was then subtracted from the original DEM to define area and depth of the depressions. The resulting DEM was then cropped to the known carbonate areas with a 1,000-meter buffer to account for possible mapping error. The resulting cropped DEM was used to locate all closed depressions greater than 9-square meters and 0.2 meters deep (N=23,140). These polygons were then reviewed for accuracy (Figure 7).

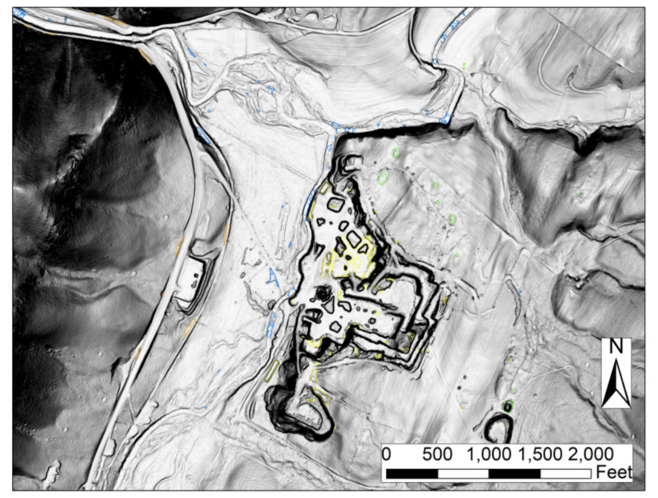

Figure 7- Each polygon must be assessed to determine if it is truly a karst closed depression. Polygons shown in blue are alluvial, and orange are false sinks next to roads. Yellow are closed depressions related to quarrying operations. Green polygons are karst features. Their volume calculations go into the karst-hazard density map.

Challenges

This project encountered challenges not faced in the pilot project in neighboring Mifflin County. The greatest challenge was the mantled Cambrian and Ordovician carbonates where residuum and colluvium created enigmatic closed depressions. Many of these features may be actual karst depressions, groundwater sapping structures, snow dune relics, periglacial patterned ground, or solifluction landforms. An additional challenge was historical human impact. The population density is nearly half of Mifflin County, but there is greater evidence of historical human activity, including iron mines, exploration pits, ore wash pits, and charcoal hearths. The third challenge was removing false sinks caused by natural phenomena such as landslides, breaks in slope, and solifluction.

Mantled karst

Although the study area has not been glaciated, residuum-mantled karst posed unexpected challenges. The Cambrian Gatesburg Formation consists of sandstone, dolomite, limestone, and quartzite. It is deeply weathered, with reported depth to bedrock being typically 100 to 200 feet, and as much as 450 feet in places (Parizek and White, 1985). This thick mantle of sand, clay, and some boulders extends beyond the Gatesburg exposures in the Nittany and Pennsylvania Furnace anticlines. Its residuum mantles the Ordovician dolomite of the Nittany Formation exposed in the intervening Marengo and Hostler synclines. This sand- and clay-rich mantle has been subject to many geomorphic processes during its long weathering history. In addition to sinkhole development, there are reported eolian influences (Cronce, 1988). There are many periglacial landforms that potentially formed in this mantle including: groundwater sapping structures, snow dune relics, periglacial patterned ground, wind-traverse corrugations, solifluction land forms, and ice wedge casts (Figures 8 and 9; Ciolkosz et al, 1986). The Cambrian and Ordovician carbonates residuum and colluvium created enigmatic closed depressions. Many of these features may be actual karst depression, though it is difficult to be sure.

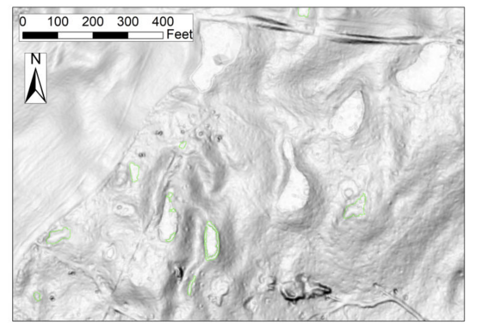

Figure 8- Slope shade image of closed depressions that seasonally hold water. The ropey texture indicates that some of these may be solifluction related, whereas others are more enigmatic. Also note "dog hole" exploration pits and possible mine in the lower right.

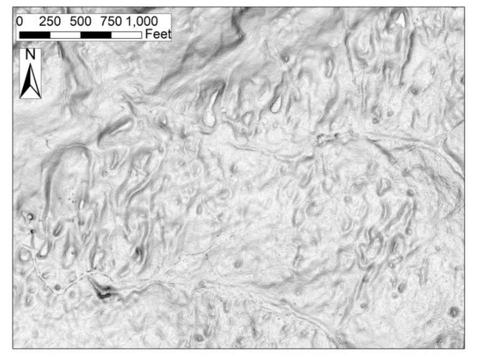

Figure 9- Slope shade image of enigmatic closed depressions which may be karst, or spring sapping, snow dune relics, or other periglacial geomorphologies.

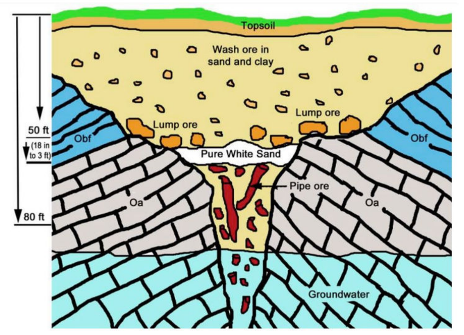

Figure 10- Diagram showing how wash ore, lump ore, and pipe ore were found in relation to each other. Depths are approximate. Figure from Fagley, 2022.

Human impact

Limonite, goethite, and kaolinite were mined in Huntingdon County starting in the late 1700s. The iron ore was mined not from bedding planes, but from pockets where the quality and quantity made it profitable for mining. As the bedrock weathered, the iron dissolved and was redeposited. Often the iron in solution was transported towards, and precipitated in, paleo-sinkholes (Fagley, 2022). The names given to the types of ore by the miners hints at this process- wash ore, lump ore, and pipe ore (Figure 10). In this study, these mines and the paleosinkholes they occupy were not included as karst features. There are many closed depressions associated with iron mining. Exploration pits abound, extraction pits were noted, and potential wash pits were located. The wash pits were places where the clay was washed away from the iron. Many flat-bottomed depressions hold water. Could they be sinkholes whose throats are clogged with wash clay? Are they naturally occurring sinkholes? With this overlap of intense historical human impact and naturally occurring karst closed depressions, the true origin becomes blurred.

Natural non-karst depressions

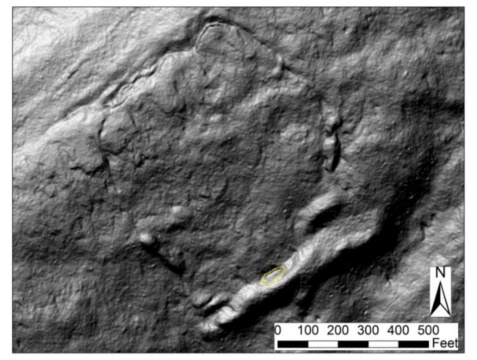

Figure 11- Slope shade imagery of landslide feature that has created closed depressions at the toe of the slide. Yellow outlines the depression.

Although Huntingdon County is along strike with the pilot study area in Mifflin County and largely includes the same formations, with the exception of the Cambrian carbonates, many natural non-karst closed depressions were noted in this study area and not in the previous study. Closed depressions were observed on the flanks and toes of creep and landslides (Figure 11). These are outside of the carbonate area but included due to the buffer used to accommodate mapping inaccuracies. Breaks in slope between Silurian Tuscarora sandstone and Clinton Group shales also displayed closed depressions (Figure 12). The Clinton Group also contains Mifflintown and Wills Creek Formations which may have limestone beds so were included in the carbonate areas. Some enigmatic hilltop closed depressions were also observed (Figure 12).

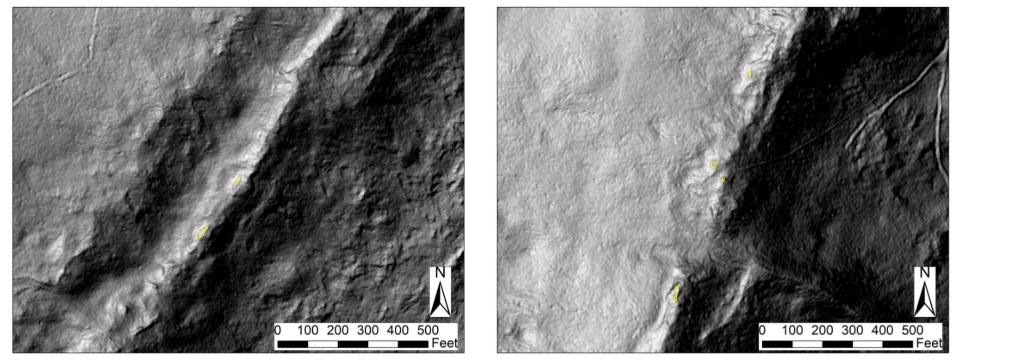

Figure 12- Slope shade imagery of naturally occurring, non-karst depressions along the crest of a sandstone ridge (left) and a break in slope (right). Yellow outlines the depressions.

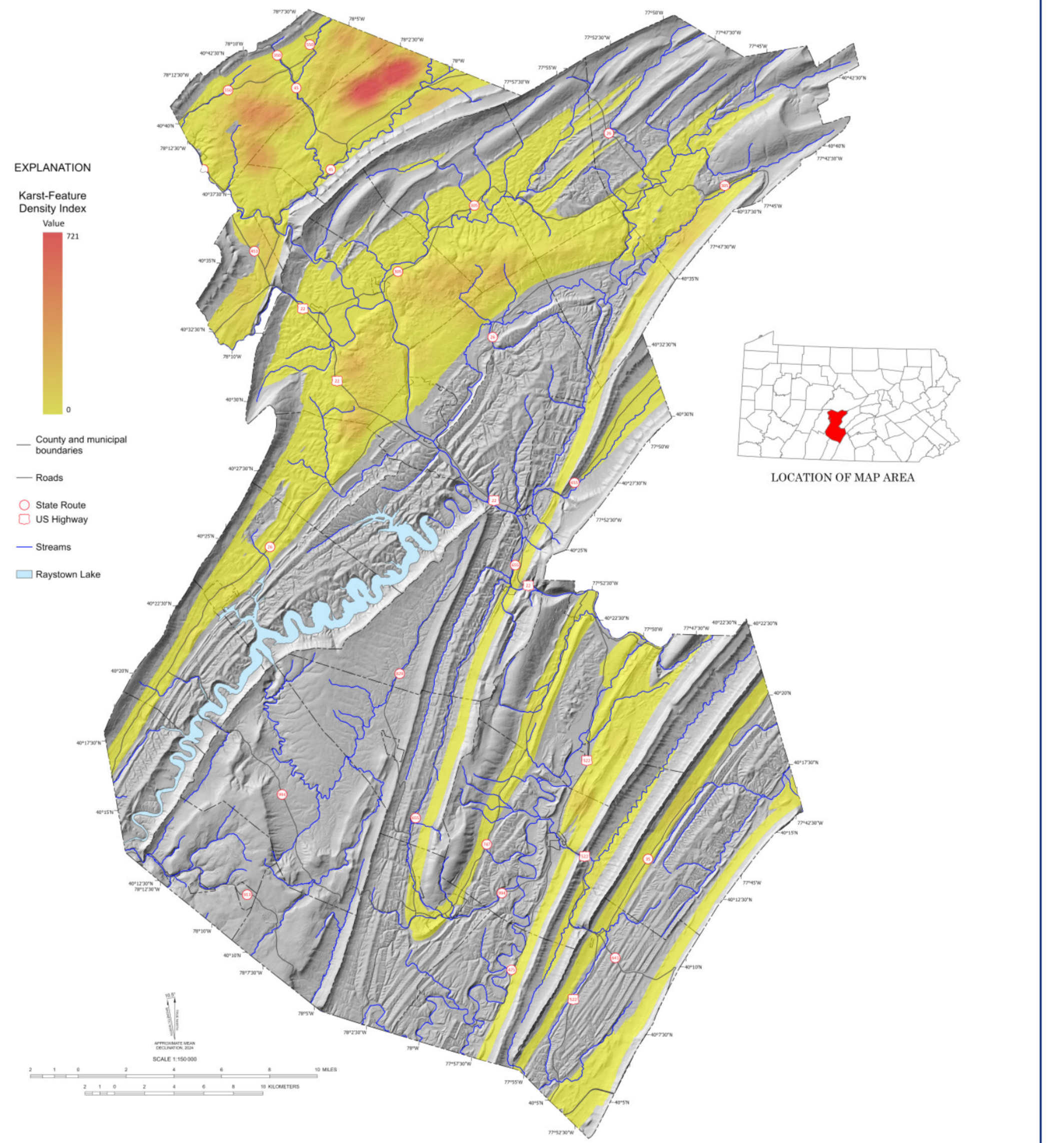

Figure 13- Karst hazard map for Huntingdon County. Karst feature are weighted by natural log of volume. Karst feature density is unitless scale.

Conclusion

During the pilot study in Mifflin County it was determined that automated sinkhole identification from QL2 lidar as outlined by Doctor and Wall (2018) is an effective method to identify closed depressions, calculate statistics, and create a karst hazard density map with limited staff and field time. It was expected that each county would have unique challenges including varying degrees of urbanization, more mantled to glaciated karst, or possible mining-related features. Huntingdon County presented several surprises. The challenge of mantled karst was the greatest, followed by human impact, and non-karst, natural, closed depressions.

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