COMBINING LIDAR, AERIAL PHOTOGRAPHY, AND PICTOMETRY® TOOLS FOR KARST FEATURES DATABASE MANAGEMENT

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Abstract

The mapping of karst features has taken on increasing importance in land use planning and zoning regulations across south east and east central Minnesota. The delineation of sinkholes, springs, and other features has traditionally depended on extensive field work, using topographic maps, and intensive networking with local landowners. The luck of the observer has also been critical as many sinkholes are rapidly refilled by landowners, concealed within extensive row crops, or hidden under tree canopies.

The application of aerial tools allows mapping across large areas. Potential karst features can be identified, and indistinct or otherwise suspicious points targeted for field verification. LiDAR mapping across Minnesota now allows high-resolution imaging (1.5 m horizontal and <15 cm vertical) of small depressions in karst landscapes without interference from vegetation. These features can be visually compared to aerial photography, both visible and infrared, flown periodically by the U.S. Department of Agriculture (USDA) to verify persistence and/or reappearance of features through time. Additionally, low angle, high-resolution Pictometry® imagery allows overhead views from several angles to further identify and verify the genesis of a given depression. In areas with previously mapped karst features, precise locations can be compared to earlier estimates of location, which is particularly useful in applications like nearest neighbor analysis.

The improved elevation mapping resulting from LiDAR work has greatly improved geologic mapping efforts based on well driller's logs. This improvement in geologic mapping allows much better correlation of karst features within stratigraphic units as well as identifying

structural controls. The geologic mapping efforts are beyond the scope of this paper.

While field verification is the ultimate standard, many obvious sinkholes can be identified, and numerous non-sinkhole depressions eliminated from consideration, helping focus valuable field time.

Introduction

There are many different types of karst features found across soluble bedrock terrains. Caves and springs represent some of the most spectacular karst features. Sinkholes on the other hand, while generally more numerous, are much more ephemeral. The appearance of a sinkhole, or its recurrence, is often inconvenient and occasionally catastrophic. Ford and Williams (2007) suggest that sinkholes are a "diagnostic" feature of karst landscapes. One pundit is quoted as saying that "the best predictors of new sinkholes are existing sinkholes" (Alexander and Lively, 1995). The mapping of sinkholes is therefore one of the primary tools in the delineation of, and assessment of risk on, karst terrains.

Mapping the distribution, size, and shape of sinkholes has always been a labor intensive effort. Extensive field work to locate points on topographic maps was combined with hours of reviewing aerial photographs into a database for further analysis (Gao et al., 2005a,b and Gao et al., 2006). Several new tools are becoming rapidly available that fundamentally change our approach to discerning, locating, and delineating sinkholes across counties and whole states.

Chief among these new tools is LiDAR (Light Detection And Ranging). The hillshade LiDAR image, Figure 1, of several large sinkhole complexes illustrates how clearly these features appear (note 3 smaller sinkholes

Figure 1. LiDAR imagery of large sinkholes east of Utica, Minnesota, with white circle highlighting sinkholes.

in the upper left). All of these large depressions show up on conventional U.S. Geological Survey (USGS) 1:24,000 topological maps. The karst of southeastern Minnesota is typified by these suffosion sinkholes where a thin veneer (less than 15 m) of glacio-fluvial sediments covers Ordovician carbonates. These depressions can be approximated as a series of intersecting conical sections as expected by subsurface sediment transport.

Airborne LiDAR is used to create Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs). These models can be combined with other geographically referenced maps and photos within a Geographical Information System (GIS) allowing the mapping of landscape features. In particular, bedrock geology, surficial sediments, depth to bedrock, and soils can put sinkholes into a geologic context.

A distinct advantage of LiDAR is its ability to “see” through vegetation mapping the land surface. This is an improvement over traditional aerial photography especially in densely wooded areas and areas with extensive agricultural cropping. Figure 2 is a conventional air photo taken in the fall, after the leaves have fallen of the trees. Even with the leaf cover off there are no obvious sinkholes, in stark comparison to the numerous sinkholes visible in the Figure 3 LiDAR image (note that Figures 2 and 3 are at the same scale, but of a different area, as Figure 1).

While traditional aerial photography looks straight down Pictometry® methods are now capturing low altitude, high-resolution views from multiple angles. Pictometry®

imagery can capture easily interpretable photos across county scale projects.

In Minnesota LiDAR mapping has been driven by the delineation of flood zones, following an August 2007 event that produced 10 inches of rain across much of southeastern Minnesota (Loesch, 2009). This has been followed up by a statewide effort, the Minnesota Elevation Mapping Project (2012), funded by the state legislature as part of the Clean Water Land and Legacy Amendment to the State Constitution. Mapping is being done at 1.5 meter horizontal spacing with 15 centimeter vertical accuracy.

In addition to improvements in DEMs due to LiDAR, similar improvements have been occurring with aerial photography. Web Map Services (WMS) compile data that can be displayed in a GIS environment without having

Figure 2. Color air photo of woodlot west of Utica, MN (Fall 2011).

Figure 3. LiDAR imagery of sinkholes in Figure 2 woodlot area.

to download all the data. The Minnesota Geospatial Information Office compiles aerial photography from numerous state and federal agencies into one easily accessible location. This data includes visible spectrum aerial photography going back to 1991 along with color infrared and Landsat imagery (MNGeo's Clearinghouse Data Catalog, 2012).

Stepping beyond traditional aerial photography, where the observer is looking straight down from high altitude, oblique imaging methods are becoming much more widely available (Kalinski, 2010). Oblique imaging, commonly referred to as pictometry, is a patented imaging process that collects images looking downward at a 40 degree angle from low altitude aircraft (Pictometry International Corporation, 2002). Typical coverage includes 12 to 20 overlapping images collected from several directions for any given point on the landscape. As pictometric images provide a bird's eye view similar to what you would see from a tall structure or mountain side, features are more intuitively interpretable and understandable.

Traditional aerial photography provides an important historical record. The USDA has flown large areas of the U.S. about every ten years since the 1930s. A US Geological Survey Digital Ortho Quadrangle (DOQ) taken in 1991, Figure 4, is readily available from Google Earth [www.google.com/earth/index.html].

Methods

The section of land in Figures 4, 5, and 6 contains downtown Utica, Minnesota in the northwest corner of the images. In this photo a newly installed, at that time, tile line is visible crossing from the lower left to the top center of the image. In addition, two sinkholes mapped by prior field work are denoted. These sinkholes (D010 and D295) occur in the top of the Prairie du Chien Limestone.

There are several other features of note in Figure 4. First, there is a remnant band of St. Peter Sandstone lying on top of the Prairie du Chien, appearing as a light colored soil north and east of the D295 label. Note that the soils in this area are relatively thin, less than 0.5 meter thick over the St. Peter rises, and up to one meter thick over the Prairie du Chien. Second, there are darker colored soils associated with the tile lines, especially along the east-west section at the top of Figure 4. The darker colors

are indicative of soils that are holding moisture, i.e. are thicker than in adjacent areas, with up to 3 to 5 meters of soil. Lastly, there is a light colored area (labeled) that is difficult to tell if it is a positive or negative feature. Given the relatively flat topography of the area, a topographic map does little to help discern whether this is a small rise or if it is a depression.

Figure 5 is a hill shade image of LiDAR data for the Figure 4 area. The hill shade image highlights topographic features by illuminating the LiDAR data with an artificial light source, in this case from the northwest. The tile lines now appear as trenches in this shaded relief image and the St. Peter mounds stand up from the surrounding landscape. A small mesa capped by the Platteville Limestone over St. Peter Sandstone is visible in the southwest corner. More subtle are several fence lines that now show up as positive features providing evidence of soil erosion in the agricultural fields.

Figure 4. Google Earth image Utica, Minnesota area April 1991.

Figure 5. Hillshade LiDAR image of Figure 4 area.

Figure 6. Pictometry® image of Figure 4 area.

A series of depressions in the top center of the figure can now be mapped as suspected sinkholes and are indicated by numbered red diamonds. Previously mapped sinkholes are denoted by red “x”s. Note that the light colored area from Figure 4 is now an obvious depression. Interestingly the tile line jogs around this depression, suggesting that it can seasonally hold water diverting construction of the tile line.

Figure 6 shows a Pictometry® image covering most of the same area as in Figures 4 and 5. This image is from 2010 and shows a landscape concurrent with Figure 5. This image is available from Bing™ Maps [www.bing.com/maps/] using the “Birds eye” view feature. The more native, or natural view, allows further interpretation of the landscape imagery.

Efforts at conservation, in particular the Conservation Reserve Program (CRP) are visible in Figure 6. The creation of berms around sinkholes and permanent vegetation help reduce direct run-in to sinkholes and allow for filtration of water as it passes into the subsurface.

As shown in Figures 4, 5, and 6, each aerial imaging method has advantages that can be used in a complimentary fashion. Used together these tools allow complete access across county-wide scales at spatial and temporal scales that were not previously available. Additionally, bedrock geologic maps and surficial sediment thickness maps can aid in the identification of sinkhole prone areas and the distribution of mapped sinkholes can be fed back into geologic maps.

Discussion

The imagery methods described so far do a good job of identifying depressions in the landscape. There

are, however, assorted depressions on the landscape that are not sinkholes; simply identifying depressions will not create a sinkhole inventory. Separating and identifying sinkholes from numerous non-karstic depressions requires an accounting of these other types of depressions. This is particularly important in glacially and fluvially altered land surfaces as are common across Minnesota.

Common non-karstic depression features include old building foundations as in Figure 7. Distinguishing characteristics are the relatively rectangular shape and its proximity to an existing farm yard. The combination of pictometry, allowing us to see the farmyard and wood lot, with the shape of the depression from LiDAR allows a definitive explanation of the observed feature. A related type of feature would be small quarry pits that were dug to extract building stone for these same barn foundations. Quarries however are usually open on one end to allow for wheeled transport.

A second type of agriculturally derived depression is the cattle wallow. Cattle, and their bison predecessors on this landscape, are known to wallow in mud to help ward off flies. These wallows can become quite deep over time.

Figure 8 shows a Pictometry® image of a wood lot grazed by cattle which includes a sinkhole and a cattle wallow. The sinkhole in the LiDAR inset of Figure 8 is a visible depression. The cattle and their associated wallow can be seen on the right side of the image. The slight ridge in the lower center of the image is a high traffic area that may provide a breeze to help further ward off the flies.

These cattle wallows, and especially bison wallows, can be quite large in size and depth. Figure 9 shows an early 20th century image from Kansas as reported by Darton in a USGS Folio (1920).

Another distinct type of non-karst depression is the tree tip-up or windthrow. Depending on the tree size, species, and soil depth, tip-ups can be significant features up to 3 to 4 meters across and more than a meter deep (José Ramón et al., 2000). Figure 10 shows a typical tree tip-up, in this case in a maple forest. A notable feature of tip-ups is that while creating an often circular depression they always create an associated mound where the root ball lands. These mounds and tip-up depression pairs can persist for decades.

Figure 7. Former barn foundation.

Figure 8. Sinkhole D904 in woodlot with nearby cattle wallow.

Figure 9. Buffalo wallow, shallow circular depression in the level surface (from Darton, 1920).

Figure 11 shows a LiDAR image of a maple and oak forest on the Kettle River plain in Pine County, Minnesota. This is an area of thin soils over sandstone bedrock. Note that there is a distinct size to these tip-up depressions. In particular, there is a definite size range where only the largest trees are vulnerable. While sinkholes are common in the area, sinkholes do not seem to form at this elevation. The low hydraulic gradient to the base level in the Kettle River of the area shown in Figure 11 is apparently not conducive to sinkhole formation.

In Minnesota, where most of the state has been recently glaciated, there are numerous depressions formed due to glacial processes and particularly due to ice block melting processes. The most recent glaciation however missed southeastern Minnesota passing to the west forming Des Moines Lobe tills. Areas overlain by Des Moines Lobe tills generally have more than 15 meters of unconsolidated sediment over bedrock. The surface expression of karst in these areas is limited (Alexander and Lively, 1995).

In areas where the depth to bedrock is less than 15 meters there may be a mixture of karst, non-karstic, and hybrid depressions on the landscape. Glacial and karst features can become intermixed and examples of composite features are known in Minnesota (Shade, 2002). In portions of Pine County Minnesota, along the Kettle River, the mixture of karst and non-karst features is common (Figure 12). The Kettle River valley is incised into the Hinckley Sandstone creating large hydraulic gradients. Sinkholes in this area are the result of dissolution of the highly cemented quartz sandstone and solutional enlargement along pre-existing fractures. In Figures 12 and 13 white circles highlight sinkhole

Figure 10. Tree tip-up. Photo by Kerry D. Woods.

Figure 11. Array of tree tip-ups from Kettle River plain, Pine County, MN.

Figure 12. Sinkholes in sandstone karst above Kettle River.

Figure 13. 2010 aerial photo of Figure 12 area.

depressions and black circles denote tree tip-ups. In addition there are numerous wetland depressions of various sizes. The wetland areas are more obvious in the aerial photography image of Figure 13.

The wetlands in Figures 12 and 13 are likely kettle depressions, or ice block melt out features related to retreat of the Superior Lobe ice sheet (Shade et al., 2002). As the surficial sediments thin towards the river bluff more sinkholes begin to appear. Several of the sinkholes in Figures 12 and 13 appear to be limiting the water levels in adjacent wetlands. The wetland depressions may eventually be entirely captured by the sinkholes.

A final type of non-karstic depression, presented in this paper, is the land slide or slump. Figure 14 shows a hill shade LiDAR image of the edge of a Platteville mesa immediately to the west of Utica, Minnesota. The Platteville Limestone provides a cap to the mesa while the steep side slopes are St. Peter Sandstone. Water is transported horizontally along bedding planes in the Platteville. Seeps form across the St. Peter slope creating frequent slumps. Potential sinkhole features, that have a different morphology from the slumps, are highlighted with red and blue circles.

Figure 15 is the same area from Figure 14 but the Pictometry® image shows slumps in the St. Peter slope where the white sandstone is exposed. The washout from the slumps frequently extends out into the farm fields below. The four potential sinkholes are obscured by the wooded slope.

Figure 14. LiDAR image of slumps and potential sinkholes (circles) west of Utica, MN.

Figure 16 shows the same area as in Figures 14 and 15 but now presents the view looking southward, or up slope. The two blue circles can now be defined as depressions into the surface at the base of the bluff without light colored wash out fans; they are therefore not slump features. These two features may be sinkholes into the underlying Prairie du Chien. The two red circled areas are still hidden within the forested slope.

Field investigations were required to definitively identify the suspected karst sinkholes. There are occasional sinkholes near the edge of the Platteville into the St. Peter as seen in the southernmost red circle. These Platteville sinkholes, particularly near bluff edges, can be the result of mechanical erosion of the poorly cemented St. Peter Sandstone along bedrock fractures (Barr and Alexander, 2009). The second red circle is a sinkhole into a St. Peter crevice. The two blue circles, based on the visual and elevation data, are likely sinkholes into the Prairie du Chien. Definitive confirmation would likely require excavation as demonstrated by Shade (2002).

Figure 15. Pictometry® view looking to the north of slumps and potential sinkholes in Figure 14.

Figure 16. Pictometry® view looking to the south of slumps and potential sinkholes in Figure 14.

Results

Over the past three years summer interns, funded by the NSF-REU program, have actively mapped sinkholes. Originally, efforts used just LiDAR but are increasingly employing aerial and Pictometry® photos. Efforts to date have been aimed at southeastern Minnesota. In addition, mapping has been supported by the Water Resources Center at the University of Minnesota (see Ramini and Alexander in these proceedings). The results of these mapping efforts are in the process being added to the Karst Features Database for Minnesota (Gao et al., 2006).

In Houston County, in the far southeastern tip of Minnesota, the number of mapped sinkholes increased from 5 to 44 after mapping in 2010 by Erik Larson. This was the first county-scale application of LiDAR based sinkhole mapping in Minnesota. A significant amount of field time was required to distinguish sinkholes from non-karst depressions. The results of these efforts can be seen in the large discussion section of this paper.

Fillmore County required a more significant effort. As part of the Fillmore County Geologic Atlas (Witthuhn and Alexander, 1995) a total of 6,199 sinkholes were mapped primarily with extensive field work using 1:24,000 USGS topographic maps as a base. In 2011, Britney Greenwaldt and Cody Bomberger mapped an additional 4,431 sinkholes in Fillmore County. They were able to confirm the location of 3,504 previously mapped sinkholes. They adjusted the location of 1,542 previously mapped sinkholes with an average correction of less than 15 meters. A significant portion of the 2,695 sinkholes that were not visible in LiDAR had been mapped through discussions with landowners and county soil conservation officers to locate filled sinkholes.

Previous mapping in Winona County had identified 672 sinkholes. Work by Rahimi and Alexander, presented in these proceedings, identified an additional 651 new potential sinkholes and refined the location of 168 sinkholes.

Work is on-going with renewed mapping efforts for Wabasha, Dodge, Steele, and Washington counties of Minnesota. The Karst Features Database, as managed by the Minnesota Department of Natural Resources, is now being used by county and state officials to help direct land use decisions. A thorough and accurate database of

sinkholes, and other karst features, is helping inform the siting large scale animal operations and municipal waste water facilities, along with many other intense types of land use.

Conclusions

Modern imaging and elevation tools can provide a wealth of information. Individually, aerial photography, pictometry, and LiDAR can significantly aid efforts to map many different types of features. Used in combination these methods can significantly reduce the time required for field mapping.

Where these new GIS coverages have been applied in Minnesota the number of mapped sinkholes has been roughly doubled. In addition, the locations of previously mapped sinkholes in these areas have been refined. Future efforts analyzing the distribution of karst features, such as with nearest neighbor analysis, will be more robust and meaningful.

None of these methods will eliminate the need for fieldwork. They do however allow investigation of areas that were previously inaccessible and allow mapping at scales that would require thousands of hours of field effort. The mapping of features using historic air photos to identify features that have been filled is beginning.

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