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Michael D. Rodgers

The College at Brockport, mrodg1@gmail.com

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**Sinkhole Analysis and Classification Using Pictometry in Genesee County, NY
and Surrounding Areas**

A Thesis

Presented to the Faculty of the Department of Environmental Science and Biology
of the State University of New York College at Brockport

in Fulfillment for the
Degree of Master of Science

Michael D. Rodgers

December 2015

Abstract

Oblique Imagery was used to assess 250 depressional features within the carbonate bedrock region of Genesee County, NY and surrounding areas. Of these features, 110 were confirmed to be sinkholes. The analysis of Pictometry Oblique Imagery, with images spanning the past 15 years, was performed to sample each individual sinkhole for each available time-step image. Parameters were created using GIS-based data and imagery characteristics, and statistically analyzed for confirmed sinkholes to assess similarities and differences between the sinkholes. A cluster analysis showed that there is a relationship between sinkholes and a variety of GIS data types. These statistically derived associations suggest that the following factors are indicative of sinkholes: Visible Depression, Secondary Characteristics, Target Soil Presence/Absence, Moisture Content, Land Use, Type (water/land), Size, and Shape. The study suggested that distance from visible escarpments and bedrock geology, two guidelines for finding karst features suggested by previous studies, were not statistically correlated to sinkholes in Genesee County and surrounding areas.

Dedication

I dedicate this thesis to my family – My parents Eugene and Tammy Rodgers, and my grandparents Marilyn and Douglas Stratton. Throughout my life my family has always been there for me and supported me and my love of science. Without them, I wouldn't be where I am today. Thank you so much for all that you have and continue to do for me.

Acknowledgements

Through the process of completing this thesis I received help from several individuals, without which this thesis would not have been possible. I thank my major advisor, Dr. Paul L. Richards, for helping me through any issues I ran across no matter how large or small, for the feedback on how to make my thesis better, and for inspiring me to become a better scientist. I thank my two other committee members for their help throughout my thesis. I thank Dr. Douglas Wilcox for making learning fun in his classes, it made graduate school go more smoothly; he also helped me become a better scientific writer, which will help me as my scientific career progresses. Dr. Aaron Gerace helped me think outside the box when my thesis needed new life, and always had questions for me that helped better my project; thank you for your help through the years. I also would like to thank Andrew Mendola of Pictometry International for teaching me how to use the Pictometry software, without which this thesis would not have happened. I thank Katherine Bailey for her help throughout my thesis with ideas to better my project, field trips to sinkholes to inspect their characteristics, and for always listening when I had random questions about my thesis. I thank Molly Stetz for her help with statistics and ideas on the interpretation of my cluster data. I also thank Marine David for GIS assistance, and for her support throughout my thesis. I thank Andie Graham for her help in studying for the Oral Comprehensive Exam and for lessening the stress that was associated with the exam. I also thank Dr. James Zollweg for his help with several GIS issues I ran into along the way. Lastly, I thank my family and friends for their support throughout my graduate studies.

Table of Contents

Abstract	i
Dedication	i
Acknowledgements	ii
List of Tables	v
List of Figures	v
Introduction	1
<i>The Problem</i>	1
<i>Background Information</i>	2
<i>The Solution</i>	6
<i>NYSDEC response</i>	7
<i>Sinkhole Identification</i>	8
<i>Pictometry Oblique Imagery</i>	9
<i>Study Area</i>	11
Methodology	11
<i>Hypothesis</i>	11
<i>Objectives</i>	12
<i>Procedure</i>	13
<i>Data Collection</i>	13
<i>Parameter Creation</i>	14
<i>Statistical Analyses</i>	15
Results	16
<i>Cluster #1</i>	17
<i>Cluster #2</i>	18
<i>Cluster #3</i>	20
<i>Cluster #4</i>	21
<i>Cluster #5</i>	22
<i>Cluster #6</i>	23
<i>Cluster #7</i>	24

<i>Cluster #8</i>	25
<i>Cluster #9</i>	27
<i>Cluster #10</i>	28
<i>Non-Cluster Group</i>	29
<i>Special Cases</i>	32
<i>Ivison Rd. Disappearing Lake</i>	32
<i>False-Positive Site</i>	33
Discussion	33
<i>Cluster Analysis</i>	33
<i>Pictometry</i>	35
<i>Future Work</i>	36
Conclusions	37
Literature Cited	39
Tables	42
Figures	44
Appendix	78

List of Tables

- Table 1. Targeted soil types found in Genesee County (after Czymbek et al, 2004). Different abbreviations correspond to differing slopes of soil surfaces..... 42
- Table 2. Categorical parameters created from Pictometry and GIS that were used in the cluster analysis for differentiation of sinkholes. Pictometry based parameters created via use of the Pictometry time-series imagery and observing the sinkhole features evident in Genesee County. Parameters may need to be expanded/contracted for use in other regions..... 43

List of Figures

- Figure 1. Annotated dendrogram of distance 2.5 clusters, using a minimum of three cases to define a cluster. This clustering result allows for the differentiation of 10 distinct groups of sinkholes characterized by certain parameters..... 44
- Figure 2a. A dry period time-step for Sinkhole #65 located on the campus of Genesee Community College in Batavia, NY. Although a drier period, some water is still evident flowing into the feature from the west..... 45
- Figure 2b. A wet period time-step for Sinkhole #65 located on the campus of Genesee Community College in Batavia, NY. Water flows are evident coming in from both the west and from the south-east. Due to the amount of water and the time of year, this is a presumed snowmelt event. Of note here is that this sinkhole crosses contour boundaries; this suggests that the micro-topography represented by these contours was not accurate at the time of this map's creation..... 45
- Figure 2c. GIS-based map product of Sinkhole #65. This sinkhole classifies as 'contains target soils' due to the overlap of the feature boundary with that of the target soils – specifically, the Aurora group. This is an erratic-shaped, small-sized sinkhole within the Onondaga Formation..... 46
- Figure 3a. Sinkhole #67 lies in a significant depression, although only falls in part of it. The sinkhole boundary crosses several contours over an elevation change of 20+ feet; this is either an error in the contour mapping or an error in the sinkhole mapping from prior studies. View from east..... 47
- Figure 3b. A mostly dry time-step for Sinkhole #67. This time-step does show some anomalies in the far eastern reaches of the feature. These are dark regions that could be caused by a number of things – shadows, moisture/water, or darkened soils. This is one of the micro-features that are tough to discern in Pictometry..... 47

Figure 3c.	GIS-based map product for Sinkhole #67. This feature contains target soils, specifically, Benson and Rubbleland. This feature is an erratic-boundary, moderately-sized sinkhole within the Onondaga Formation.	48
Figure 4a.	This is dry-period time-step of Sinkhole #97 in Caledonia, NY. This feature is a very evident sinkhole feature, lying nicely within the contours. It appears to be a dry pond basin, possibly a vernal pool that refills with snowmelt. View from the east.....	49
Figure 4b.	A wet-period time-step for Sinkhole #97. This shows the pond basin filled with water from a likely snowmelt event. This time-step further enhances the probability that this is a vernal pool sinkhole.....	49
Figure 4c.	GIS-based map product for Sinkhole #97. This shows the feature itself containing shallow soil – from the Farmington group; it is not initially classified as a target soil in Genesee County; however, it is certainly a shallow-to-bedrock soil interacting with karst features.....	50
Figure 5a.	Sinkhole #4 in Corfu, NY. Two pond outlets located on right side of pond (north). Small temporary inlet is present coming out of the rock spoil pile to the west (top) of the image. This inlet feature is not present in all time-steps of Pictometry. View from east.....	51
Figure 5b.	Sinkhole #4 is a small, smooth-shaped feature. Two spoil rock piles with sub-angular boundaries are visible upslope of the sinkhole. This feature is permanently inundated with water, and is the basin for runoff from the upslope fields.....	51
Figure 5c.	GIS-based map product for Sinkhole #4. This is a smooth, small-sized feature in the Onondaga Formation. This contains target soils, albeit barely – both Aurora and Benson groups are present.....	52
Figure 6a.	Sinkhole #62 in Oakfield, NY encompassing Phelps Pond with contours enabled. This shows the steep slopes leading into Phelps Pond, with surrounding wooded regions and farm fields nearby. This is a large natural basin for runoff to accumulate in. Surrounded by farm fields around most of the feature, this is a likely candidate for increased pollution of the groundwater table.....	53
Figure 6b.	GIS-based map product for Sinkhole #62. This smooth, moderately-sized sinkhole lies almost perfectly within a gap in the target soil, although it does slightly overlap – This gap is due to the water from the pond itself. It does have inclusion of the Benson group soil. This feature lies extremely close to the Onondaga escarpment, being just north of the feature, within the Akron-Bertie Formation.....	54
Figure 7a.	Sinkhole #71 in Caledonia, NY. Pictometry with contours denoting two ridges parallel to the long axis of the sinkhole within the farm field	

	portion of the feature. This smooth, small-sized feature is a funnel for the upslope farm field runoff. View from north.....	55
Figure 7b.	Sinkhole #71 Pictometry view from north; zoomed in to show boulders and sub angular rocks scattered through the farm field. These sub-angular rocks are indicative of shallow depth-to-bedrock and karstic terrain.....	55
Figure 7c.	GIS-based map product of sinkhole #71. This sinkhole is within the Onondaga Formation. This shows the feature laying completely within the Farmington group soil; although not a target soil by definition, it is a shallow soil that lies over karst terrain.....	56
Figure 8a.	Sinkhole #15 in Batavia, NY. This is from a dry time-step. The feature lies within a nice low-point in the contours within this farm field. Evident is slight soil discoloration, hinting at potential soil-type changes or differences in moisture content.....	57
Figure 8b.	Sinkhole #15 during vegetation growth period. A barren spot is located within the sinkhole, likely due to increased moisture prohibiting plant growth.....	57
Figure 8c.	Moist time-step for Sinkhole #15. Spring snowmelt has resulted in a temporary lake appearing in the middle of this sinkhole feature. This moist location matches the absent vegetation location from the prior figure.....	58
Figure 8d.	GIS-based map product for Sinkhole #15. This feature is within the Onondaga Formation and is absent of target soils. It is an erratic boundary feature that is moderately-sized.....	59
Figure 9a.	Sinkhole #16 located on Bartof Rd. in Stafford, NY. This is a classic shallow depth-to-bedrock sinkhole feature. The feature itself crosses contours but has micro-topographic depression features throughout that collectively comprise the sinkhole.....	60
Figure 9b.	Sinkhole #16 in the early spring before vegetation growth. Obvious are large clusters of sub-angular boulders, indicating shallow depth-to-bedrock. Note the soil discoloration due to enhanced moisture in micro-relief regions. View from north.....	60
Figure 9c.	GIS-based map product for Sinkhole #16. This feature is mostly smooth, moderately sized and lies within the Onondaga Formation. This sinkhole has interaction with the target soil, specifically, the Aurora series.....	61
Figure 10a.	Sinkhole #40 in Stafford, NY. This feature lies fairly squarely in the center of a depression as indicated by contours. At the center of this feature is a darkened soil region, likely due to enhanced moisture. To the east of the feature is a rock spoil pile, indicative of stony fields and potentially shallow depth-to-bedrock.....	62

Figure 10b. Close-up of Sinkhole #40, with a spoil pile to the east of the feature (left of image). Scattered throughout both fields associated are sub-angular boulders. View from north.....	62
Figure 10c. GIS-based map product of Sinkhole #40. This sinkhole is smooth and small-sized, and is within the Onondaga Formation. Target soils are absent in feature, but present nearby.....	63
Figure 11a. Sinkhole #46 is a dry, land-based feature in LeRoy, NY. It is dominated by shrubs and soil. This feature encompasses two low points in topography, as noted by contours.....	64
Figure 11b. Sinkhole #46 with spring growth evident. This feature is still absent any noticeable moisture on the surface, and apart from the shrubs, little else appears to grow within the feature.....	64
Figure 11c. GIS-based map product for Sinkhole #46. This sinkhole lies within the Onondaga Formation and is completely filled with target soils – specifically from the Benson and Wassiac groups. A key feature of note is the close proximity of another sinkhole – sinkhole #101 – just to the south and east of #46.....	65
Figure 12a. This time-step shows Sinkhole #7 during a wet stage, likely from a snowmelt event. It is surrounded on three sides by farm fields, meaning this feature is likely inundated with farm-based pollution runoff.....	66
Figure 12b. A drier time-step for Sinkhole #7; while most moisture has left the sinkhole itself, soil discoloration, likely due to moisture, is observed in the surrounding fields.....	66
Figure 12c. GIS-Based map product for Sinkhole #7. This shows that the sinkhole lies fully within the Onondaga Formation and has no nearby target soils associated with it.....	67
Figure 13a. Sinkhole # 26 is located along a stream section, at the low-point between to farm fields. The surrounding area appears quite moist, while inside the feature is very brush-filled and non-farmed, a sign of high moisture content extending away from the stream itself.....	68
Figure 13b. GIS-Based map product for Sinkhole #26. This feature is seen as laying solely within the Onondaga Formation (Dob) and having no nearby target soils.....	69
Figure 14a. A wet time-step for Sinkhole #66. This shows the feature after a snowmelt, creating a vernal pool.....	70
Figure 14b. Another wet time-step for Sinkhole #66. With contours enabled, it becomes apparent how steep the cliffs of this feature are, specifically on the northern and southern edges.....	70

Figure 14c. Dry time-step for Sinkhole #66; this feature is completely absent of water in the visible imagery.....	71
Figure 14d. Looking along the fetch of Sinkhole #66 (from the west) it shows obvious ponding with trees throughout the flooded region.....	71
Figure 14e. Looking along the fetch of the pond in Sinkhole #66, during a dry time-step, the feature appear completely dry and barren.....	72
Figure 14f. GIS-based map product for Sinkhole #66, this feature lies mainly within the Akron-Bertie Formation, while extending slightly into the Camillus group. Target soils span nearly the entire feature, in the form of the Rubbleland series, while a small pocket is absent target soils in the center, due to the ponding that takes place.....	73
Figure 15a. Moist time-step of the disappearing lake at Ivison Rd. in Sinkhole # 25. Not only is there ponding at the very center, but visible ‘stream’ formation is seen in the southwest portion of the feature.....	74
Figure 15b. Dry time-step of Sinkhole #25. Although absent of water, the Ivison Rd. disappearing lake still shows signs of soil discoloration, likely due to enhanced sub-surface moisture.....	74
Figure 15c. GIS-based map product of the Ivison Rd. disappearing lake. This feature lies fully within the Camillus group and has no target soils within; however, it is surrounded on three sides by the Wassiac group target soil.	75
Figure 16a. Close up of the County Building 2 false-positive site. Apparent in the imagery are exposed stones and a rock outcrop, usually indicative of shallow soils when in karst terrain.....	76
Figure 16b. Zoomed-out look at the false-positive site at County Building 2. Note the topographic low in the middle-right, which initially was mistaken as a sinkhole.....	76
Figure 16c. GIS-based map product for the County Building 2 false-positive site (unmarked, center of image). The feature is within the Onondaga Formation, squarely in karst terrain, with target soils nearby, both of the Benson and Wassiac series’	77

Introduction

The Problem

Karst areas are known for their agricultural productivity. However, karst watersheds are vulnerable to surface and groundwater contamination because of complex surface-water/groundwater interactions, including dissolution fast pathways to the subsurface. This is important because approximately 20% of the U.S. (40% of the eastern U.S.) is karst (Quinlan 1989), and agricultural runoff is one of the major causes of surface-water contamination in the United States (USGS, 1999). The Onondaga Formation is a known karst lithology in New York State that is heavily farmed and is an important aquifer for domestic water supplies. A 2007 event in the township of Stafford, NY has underscored the sensitivity of this geologic unit to groundwater contamination. This formation has suffered several incidents of well contamination as a result of the application of fertilizer. In the well-publicized 2007 incident, 35 wells were contaminated by one farmer (The Daily News, 2007). The tragic aspect of this event is that the farmer was following reasonable management guidelines proposed by his consultant, Western New York Crop Management. National Resources Conservation Service [NRCS] personnel evaluated the suspected area of the source of the contamination and discovered a small sinkhole that, upon further digging, yielded a zone of fractured limestone. The feature was very shallow and not recognizable from the field. Although the origin of contamination is still in dispute, karst-related flow processes have been suspected, and the New York State Department of Environmental Conservation [NYSDEC] has charged the farmer for

contaminating the wells. The problem with this incident is that the farmer was following widely accepted protocol for the area, and the buried fracture conduit that is suspected to be the actual origin of the material was small and not easily observed from the surface. In the months following this incident, federal authorities authorized a 1.3 million dollar grant to bring public water to some of the impacted residents. Well contamination events from manure application in sinkholes have also occurred in 2004, 2010, 2014, and last year in 2015. In the 2010 event, the contamination site was located in a disappearing lakes site, a karst area subject to widespread groundwater flooding from the subsurface. The problem of manure contamination via sinkholes has unfortunately become chronic in western NY.

Background Information

Palmer (1991) set the baseline understanding for the development of depressions in karst areas. Carbonate bedrock, especially limestone, is highly susceptible to cave and sinkhole formation because of its solubility to acidic rainwater. Sinkhole development is influenced by dissolution, subsidence, and ultimately, collapse. Sinkholes form concurrently with the cave system via enlarging passages within the karst. This passage allows for more material to be removed, which further enlarges conduits and sinkholes. The morphology of the system is influenced by the location of the water table, the distribution and density of fractures, as well as amount of groundwater recharge and discharge from the system. Depressional areas that form from these processes can drain several square kilometers of the landscape, which has large implications on the likelihood of groundwater contamination; especially farm

fields with manure. Sinkholes that capture streams (e.g., swallets) can drain much larger areas.

Groundwater flow in karst-forming limestones, like the Onondaga Formation, are complicated and exacerbate the manure contamination problem in several different ways. First, they are dynamic and hard to predict (White, 2002). Second, water flow in the subsurface of karst is capable of delivering all types of pollutants (Vesper et al. 2001; Crain, 2006), including bacteria (Wallace, 1993; Mahler et al. 2000; Davis et al. 2005) and particulates (O Atteia, 1997). Third, karst terrain provides 40% of the land area east of the Mississippi River (Quinlan 1989). Even New York, a state that is not well-known for karst and has no special regulations regarding urban development in storm water and waste management in karst settings, contains considerable areas of karst (Goodman et al. 1994). Very little work has been done on the effectiveness of non-point-source pollution and storm water best management practices [BMPs] in karst settings such as septic fields, storm water retention; and urban runoff; however it has long been recognized that agricultural and urban land uses overlying karst need extra protection to protect groundwater resources (Kemmerly, 1981; Fischer et al. 1993; Hubbard and Balfour, 1993; Ray and O'Dell, 1993; Goodman et al. 1994).

The unique position of the Onondaga Formation at the base of the Alleghany plateau and its interception of northward flowing streams in western NY has made it especially sensitive to groundwater contamination from sinkholes. Highlands to the south provide extensive recharge areas and high water-table gradients, which cause this

unit to intercept large groundwater fluxes. Transducers located in sinkholes in the eastern part of the study area indicate that the regional peizometric surface is close to the ground elevation in early spring (Richards et al. 2007). The transducer data indicate that water tables can periodically rise close to the base of the soil zone and, in some places, above the ground surface. This helps to explain the odd flooding events and disappearing lakes that sometimes occur in the Onondaga Formation (Rhinehart, 2005; Richards, 2007; Daniluk, 2009; Voortman and Simons, 2009). This phenomenon will exacerbate contamination, by flushing manure and septic wastewater directly from the soil and land surface. Another issue is that streams draining large agricultural areas south of the Onondaga Formation commonly flow into sinkholes within the Onondaga Formation. The reason for this is that streams commonly flow along fracture zones because they tend to comprise the lower parts of the Onondaga plateau; these are the places where enhanced weathering and sinkhole development take place.

Glacial meltwaters from the retreat of the last ice advance have stripped away much of the overburden, leaving behind thin soils and sediments (Fairchild, 1909). Thin soils aggravate the problem of non-point-source pollution because the filtering effect of soils is reduced. Pollutants stored in the soil zone, such as manure, do not have to travel far to reach the water table. The Onondaga Formation in the study area is heavily fractured, and undergraduate theses on fractures conducted by Fronk (2001) and Payne (2009) suggest that many are wide (up to 0.1 m). These fractures are wide enough to transport particulates from the soil horizon or surface. Many soils have macropores and desiccation fractures resulting from wetting and drying cycles, and so the potential for

washing septic wastewater and fertilizer directly into conduits is high, especially when the soil is thin. Glacial meltwaters have also obscured some sinkholes by depositing sediment on top of them. Their presence is not always obvious from the surface. This is especially true for sinkholes in an immature stage of development where collapse has not taken place.

Previous unpublished assessments of karst-related well contamination suggest that snow-melt events may play an important role in washing pollutants directly into fractures. Flow can occur laterally on frozen soils until it reaches a sinkhole feature. Because sinkholes are hydrologically active and are closer to the water table, they are warmer and may not be frozen. Transport to the groundwater table is likely. Snowpack melting may also contribute to groundwater mounding in areas where fractures are unable to convey the combined volumes of surface water and groundwater inputs. Such mounding will cause temporary shifts in groundwater flow paths and could flush pollutants directly out of the epikarst zone. There are some other geological conditions that could aggravate water mounding. South of the Onondaga Formation, the Oatka Creek shale has been shown by pump tests (Malcolm Pirnie, 2005) to have very low permeability. Subsurface storm runoff from this unit probably follows the bedrock / sediment layer interface into the Onondaga Formation. Flow from this unit is probably not uniform but is concentrated along northeast trending fracture traces which could convey it across the Onondaga Formation. Karst-related flooding at Quinlan and Britt Roads in LeRoy, NY, located far from the southern contact of the formation, are examples of this (see Voortman and Simon, 2009). Uneven fracture distribution within

the Onondaga Formation may also cause groundwater mounding. When combined with large precipitation and snow-melt events, groundwater influxes may temporarily exceed the capacity of fractures to discharge water away, resulting in dynamic water table rises. These water table rises may wash pollutants out of the soil zone and can cause pollutants to move in directions that are significantly different than the normal peizometric gradient (or surface gradient). Thus, description of the peizometric surface during active hydrologic events in the springtime are critical to understand in order to predict where pollutants might travel and where soils are close to the water table.

The Solution

Protecting groundwater resources in the Onondaga Formation will require mapping of areas that by virtue of their sinkholes, underlying fractures, thin sediment mantle, and distance to the water table are likely to be strongly hydrologically-connected to the groundwater table. This thesis will provide an essential data layer that will allow us to develop a comprehensive map of groundwater-sensitive areas. This product can be used by planning boards for developing rural areas wisely and crop advisors for providing good advice to farmers. The best solution is to identify sensitive areas first and manage agricultural waste accordingly. Protecting streams in karst areas using BMPs such as buffering is not effective because groundwater flow can short-circuit buffers and flow directly into the stream through fractures and conduits. Many rural domestic water supplies are obtained from shallow wells within the Onondaga Formation. The cost of putting all residents on public water is prohibitive. There is an urgent need to develop protocols for identifying sinkholes and hydrologically

connected fracture zones and dissolution features from widely available GIS and topographic data. In this and other karst regions, a reliable methodology is needed to identify areas that are most vulnerable to groundwater pollution. Mapping these sensitive areas is essential for successfully applying best management practices for protecting the region's water supplies.

NYSDEC response

In New York State, manure contamination is not taken lightly. The NYSDEC, the governmental agency responsible for addressing non-point-source pollution issues, has recently implemented a new set of guidelines to restrict the use of manure in Confined Animal Feeding Operations [CAFOs] over thinly soiled targeted regions (Czymbek et al. 2011). Guidelines restrict the use in the spring, as it is the time of the year when it has the most impact on groundwater. The targeted regions were determined by Czymbek et al. (2004) to be soils that exist over thinly-soiled karst areas, shown in Table 1. The NYSDEC guidelines also state that manure application cannot occur if it is within 100 feet of a sinkhole; therefore, it must also follow the spring restrictions. The same day rule of incorporation must also be followed in watersheds associated with swallets, which are sinkholes that capture streams. Implementation of these guidelines will be difficult because most sinkhole and karst areas in New York State have yet to be mapped. In addition, the targeted soils do not always occur over karst regions, meaning that a better understanding of the region is vital to knowing how to implement the guidelines set forth by the NYSDEC.

Sinkhole Identification

Previous studies have used a variety of approaches to identify sinkholes. These approaches include topography data, ortho-imagery, boreholes, Ground Penetrating Radar [GPR], field assessment, and electro-resistivity surveys. Each of these approaches has advantages and disadvantages. Topography can be analyzed in contour maps to identify the location of depressional features that may be sinkholes. Similarly, GIS visualization algorithms utilizing Digital Elevation Models [DEMs], such as hill shades, can be used to identify changes in relief such as fractures, escarpments, and sinkhole walls that are associated with sinkholes. The problem comes with the scale of the topography data. The 10-meter scale topography available in most areas in New York State can only be used to discern larger sinkhole features, which are rare and easy to identify in the field already. Light Detection and Ranging [LiDAR] derived high resolution data are useful for mapping small sinkholes, but the detail comes at the price of a long period required for analysis. Furthermore, a criterion is needed to differentiate sinkholes from small anthropogenically created depressions that are ubiquitous in the landscape. This means that additional land cover and orthography data are essential in the analysis. Boreholes can be used to identify thinly-soiled karst areas, but the data are expensive, and the spacing required to intersect with sinkhole features is usually unavailable. GPR can be used to identify sinkhole features by making subsurface features visible. It can also provide valuable information on depth to bedrock. The problem is that any clay in the soil will effectively block the signal, restricting its use to specific soil types. Furthermore, calibrating the instrument to identify the effective

dielectric constant of the profile is difficult if there aren't any features available that have a known depth. This makes the depth of the features within the profile uncertain. In the new karst management guidelines, what constitutes thinly-soiled karst is considered to be anywhere where the depth to bedrock is 4 feet. The GPR needs to have sufficient depth accuracy to determine this critical depth. GPR is often used with Electro-resistivity profiles to identify karst areas. The latter is not subject to signal loss by clay. Both Electro-resistivity and GPR are subject to the inverse problem that limits the usefulness of remote sensing. Ground-truthing information must be available to interpret the data. Such data are not usually available unless there are boreholes and trenches present. Field surveys appear to be the best method of locating sinkholes, but they require a lot of resources and person power; they are subject to obtaining landowner permission, which is sometimes difficult to do. They are usually conducted after the area has been assessed using these other previously discussed methods. Gutierrez et al. (2008) studied sinkhole formation in karst regions. That study used DEMs, recent and historical maps, as well as remotely sensed data to identify sinkholes. They pointed out that temporal changes in sinkhole morphology need to be understood better to determine how sinkholes form. This study uses a similar, multi-layered, approach for sinkhole identification; however, it will incorporate oblique imagery in the analysis, which has never been used in karst mapping.

Pictometry Oblique Imagery

A new type of remote sensing data has just been developed that may facilitate the identification of sinkholes. These data come from Pictometry oblique imagery. The

imagery is true color oblique imagery that is taken from an angle off-nadir. This perspective view should improve the identification of sinkholes because it is easier for the human eye to see depth at an angle. The aerial photography commonly used in karst mapping is traditional ortho-photography which is taken from a top down approach (0 degrees). This oblique imagery is taken from a 40 degree angle. This angle allows for substantial depth within the image to be seen. This is useful, as it allows for the detection of features on the surface (exposed bedrock, depressional areas, etc.) to be seen; whereas, in normal, direct aerial imagery, such features would be much harder to detect. Oblique imagery has been used in multi-sensor imagery georeferencing (Mostafa 2010), detection of tree and building heights, and object depth; but it has not been used to describe terrain features such as exposed bedrock, depressions, and sinkholes. According to Lemmens et al. (2007), the Pictometry images are obtained by using a 5-camera sensor system. This sensor system is comprised of a camera directed nadir, as well as four cameras 40 degrees off-nadir that point front, back, left, and right of trajectory. The image sets from Pictometry across New York State are comprised of geo-referenced data on a 6-inch resolution scale. This incredible detail allowed for the detection of very small features in the study area. This thesis will develop guidelines for the best use of this imagery in identifying karst features, including criteria for distinguishing sinkholes from quarries, gravel pits, glacial depressions, and anthropogenic depressions.

Study Area

Genesee County was chosen for the study area due to its proximity to known karst features in western New York, primarily the Onondaga Formation and Akron-Bertie Formation. These geology regions are known to contain sinkholes, which gives a good validation field for techniques developed in this study. The study region was extended to include small portions of southwestern Monroe County and northwestern Livingston County, as the karst/sinkhole region of the limestone is known to extend into those counties. Previous mapping of karst in the study area was conducted by Reddy and Kappell (2010) and Richards et al. (2010); the latter mapped sinkholes in the study area. Sinkholes were commonly found to be located on fracture traces. That study also observed numerous sites where bedrock at the surface was not associated with sinkholes. In addition, a thesis by Rhinehart (2005) studied disappearing lake phenomena in three sinkholes located on the Onondaga Formation in Leroy, NY. This thesis suggests that sinkholes in the study area are hydrologically active and are capable of washing pollutants into the subsurface.

Methodology

Hypothesis

Prior work on this topic has suggested that targeted soils (soil pedons that occur on carbonate bedrock with a maximum profile thickness of four feet), mapped by the soil survey in Genesee County (Wulforst et al 1969) and selected in the study by Cyzmmek et al. (2011), are located on thinly soiled karst. Pictometry imagery should show evidence of targeted soil/karst interaction via the presence of surface bedrock

exposure, moisture characteristics, and micro relief, which is indicative of bedrock terracing. This hypothesis is tested by examining random areas across Genesee County, searching for these features on both targeted and non-targeted soils. Results were compared to locations that existing well data have proven not to be thinly-soiled karst regions; if these features do indicate thinly-soiled areas, they should show a much higher frequency of exposed bedrock and micro relief at the surfaces than areas that are not thinly-soiled. I also assessed if any stony soils in the field, that are not located on thinly soiled areas, had the potential to be misinterpreted. Oil and gas well data were also used to validate whether or not the targeted soils are present over karst regions or shallow bedrock regions. Exposed bedrock and glacial deposits may be confused with one another in the oblique imagery interpretations, thus using well data to determine depth-to-bedrock is a vital piece to understanding these features.

Objectives

- Identify a subset of depressional areas/sinkholes and thinly soiled karst areas in Genesee County using Oblique Imagery, available water and gas well logs and ground-truthing.
- Determine which of the targeted soil types (Table 1) are actually associated with thinly soiled karst areas by comparing mapped soils and well data, and visually and statistically analyzing their distribution relative to karst features.
- Develop the best approach for identifying karst features from the Oblique Imagery; including, but not limited to, developing a set of observational parameters to assess sinkhole characteristics.

Procedure

To assess Genesee County as a whole, oblique imagery was overlaid with available hydrography data, wetlands, targeted soils, faults, DEC water wells, and oil and gas wells. Quaternary geology mapping by Muller (1977) was also considered. 250 depressions were identified and mapped using onscreen digitizing techniques. Sinkholes were identified from the depressions by excluding glacial kettles (and other depressions located on thick glacial deposits) and anthropogenic depressions. Of the initial 250 depressions, 110 were confirmed to be sinkholes. Select sinkholes were verified in the field.

Data Collection

Using the Pictometry Online Interface (pol.pictometry.com), a set of oblique images for New York was assessed in my study area. I also assessed available karst mapping in GIS format from Richards et al. (2010), as well as a soils dataset for Genesee County (SSURGO data from the NRCS; reference). I focused on Genesee County and bordering regions and used the soil survey maps as a guideline for where to look in the county for potentially interesting features. To analyze the imagery, I went through the sets of time-series-based images looking for any exposed rocks, sinkholes, and depressions that could be indicative of thinly-soiled karst areas. I evaluated land-use/land-cover and moisture in the depressions and the area surrounding these features. I also analyzed the size (area, as well as major and minor axes) and shape (based on relative boundary smoothness/irregularities) of the sinkholes, their subsurface geology, and location of targeted soils. These semi-quantitative descriptors

allowed for the use of statistics through a Cluster Analysis to classify sinkhole/depressional areas and determine if there are any additional similarities and differences between these features. I also evaluated whether time-sequence analysis of oblique imagery can determine if targeted soils are potentially close to the bedrock surface. Georeferenced imagery, oil and gas well data, soils data, sinkhole boundaries, hydrology, and county information were compiled in ArcGIS to create high quality maps of the region. Screenshots of different time-series images within Pictometry were taken to illustrate key features in representative sinkholes for each cluster case.

Parameter Creation

Using Pictometry and GIS, parameters were constructed to use in cluster analysis to differentiate the sinkholes. All parameters were compiled in categorical form to be analyzed in the cluster analysis (Table 2). Parameters were created by studying the region for characteristics that may be visible from aerial imagery, assessing what may potentially have physical impacts on a sinkhole formation (or current visible state), and then finally individually looking through each sinkhole -- including all time-series images for each-- and determining the best classification within Pictometry and GIS. Parameters created include categorical representations of Land Use, Moisture Content, Main Characteristics, Land/Water-Based, and Visibility of Sinkhole via Pictometry, and Target Soil Presence/Absence, Sinkhole Shape, Sinkhole Size, Distance to Escarpment, Bedrock Geology, Sinkhole Major Axis, and Sinkhole Minor Axis via GIS. These parameters were extracted to examine individual sinkholes in-depth and explore other potential relationships within the data.

Statistical Analyses

Cluster Analysis has been shown in prior studies to be an adequate method to assess sinkhole distributions (Gao et al 2005; Shim et al 2010). Mooi and Sarstedt (2011) mentioned that there is no standard minimum sample size; however, they noted that a 2^m -relationship (with m equaling amount of clustering variables) is generally used. Cluster Analysis was computed in SPSS 22 using targeted soil presence/absence, sinkhole shape, sinkhole size, land use, moisture content, secondary characteristics, land/water based, and visibility within Pictometry as the clustering variables. Distance to the nearest escarpment, major and minor axes, and bedrock geology were omitted from clustering after initial testing determined that these fields muddied the results, giving no apparent clustering.

Clusters were created in SPSS 22 using the hierarchical clustering method, with a between-groups linkage and squared Euclidean distance; no data standardization was used. Several combinations of the aforementioned variables were assessed, yet most produced little to no clustering of sinkholes. Different combinations were tried to determine if any potential relationships between the parameters occurred. For this data set, the only set of parameters that provided reasonable clustering were clusters based on Target Soil Presence/Absence, Sinkhole Shape, Sinkhole Size, Land Use, Moisture Content, Main Characteristics, Land/Water-Based, and Visibility of Sinkhole within Pictometry. A distance of 2.5 was used to separate the clusters, while a minimum of 3 cases were needed to be considered a cluster. The distance of 2.5 corresponds to a within-cluster data similarity of 97.5%; this level was chosen to ensure that a majority

of parameters were the same within-cluster to prevent clusters that contained a large variety of parameters. Using this method, 10 distinct clusters were identified, with a large region of non-clustered data as an 11th case as seen in Figure 1. Clusters contained similar sinkholes within the confines of a given cluster and were different from other clusters by at least one parameter. To understand the similarities and differences, it is important to look at the individual clusters.

Results

The results suggest that sinkholes varied in size from under 1,000 m² to over 1,000,000 m² in area; this resulted in large differences in size within the three defined categories for sinkhole size. The sinkholes were variable in shape, having either smooth boundaries or erratic boundaries. There were two possibilities for target soil interaction – presence or absence. Many sinkholes did not contain any targeted soils. The sinkholes were either visible in Pictometry, not visible in Pictometry, or evident based on other characteristics observed; the main difference between visible and evident is that visible sinkholes had obvious depressions, whereas evident were presumed due to exposed bedrock and other characteristics. Land-use classification was determined by 75% or more of the feature and considered mixed if one type did not dominate; land uses included field/soil, wooded, open water, shrub/vegetated, and mixes of land use. The secondary characteristics of the sinkholes included discolored soil, wooded, water, wetland, mowed, and shrub. Moisture content also had variability in that wet or dry could be observed for a given sinkhole; when sinkholes had time-steps that appeared wet, and others that appeared dry, they were classified as wet. A surface type was

established to differentiate between features that were land-based and those that were water-based, such as in ponds, wetlands, and streams. The cluster analysis on these data suggests that there are 10 classes of sinkholes that have similar features within each class. These clusters will be described in the sections below:

Cluster #1

This cluster is made up of 14 sinkholes. All sinkholes in this cluster overlap with target soils to some degree, are small in size, are land-based, have a wooded/forested land use, appear dry for most of the year (but experience spring flooding due to snowmelt), have wooded secondary characteristics, and most are not evident in Pictometry prior to overlaying contours. Most of the sinkholes in this class lie within the Onondaga Formation. Shape varies in this cluster, with seven sinkholes showing smooth boundaries and seven showing erratic boundaries. The sinkholes in this cluster do not appear as depressions (without contours enabled), unless a spring snowmelt event is observed; with contours enabled, most sinkholes lie in obvious contour low points.

The representative sinkhole for Cluster #1 is Sinkhole 65, located on Hawley Dr. on the campus of Genesee Community College in Batavia, NY. #65 was not an evident sinkhole in Pictometry, even with contours enabled, unless a snowmelt event was noted during the time series (Figures 2a & 2b). In dry time-steps, this sinkhole appears to be a stand of trees in the middle of a field. During presumed snowmelt time-steps, this feature becomes the center of water flow from at least three surrounding directions,

with water inundating the tree stand and ponding up all around it. Pictometry contours appear to be a problem on this site, with a gradient from the northeast to the southwest; this gradient crosses over the sinkhole feature with a 6-7 ft change in elevation from one side of the feature to the other. Mapping the moisture boundaries for the ponding that takes place, it becomes apparent that the contours are mapped wrong on this small scale feature since they cross the assumed constant height of the water surface. This becomes one of the rare cases where mis-mapped contours can become a deterrent to finding depressions (and thus potential sinkholes) using Pictometry.

The geologic features of #65 are that the sinkhole fully lies within the Dob bedrock geology (Onondaga Formation), while it is surrounded by AuA, AuB, and WsB target soils. The sinkhole as mapped, mostly lies outside of the target soils (Figure 2c); however, the boundary crosses into AuA in two spots, thus classifying it as containing target soils.

Cluster #2

This cluster consists of just three sinkholes. All of the sinkholes in this cluster are moderate in size with erratic sinkhole boundaries. They are all land-based, wooded/forested in land use, and generally appear dry. These sinkholes have wooded secondary characteristics and are not apparent as sinkholes in Pictometry. All of the sinkholes in this cluster lie on the Onondaga Formation. The only differences between the sinkholes in this cluster are that two of the three have interaction with the target soils, while one of them does not. When contours are enabled for these sinkholes, they

do tend to lie fairly close to the low regions, showing they do indeed exist in depressional areas.

The representative sinkhole for Cluster #2 is Sinkhole 67, located off of Lime Rock Rd. in Mumford, NY, just over one kilometer outside of Genesee County. #67 is generally not evident in Pictometry, due to being covered with trees; however, a couple dips in canopy height can be observed in the feature. These dips, however, are also seen in the surrounding, non-sinkhole area and thus cannot be considered a solid visual indicator of a sinkhole. With contours enabled on this site (Figure 3a), it does become evident that this site lies in part of a significant depression in the landscape. The western edge of the sinkhole feature appears to cross over 20+ feet in elevation; this is either an error in sinkhole mapping or an error in contour creation. In some spring time-steps (Figure 3b), this site appears to have some dark spots in it; whether this is shadow, moisture/water, or something else is un-determined. If it is water (likely due to a snowmelt in this case), it is a piece of visual evidence that a sinkhole (or at least a depression) is present in this site, beyond just the contour analysis.

#67 lies completely within the Dob geologic formation (Onondaga Formation) with Ro target soils in and around it (Figure 3c). Part of this sinkhole is absent of target soils. Of note for this sinkhole is the location of the aforementioned dark regions, which may be moisture. These match up well with the areas of the sinkhole that are absent the thin, target soils. This makes sense, since a thin soil would likely allow for quicker

infiltration; thus, having a thicker soil in the moist region would likely slow infiltration of the snowmelt.

Cluster #3

This cluster is made up of seven sinkholes. None of the sinkholes in this cluster are in the proximity of the target soils as they are mapped. Five of the sinkhole have smooth boundaries, while two of them have erratic boundaries. Six of the seven sinkholes lie on the Onondaga Formation. All of the sinkholes in this cluster are small and are land-based, with a wooded/forested land use. Six of the seven appear dry, while one showed signs of moisture, and most have wooded secondary characteristics. Five of the seven sinkholes were not evident in Pictometry without contours; however, two were evident. The two that were evident had boundaries that followed tree-lines, and/or followed target soil boundaries, and/or showed signs of moisture.

The representative sinkhole for this cluster is Sinkhole #97, located off of Graney Rd. in Caledonia, NY, just under three kilometers outside of the Genesee County border. #97 is evident in Pictometry as a dry pond bed, surrounded by a stand of trees. This feature becomes even more apparent after turning contours on, which shows that the feature lies directly in a depression (Figure 4a). In some time-steps, this feature actually fills in with water, likely due to snowmelt, forming a vernal pool (Figure 4b). This is very strong visual evidence for the presence of a sinkhole. With agricultural fields nearby, surrounding about half of this feature, this site is one that may get added constituents (pollution, manure, etc.) due to runoff, snowmelt, etc.

The geology of #97 is a feature lies completely within the Dob bedrock geology (Onondaga Formation). The feature fits well over an area of non-target soils, an absence in an otherwise expansive swath (Figure 4c) with some slight overlap, causing some shallow soils to be in the sinkhole. The soils in question are Fa, not the target soils, but shallow soil nonetheless.

Cluster #4

This cluster is made up of four sinkholes. All of the sinkholes in this cluster have interaction with target soils. They all lie within the Onondaga Formation. All four sinkholes have smooth boundaries, are small in size, are wet, and classify as open water in both class and characteristics. Three of the four have water as their land use, while one sinkhole is split between water and land. All four of these sinkholes were visible in Pictometry; this is due to the blatant ponding of these four features.

The representative sinkhole for this cluster is Sinkhole #4, located off of Gorton Rd, in Corfu, NY of Genesee County. #4 is visible in Pictometry as a small pond with two outlets and only a temporary inlet in some time-steps (Figure 5a) at the base of a steep depression along farm fields and a wooded region. Key features to note at this site are two spoil rock piles nearby with sub-angular boulders and trees, both upslope from the sinkhole (Figure 5b). The temporary inlet that forms appears to drain directly out of a rock pile; the water flow and rock amount and shapes would indicate that bedrock is close to the surface at this place, and that this is groundwater seeping out and feeding this pond, in addition to runoff over the sloped land. With such a steep

incline leading into this ponded sinkhole, coupled with farm fields immediately nearby, this feature is potentially highly susceptible to pollution from manure runoff.

The geology of #4 is the sinkhole feature laying completely within the Dob geology (Onondaga Formation). Target soils nearly completely surround this feature yet only barely appear inside of the feature (mainly due to this feature being a pond) as seen in (Figure 5c). The target soils observed in and around this feature are the AuA, BeB, and BeD soils of the Aurora and Benson groups. One last thing to note about this feature is that not far north from it is another sinkhole feature (Sinkhole #5), and the overland flow from #4 outlets directly leads into it.

Cluster #5

This cluster is made up of nine sinkholes. Only one of the nine sinkholes has any immediate interaction with the target soils. Four of the nine sinkholes lie in the Onondaga Formation, while five of the nine lie within the Akron-Bertie Formation. Eight of the nine have smooth boundaries. Five are small-sized, while four are moderately-sized sinkholes. All of the sinkholes in this cluster have a water land use, an open water characterization and a wet moisture regime. Eight of the nine are a water class - the last being a wooded/water mix. Every sinkhole was visible in Pictometry due to being a ponded, depression feature.

The representative sinkhole for this cluster is Sinkhole #62, which encompasses Phelps Pond in Oakfield, NY within Genesee County. #62 is visible in Pictometry as the open water pond known as Phelps Pond, which is surrounded mostly by steep slopes

of wooded regions, with farm fields on the two ends of the narrow pond, as well as additional fields surrounding the wooded slopes. In places, there are elevation changes between the pond's surface and the plateau of the slope by as much as 65+ ft as seen in (Figure 6a). The wooded region around most of the pond likely serves as a buffer zone for any potential pollution in the runoff, as well as to slow the runoff as it moves toward the pond.

The geology of #62 has it sitting fully within the Sab geology (Akron-Bertie Formation). Target soils nearly completely surround the feature, while parts clip into the sinkhole boundary (Figure 6b). Target soils in the immediate area are BeD, BeE, and WsB, Benson and Wassaic soils, with the AuA group (Aurora) farther upslope of the sinkhole.

Cluster #6

This cluster consists of four sinkholes. All sinkholes in this cluster have some interaction with the target soils. They all lie within the Onondaga Formation, are small in size, and have smooth boundaries. They are all land-based features with land use split within each feature between wooded and field (w/f). Three of the four sinkholes have wooded as a dominant characteristic, while the fourth is dominated by shrubs. They all appear dry, and the sinkholes do not appear evident in Pictometry.

The representative sinkhole for this cluster is Sinkhole #71, roughly 750 meters north of Rt 5. in Caledonia, NY in Livingston County. In Figure 7a from Pictometry, ridges within the field, parallel to the long axis of the sinkhole, are evident - noted by

the densely packed contours. These ridges indicate sloped land leading into this sinkhole; however, the ridges only partially encompass the entire feature, showing that this is likely a low point in the land. This means that more evidence is needed to support this feature being a sinkhole. Figure 7b is a zoomed-in version of the prior figure, with contours disabled. This shows several exposed rock fragments, appearing to be sub-angular boulders, within the farm field around and inside the feature; a few of these may even be exposed bedrock. This is indicative of shallow soil.

The geology of #71 (Figure 7c) shows the sinkhole laying completely within the Dob geology (Onondaga Formation), completely full of the Fa group soils, the Farmington group. Adding all of these visual and mapped factors together, it is evident that this feature is likely a sinkhole. Since this sinkhole lies over limestone bedrock, has shallow soils, and is partly farmed, this feature needs to be buffered according to the regulation guidelines.

Cluster #7

This cluster is made of only three sinkholes. They have no proximity with target soils. They each lie within a different bedrock geology type, although geology was not a factor in clustering. Two of the three have smooth boundaries. They are all moderately sized, land-based, dry moisture levels, and are field land use. Their main characteristic is soil, and they are not evident in Pictometry without contours; although, evidence is there for modified growth in some time-steps. With contours on, these features become more apparent.

The representative sinkhole for this cluster is Sinkhole #15, off of Lewiston Rd. in Batavia, NY - just north of I-90. Figure 8a from Pictometry has the 2013 time-step showing a dry barren field, with the sinkhole feature sitting between two high points in the surrounding fields. The prior time-step from 2010, shown in Figure 8b shows the fields with greenery beginning to grow, while a spot with no growth is within the center of the feature. This is likely due to increased flow and/or concentration of water in this region. One time-step farther back (Figure 8c) shows a field with a small region inundated by water, likely as a disappearing lake feature, and located in the same position as the absent vegetation from the previous feature. These three time-steps show that the main sinkhole itself is likely this focused depression where water can be more concentrated, while the surrounding region is a depression that feeds into the main sinkhole.

The geology of #15, as shown in Figure 8d, illustrates this feature as laying completely within the Dob geology (Onondaga Formation). There are no mapped shallow soils within roughly 300 m of the feature, with the closest target soil shown to be the BeB (Benson) group soil.

Cluster #8

This cluster is made up of eight sinkholes. Every sinkhole in this cluster has an interaction with the target soils in some form. Seven of the eight sinkholes lay within the Onondaga Formation, while one is within the Akron-Bertie. Half have smooth boundaries, while the other half have erratic boundaries. They are all moderate in size,

land-based, and the main land use is field. They all appear to be dry moisture content in most time-steps, and seven of eight have a main characteristic of soil, while the eighth has shrub. Only one of the eight features was partially evident as a sinkhole via Pictometry prior to enabling contours.

The representative sinkhole for this cluster is Sinkhole #16, located off of Bartof Rd in Stafford, NY. Figure 9a shows a sinkhole feature that cuts across contours, unlike a depression; however, it is the micro-topography of this feature that helps classify #16 as a sinkhole. Evident within the boundaries of #16, seen in Figure 9b, are micro-relief features that are small-scale depressions within the larger feature. Scattered throughout the feature, as well as surrounding #16, are bedrock outcrops and sub-angular boulders; both indicative of very shallow soil.

The geology of #16, as seen in Figure 9c, lies completely within the Dob bedrock geology (the Onondaga Formation). AuA soils from the Aurora group push into the sinkhole, and NeA and WsB (Newstead and Wassaic) soils also exist nearby. The limestone bedrock and shallow soils help point to the pitted, depressed micro-topography of this feature that as a whole does not appear to be a depression based on contours; in fact, it is a series of depressions in a larger region, likely formed in the pitted bedrock surface of the limestone, forming miniature sinkholes comprising one large feature.

Cluster #9

This cluster is made up of three sinkholes. None of the sinkholes in this cluster have interaction with the target soils. Two of the three sinkholes are within the Onondaga Formation. They all have smooth boundaries and are small in size. They are all land-based with field land use. All three appear to be dry in moisture content, and all have soil as the dominant characteristic. Only one of the three sinkholes was evident in Pictometry prior to enabling contours.

The representative sinkhole for this cluster is Sinkhole #40, located off of Bartof Rd. in Stafford, NY. Figure 10a shows #40 mostly within the minimum of the contours. Some soil in this feature appear discolored, potentially indicative of added moisture or differing soil types. Of note to the east of #40 is a rock spoil pile with shrubs growing on it in the middle of the field. This sort of spoil pile is likely due to a bedrock outcropping and abundant rock fragments spread through the field; farmers need an easy location to drop off large rocks plowed up from the field and generally choose an un-farmable location to place them. Figure 10b gives a northerly perspective of the feature that shows dozens of rock fragments in the field within the boundaries of #40. This adds support to the idea that there is potentially shallow bedrock nearby.

The geology of #40, shown in Figure 10c, lists the sinkhole as completely within the Dob geology (Onondaga Formation), with no target soils within the feature. Of note is the WsB (Wassaic group) target soil just to the east of the feature, which corresponds

nically with the rock spoil pile and potential exposed bedrock. This adds evidence for nearby near-surface bedrock and gives support to this feature being a sinkhole.

Cluster #10

This cluster is made up of 21 sinkholes, by far the largest cluster sampled. Twenty of the 21 sinkholes in this cluster have interaction with the target soils. All 21 sinkholes lay within the Onondaga Formation. Eleven have smooth boundaries, while 10 have erratic. All 21 sinkholes are small in size, land-based, and are of the field land use. They all appear dry in terms of moisture content. Ten of the sinkholes have a main characteristic of shrub, while the other 11 have soil as their dominant characteristic. Twenty of the 21 sinkholes were not visible in Pictometry, while the last was evident and visible in Pictometry.

The representative sinkhole for this cluster is Sinkhole #46, located off of Flint Hill Rd. and Lime Rock Rd. in LeRoy, NY. Figure 11a shows the rough topography of #46; the sinkhole itself spans across three local minimums. The terrain is potted and covered with sporadically dense shrubbery. Figure 11b gives a better look at the shrubbery with the western half of the feature fairly densely covered and the eastern half fairly free of shrubs. No obvious signs of depressions are visible. The dense shrub regions in an otherwise barren region hints at a localization of water, which could be due to depressions altering overland flow.

The geology of #46 is shown in Figure 11c; it shows the entire feature laying within the Dob bedrock (Onondaga Formation), while being completely filled with target soil.

Within #46 are BeB, and WsB soils (Benson and Wassiac groups). The complete coverage of target soils mean this is a shallow depth to bedrock over limestone, meaning the pitted nature of karst in this area has likely rendered this feature into a sinkhole.

Non-Cluster Group

This group is made up of 11 sinkholes that did not classify into any of the prior clusters. The sinkholes in this group shared a mix of traits; hence, they did not cluster well. They were either open-water, or wooded in nature. They were mostly water-based or water/land mix-based feature. They were all wet. A split was seen in that some were small, some were moderate, while some had smooth boundaries, while others were erratic. All three categories were present for Pictometry evidence – yes, no, and evident. Additionally, eight had no target soils. The three main bedrock types were also observed – Onondaga, Akron-Bertie, and Camillus. This jumbling of parameters is what kept these sinkholes from being clustered with one another at the defined clustering level.

There are three representative sinkholes for this non-cluster group, to show the differences that exist within this group, both from one another and from the actual clusters obtained. The representative sinkholes are Sinkhole #7, Sinkhole #26, and Sinkhole #66.

Sinkhole #7 is located off of Indian Falls Rd. in East Pembroke, NY. As seen in Figure 12a, it appears to be a vernal pool wetland, down slope of farm fields that

surround it on three sides, while homes and a road lie on the last side. In other time-steps, you can see that a good majority (if not all) of the moisture has left the feature, as seen in Figure 12b; of note are the apparent wet spots within the fields surrounding the feature, suggesting microtopographic lows that may indeed feed into the larger sinkhole feature. This sinkhole is moderately-sized and has a smooth boundary. It is wet, has a wooded/wet mix land use (due to the apparent vernal pool nature of this feature), and is wooded as a secondary characteristic. Due to the shape of the feature, corresponding to the wooded region, the standing water, and the visible depression, this feature is deemed visible in Pictometry. The geology of Sinkhole #7 is that it fully lies within the Onondaga Formation. Figure 12c shows that there are no target soils in the vicinity of this feature, meaning there is a large depth-to-bedrock within this feature.

Sinkhole #26 is located off of Quinlan Rd. in LeRoy, NY. It is a low spot along a small stream, located in the depressional mid-point between to farm fields. Seen in Figure 13a, this feature is full of brush, trees, and shrubs from where farmers have decided not to farm this land, presumably due to the enhanced moisture due to the sinkhole. Also visible are wet spots within the field that are likely associated with the feature and flow into it either overland or via subsurface flow. This feature is classified as a mix of both water and land-based, it is wooded/wet mix land use, is wet moisture content, and is wooded as a secondary characteristic. It is small-sized with a smooth boundary and not evident in Pictometry without adding in contours. This feature lies within the Onondaga Formation and has no interaction with the target soils, as seen in Figure 13b.

Sinkhole #66 is located off of Flint Hill Rd. in Mumford, NY, in the woods near Oatka Creek. This feature is another one of the presumed vernal pool sinkhole features. It consists of a small stream that goes into a wooded pond in the center of the elongated depression (Figure 14a). Figure 14b shows just how severe of a drop of this pond lies within, changing by over 25 feet of elevation on some sides of the temporary pond; Figure 14c shows a dry time-step of this feature. Figures 14d and 14e show a more close-up view of the pond itself, looking along the fetch of the pond from the west. In these figures, you can clearly see the drastic changes that take place from a wet period to a dry period with regards to moisture. This sinkhole is moderately-size and has an erratic boundary. It is classified as a water/land-based mix due to its presumed vernal nature, with a wooded/water land use mix, wet moisture content, and wooded secondary characteristic. Due to its vernal pool nature and the fairly obvious depression in the visible imagery, it is classified as evident in Pictometry. Figure 14f shows the geology of Sinkhole #66 as lying mainly within the Akron-Bertie Formation (with a small part over the Camillus group) and interacting with the target soils, specifically Rubbleland with the Benson series, also nearby.

These three representative sinkholes share some parameters, most notably the wet, wooded nature of the features; however, they have drastic differences as well. Specifically, they vary in their size, boundary, geology, targeted soil presence/absence, and whether they are obvious as depressions/sinkholes within the Pictometry imagery. These factors are what led to their lack of classification using these developed cluster parameters.

Special Cases

In comparison to the representative sinkholes from the given clusters, there were a couple special cases that stood out in general among all of the sinkholes in this study. These two special cases were sites that stood out in imagery, yet did not fall into the created clusters. The first is a disappearing lake site, which is a key site for potential pollution. The second is a site that shows characteristics of being a sinkhole visually, yet is not a sinkhole at all. These two features will be discussed in the two following subsections.

Iverson Rd. Disappearing Lake

A specific sinkhole site of interest to this study, is Sinkhole #25 – the Iverson Rd. disappearing lake. This sinkhole feature spans across two different farm fields and frequently appears at least partially flooded in the spring (Figure 15a); however, even when not flooded in the spring, prior to vegetation growth, this feature still appears with discolored soils, as seen in Figure 15b. The main culprit for this flooding is snow melt events. Sinkhole #25 is a moderately-sized feature with a smooth boundary. It is land-based, with farm field as its main land use. It appears wet and has discolored soil as a secondary characteristic. This feature is visible in Pictometry due to its abundant flooding and visible depression prior to adding contours to the imagery. This feature lies within the Camillus formation, outside of the mapped karst terrain. It has no interaction with the target soils, as seen in Figure 15c; however, the Wassiac group nearly completely surrounds this feature. This site is known to have pollution issues, and it is one that does not fall into the clusters as defined by this study. When running

the clustering in SPSS, this feature fell outside of all clusters, including the ‘non-cluster group.’ It did not match up with any cluster until a distance of 6, which was far too large for this study.

False-Positive Site

Genesee County Building 2 is a key false-positive site analyzed in this study. This site had visible exposed rock in Pictometry imagery, shown in Figure 16a, as well as a mapped topographic low (Figure 16b) surrounded by rocky mounds; this made it a key candidate for a sinkhole. The geology of the feature, shown in Figure 16c, is that the region lies solely within the Onondaga Formation and has nearby target soils, both Benson and Wassiac series. However, upon analyzing the oil and gas well data for this site, it was noted that depth-to-bedrock was greater than 20 feet. This means that the soils in this area may have been identified incorrectly. This could in-part have been caused by the fact that the exposed rock pieces were limestone, and it was assumed that they were bedrock/bedrock fragments. Solely going by Pictometry, this feature would have been classified as a sinkhole; so, this feature shows that it is imperative to have checks and balances in place to check whether what is seen is a sinkhole or not.

Discussion

Cluster Analysis

Through the analysis of the clustering done on this sinkhole data set, it is clear that there are relevant patterns present. Certain parameters tended to influence the clustering more than others, namely the target soils, land use, and moisture content;

although, all had obvious influences. How the sinkholes were split into 10 clusters, with a non-cluster transition group, made physical sense; clusters obtained were wooded, water-based, or farm fields, primarily, further split by presence and absence of target soils, their moisture contents, and their overall sizes. It would be interesting to see how the addition of any future determined parameters may (or may not) influence this data set. Overall, what these clusters mean is that you may be able to refine your methodology for finding sinkholes depending on the land uses of the region you are studying. For instance, if you know specifically that you are analyzing solely farm fields, you then know that visually you should look for soil discoloration, presence/absence of moisture, and exposed bedrock/boulders (which was not a parameter in this study but is a good candidate for a future parameter).

The non-cluster group is an important group to note in this study, as it made up roughly 20% of the sinkholes observed in the study region. Although these did not fall into any of the defined clusters at the assigned clustering distance, they did fall into clusters when observing a larger cluster distance of 5 (which provided 4 large, generalized clusters). This means that there are some obvious similarities among these sinkholes with those in the clusters. Specifically, this cluster group seemed to bridge the gap between the open water and wooded sinkholes, to those in the field. Specifically, the sinkholes in the non-cluster group were wetland-type sinkholes, or seasonally wet, merging from the wooded and open water types into the field based. This gap is important to note if these methods are expanded to karst regions with abundant wetlands.

Pictometry

This study demonstrated that the oblique imagery was useful to find sinkholes. Having an oblique image set via Pictometry is a significant improvement over ortho-imagery, because you get four different views of the same site. Time-series data proved to be essential for observing changes in standing water, presence or absence of rock, which seem to be indicative of karst features. It should be noted that prior to 2013, Pictometry was using a year-to-year elevation model (likely based off of the USGS topography); since 2013, they are using LiDAR-generated topography, which should be far more accurate, thus erasing topographical errors in the time-steps since then. Unfortunately, USGS topography is not very accurate at this scale and thus is not useful for finding sinkholes.

Overlaying sets of known sinkhole boundaries with the imagery was useful for training the observer to identify sinkholes in the imagery. This training was useful for quality control, checking features that are thought to be sinkholes, and finding false positives. Having this practice will assist in implementing this type of study in other regions where no sinkholes have been mapped. This analysis can further be applied to the analysis of the potential farm-field based pollution that is important in Genesee County, based on the guidelines set forth by Cyzmmek et al. (2011). Pictometry can also be used to observe these areas of interest visually for changes in land use, moisture content, and vegetation changes, which may be helpful for identifying sinkholes that are at the risk of manure contamination. The approach can easily be extended to other parts of New York State because Pictometry Imagery is available in all counties.

Although the use of Pictometry ended up being a vital tool for determining sinkholes, it is apparent that one needs a variety of spatial data to be able to assess a sinkhole fully; specifically, having access to further GIS-based data sets is important to the study. Having a sinkhole data set that was based on pre-examined LiDAR data and hill-shading techniques proved useful in locating the sinkholes initially, as well as to train me in what to look for in Pictometry to find the features. Having the known geology and soils layers were important for understanding how to interpret the sinkholes in relation to important karst and shallow soil regions, which would have been impossible to do with the imagery alone. Having oil and gas well data was also important for ‘ground-truthing’ thinly-soiled areas that appeared to be sinkholes based on their visual characteristics in Pictometry, but in fact, were false positives. So, while I am advocating for the use of Pictometry imagery to aid in finding sinkholes, it must be used in conjunction with other data sets to understand what is being seen.

Future Work

There are several ways that this project could be expanded upon in the future: new parameter development, new statistics, additional image sets, and expansion to other regions. First would be the potential development of new parameters (or expansion of existing parameters) to add into the clustering algorithm -- specifically of note, visible rock fragment presence/absence. Adding more land uses, etc. will also be important, as this methodology is used in other regions. Possibly including distance to escarpment and geology type may provide useful relationships elsewhere (although it

did not appear to in terms of statistical analysis in this study when attempted). Using multiple variable regression analysis may also be able to detect trends or relationships between the parameters. As more and more image sets are made by Pictometry, more time-steps will be available to analyze these features; additionally, finer resolution as we move through time will allow for micro-features and smaller-scale rock fragments and moisture to be observed. Finally, this methodology can be expended to Albany County in New York (or to the entire state). It is known that Albany County has a lot of karst terrain, specifically sinkholes, fractured exposed bedrock, and cave systems. Applying a Pictometry analysis to the karst regions of Albany is sure to provide some very interesting results.

Conclusions

This thesis evaluated 250 depressions in the study area; of these, 110 were confirmed to be sinkholes. This study demonstrated that sinkholes were easier to identify with oblique imagery than in conventional aerial photography because of the improved perspective gained by seeing the feature at a 40 degree angle. Also, the ability to observe from four different directions was important, as often the feature is obscured in part by canopy cover. The ability to inspect several years of data was useful because spring photography commonly captures karst-related flooding, as well as runoff directly into the feature. In a few places, these flooding scenes were a better description of the location of the depression than the topography data, which often does not capture the true topography at that scale. That the imagery is geo-rectified was also a plus

because other GIS data that are associated with the presence of karst (such as fracture traces and targeted soils) can be uploaded and plotted in the Pictometry Online interface with the imagery. The cluster analysis clearly shows that there is a relationship between sinkholes and a variety of GIS data types. These statistically derived associations suggest that the following factors are indicative of sinkholes: Visible Depression, Secondary Characteristics, Target Soil Presence/Absence, Moisture Content, Land Use, Type (water/land), Size, and Shape. The study suggested that distance from visible escarpments and bedrock geology was not statistically correlated to sinkholes in Genesee County and surrounding areas.

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Tables

Table 1. Targeted soil types found in Genesee County (after Czymmek et al, 2004). Different abbreviations correspond to differing slopes of soil surfaces.

Soil Type	Abbreviations
Aurora	AuA, AuB
Benson	BeB, BeD, BeE
Farmington	Fa
Newstead	NeA
Rubbleland	Ro
Wassaic	WsB

Table 2. Categorical parameters created from Pictometry and GIS that were used in the cluster analysis for differentiation of sinkholes. Pictometry based parameters created via use of the Pictometry time-series imagery and observing the sinkhole features evident in Genesee County. Parameters may need to be expanded/contracted for use in other regions.

Parameter	Subset	Explanation	From
Target Soil	Present	Target soil present in / intersected sinkhole.	GIS
	Absent	Target soil not present in/did not intersect sinkhole.	
Shape	Smooth	Smooth sinkhole boundary	GIS
	Erratic	Sharp/jagged sinkhole boundary	
Size	Small	Sinkhole < 25,000 m ²	GIS
	Moderate	25,000 m ² < Sinkhole < 100,000 m ²	
	Large	Sinkhole > 100,000 m ²	
Type	Land	Land-based sinkhole.	Pict.
	Water	Water-based sinkhole; i.e. pond, creek, etc.	
	Both	Mix of land-based and water-based.	
Moisture Content	Wet	Constant signs of moisture in at least part of sinkhole.	Pict.
	Dry	No signs of moisture in any part of sinkhole.	
	Both	Moisture is seasonal depending upon precipitation.	
Land Use Class	Wooded	Heavily forested, >~75% of sinkhole.	Pict.
	Water	Water dominated, >~75% of sinkhole.	
	Wooded/Water	Water and forested mix, >~75% of sinkhole.	
	Field/Soil	Field (farm / barren) dominated, >~75% of sinkhole.	
	Wooded/Field	Forested and field dominated mix, >~75% of sinkhole.	
Main Characteristic	Open Water	Pond or creek is most notable feature in sinkhole.	Pict.
	Wooded	Tree outcrop or forest area is notable in sinkhole.	
	Shrub	Shrubbery is most notable feature in sinkhole.	
	Soil	Bare exposed soil is most notable feature in sinkhole.	
	Wetland	Wetland is most notable feature in sinkhole.	
	Mowed	Mowed grass or yard is most notable feature in sinkhole.	
Visibility in Pictometry	Yes	Without contours, sinkhole is visible.	Pict.
	No	Without contours, sinkhole is not visible.	
	Evident	Without contours, sinkhole is evident via other parameters.	

Figures

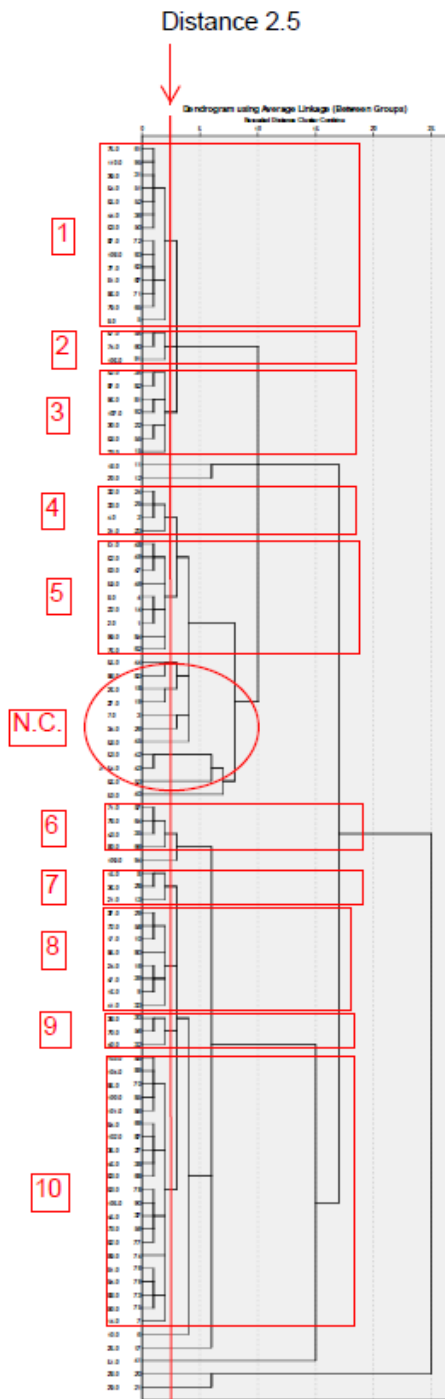


Figure 1. Annotated dendrogram of distance 2.5 clusters, using a minimum of three cases to define a cluster. This clustering result allows for the differentiation of 10 distinct groups of sinkholes characterized by certain parameters.

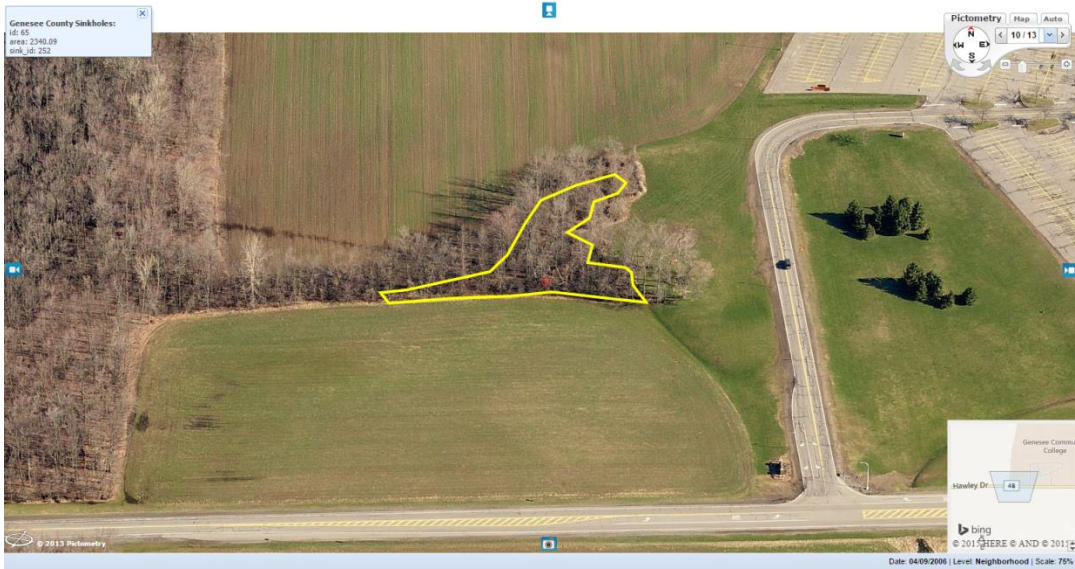


Figure 2a. A dry period time-step for Sinkhole #65 located on the campus of Genesee Community College in Batavia, NY. Although a drier period, some water is still evident flowing into the feature from the west.

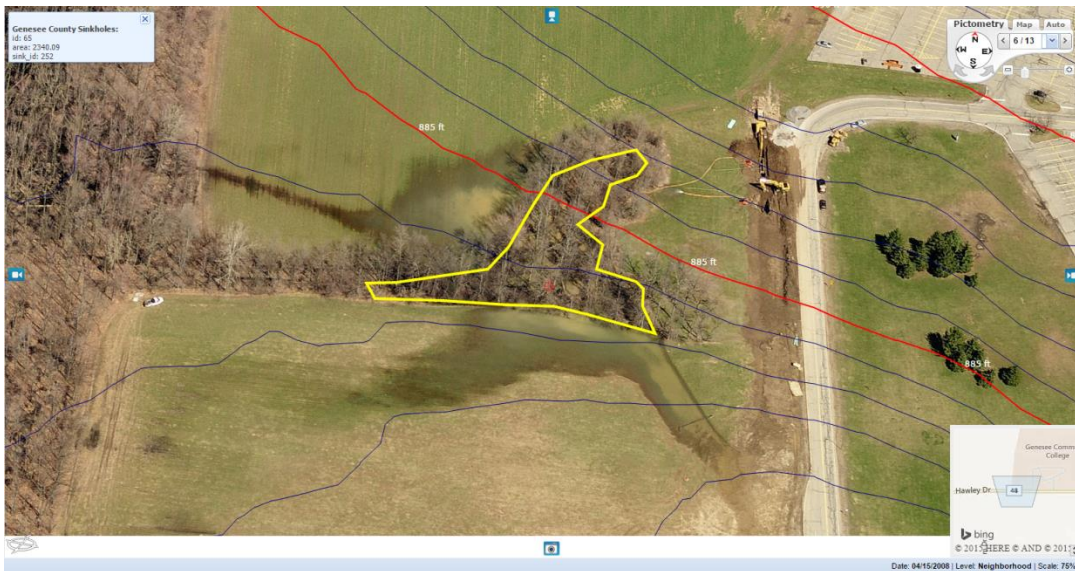
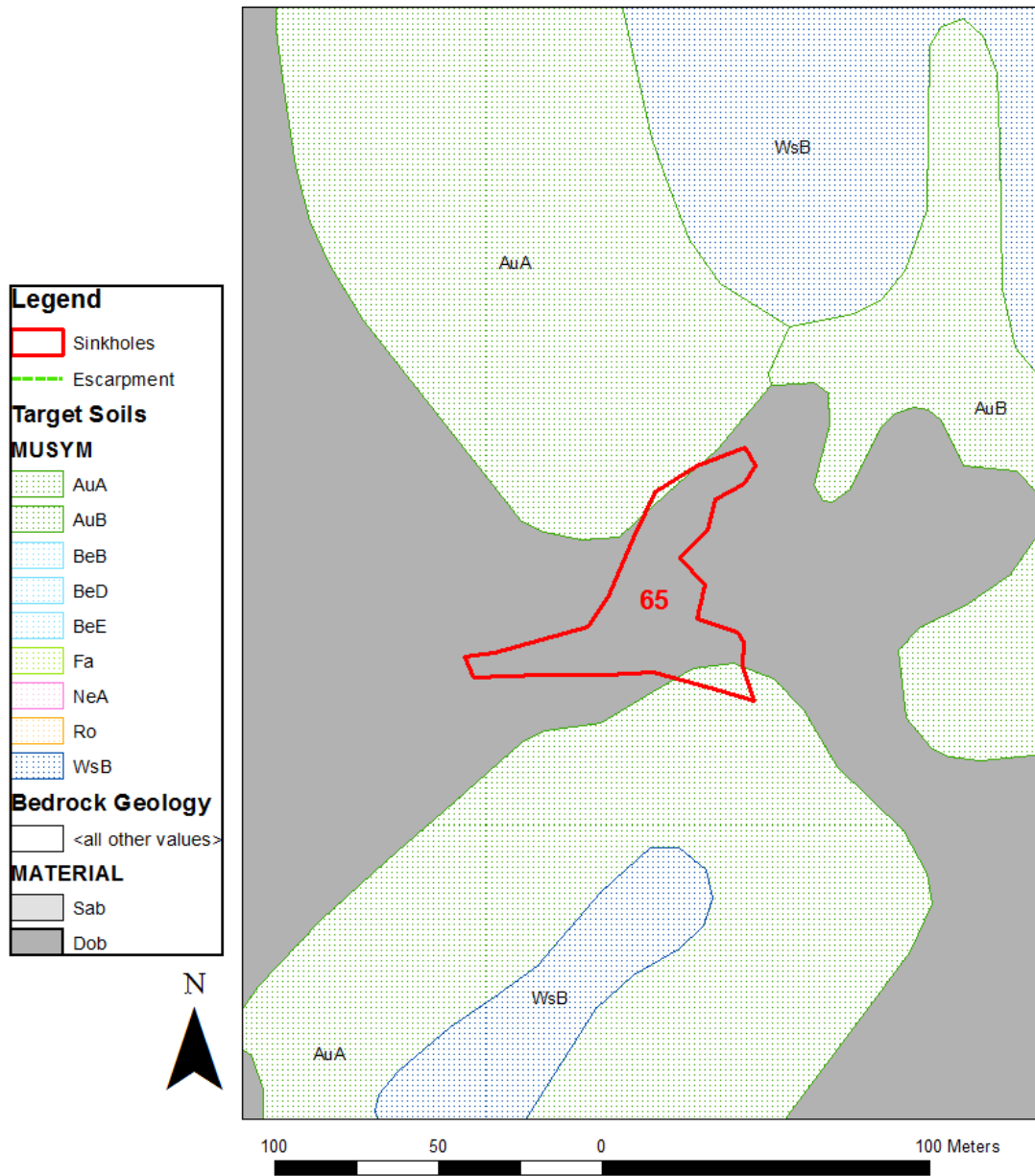


Figure 2b. A wet period time-step for Sinkhole #65 located on the campus of Genesee Community College in Batavia, NY. Water flows are evident coming in from both the west and from the south-east. Due to the amount of water and the time of year, this is a presumed snowmelt event. Of note here is that this sinkhole crosses contour boundaries; this suggests that the micro-topography represented by these contours was not accurate at the time of this map's creation.

Sinkhole #65



Author: Michael D. Rodgers

Figure 2c. GIS-based map product of Sinkhole #65. This sinkhole classifies as ‘contains target soils’ due to the overlap of the feature boundary with that of the target soils – specifically, the Aurora group. This is an erratic-shaped, small-sized sinkhole within the Onondaga Formation.

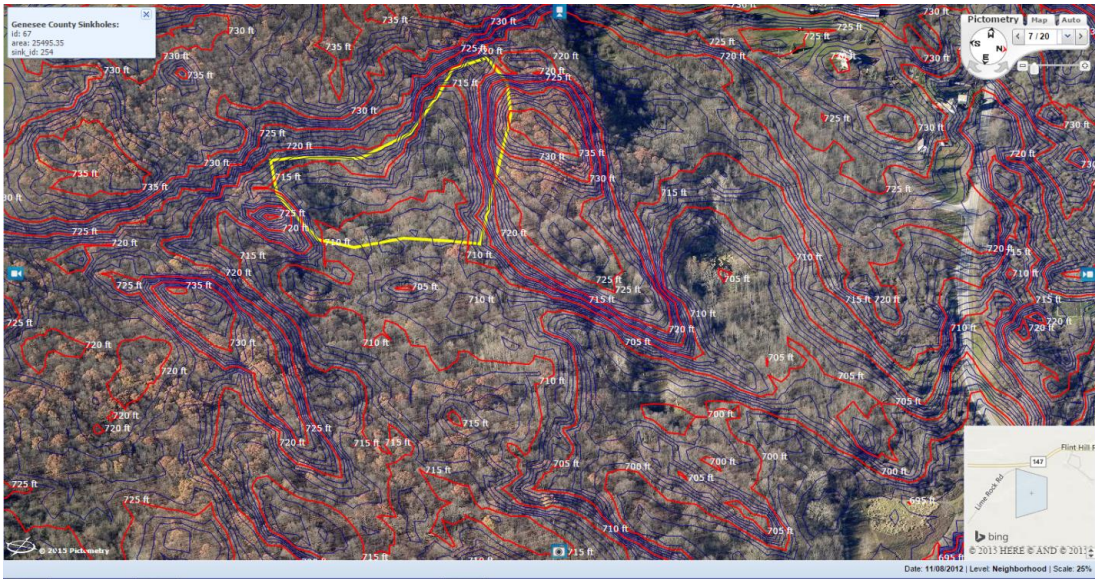


Figure 3a. Sinkhole #67 lies in a significant depression, although only falls in part of it. The sinkhole boundary crosses several contours over an elevation change of 20+ feet; this is either an error in the contour mapping or an error in the sinkhole mapping from prior studies. View from east.

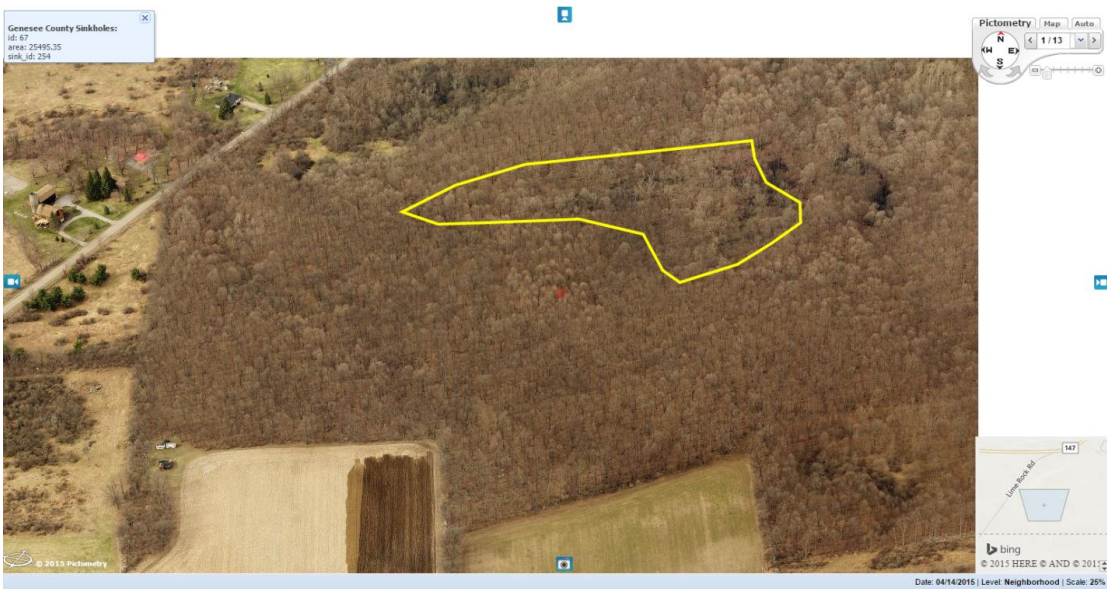
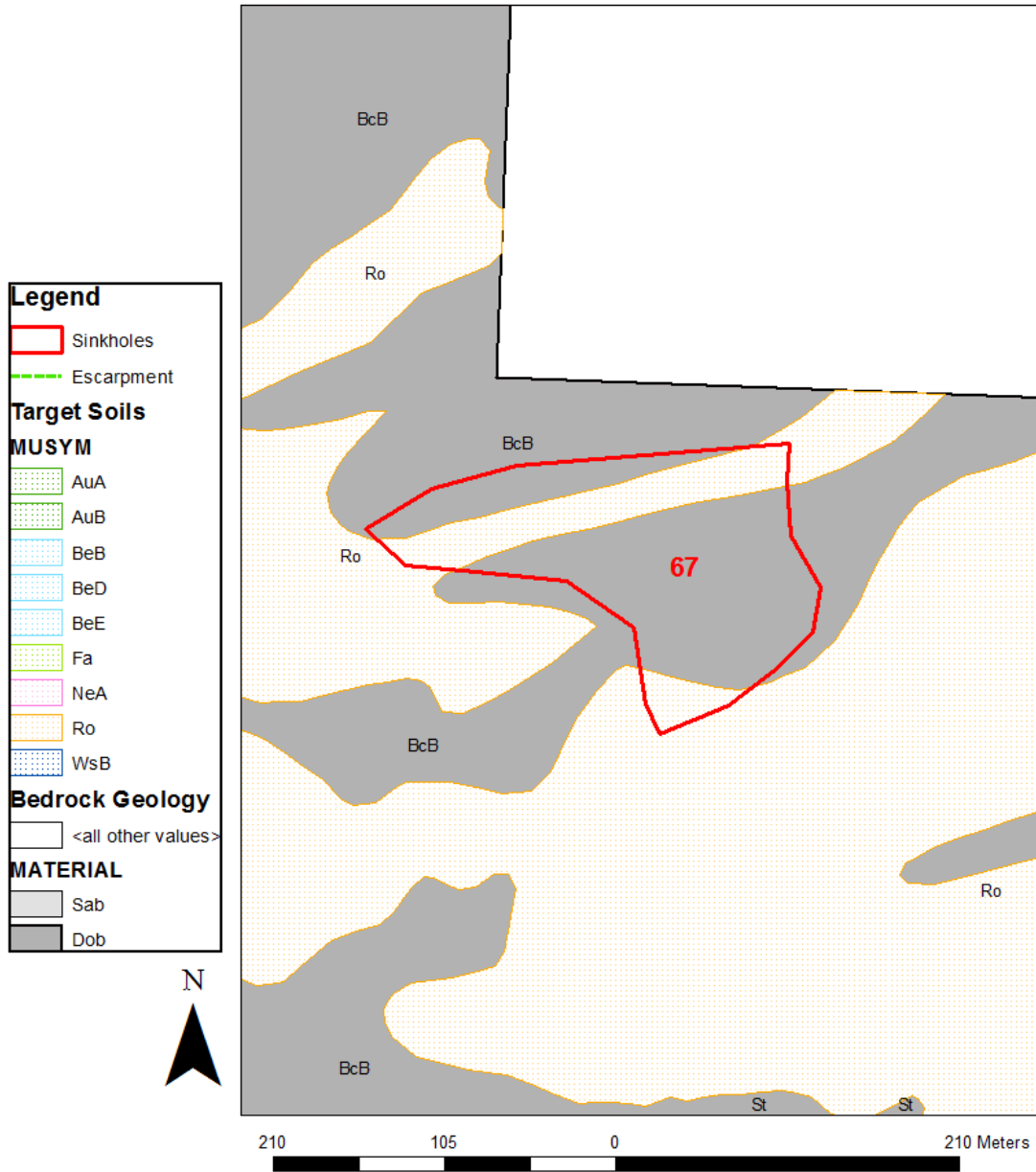


Figure 3b. A mostly dry time-step for Sinkhole #67. This time-step does show some anomalies in the far eastern reaches of the feature. These are dark regions that could be caused by a number of things – shadows, moisture/water, or darkened soils. This is one of the micro-features that are tough to discern in Pictometry.

Sinkhole #67



Author: Michael D. Rodgers

Figure 3c. GIS-based map product for Sinkhole #67. This feature contains target soils, specifically, Benson and Rubbleland. This feature is an erratic-boundary, moderately-sized sinkhole within the Onondaga Formation.



Figure 4a. This is dry-period time-step of Sinkhole #97 in Caledonia, NY. This feature is a very evident sinkhole feature, lying nicely within the contours. It appears to be a dry pond basin, possibly a vernal pool that refills with snowmelt. View from the east.

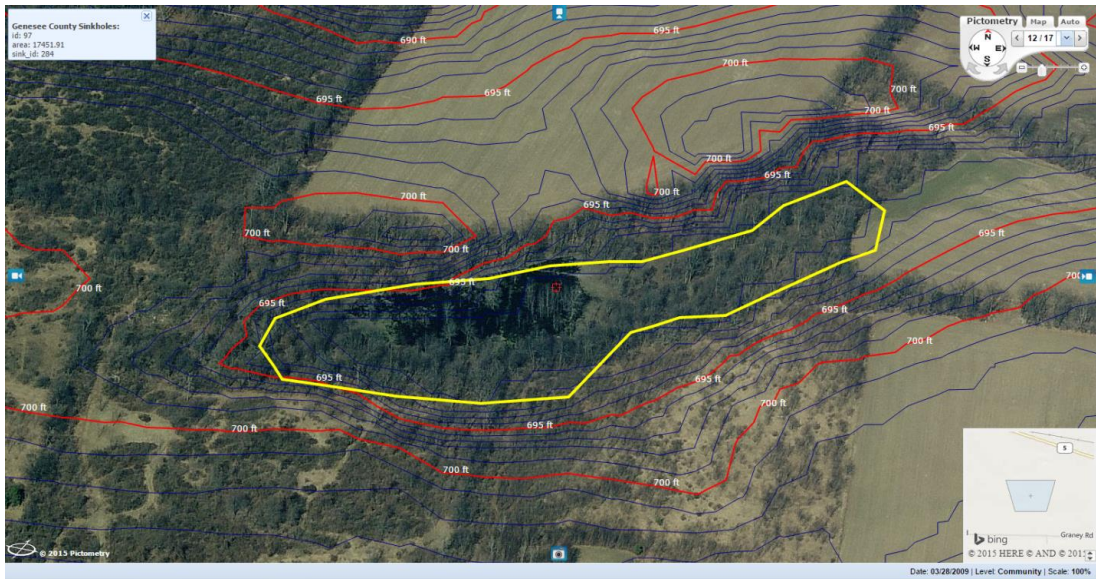
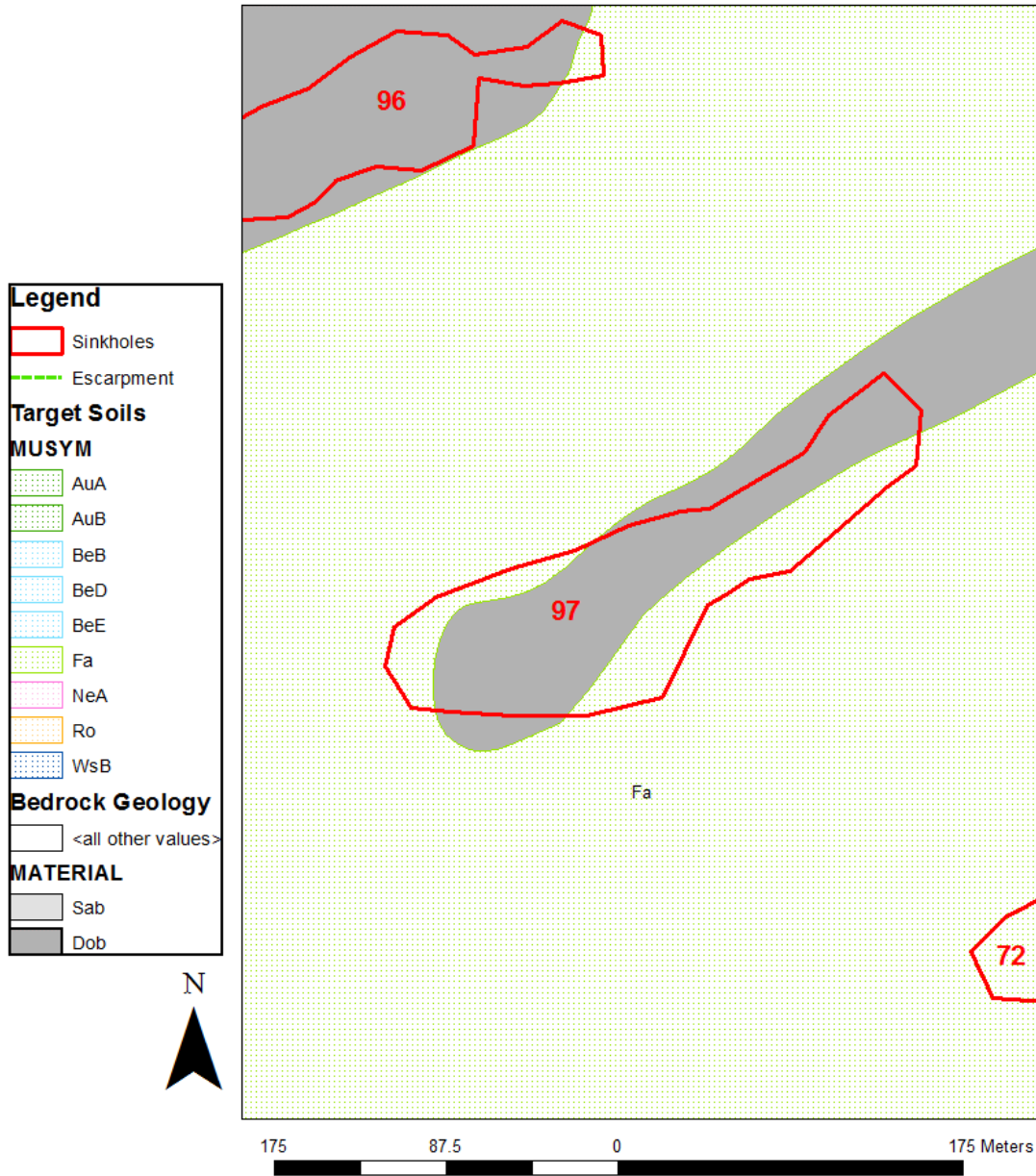


Figure 4b. A wet-period time-step for Sinkhole #97. This shows the pond basin filled with water from a likely snowmelt event. This time-step further enhances the probability that this is a vernal pool sinkhole.

Sinkhole #97



Author: Michael D. Rodgers

Figure 4c. GIS-based map product for Sinkhole #97. This shows the feature itself containing shallow soil – from the Farmington group; it is not initially classified as a target soil in Genesee County; however, it is certainly a shallow-to-bedrock soil interacting with karst features.

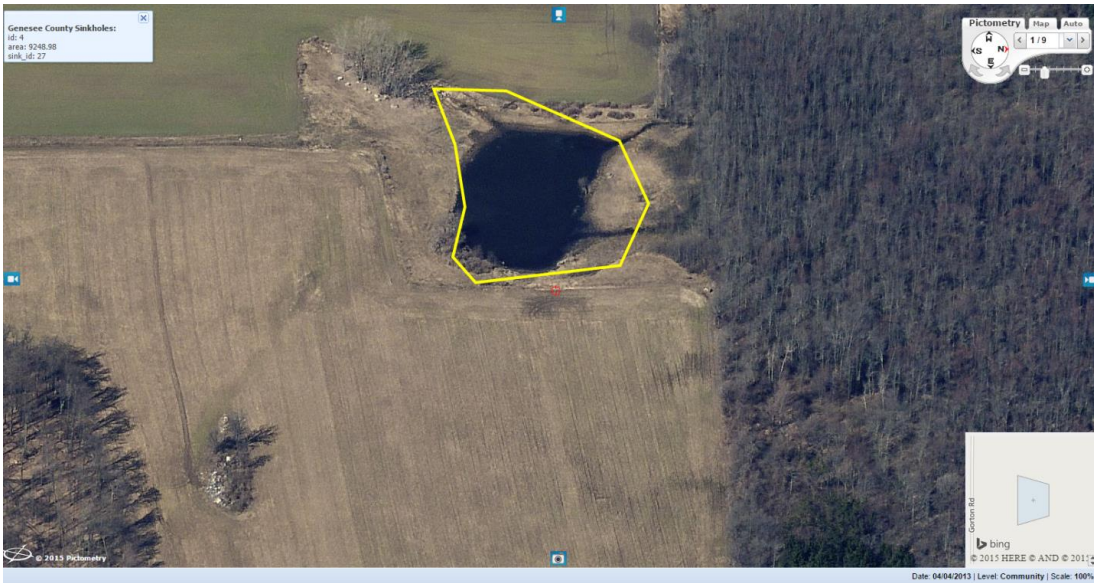


Figure 5a. Sinkhole #4 in Corfu, NY. Two pond outlets located on right side of pond (north). Small temporary inlet is present coming out of the rock spoil pile to the west (top) of the image. This inlet feature is not present in all time-steps of Pictometry. View from east.

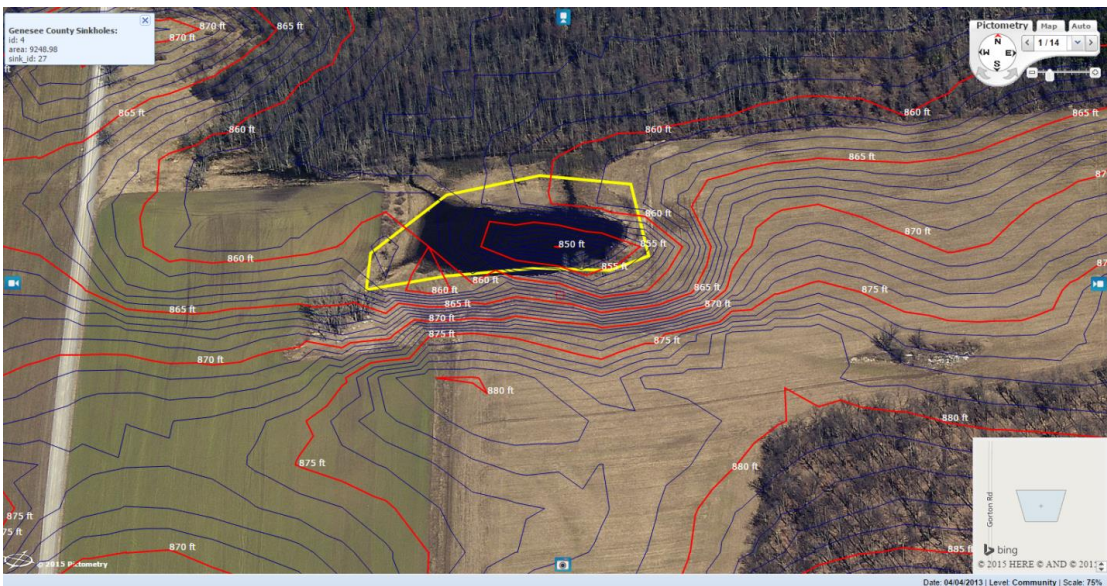
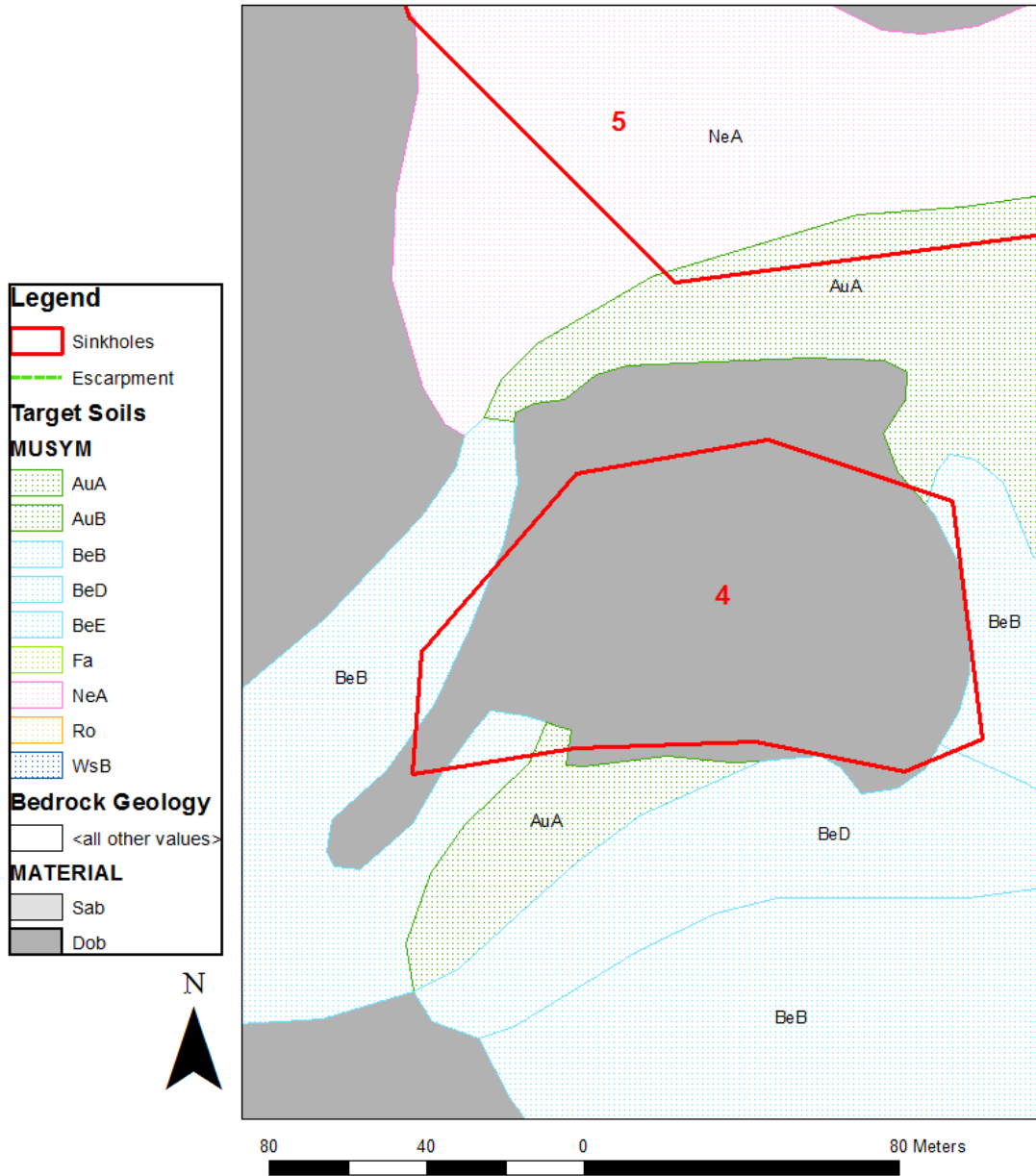


Figure 5b. Sinkhole #4 is a small, smooth-shaped feature. Two spoil rock piles with sub-angular boundaries are visible upslope of the sinkhole. This feature is permanently inundated with water, and is the basin for runoff from the upslope fields.

Sinkhole #4



Author: Michael D. Rodgers

Figure 5c. GIS-based map product for Sinkhole #4. This is a smooth, small-sized feature in the Onondaga Formation. This contains target soils, albeit barely – both Aurora and Benson groups are present.

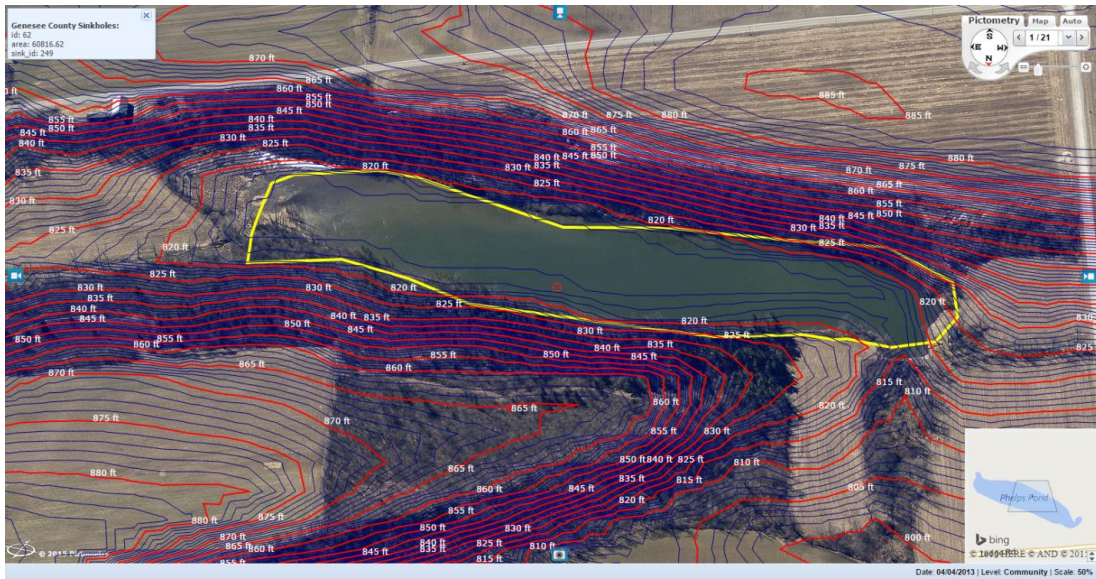
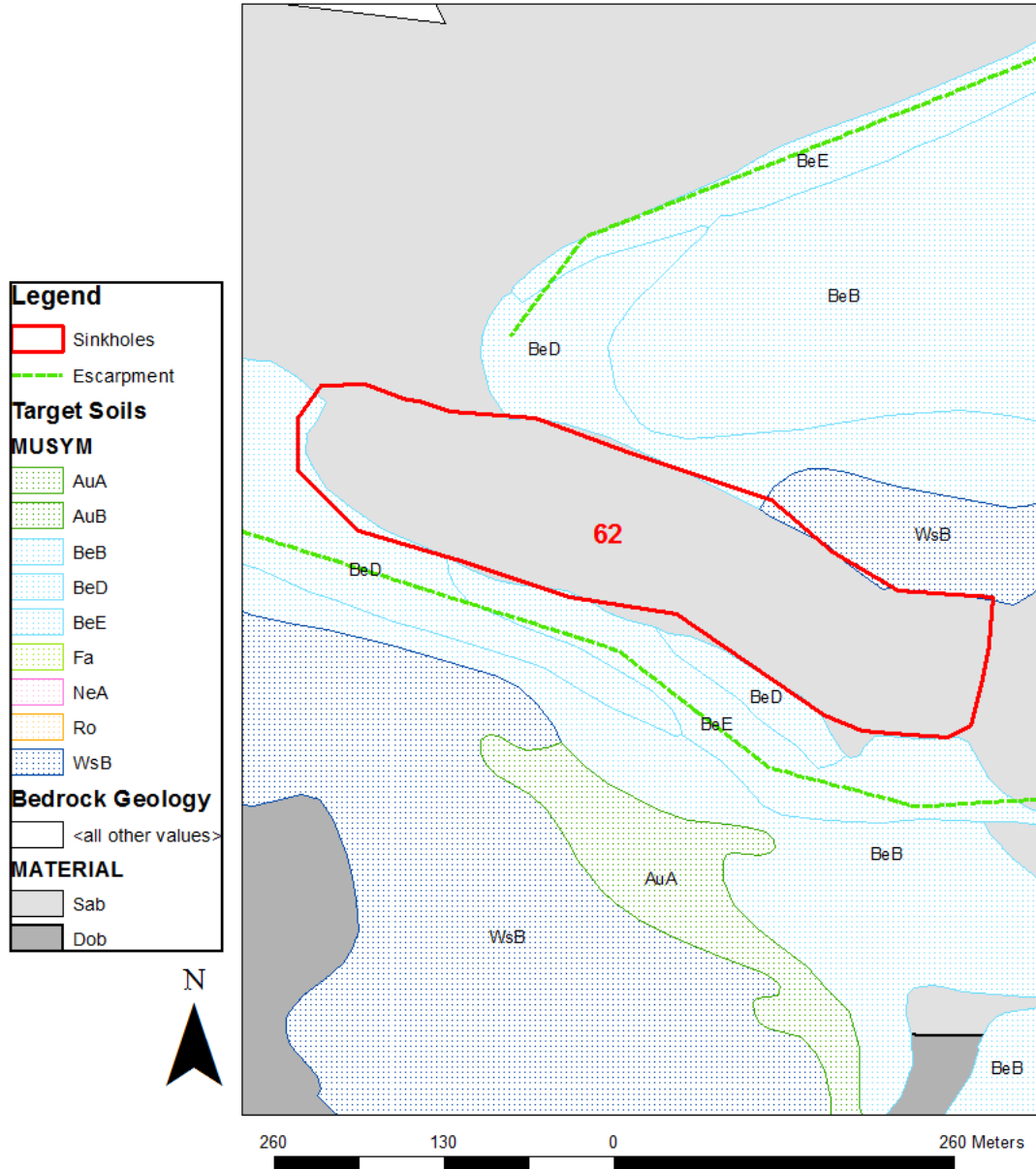


Figure 6a. Sinkhole #62 in Oakfield, NY encompassing Phelps Pond with contours enabled. This shows the steep slopes leading into Phelps Pond, with surrounding wooded regions and farm fields nearby. This is a large natural basin for runoff to accumulate in. Surrounded by farm fields around most of the feature, this is a likely candidate for increased pollution of the groundwater table.

Sinkhole #62



Author: Michael D. Rodgers

Figure 6b. GIS-based map product for Sinkhole #62. This smooth, moderately-sized sinkhole lies almost perfectly within a gap in the target soil, although it does slightly overlap – This gap is due to the water from the pond itself. It does have inclusion of the Benson group soil. This feature lies extremely close to the Onondaga escarpment, being just north of the feature, within the Akron-Bertie Formation.

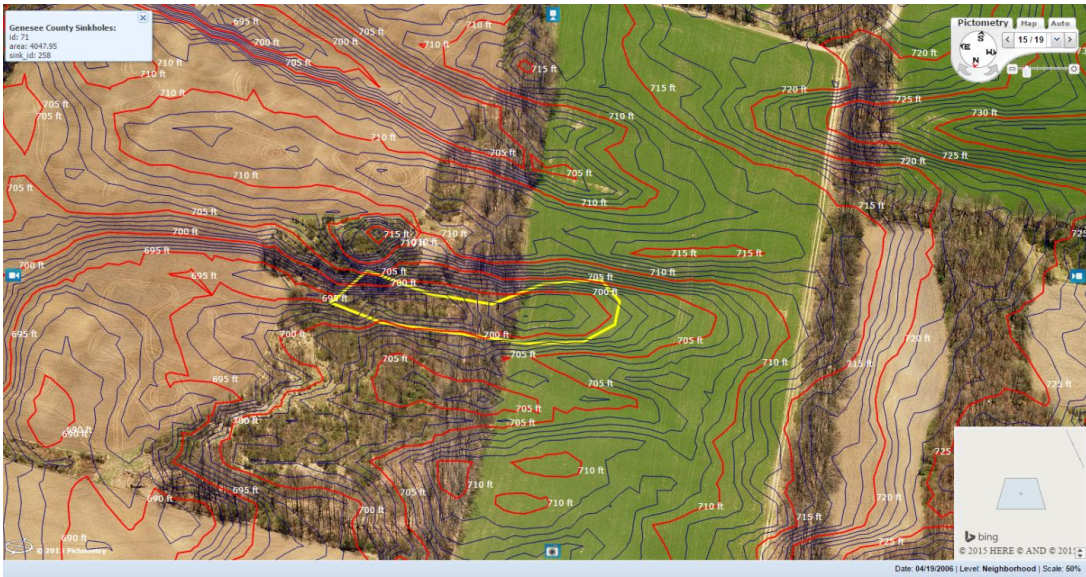


Figure 7a. Sinkhole #71 in Caledonia, NY. Pictometry with contours denoting two ridges parallel to the long axis of the sinkhole within the farm field portion of the feature. This smooth, small-sized feature is a funnel for the upslope farm field runoff. View from north.

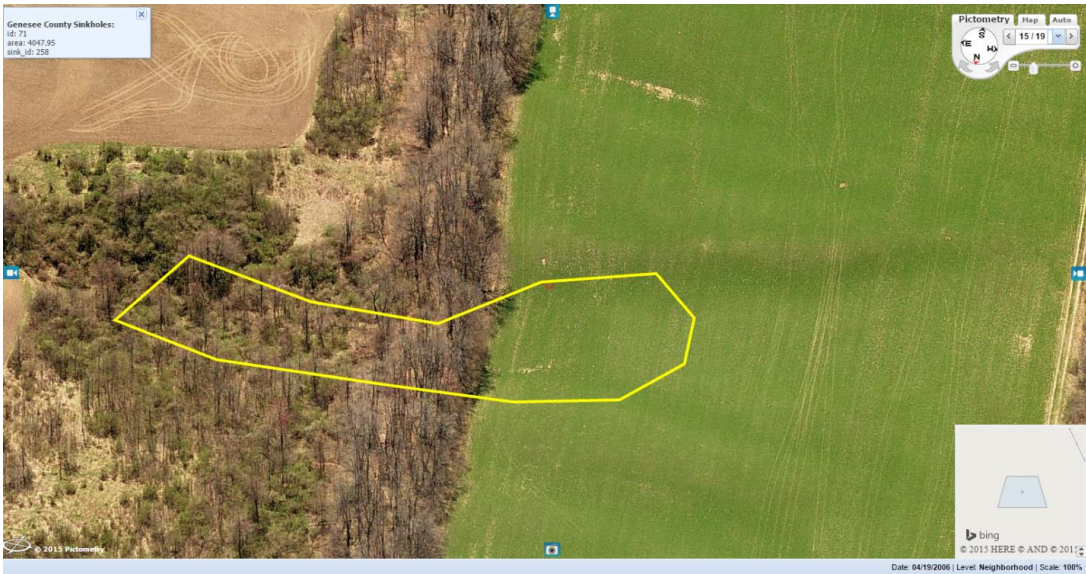
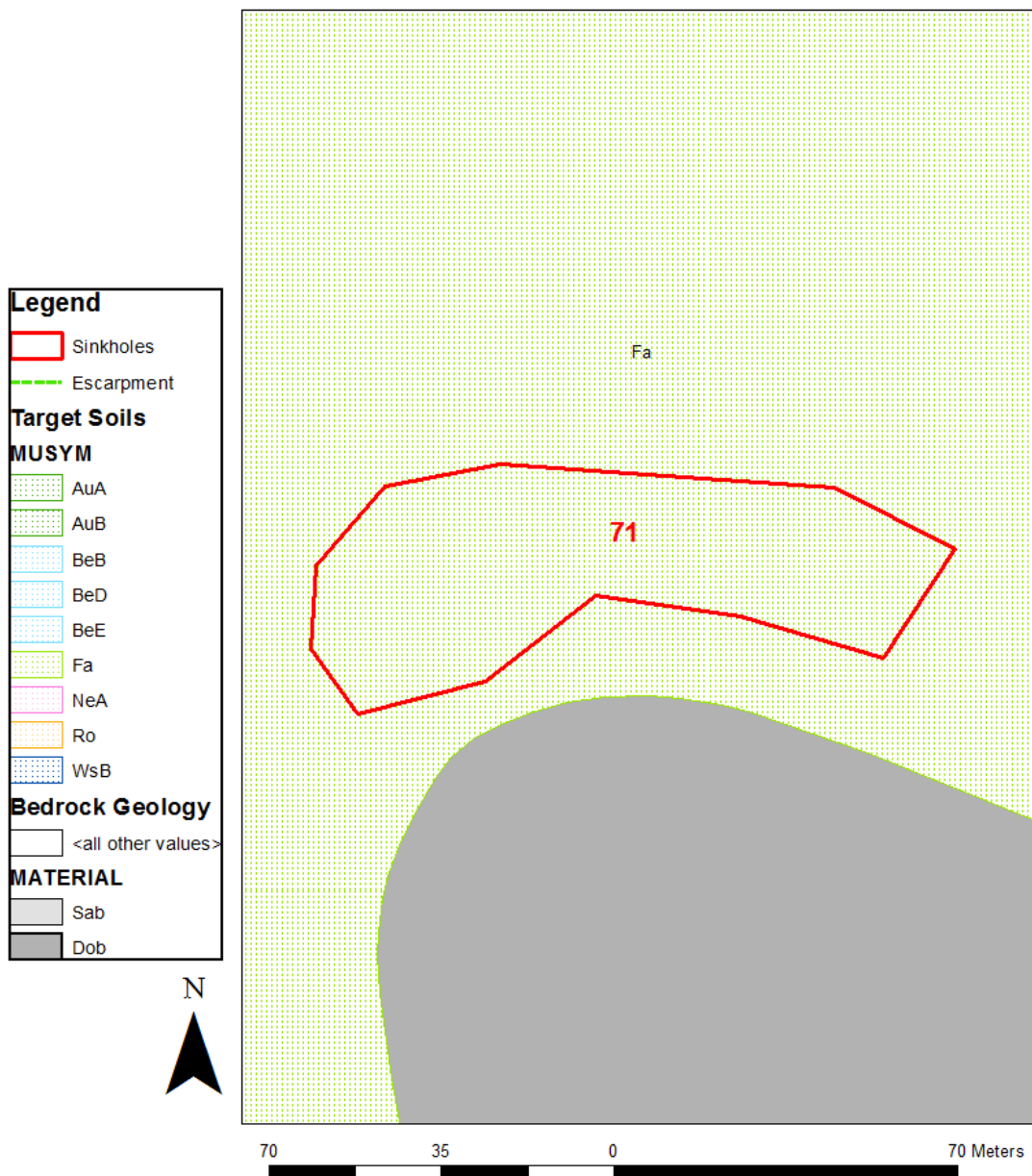


Figure 7b. Sinkhole #71 Pictometry view from north; zoomed in to show boulders and sub angular rocks scattered through the farm field. These sub-angular rocks are indicative of shallow depth-to-bedrock and karstic terrain.

Sinkhole #71



Author: Michael D. Rodgers

Figure 7c. GIS-based map product of sinkhole #71. This sinkhole is within the Onondaga Formation. This shows the feature laying completely within the Farmington group soil; although not a target soil by definition, it is a shallow soil that lies over karst terrain.

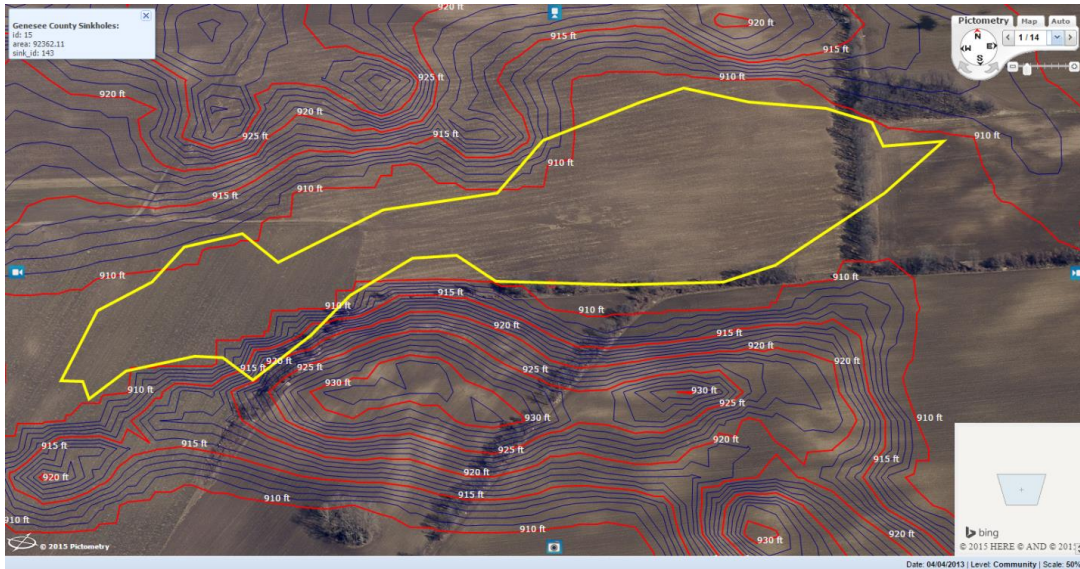


Figure 8a. Sinkhole #15 in Batavia, NY. This is from a dry time-step. The feature lies within a nice low-point in the contours within this farm field. Evident is slight soil discoloration, hinting at potential soil-type changes or differences in moisture content.

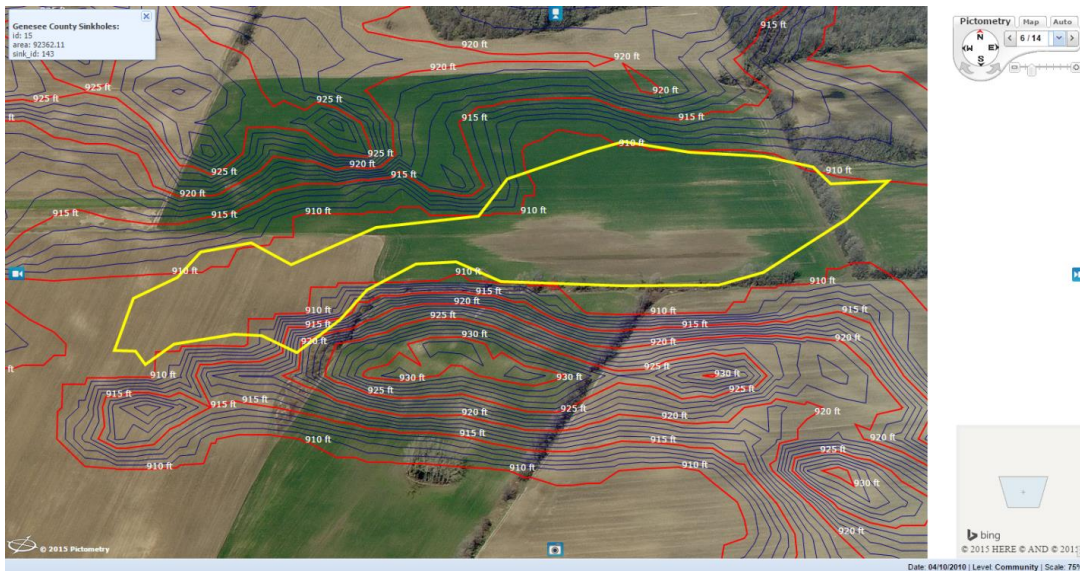
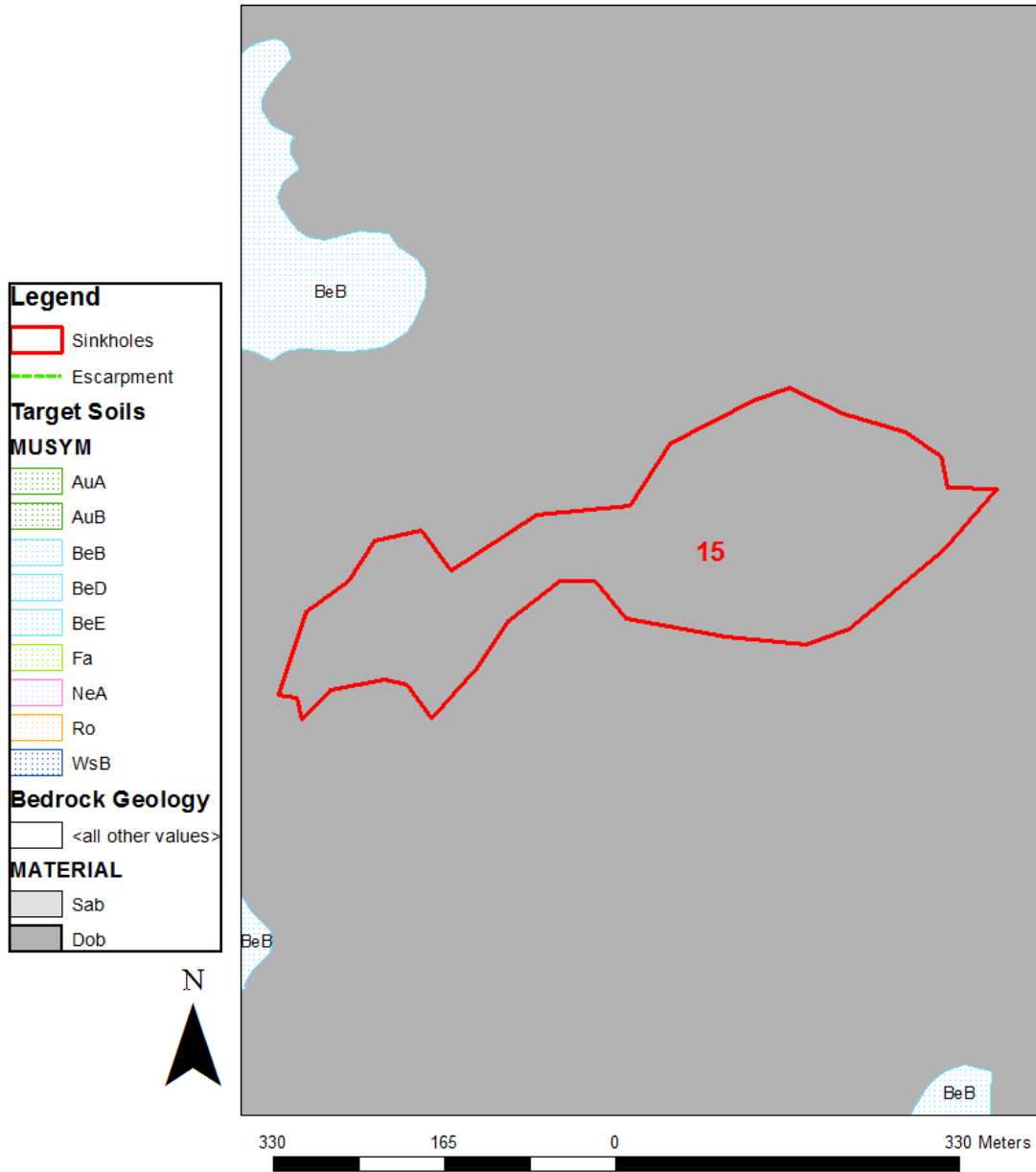


Figure 8b. Sinkhole #15 during vegetation growth period. A barren spot is located within the sinkhole, likely due to increased moisture prohibiting plant growth.



Figure 8c. Moist time-step for Sinkhole #15. Spring snowmelt has resulted in a temporary lake appearing in the middle of this sinkhole feature. This moist location matches the absent vegetation location from the prior figure.

Sinkhole #15



Author: Michael D. Rodgers

Figure 8d. GIS-based map product for Sinkhole #15. This feature is within the Onondaga Formation and is absent of target soils. It is an erratic boundary feature that is moderately-sized.

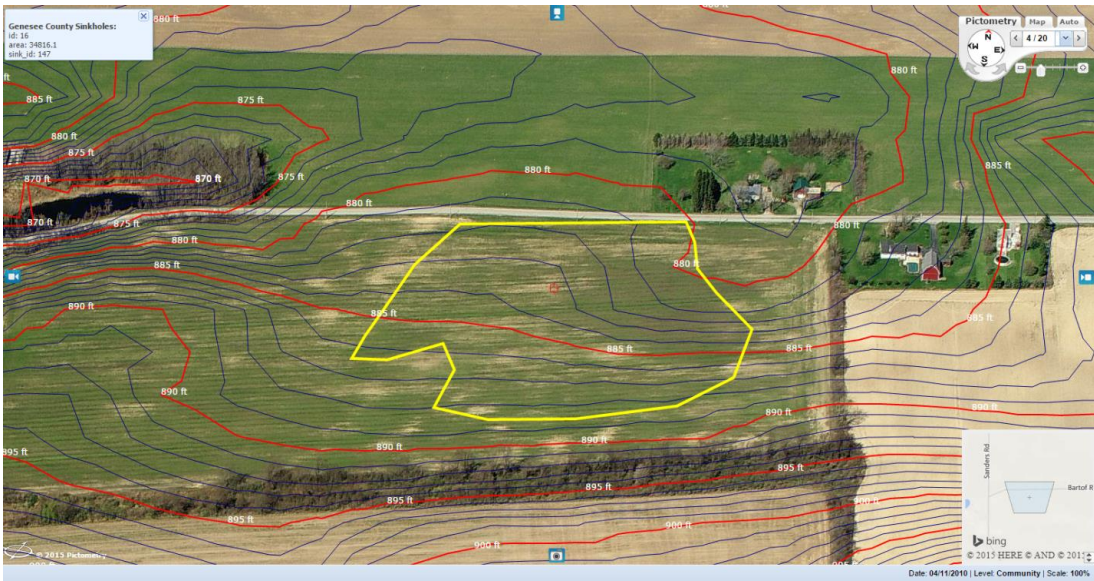


Figure 9a. Sinkhole #16 located on Bartof Rd. in Stafford, NY. This is a classic shallow depth-to-bedrock sinkhole feature. The feature itself crosses contours but has micro-topographic depression features throughout that collectively comprise the sinkhole.

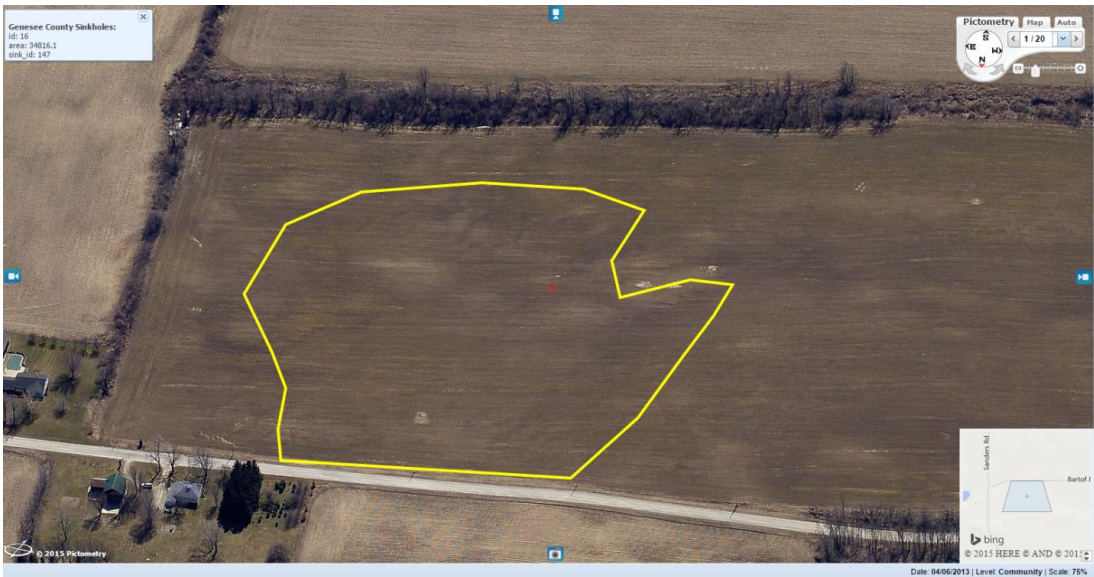
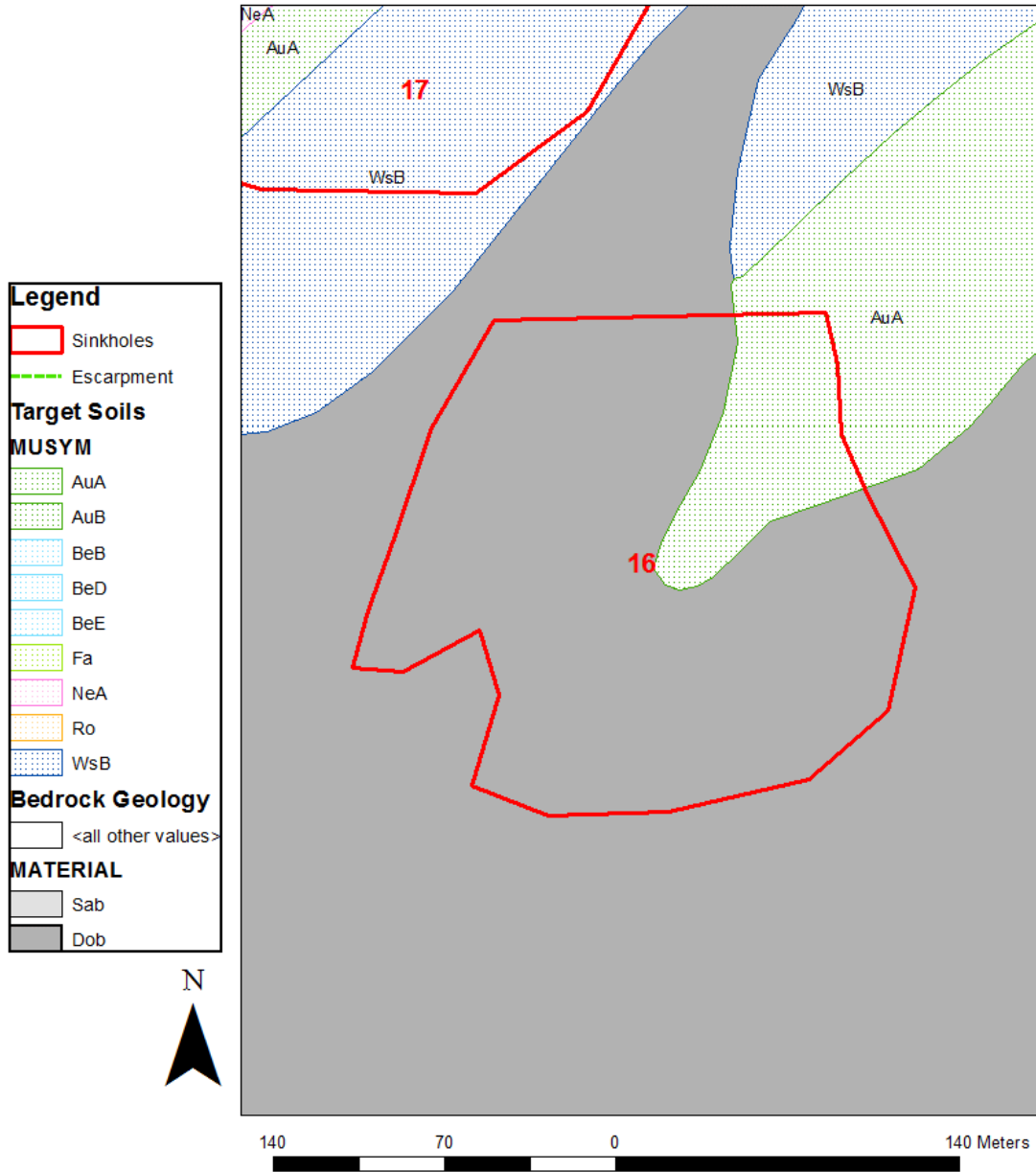


Figure 9b. Sinkhole #16 in the early spring before vegetation growth. Obvious are large clusters of sub-angular boulders, indicating shallow depth-to-bedrock. Note the soil discoloration due to enhanced moisture in micro-relief regions. View from north.

Sinkhole #16



Author: Michael D. Rodgers

Figure 9c. GIS-based map product for Sinkhole #16. This feature is mostly smooth, moderately sized and lies within the Onondaga Formation. This sinkhole has interaction with the target soil, specifically, the Aurora series.

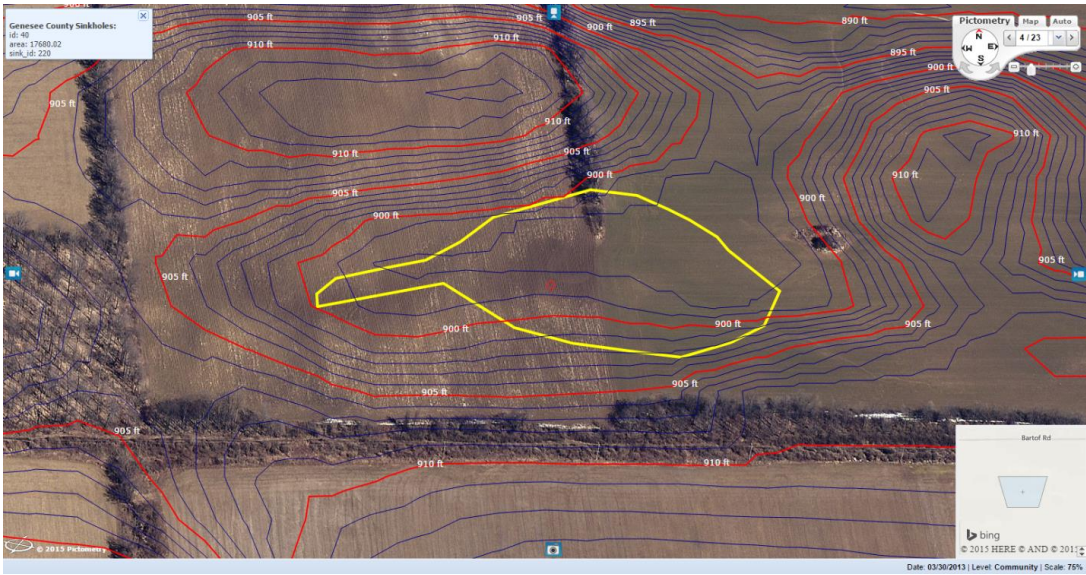
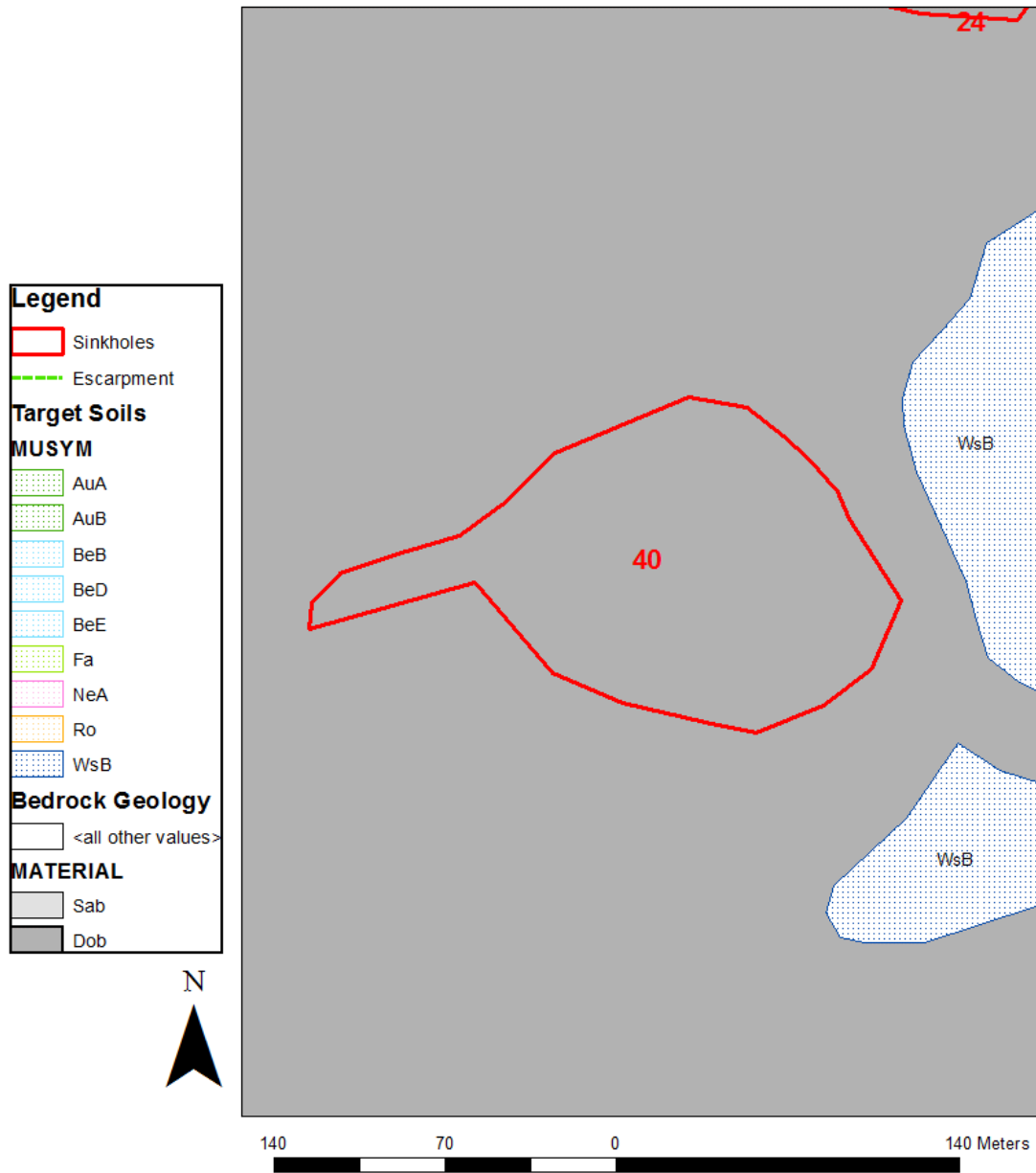


Figure 10a. Sinkhole #40 in Stafford, NY. This feature lies fairly squarely in the center of a depression as indicated by contours. At the center of this feature is a darkened soil region, likely due to enhanced moisture. To the east of the feature is a rock spoil pile, indicative of stony fields and potentially shallow depth-to-bedrock.



Figure 10b. Close-up of Sinkhole #40, with a spoil pile to the east of the feature (left of image). Scattered throughout both fields associated are sub-angular boulders. View from north.

Sinkhole #40



Author: Michael D. Rodgers

Figure 10c. GIS-based map product of Sinkhole #40. This sinkhole is smooth and small-sized, and is within the Onondaga Formation. Target soils are absent in feature, but present nearby.

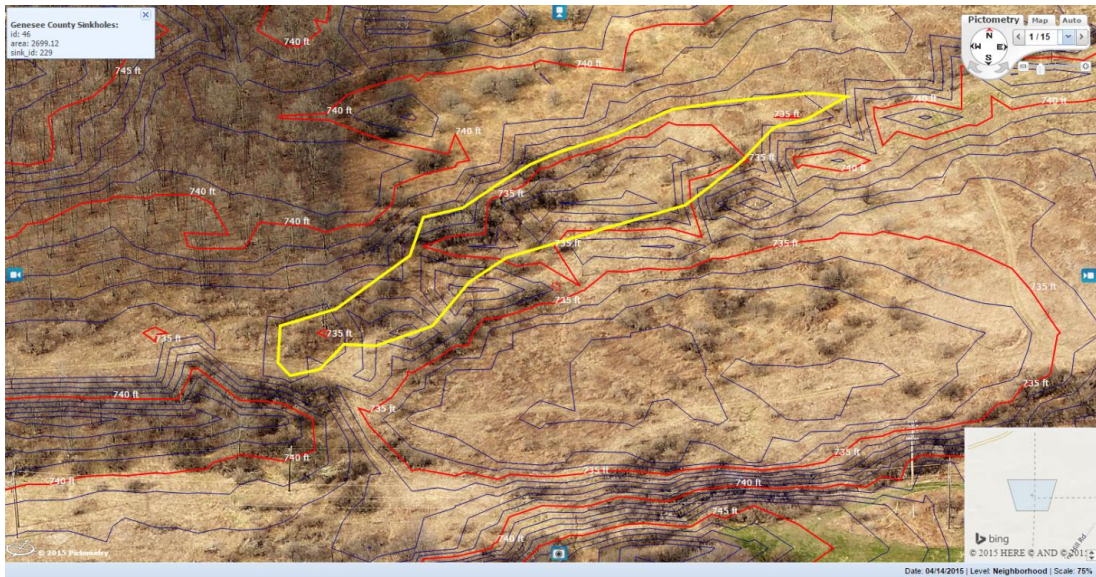
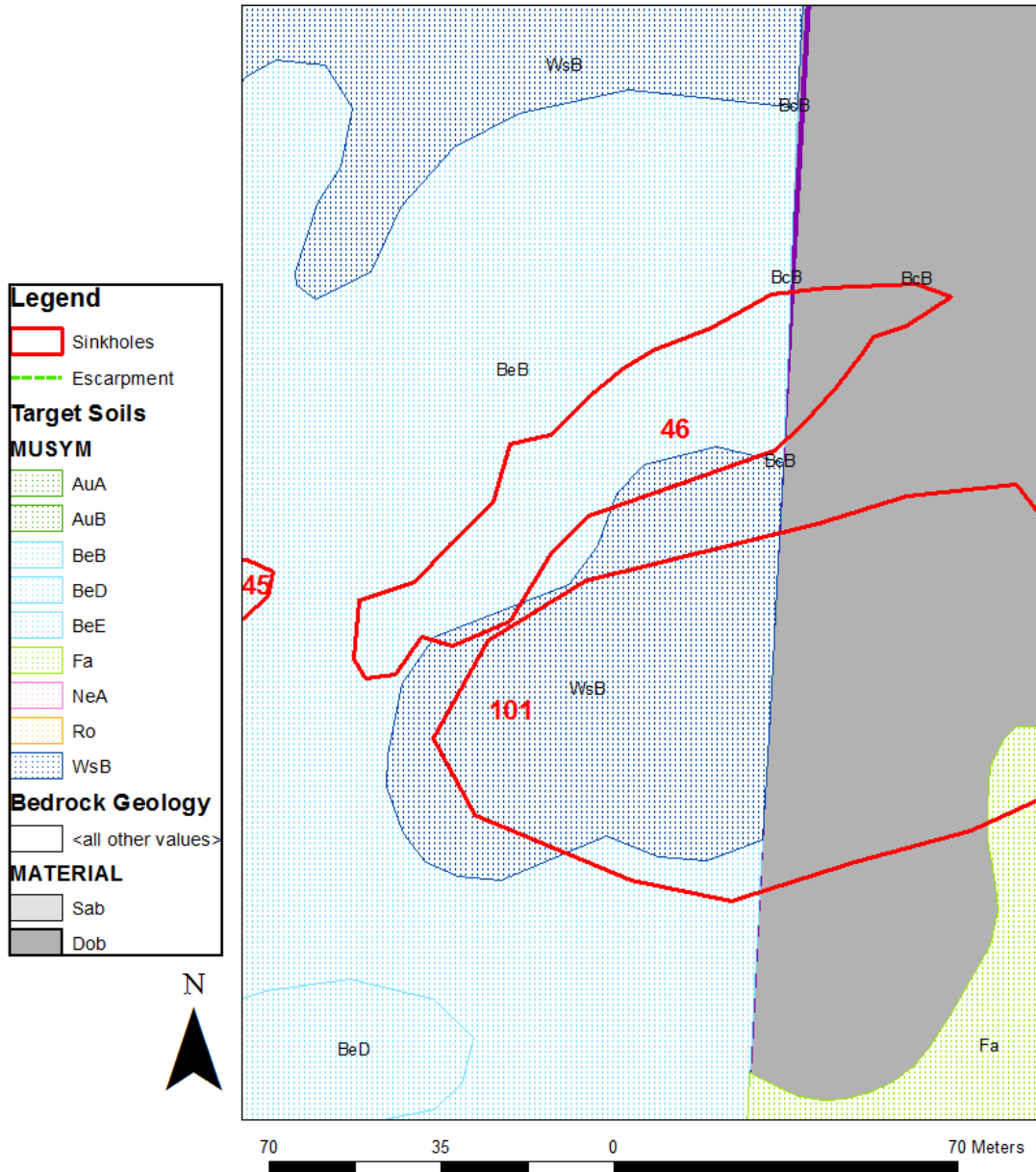


Figure 11a. Sinkhole #46 is a dry, land-based feature in LeRoy, NY. It is dominated by shrubs and soil. This feature encompasses two low points in topography, as noted by contours.



Figure 11b. Sinkhole #46 with spring growth evident. This feature is still absent any noticeable moisture on the surface, and apart from the shrubs, little else appears to grow within the feature.

Sinkhole #46



Author: Michael D. Rodgers

Figure 11c. GIS-based map product for Sinkhole #46. This sinkhole lies within the Onondaga Formation and is completely filled with target soils – specifically from the Benson and Wassiac groups. A key feature of note is the close proximity of another sinkhole – sinkhole #101 – just to the south and east of #46.

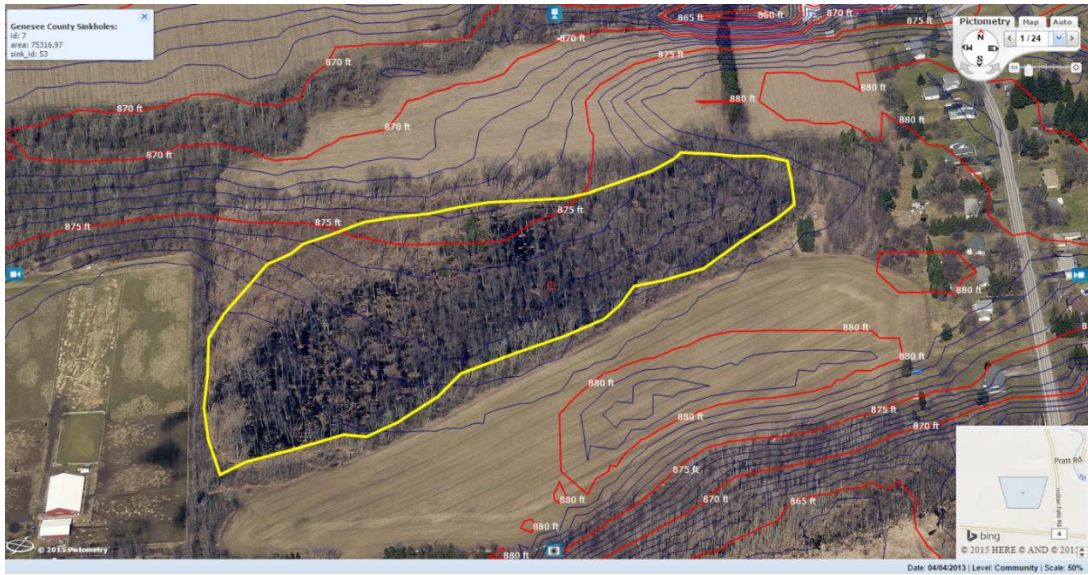


Figure 12a. This time-step shows Sinkhole #7 during a wet stage, likely from a snowmelt event. It is surrounded on three sides by farm fields, meaning this feature is likely inundated with farm-based pollution runoff.

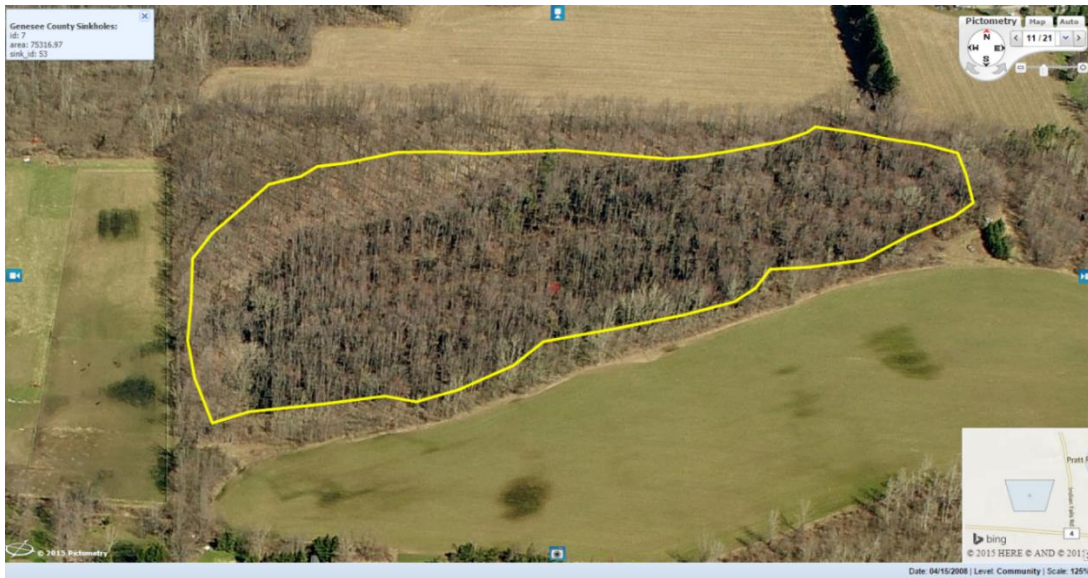
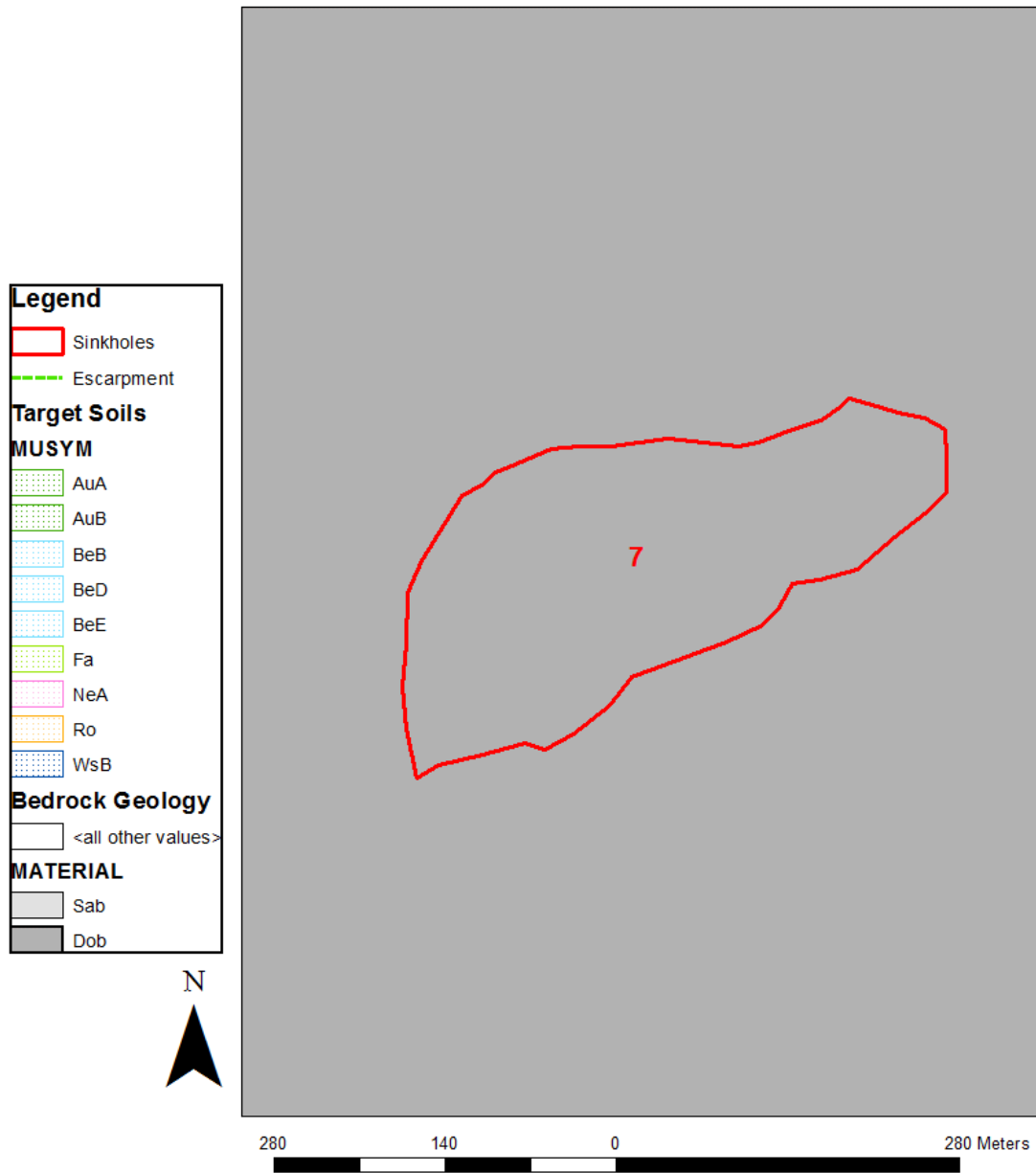


Figure 12b. A drier time-step for Sinkhole #7; while most moisture has left the sinkhole itself, soil discoloration, likely due to moisture, is observed in the surrounding fields.

Sinkhole #7



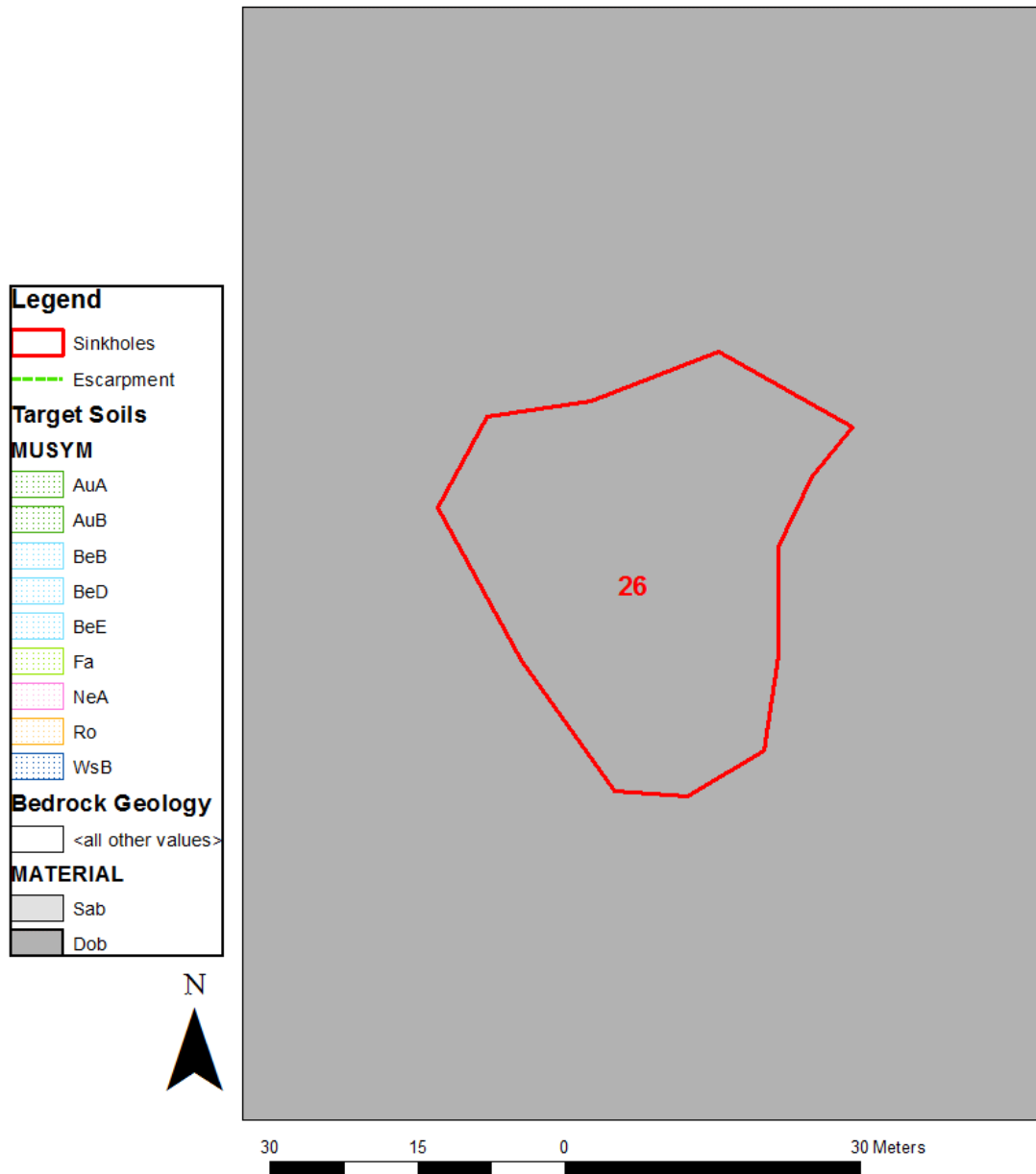
Author: Michael D. Rodgers

Figure 12c. GIS-Based map product for Sinkhole #7. This shows that the sinkhole lies fully within the Onondaga Formation and has no nearby target soils associated with it.



Figure 13a. Sinkhole # 26 is located along a stream section, at the low-point between to farm fields. The surrounding area appears quite moist, while inside the feature is very brush-filled and non-farmed, a sign of high moisture content extending away from the stream itself.

Sinkhole #26



Author: Michael D. Rodgers

Figure 13b. GIS-Based map product for Sinkhole #26. This feature is seen as laying solely within the Onondaga Formation (Dob) and having no nearby target soils.

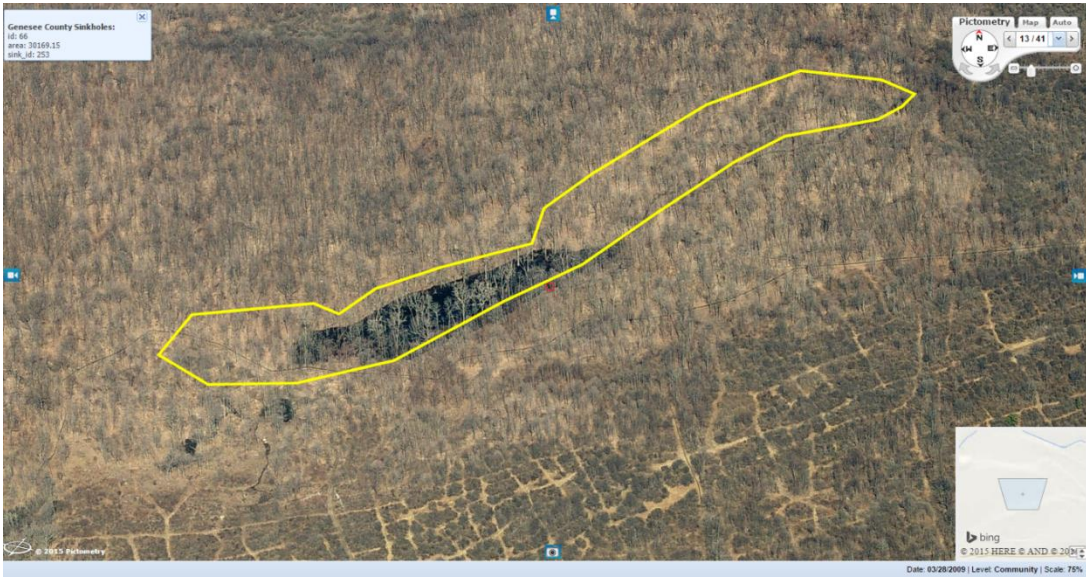


Figure 14a. A wet time-step for Sinkhole #66. This shows the feature after a snowmelt, creating a vernal pool.

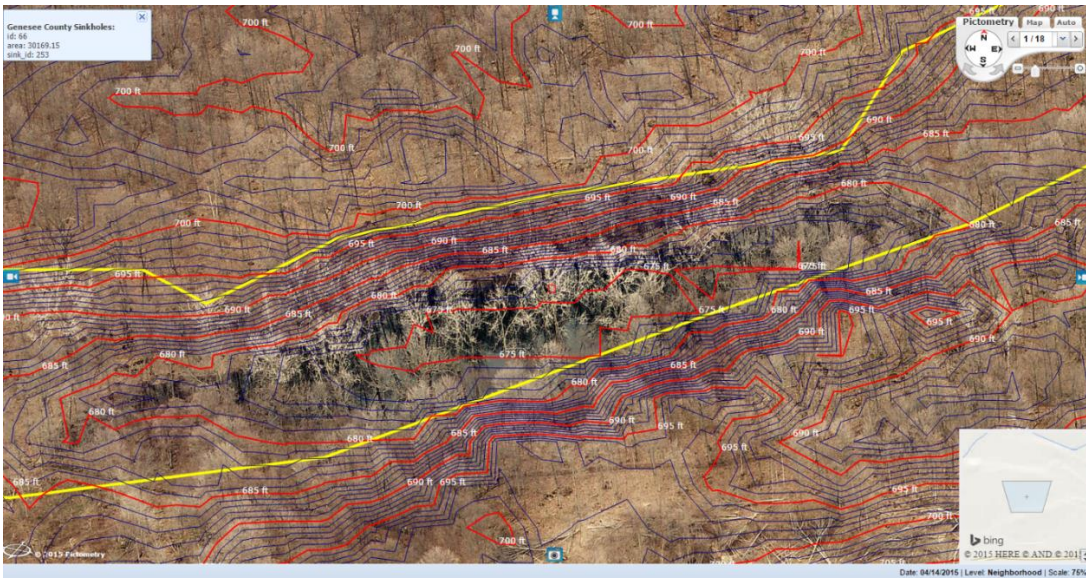


Figure 14b. Another wet time-step for Sinkhole #66. With contours enabled, it becomes apparent how steep the cliffs of this feature are, specifically on the northern and southern edges.

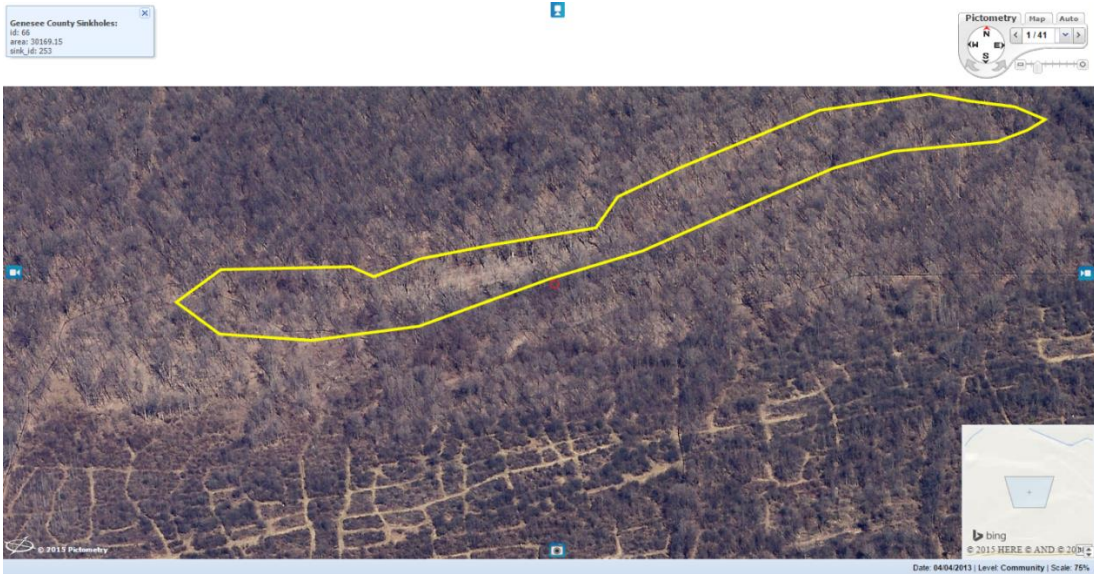


Figure 14c. Dry time-step for Sinkhole #66; this feature is completely absent of water in the visible imagery.

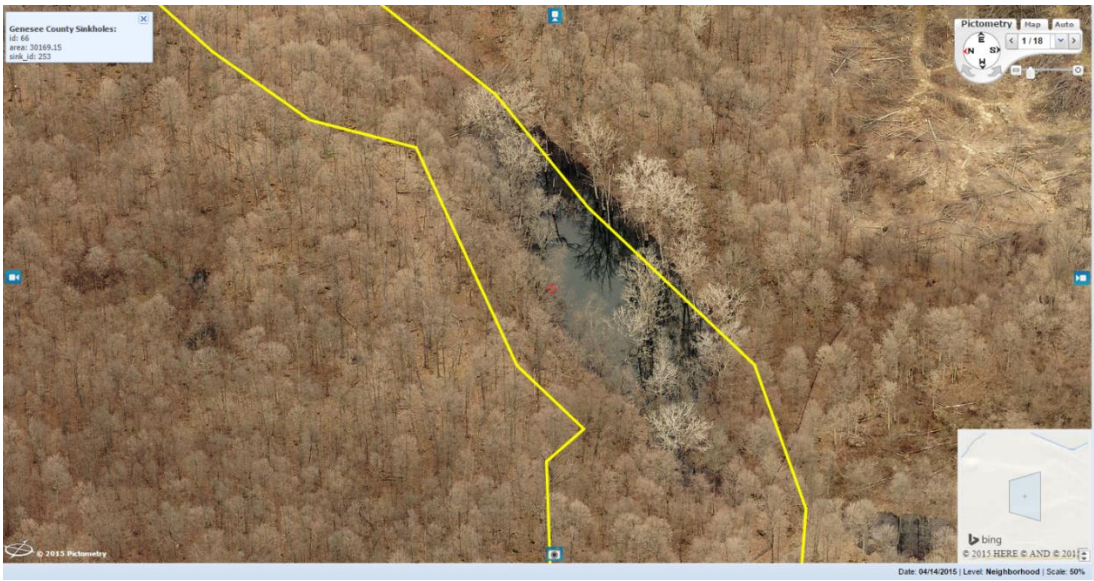
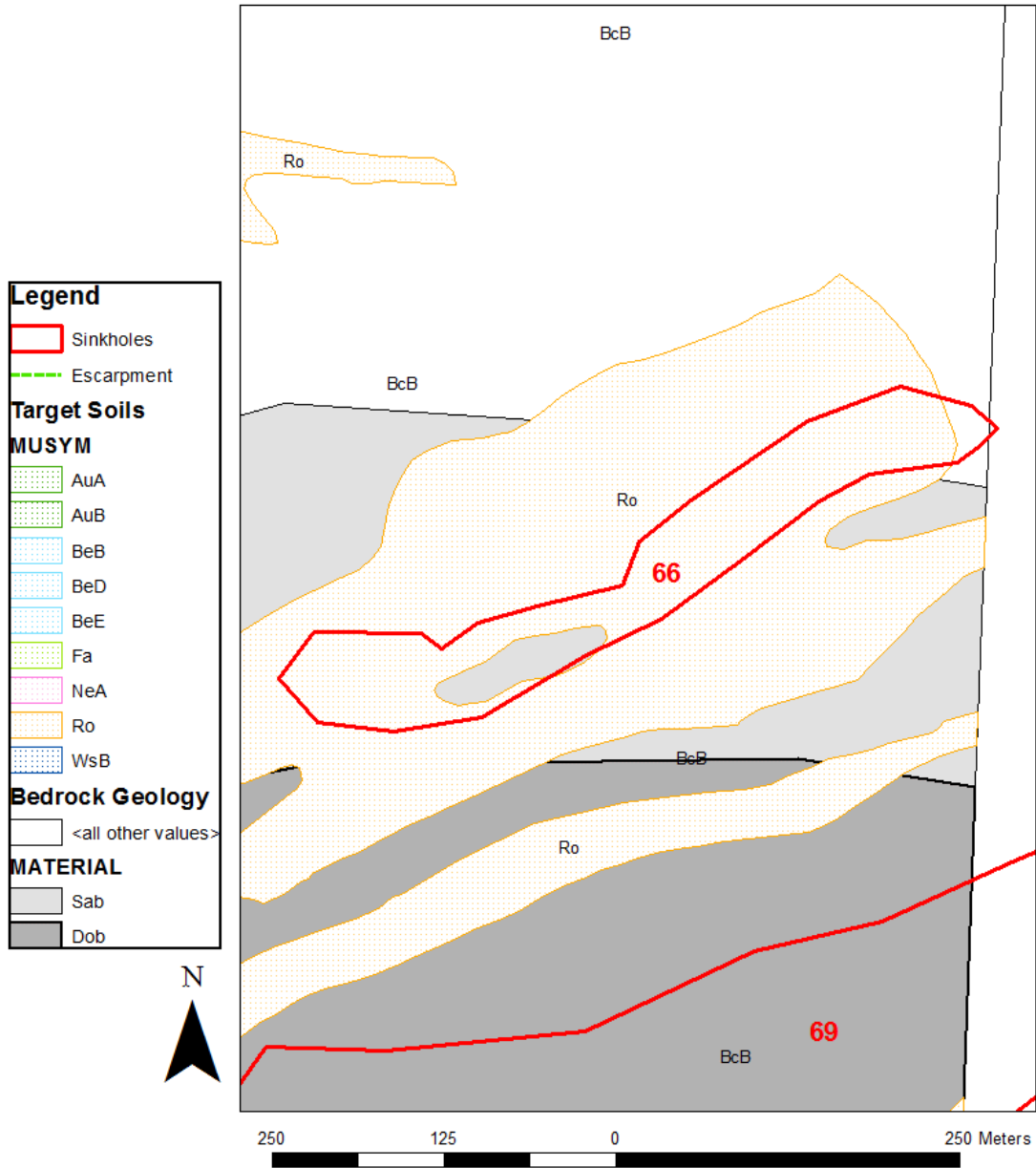


Figure 14d. Looking along the fetch of Sinkhole #66 (from the west) it shows obvious ponding with trees throughout the flooded region.



Figure 14e. Looking along the fetch of the pond in Sinkhole #66, during a dry time-step, the feature appear completely dry and barren.

Sinkhole #66



Author: Michael D. Rodgers

Figure 14f. GIS-based map product for Sinkhole #66, this feature lies mainly within the Akron-Bertie Formation, while extending slightly into the Camillus group. Target soils span nearly the entire feature, in the form of the Rubbleland series, while a small pocket is absent target soils in the center, due to the ponding that takes place.

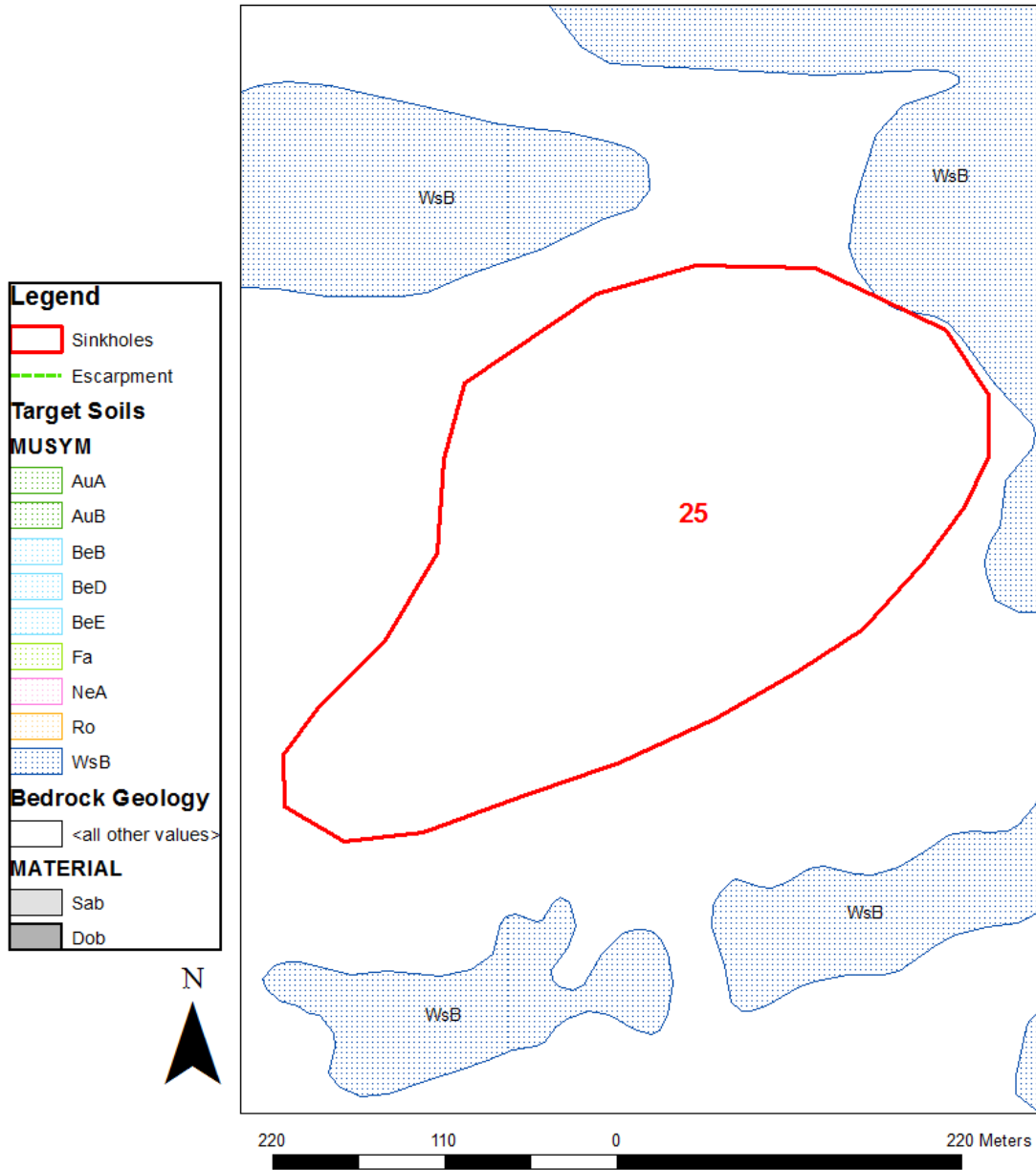


Figure 15a. Moist time-step of the disappearing lake at Ivison Rd. in Sinkhole # 25. Not only is there ponding at the very center, but visible ‘stream’ formation is seen in the southwest portion of the feature.



Figure 15b. Dry time-step of Sinkhole #25. Although absent of water, the Ivison Rd. disappearing lake still shows signs of soil discoloration, likely due to enhanced sub-surface moisture.

Iverson Disappearing Lake



Author: Michael D. Rodgers

Figure 15c. GIS-based map product of the Iverson Rd. disappearing lake. This feature lies fully within the Camillus group and has no target soils within; however, it is surrounded on three sides by the Wassiac group target soil.

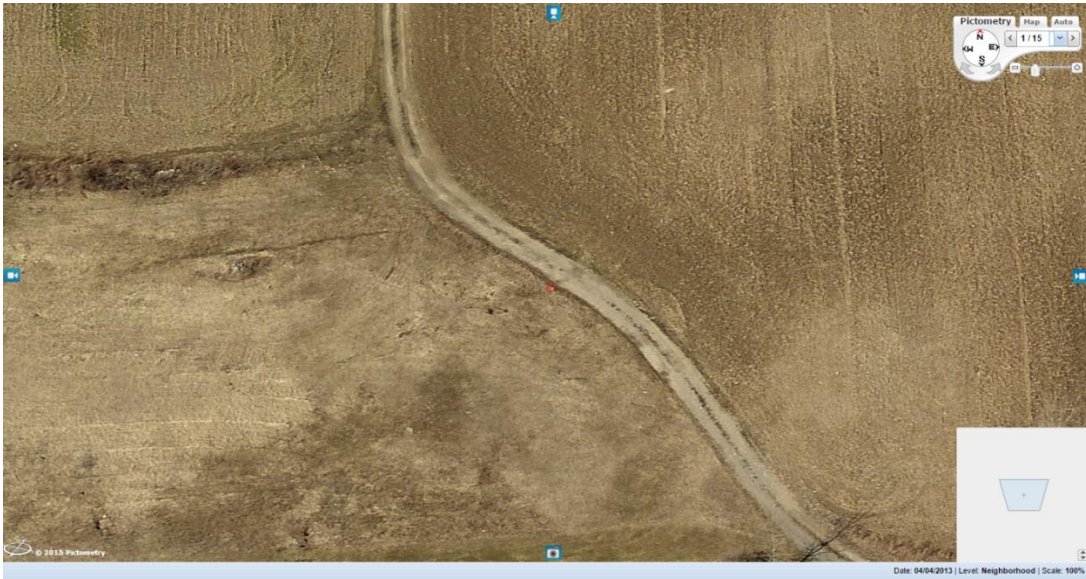


Figure 16a. Close up of the County Building 2 false-positive site. Apparent in the imagery are exposed stones and a rock outcrop, usually indicative of shallow soils when in karst terrain.

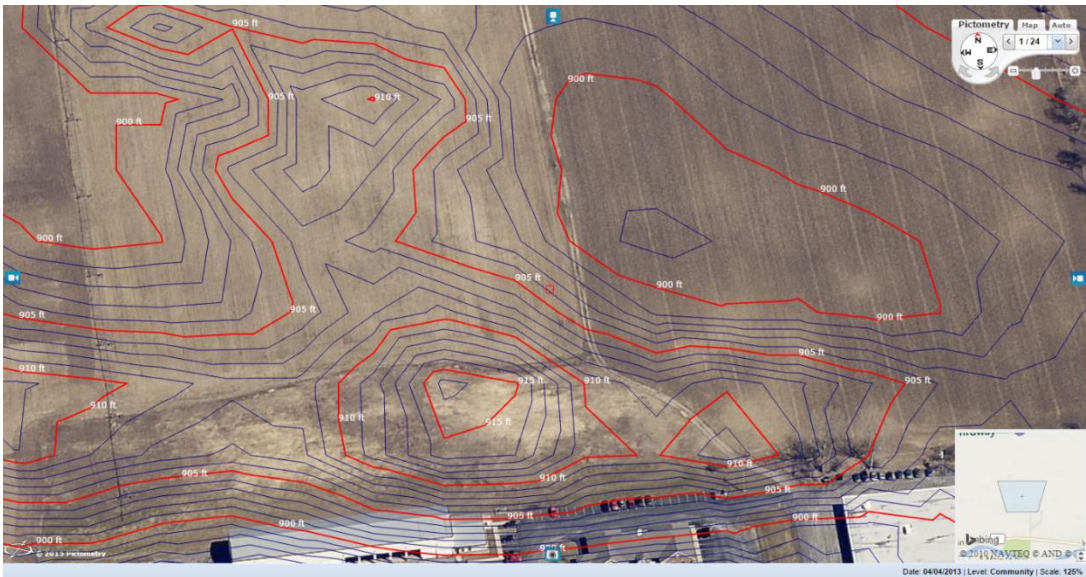
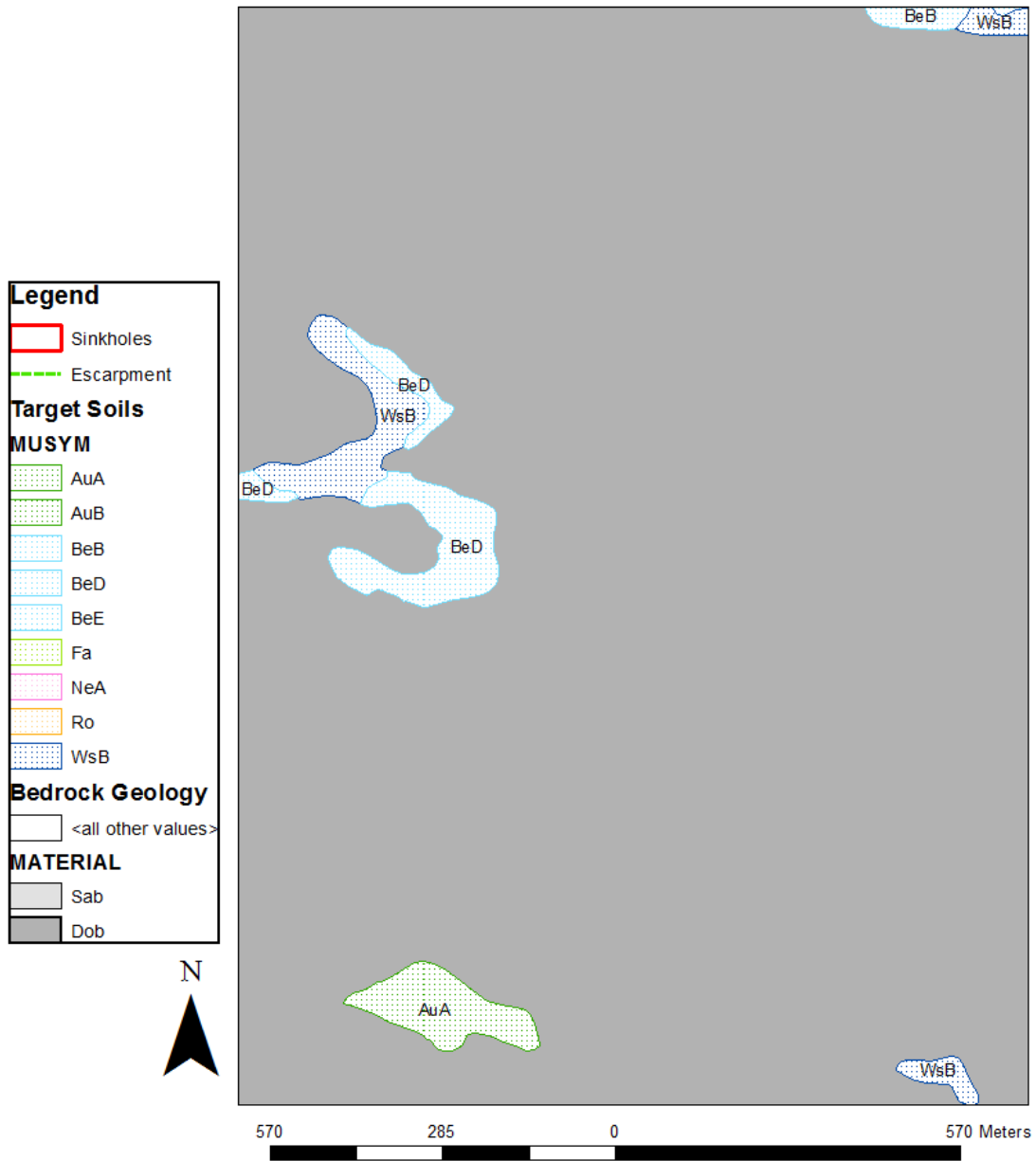


Figure 16b. Zoomed-out look at the false-positive site at County Building 2. Note the topographic low in the middle-right, which initially was mistaken as a sinkhole.

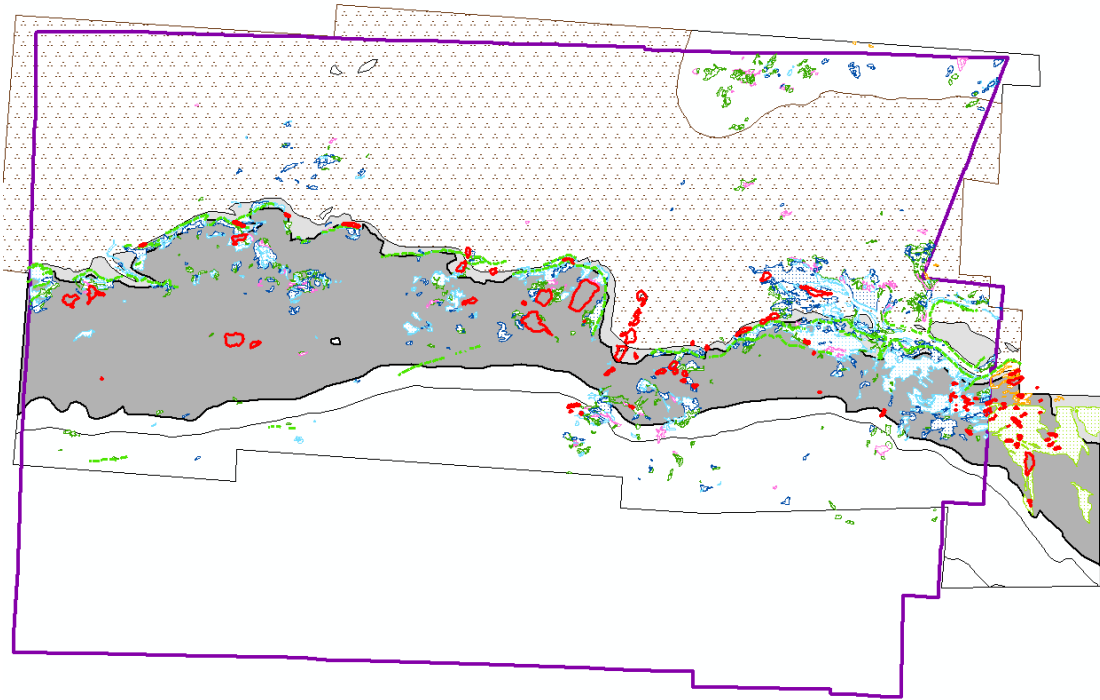
County Building 2



Author: Michael D. Rodgers

Figure 16c. GIS-based map product for the County Building 2 false-positive site (unmarked, center of image). The feature is within the Onondaga Formation, squarely in karst terrain, with target soils nearby, both of the Benson and Wassiac series’.

Appendix



Map of Genesee County, NY, with extreme reached of southwestern Monroe County and northwestern Livingston County visible at right of image. Red polygons correspond to the 110 sinkholes in this study. Target Soils (various colored polygons), Bedrock (dark and light grey swaths that cross the county), and Bedrock Escarpments (green dashed lines) are also visible within the image.