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Identifying Sinkholes Using a Geographic Information System (GIS)

A Senior Honors Thesis

Submitted in Partial Fulfillment of the Requirements
for Graduation in the Honors College

By
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Geology & Water Resources Major

The College at Brockport
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Abstract

Sinkholes are closed depressions in soil or bedrock that form through chemical dissolution of carbonate rock in karst regions. Several studies have identified geologic and hydrologic features that promote sinkhole formation and influence their spatial distribution. This study used a GIS to analyze the relationships between sinkholes and proximity to faults, proximity to streams, and soil thickness in Genesee County, NY. It was hypothesized that a higher frequency of sinkholes (more than half of the number of sinkholes) would occur 1,000 meters or less from a fault, 150-450 meters from a stream, and in areas with one meter or less of soil thickness. Each factor was evaluated individually using previously mapped sinkholes within the study area. A Euclidean distance function with a ten-meter resolution was used to calculate the distance from each sinkhole to the nearest fault and stream. In the study area, 38% of the sinkholes were located within 1,000 meters of a fault, and 22% of the sinkholes were located within 150-450 meters of a stream. These results do not support the hypothesis. However, 50% of the sinkholes occurred less than 450 meters from a stream. Sixty-three percent of the sinkholes occurred in areas with thin (one meter or less) carbonate soils, which supports the hypothesis. The results of this study suggest that: 1) proximity to faults and streams as well as soil thickness may be useful parameters for predicting the likelihood of sinkhole formation in karst regions, and 2) mapping these factors may be a useful strategy for identifying sinkholes remotely in a GIS.

Introduction

Karst is a terrain underlain by soluble rock, such as limestone or dolostone, which contains diagnostic geomorphic features including sinkholes, swallets, and caves. Approximately ten percent of the Earth's surface is occupied by karst, as well as 20% of the land area in the continental U.S. (Palmer, 1991). Karst is common in areas such as the Appalachian Valley and Ridge and many coastal settings such as Florida.

A sinkhole is a closed depression in soil or bedrock that commonly forms in karst areas. A sinkhole complex refers to a land area containing multiple individual sinkholes that are located close together. Many studies have found that sinkholes tend to form in clusters because certain areas have optimal conditions for sinkhole formation (Hack, 1965; Doctor and Doctor, 2012). Natural sinkhole formation is controlled by a combination of several driving and resistive forces. The primary driving force in the geomorphic system is the dissolution of carbonate rock by rainwater, which is slightly acidic. Limestone is mostly composed of calcium carbonate ($CaCO_3$), and when acid is introduced in the form of hydrogen ($H+$) ions, a chemical reaction occurs to form bicarbonate (HCO_3^-) ions. These bicarbonate ions are very soluble in water. Other driving forces include gravity, slope, corrasion of soil and rock, groundwater discharge, and groundwater pH. The primary resisting forces in the geomorphic system include the lithology of the rock, cohesion of sediment, presence of vegetation, and the stratigraphic relationships between soluble and insoluble rock.

Growing concerns for water quality and other environmental issues have given rise to recent karst research (Hyland et al., 2006). Much of the world’s population depends on water supplied from karst aquifers, making it is essential to protect this valuable resource. Sinkholes create the risk of damaging property and endangering lives if developed in highly populated or well-traveled areas (Todd and Ivey-Burden, 2016). Regions containing sinkholes are at high risk for several environmental hazards including groundwater contamination, greater potential for surface collapse, and accelerated erosion. The chance for groundwater contamination is higher in areas with sinkholes because they provide contaminant transport by offering preferential pathways for surface runoff pollutants to flow into the groundwater system. The presence of thin soils contributes to this risk of potential groundwater contamination because of the relatively small soil-water retention and filtering capacity of the soil. This allows the water to quickly flow downward into the carbonate rock aquifer with minimal filtration or adsorption (Czymmek et al., 2004).

The purpose of this study was to analyze the relationships between sinkhole distribution and geologic and hydrologic factors in a GIS environment. A Geographic Information System (GIS) is a framework that can store, organize, manipulate, analyze, and display various spatial data. Some advantages of using a GIS for environmental research include its unique ability to overlay and analyze multiple independent data layers simultaneously, and its capability of improving the communication of complex spatial information using maps. Recent technological advances in GIS have enabled researchers to study karst terrain in more depth because GIS applications allow researchers to map certain factors that predict where sinkholes may occur (Hyland et al., 2006). Modern landscape analysis techniques, such as GIS, LiDAR, and other remote sensing tools, show great potential for improving sinkhole mapping in karst regions.

The primary objective of this study was to test if proximity to faults, proximity to streams, and soil thickness are useful parameters for predicting future sinkhole development. This study was designed to test the hypothesis that a higher frequency of sinkholes (more than half of the number of sinkholes) will occur 1,000 meters or less from a fault, 150-450 meters from a surface stream, and in areas with 1 meter or less of soil cover thickness.

Background

Three types of natural sinkholes are observed on Earth and are classified based on their genesis, relationship to the land surface, and hydrogeologic regime (White, 1988). One type is a solution sinkhole, which is a deep impression in the ground that slowly develops because of gradual enlargement of the sinkhole through chemical weathering by acidic water (Figure 1). Aggressive dissolution occurs in secondary porosity features in the carbonate rock such as faults, fractures, and bedding planes, which concentrate and accelerate the chemical breakdown of the rock along these structural features. Solution sinkholes are most common in areas with very thin soil cover, exposing the bedrock below to continual erosion by water. Another type of sinkhole is a subsidence sinkhole. This type forms when clay or sand permeates through cracks in the carbonate rock, and over time a cavity is created in the subsurface. Subsidence sinkholes tend to develop gradually where the covering sediments are permeable. The third type of sinkhole is a collapse sinkhole, which forms because of a land surface failure, causing the overlying sediment to fall down into a subsurface chamber. These subsurface cavities trigger surface collapse when there is instability in the overburden and the roof of the chamber can no longer support the weight of the overlying mass. Collapse sinkholes may develop abruptly (over a period of hours) and cause damage to life and property.

Hyland et al. (2006) used geospatial techniques to determine the relationship between sinkhole distribution and four major landscape factors: 1) bedrock type, 2) soil depth to bedrock, 3) proximity to geologic faults, and 4) proximity to surface streams. They found that sinkhole occurrence increased with proximity to faults, with almost 25% of the sinkholes occurring less than 230 meters away from a fault. Hack (1965) argued that there is a relationship between sinkhole occurrence and the presence of geologic faults and found that sinkholes tended to occur in close proximity to faults. Ozdemir (2015) also found that the probability of sinkholes increased at sites close to faults and that most sinkholes were located within 1,000 meters of a fault, which is the interval that was used to form part of the hypothesis in this study.

Hack (1965) also argued that there is a relationship between sinkhole occurrence and the presence of a nearby stream. He found that sinkholes were more abundant along large streams and that the majority of sinkholes were not located directly adjacent to streams, but rather occurred 180-425 meters away. Similarly, Hyland et al. (2006) found that sinkholes were sparse near streams and most abundant 182-427 meters away from a stream. Ozdemir (2015) also found that sinkholes were rare directly along streams, but observed that sinkholes were most abundant 2,000–3,000 meters away from a stream, which is a much larger distance than the results of Hack (1965) and Hyland et al. (2006). Hack (1965) and Hyland et al. (2006) both found sinkholes to be most abundant approximately 150-450 meters away from a surface stream, which is the interval that was used to form part of the hypothesis in this study.

Cyzmmek et al. (2004) suggested that soil thickness is a useful parameter for predicting the distribution of karst features. They argued that areas with carbonate soils of less than 40 inches (≈1 meter) thick have an increased chance of containing karst features. Similarly, Reddy and Kappel (2010) investigated the focused recharge to the carbonate rock aquifer in Genesee County, NY. They argued that the presence of a sinkhole depends on several factors including bedrock geologic structure (fractures, joints, faults), surface hydrology, subsurface hydrogeology (preferential-flow pathways formed by the dissolution of the carbonate bedrock along existing geologic structures), and thickness of soils overlying the carbonate bedrock. They found that the presence of shallow soils (≤ 40 inches thick) was a critical consideration when identifying karst-sensitive areas. Todd and Ivey-Burden (2016) developed a methodology for using GIS data to create sinkhole susceptibility maps that pinpointed regions where future sinkhole development was likely. They incorporated five risk factors that were previously shown to play a role in sinkhole formation, some of which included bedrock type, proximity to faults, and soil depth to bedrock. Todd and Ivey-Burden (2016) and Perrin et al. (2015) found that soil cover thickness had a minimal influence on predicting sinkhole occurrence. A soil thickness range of 1 meter (≈40 inches) or less was used to form part of the hypothesis in this study because this threshold was the consensus of a majority of previous studies that performed similar analyses in karst areas that are comparable to this study.

Geologic Setting

The area of interest includes karst regions in Genesee County, NY where carbonate bedrock is present. This area extends to include small portions of northwestern Livingston County and southwestern Monroe County, as sinkholes are known to extend into these counties (Figure 2). This study area was chosen because it includes karst regions that contain many known sinkholes in western NY. In Genesee County, carbonate bedrock of the Onondaga Limestone (Lower Devonian) and the Akron-Bertie Formation (Upper Silurian) crops out along a two-five mile wide band that trends east-west through the middle of the county (Figure 3). The Akron-Bertie Formation and the Onondaga Limestone form a carbonate bedrock sequence that is approximately 180 feet thick and dips gently to the south. These units transmit water through solution-enlarged fractures, bedding planes, and other openings, which drives the formation of sinkholes. The Akron-Bertie Formation is stratigraphically below, and crops out north of the Onondaga Limestone. The Bertie Formation is approximately 45 feet thick and consists mostly of dolostone and dolomitic limestone with interbedded shale and gypsum. The Akron Dolostone is a fine-grained dolostone with a thickness of about five feet. The Onondaga Limestone is approximately 130 feet thick and forms the upper two-thirds of the carbonate bedrock sequence, consisting of highly fractured cherty limestone. The Onondaga Limestone is resistant to erosion and forms an escarpment at the land surface along the north side of the study area (Reddy and Kappel, 2010).

The type and thickness of soils observed in the study area are the result of multiple glaciations. Present-day sediments were deposited during and after the last glacial episode, the late Wisconsinan glaciation. The glacial sediments in the study area consist mostly of unstratified deposits (till) and stratified deposits (glaciolacustrine and glaciofluvial sediment). Post-glacial stratified sediments include peat and muck formed in wetlands, and alluvium deposited by streams (Reddy and Kappel, 2010). The soils overlying the carbonate bedrock generally have a high carbonate content, and were derived from the erosion of the Onondaga Limestone and the Akron-Bertie Formation. Some of these carbonate soils with thicknesses less than 1 meter include the Aurora, Benson, Newstead, and Wassaic (Czymmek et al., 2004).

The major structural feature in this part of New York is the Clarendon-Linden Fault Complex (CLFC), which forms a southwest to northeast series of faults throughout the bedrock sequence. The CLFC is a broad zone of small reverse faults with small displacements, which has smaller faults located nearby to the east, and is responsible for much of the seismic activity in the region (Jacobi, 2002). The CLFC is also partially responsible for the surface water drainage pattern in Genesee County, with Black, Oatka, Tonawanda, and Oak Orchard Creeks draining approximately to the north (Reddy and Kappel, 2010).

Data and Methodology

This research involved three major steps: 1) collect and organize existing data from various online databases, 2) overlay these geologic and hydrologic data using a GIS, and 3) determine the spatial relationships between sinkholes and these geologic and hydrologic factors using various geoprocessing tools in ArcMap.

Sinkholes data inventory

Sinkholes are the most common, and perhaps the most useful, karst landforms for mapping the extent and type of karst because they are indicators of bedrock dissolution, and can be recognized through remote sensing techniques (Kastning and Kastning, 1997; Basso et al., 2013). The sinkholes data used in this study came from a combination of several previous studies that mapped karst features in Genesee County (Reddy and Kappell, 2010; Richards et al., 2010; Rodgers, 2015). This data set is a shapefile containing 109 sinkhole polygons of various shapes and sizes, with areas ranging from approximately 300 square meters to 1,000,000 square meters. These sinkholes data were overlaid with several other data sets including faults, surface streams, and soils using a GIS. The purpose of this was to conduct spatial analyses with these sinkholes and each factor to determine the spatial relationships between them. In order to test the hypothesis, each factor was assessed individually to determine if a higher frequency of sinkholes occurs within the intervals defined in the hypothesis.

Proximity to faults

The faults data for this study originated from Jacobi (2002), who mapped major fault traces across New York. These features were digitized and uploaded to an ArcGIS-Online database where the data were accessed. This data set is a shapefile containing 162 georectified polylines that represent the fault traces, ten of which intersect Genesee County. The faults data were downloaded, added into ArcMap, and overlaid with the sinkholes data. These data were clipped using the clip tool to only include faults within the study area (Figure 4). A Euclidean distance function with a 10-meter resolution was used to calculate the distance from each cell in the sinkhole raster to the nearest fault (Figure 5). These distances were averaged and added to the sinkholes attribute table by assigning each sinkhole a new attribute of 'distance to fault'. The distance-to-fault data were used to generate a histogram in Minitab to illustrate the relationship between the relative frequency of sinkholes and distance from a fault.

Proximity to streams

The streams data for this study came from the online U.S. Geological Survey (USGS) National Hydrography Dataset (USGS, 2017). This hydrography data set is a shapefile that contains a large number of georectified surface streams in New York. These data were downloaded, added into ArcMap, and overlaid with the sinkholes data. The streams data were clipped using the clip tool to only include streams within the study area (Figure 6). A Euclidean distance function with a 10-meter resolution was used to calculate the distance from each cell in the sinkhole raster to the nearest stream (Figure 7). These distances were averaged and added to the sinkholes attribute table by assigning each sinkhole a new attribute of 'distance to stream'. The distance-to-stream data were then used to generate a histogram in Minitab to illustrate the relationship between the relative frequency of sinkholes and distance from a stream.

Thickness of soils

The soils data for this study originated from the Genesee, Livingston, and Monroe Counties Online Soils Surveys (USDA, 2017). These data sets are shapefiles containing all of the different soils within each of the three counties. Each soil is characterized by various soil attributes including soil thickness and soil type/description. These soils data were downloaded, added into ArcMap, and overlaid with the sinkholes data. A table join was used to merge the attributes of the soils data from each of the three counties together, creating a single data layer. This new soils layer was clipped to only include soils within the study area using the clip tool. The ‘select by location’ tool was used to identify all of the sinkholes that intersected thin carbonate soils within the study area. Each individual sinkhole was then assigned a soil thickness value based on the soil that it intersected. These soil thickness values were added to the sinkholes attribute table by assigning each sinkhole a new attribute of ‘soil thickness’. The soil thickness data were then used to generate a table to show the relationship between the frequency of sinkholes and soil cover thickness.

Results

The distance-to-fault data were used to generate a histogram in Minitab, which illustrates the relationship between the relative frequency of sinkholes and distance to a fault (Figure 8). In the study area, 38% of the sinkholes were located within 1,000 meters of a fault. The results indicate that 50% of the sinkholes occurred less than 1,139 meters from a fault. These results do not support the hypothesis because only 38% of the sinkholes occurred within 1,000 meters of a fault, as opposed to the 50% of sinkholes that were hypothesized to occur within the 1,000-meter fault buffer.

The distance-to-stream data were used to generate a histogram in Minitab, which illustrates the relationship between the relative frequency of sinkholes and distance to a stream (Figure 9). In the study area, 22% of the sinkholes were located 150-450 meters from a stream. The results indicate that 50% of the sinkholes occurred less than 450 meters from a stream. These results do not support the hypothesis because only 22% of the sinkholes occurred 150-450 meters from a stream, as opposed to the 50% of sinkholes that were hypothesized to occur within the 150-450-meter interval.

The soil thickness data were used to generate a table to show the relationship between the frequency of sinkholes and soil thickness (Table 1). In the study area, 63% of the sinkholes were located in areas with 1 meter or less of soil thickness. These results support the hypothesis because a higher frequency of sinkholes occurred in areas with 1 meter or less of soil thickness. The soils that contained the most sinkholes included the Benson soil with 28 sinkholes and the Aurora soil with 14 sinkholes. Lesser amount of sinkholes occurred in the Wassaic, Newstead, and Farmington soils. Descriptions of these thin carbonate soils that contained sinkholes are provided in Table 2. This table lists the soil series names as well as a description of the soil composition, slope, and parent bedrock material.

Discussion

Ozdemir (2015) found that most sinkholes were located within a 1,000-meter fault buffer zone, whereas this study found more than half of the sinkholes to be located within 1,139 meters of a fault. He argued that the strong positive relationship between the proximity to faults factor and sinkhole occurrence was because cavities tend to be guided by faults. He further explained that these voids enable water to flow through the bedrock, which allows for dissolution of the carbonate rock leading to sinkhole formation. The results of Ozdemir (2015), Hack (1965), and Hyland et al. 2006), somewhat agree with this study because these studies all found a fairly strong positive relationship between proximity to faults and sinkhole occurrence. This consensus is likely attributed to the fact that voids created by faults enable large volumes of water to be transported through the bedrock, thus inducing dissolution of carbonate rock and leading to sinkhole formation.

Several previous studies including Hack (1965), Hyland et al. (2006), and Ozdemir (2015) all found that a majority of sinkholes tended not to occur directly on or adjacent to streams, but rather approximately 150-450 meters away. These findings differ from the results of this study because a large percentage of sinkholes occurred on or adjacent to streams. Ozdemir (2015) also observed that sinkholes were most abundant 2,000–3,000 meters away from a stream. One possible explanation for this variation in results is that the sinkhole distribution pattern found in this study may not be the direct result of local hydrology, but rather of the local landscape morphology. Areas directly adjacent to streams may have common slopes that are optimal for sinkhole development because of the steepened hydraulic gradient and the resulting increase of groundwater flow in those areas. Another possible explanation is that the circulation of groundwater may have been concentrated at various distances away from streams because of dissimilarities in the carbonate-rock aquifers in these different study areas. For example, Ozdemir (2015) used a study area where groundwater exploitation for irrigation was common. This may have led to a drastic decline or fluctuation in the water table, which would accelerate sinkhole formation.

Cyzmmek et al. (2004) and Reddy and Kappel (2010) argued that the presence of thin carbonate soils was a critical component when identifying karst areas. This argument is supported by the results of this study because a more than half of the sinkholes occurred in areas with 1 meter or less of soil thickness, and where soils were derived from carbonate bedrock (primarily limestone). The soils found to have sinkholes in this study strongly agree with the findings of Cyzmmek et al. (2004) because both studies suggest that the Benson, Aurora, and Wassaic soils are the most likely soils to contain sinkholes in the study area. Todd and Ivey-Burden (2016) and Perrin et al. (2015) found that soil cover thickness had a minimal influence on predicting sinkhole occurrence, whereas the results of this study suggest otherwise. This variation may result from differences in soil slopes and/or parent bedrock material in these different study areas.

An extended analysis combined all three prediction factors to determine areas where sinkholes are most likely to occur. For this analysis, the soil probabilities were based on area instead of frequency, to account for the differences in sinkhole sizes. A mathematical index was created by adding the probabilities of the three factors together for each cell using raster arithmetic in ArcMap. The weights of the faults and streams factors remained constant, whereas the weight of the soil factor increased by 10X for thin carbonate soils. This decision was based on the fact that sinkholes are more likely to form in thin carbonate soils, and this factor would have been underrepresented in the model otherwise. The resulting model produced a map that identifies areas with the highest mathematical index value, which corresponds to areas where sinkholes are most likely to occur (Figure 10). This model does not claim to provide the actual probability of a sinkhole occurring in a certain area, but rather an index where the higher the value, the more likely a sinkhole will occur there. The sinkhole data was overlain with the model to determine how well the model predicts sinkholes. This map shows that many sinkholes were located in areas that the model indicated to have a high probability of sinkhole occurrence. However, other high probability areas contained very few or no sinkholes (Figure 11). These areas in particular would be prime locations to revisit for future sinkhole identifications in the field.

Conclusions

In this study, the spatial distribution of sinkholes and the factors that have been shown to influence sinkhole occurrence were studied in a GIS environment. When predicting future sinkhole formation in carbonate bedrock, it is generally assumed that future sinkhole development will occur under the same or similar conditions as past sinkhole development.

Thirty-eight percent of the sinkholes occurred within the hypothesized 1000-meter fault buffer zone. Additionally, more than half of the sinkholes occurred less than 450 meters from a stream, which was the upper limit of the hypothesized distance-from-a-stream interval. Furthermore, more than half of the sinkholes occurred in areas with thin (≤ 1 meter thick) carbonate soils, which supports the hypothesis. The results of this study, along with several previous studies, suggest that it is possible to produce reasonably accurate predictions on the occurrence and spatial distribution of sinkholes using proximity to faults, proximity to streams, and soil thickness as guiding factors. However, further studies are required to refine the relationships found in this study between sinkhole distribution and these three factors. A better understanding of these spatial relationships could improve the accuracy and reliability of future sinkhole predictive models.

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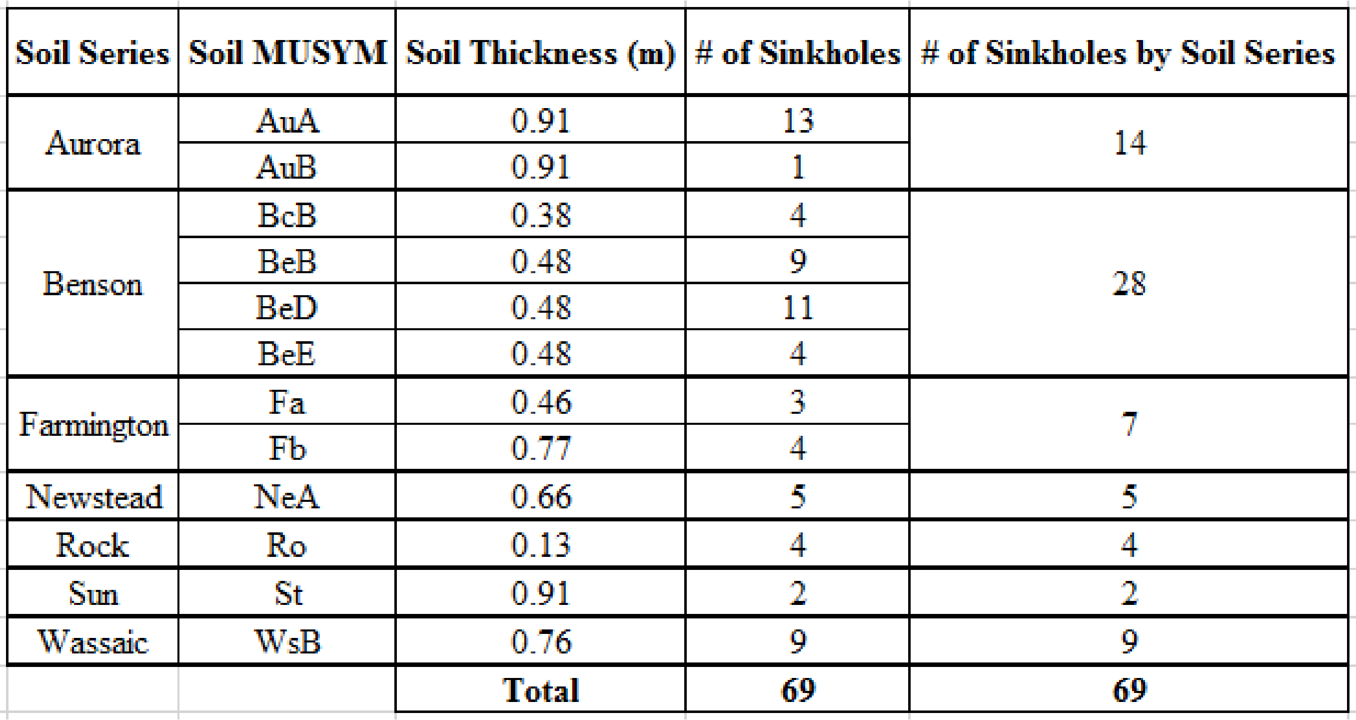
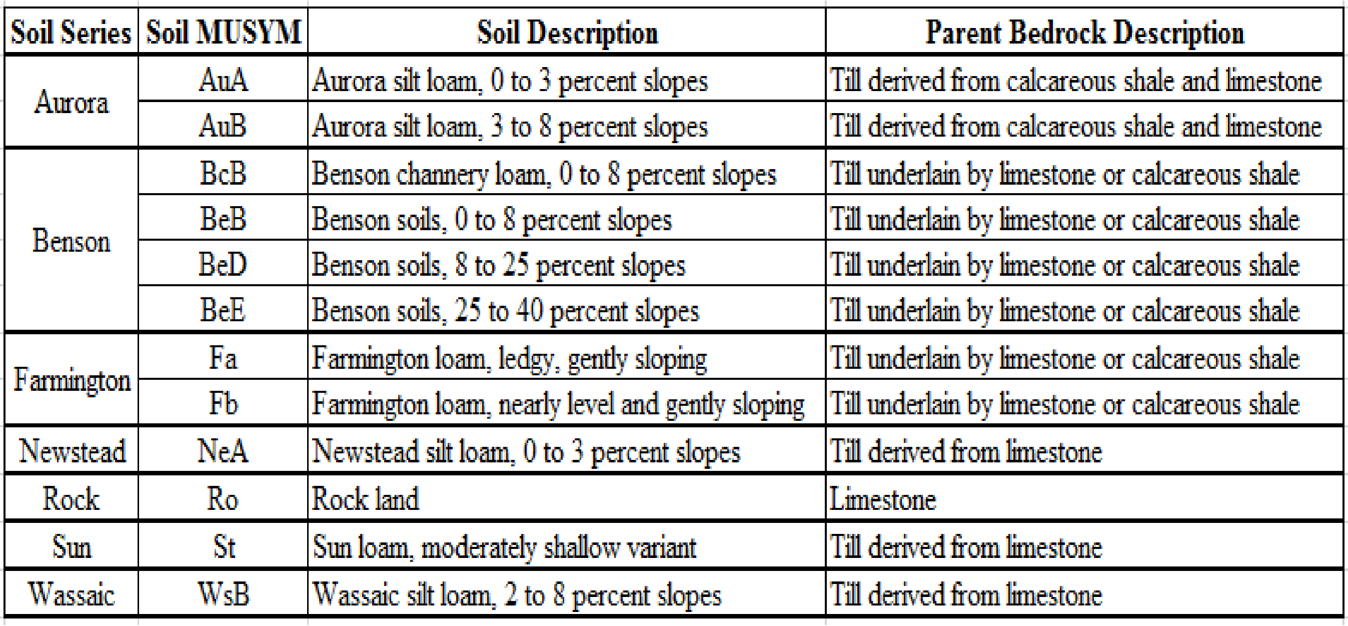
Tables



Soil Series	Soil MUSYM	Soil Thickness (m)	# of Sinkholes	# of Sinkholes by Soil Series
Aurora	AuA	0.91	13	14
	AuB	0.91	1	
Benson	BcB	0.38	4	28
	BeB	0.48	9	
	BeD	0.48	11	
	BeE	0.48	4	
Farmington	Fa	0.46	3	7
	Fb	0.77	4	
Newstead	NeA	0.66	5	5
Rock	Ro	0.13	4	4
Sun	St	0.91	2	2
Wassaic	WsB	0.76	9	9
		Total	**69**	**69**

Table 1. List of thin carbonate soils with thicknesses of less than 1 meter that contain sinkholes in the study area. The table shows that 69 out of 109 sinkholes (63%) occurred in areas with carbonate soils that are 1 meter or less in thickness, which supports the hypothesis.



Soil Series	Soil MUSYM	Soil Description	Parent Bedrock Description
Aurora	AuA	Aurora silt loam, 0 to 3 percent slopes	Till derived from calcareous shale and limestone
	AuB	Aurora silt loam, 3 to 8 percent slopes	Till derived from calcareous shale and limestone
Benson	BcB	Benson channery loam, 0 to 8 percent slopes	Till underlain by limestone or calcareous shale
	BeB	Benson soils, 0 to 8 percent slopes	Till underlain by limestone or calcareous shale
	BeD	Benson soils, 8 to 25 percent slopes	Till underlain by limestone or calcareous shale
	BeE	Benson soils, 25 to 40 percent slopes	Till underlain by limestone or calcareous shale
Farmington	Fa	Farmington loam, ledgy, gently sloping	Till underlain by limestone or calcareous shale
	Fb	Farmington loam, nearly level and gently sloping	Till underlain by limestone or calcareous shale
Newstead	NeA	Newstead silt loam, 0 to 3 percent slopes	Till derived from limestone
Rock	Ro	Rock land	Limestone
Sun	St	Sun loam, moderately shallow variant	Till derived from limestone
Wassaic	WsB	Wassaic silt loam, 2 to 8 percent slopes	Till derived from limestone

Table 2. List of thin carbonate soils with thicknesses of less than 1 meter that contain sinkholes in the study area. The table provides descriptions of the soil compositions and slopes, along with descriptions of the parent carbonate bedrock.

Figures

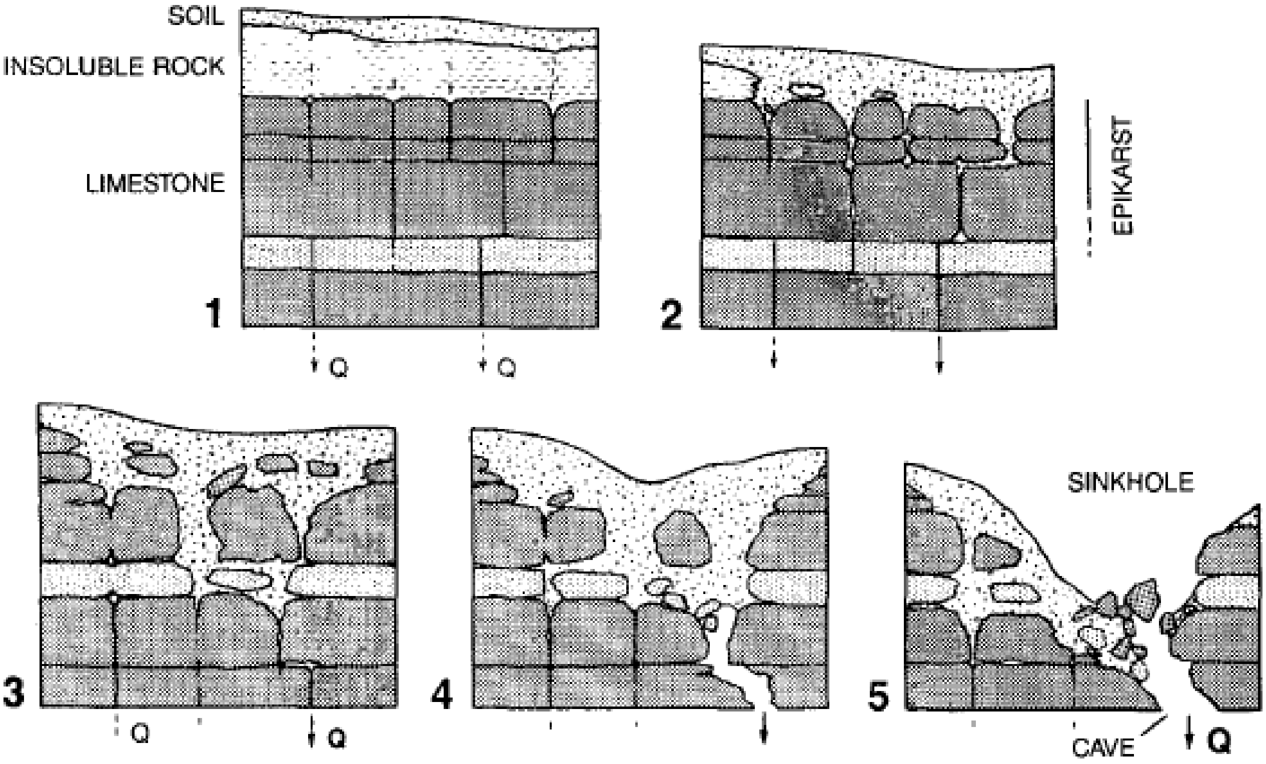


Figure 1. Typical development of a solution sinkhole divided into five stages. Most sinkholes in the study area were observed in stage 3 of development.

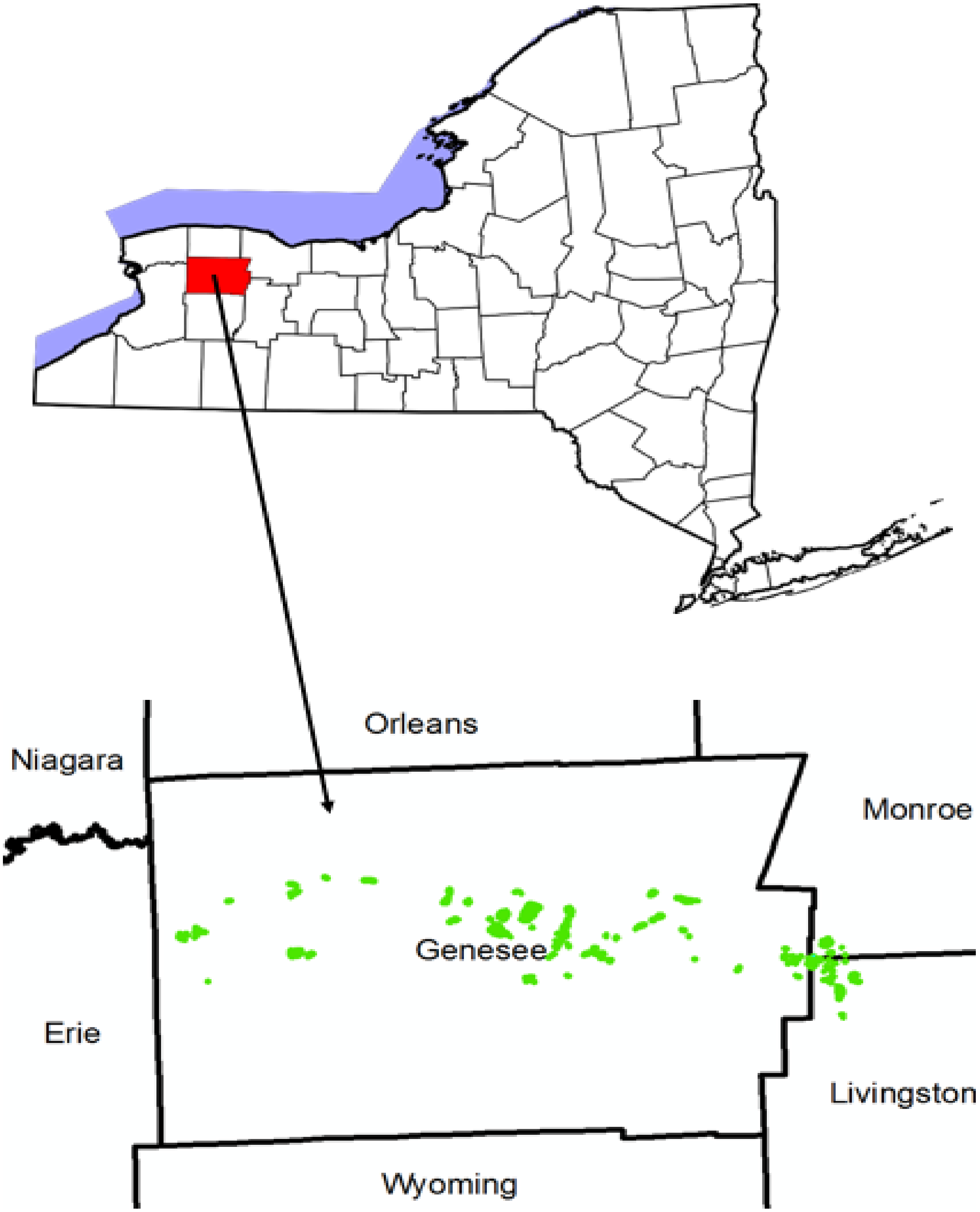
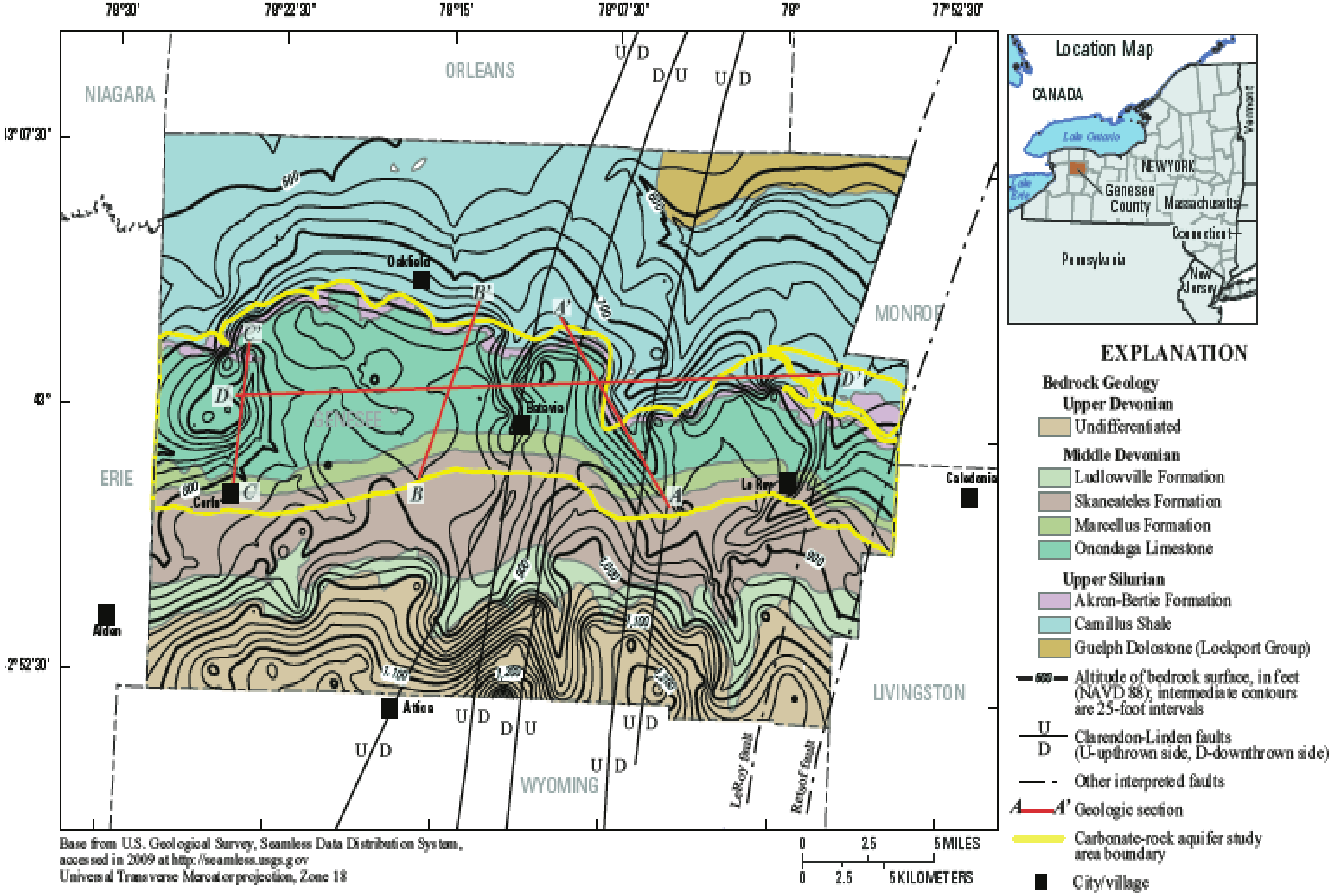


Figure 2. (Top) Map of NY with county boundaries outlined in black and Genesee County shaded in red. (Bottom) Map of the study area including Genesee County and parts of Livingston and Monroe counties. The green markers represent known sinkholes within the study area.



Base from U.S. Geological Survey, Seamless Data Distribution System, accessed in 2009 at http://seamless.usgs.gov
Universal Transverse Mercator projection, Zone 18

Bedrock Geology from New York State Museum, 1:250,000

Figure 3. Geologic map of Genesee County showing the stratigraphic relationships between the Onondaga Limestone and the Akron-Bertie Formation. These two bedrock layers, along with small portions of the Camillus Shale, create the carbonate bedrock sequence that contains all of the sinkholes.

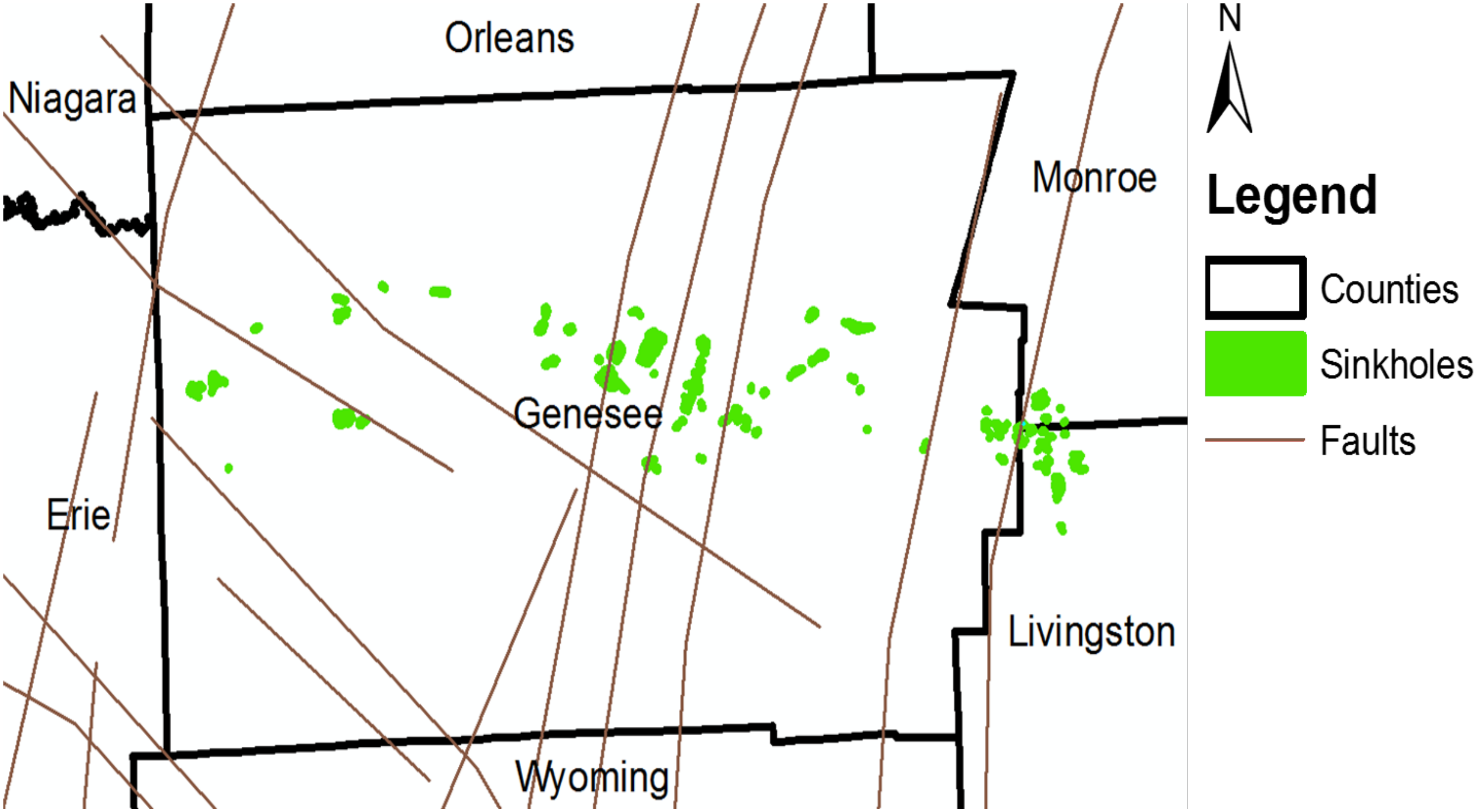


Figure 4. Map of study area containing sinkholes and fault traces. The Clarendon-Linden Fault Complex (CLFC) is represented by the three parallel fault traces trending southwest to northeast through the center of Genesee County.

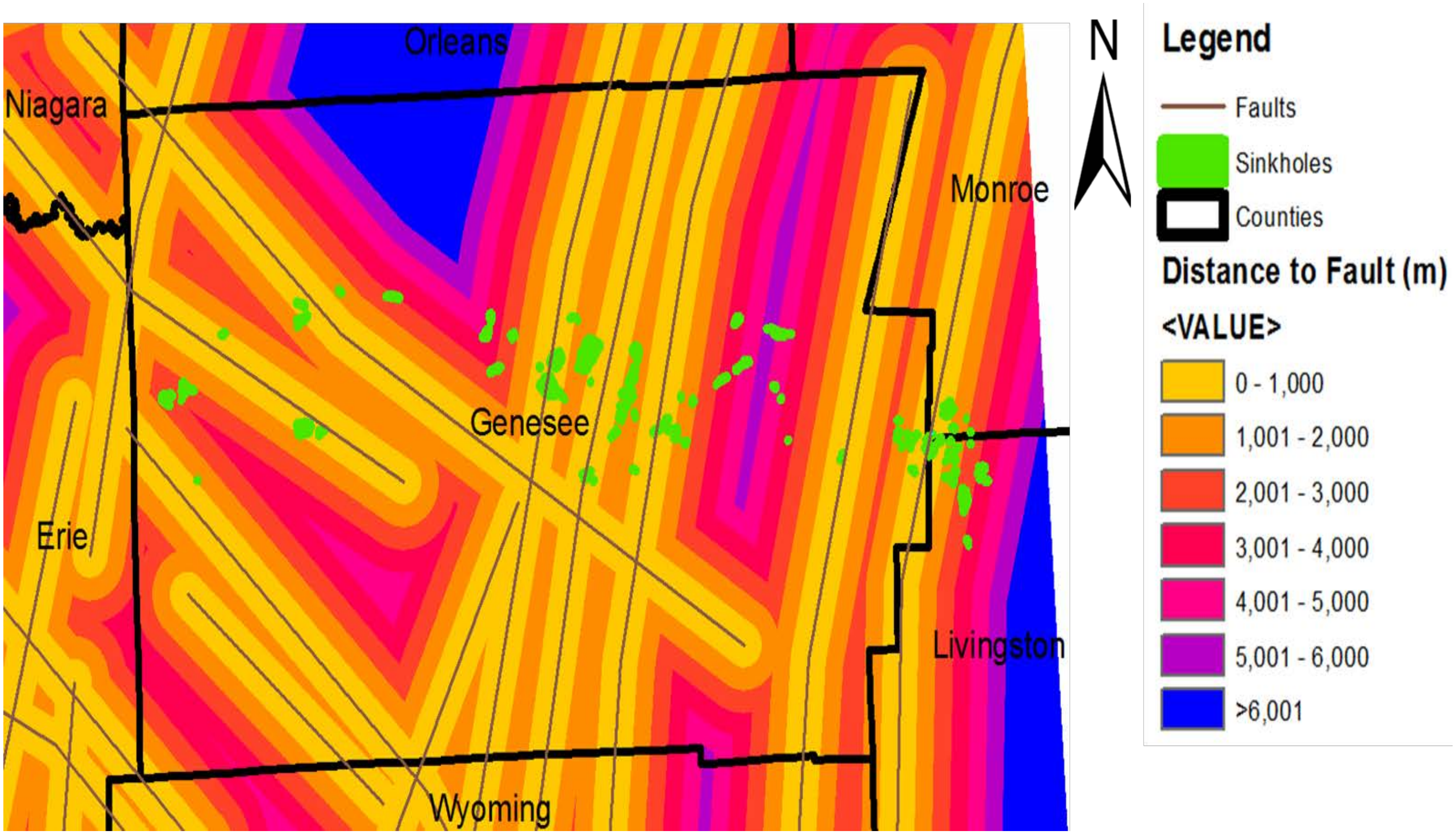


Figure 5. Map of study area with fault trace buffer zones indicated at equal-distance intervals away from a fault. Values are lowest at regions closest to the faults, increasing outwardly as distance increases from faults.

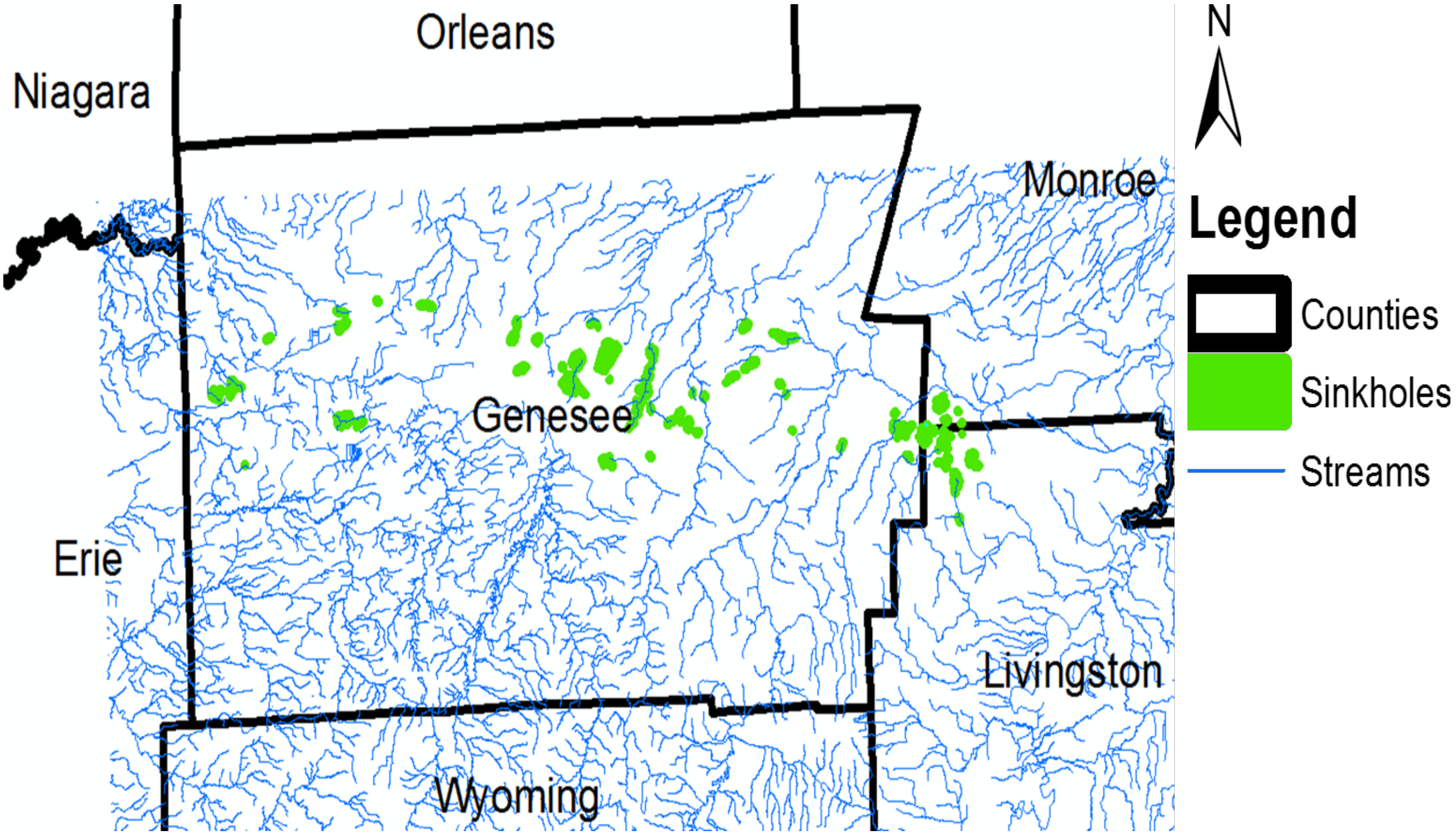


Figure 6. Map of study area containing sinkholes and surface streams. The map shows that many sinkholes occur directly on or adjacent to streams, which differs from the results of several previous studies.

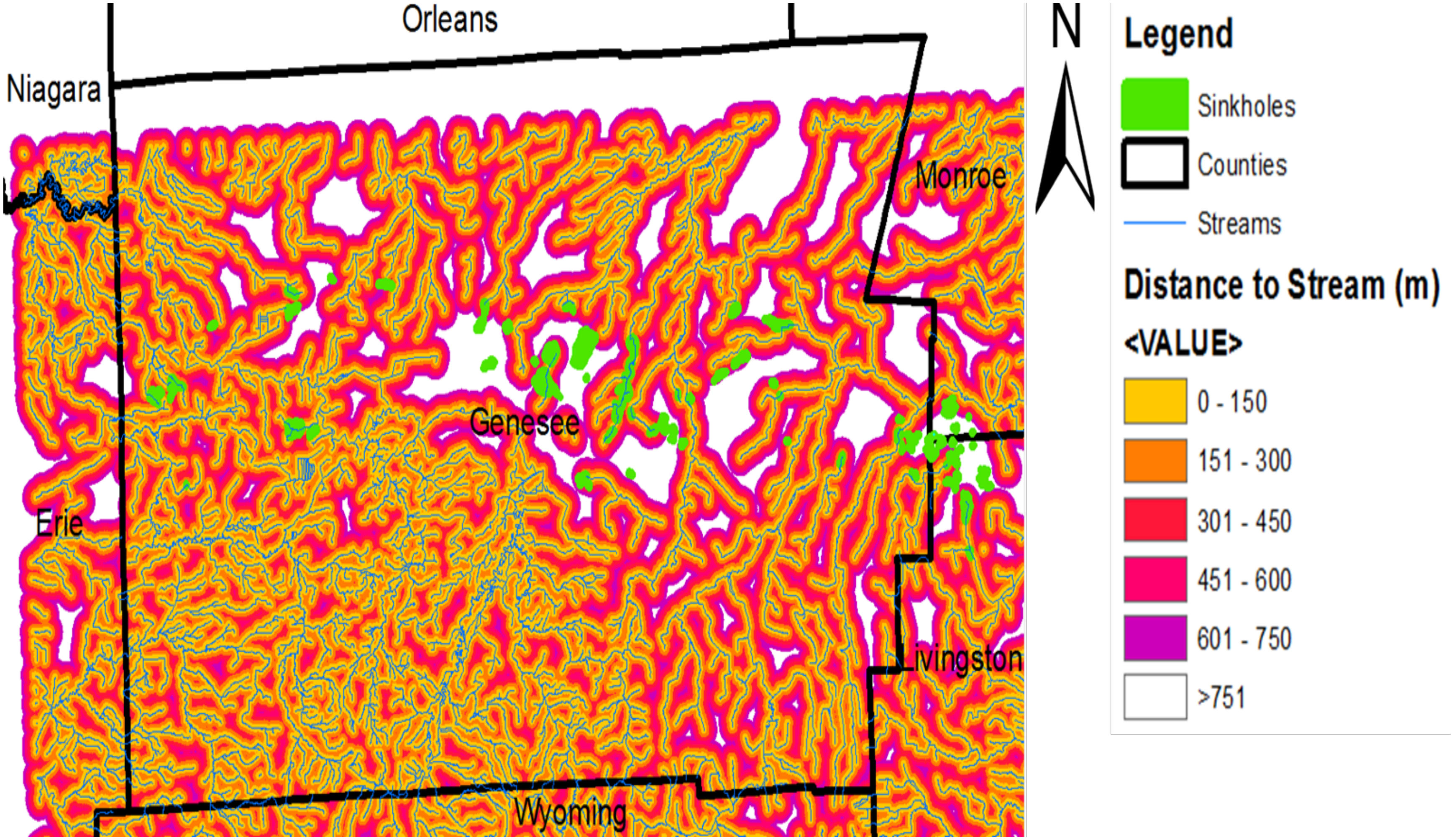


Figure 7. Map of study area with stream buffer zones indicated at equal-distance intervals away from a stream. Values are lowest at regions closest to the streams, increasing outwardly as distance increases from streams.

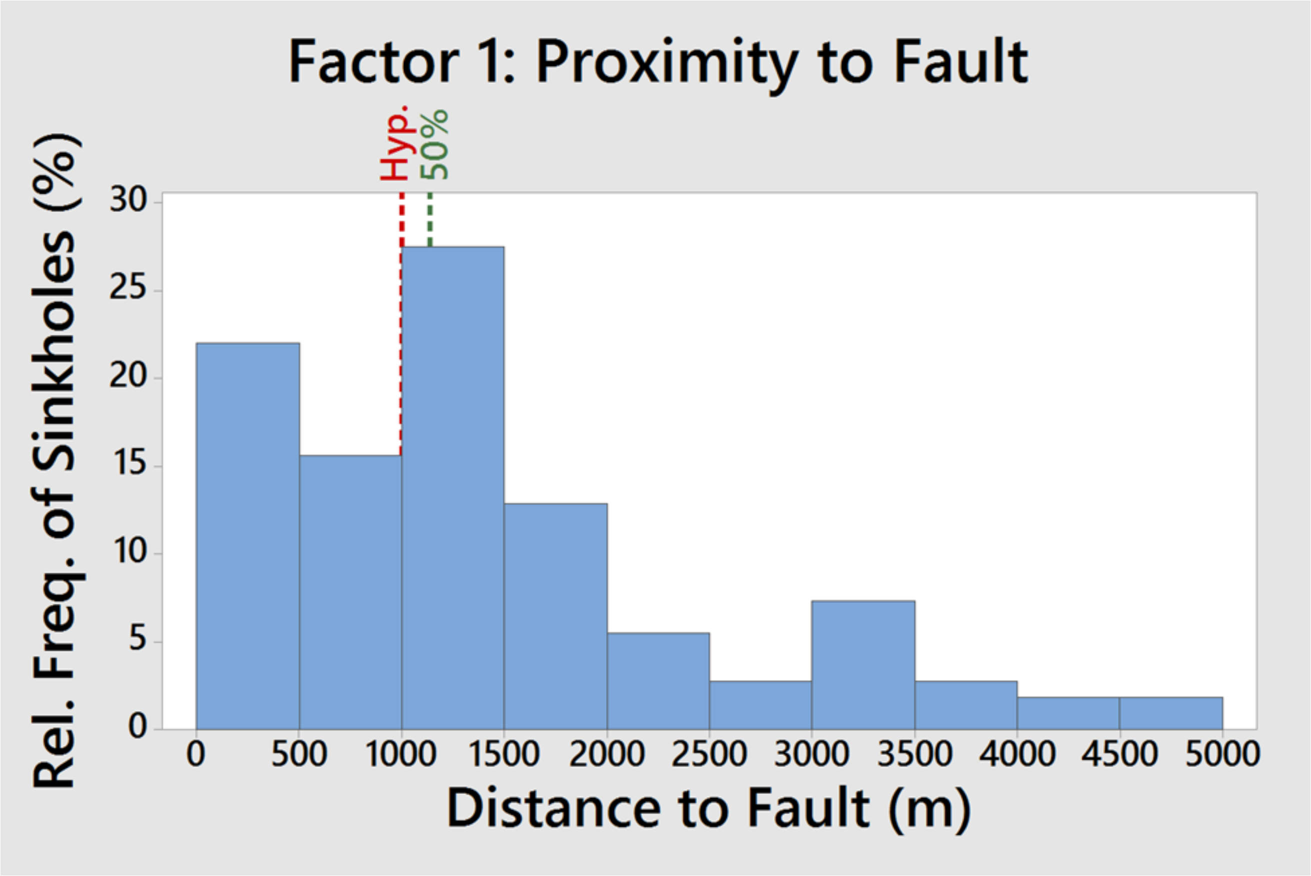


Figure 8. Relative frequency histogram showing the relationship between sinkholes and distance to a fault. Thirty-eight percent of the sinkholes occurred less than 1,000 meters from a fault, whereas 50% of the sinkholes were located within 1,139 meters of a fault, which does not support the hypothesis.

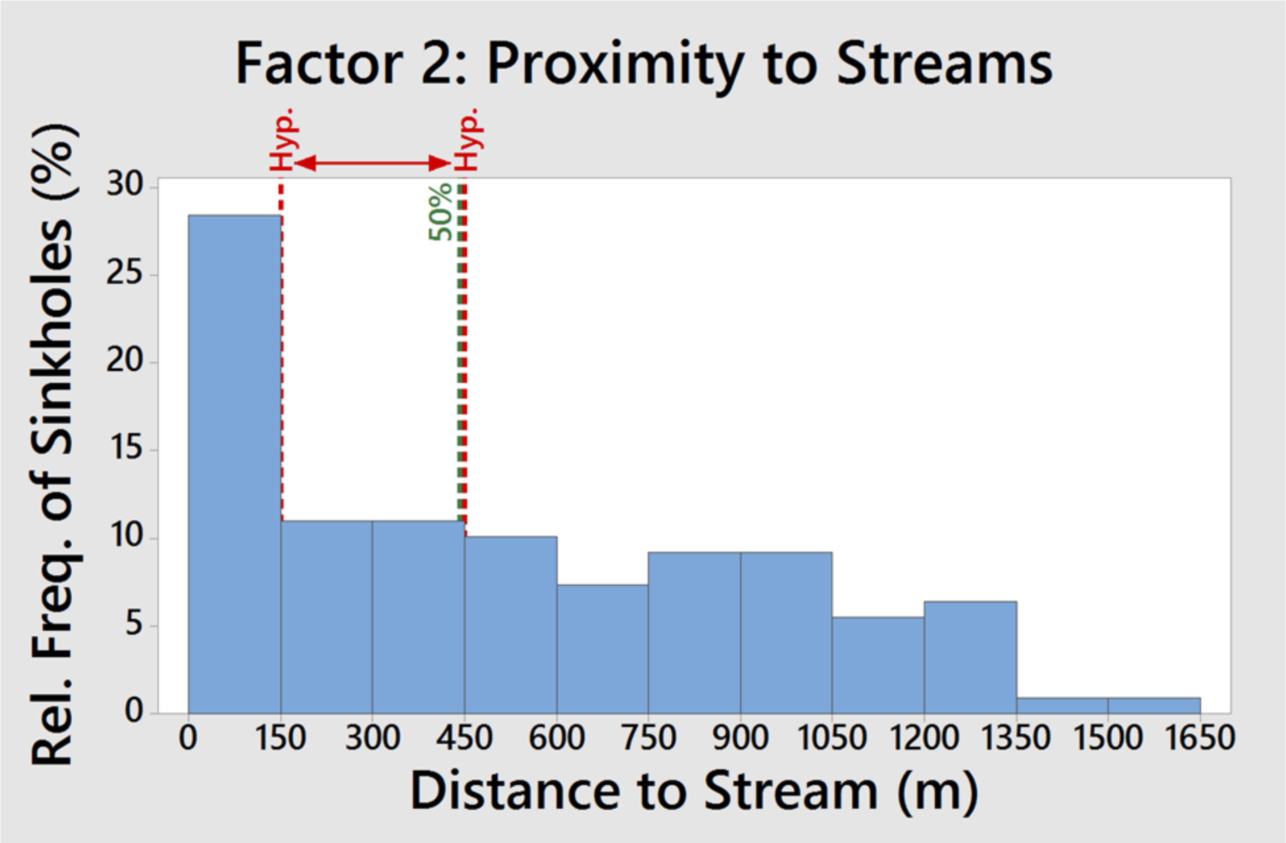


Figure 9. Relative frequency histogram showing the relationship between sinkholes and distance to a stream. Twenty-two percent of the sinkholes were located 150-450 meters from a stream, whereas 50% of the sinkholes were located less than 450 meters from a stream, which does not support the hypothesis.

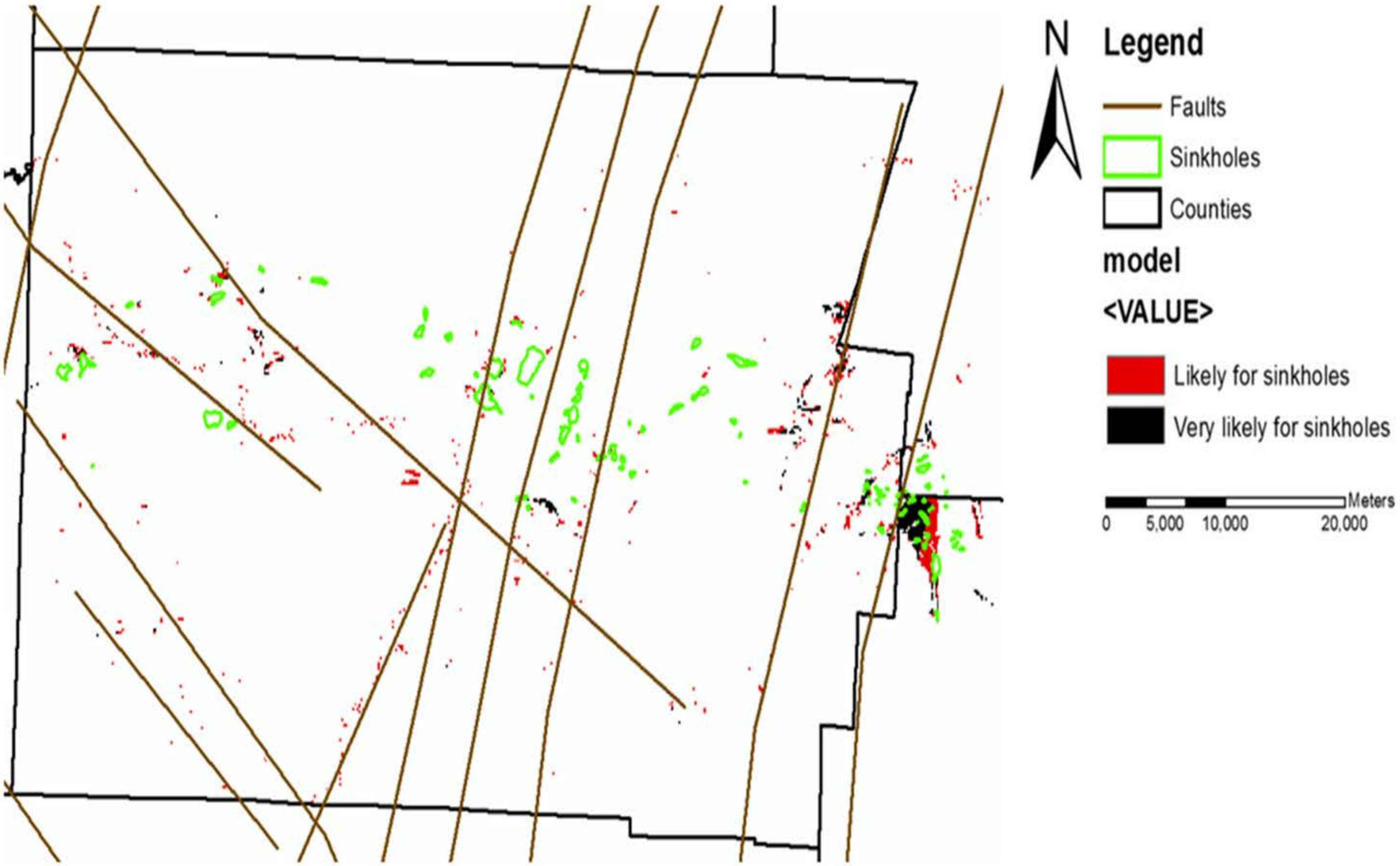


Figure 10. Factor combination model mapped with locations of known sinkholes and fault traces.

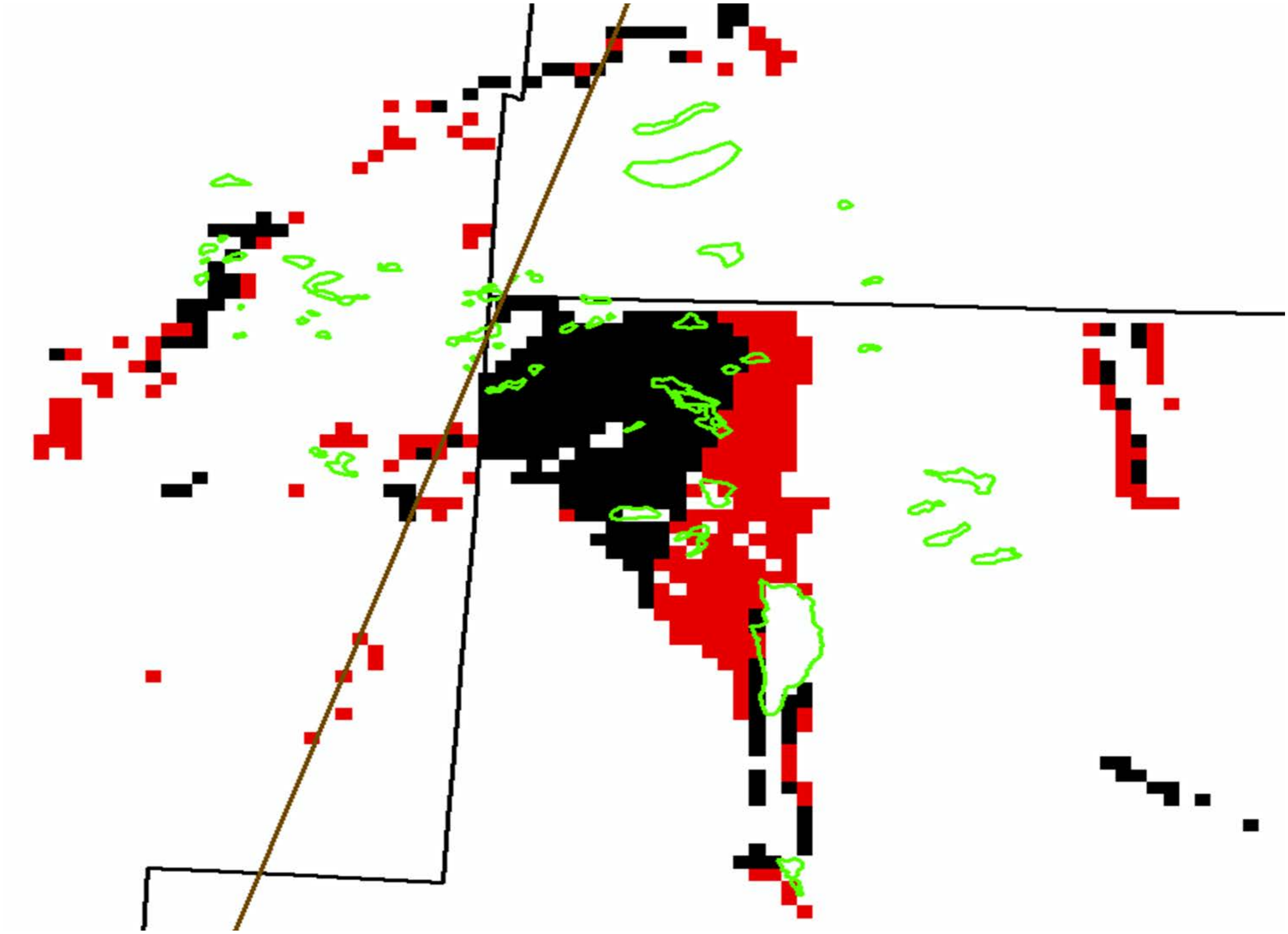


Figure 11. A zoomed-in portion of the factor combination model located near the intersection of all three county boundaries. Many sinkholes occur within the model's "very likely" zones (black cells) and "likely" zones (red cells). The black and red cells that do not contain sinkholes would be prime locations to revisit for future sinkhole identifications in the field.