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Spatial, Geologic, and Land Use Characteristics of Sinkholes in a Karst Landscape: Waverly, Iowa

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SPATIAL, GEOLOGIC, AND LAND USE CHARACTERISTICS OF SINKHOLES IN A KARST LANDSCAPE: WAVERLY, IOWA

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Abstract

The city of Waverly and its surrounding area in the Waverly Quadrangle has the fortune of having a large supply of groundwater that is easily accessible. However, the karst landscape that comprises much of the quadrangle has made the groundwater supply vulnerable to degradation from point and non-point contamination. Thus, it is crucial to explore the properties of sinkholes in the region to determine their threat to groundwater. To determine this threat, it is necessary to examine the characteristics of where and under what circumstances sinkholes develop. The Waverly Quadrangle is located entirely within the Iowan Surface. The bedrock in this region is mainly Silurian and Devonian aged limestone and dolomite rock. However, the Silurian-Devonian bedrock that underlies this area is also characterized by karst features. There are four major factors that are identified as contributing to the formation of karst topography: 1) groundwater flow rate; 2) characteristics of the water; 3) characteristics of the bedrock; and 4) initial presence of joints and cracks. Karst features, especially sinkholes, act as conduits to the groundwater from the surface. Along with the water that may flow into a sinkhole is any containments is picks up along the way. The findings of this study will describe and discuss: 1: the particle size analysis results from the four sampled sinkholes; 2) the spatial distribution of sinkholes in the Waverly Quadrangle; 3) the results of the GIS analyses on the geologic factors affecting sinkhole distribution; and 4) land use patterns in the areas surrounding sinkholes. This study found that sinkholes tend to develop in clusters, especially where: the soil is a loam or fine sandy loam texture, the bedrock is of Devonian aged limestone from the Cedar Valley Group and the depth to bedrock is less than 25 feet. In addition, this study found that row crop agriculture consists of 44% of the land surrounding sinkholes. This leads me to recommend more research in the Waverly Quadrangle, especially the determination of sinkhole drainage area and water flow paths, and the implementation of best management practices.

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Introduction

The city of Waverly and its surrounding area has the fortune of having a large supply of easily accessible groundwater. However, the karst landscape that comprises much of the quadrangle has made the groundwater supply vulnerable to degradation from point and non-point contamination. Karst landscapes are characterized by fractures in the bedrock, caves, springs, blind valleys and sinkholes (Cook et al., 2008; Hallberg & Hoyer, 1982; Prior, 1991; Whitley, 1977). Sinkholes are of special significance since they may act as a direct conduits between surface water and the groundwater systems. Water that drains off the land can flow into the sinkhole and reach the bedrock aquifer in minutes without being filtered naturally by the Quaternary aged material overly the bedrock (Hallberg & Hoyer, 1982; Magdalene & Alexander, 1995). With agriculture being a primary use of land near Waverly, the contamination of groundwater from fertilizers, pesticides, and animal sewage are of particular concern (City of Waverly Water Division, 2008a; Cook et al., 2008; Hallberg & Hoyer, 1982; City of Waverly Water Division, 2008b). Thus, it is crucial to explore the properties of sinkholes in the region to determine their threat to groundwater quantity. To determine this threat, it was necessary to examine the spatial and geologic characteristics and the land use practices surrounding them.

Study Area

The Waverly Quadrangle is located in northeast Iowa, and it is bounded by 42° 37' 20" and 42° 45' N latitude and 92° 30' and 92° 22' 30" W longitude, which places it mostly within southwestern Bremer County, with just a small portion reaching down into northwestern Black Hawk County (Figure 1). The city of Waverly lies in the northwest corner of the Waverly Quadrangle and the smaller town of Janesville lies in the southwest corner of the quadrangle. The Cedar River flows through the quadrangle, making its way through Waverly and Janesville from north to south. Waverly's estimated population in 2007 was 9,269, and Janesville's estimated population was 870 (US Census, 2008). In addition, the Waverly Quadrangle has a large rural population not documented in the city's census data. Annually, this area receives approximately 68.4 inches of precipitation, 32.9 of it as rain and 35.5 inches as snow (waverlyia.com).

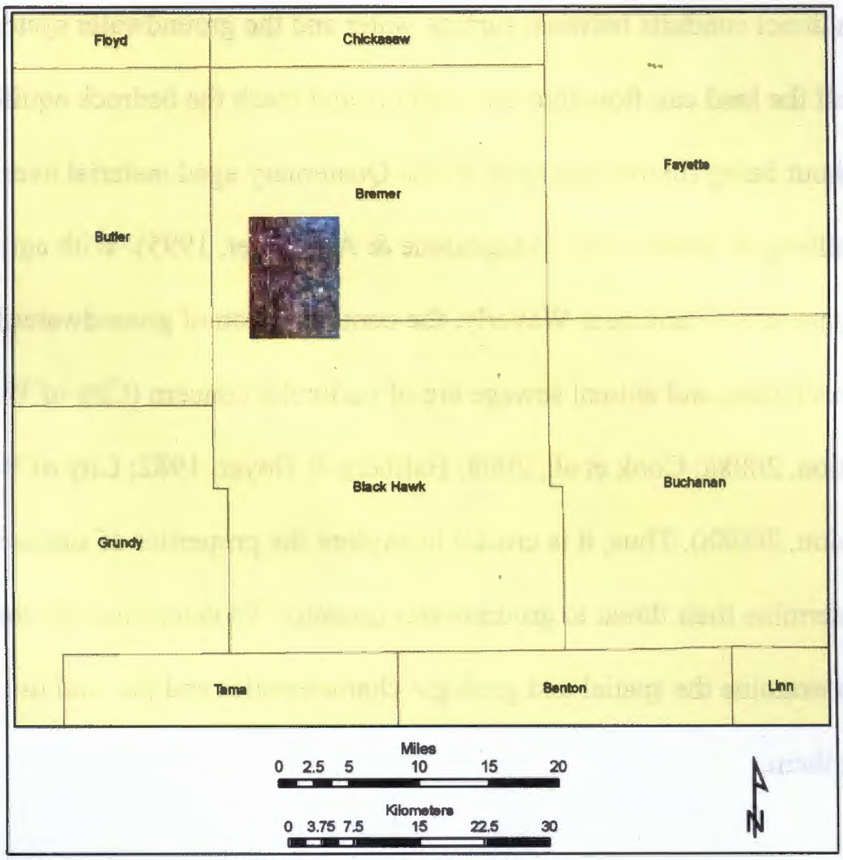

Figure 1: The Waverly Quadrangle in relation to surrounding counties (Photo modified from U.S. Department of Agriculture, 2008a & 2008b; County boundaries from Giglierano & Mohan, 1990)

The Waverly Quadrangle is located entirely within the Iowan Surface (Cook et al., 2008; Prior, 1991). The Iowan Surface was glaciated multiple times during the Pre-Illinoian glacial period between 2.2 million and 500,000 years ago, laying down layers of glacial till (Cook et al., 2008; Prior, 1991). These layers of glacial till, along with the soil developed on it, will be referred to in this paper as the surficial geology and Quaternary aged material. During the Wisconsin glacial period, 21,000-16,500 years ago, the Iowan Surface experienced intense freeze-thaw cycles and slopewash that caused the leveling of the landscape (Cook et al., 2008; Prior, 1991). Since this area was not glaciated during Wisconsin Glaciation, it does not have any glacial till representing the Wisconsin period, but a layer of windblown glacial silt, or loess, did accumulate on the surface. Other characteristics of the Iowan Surface include low relief (Figure 2), glacial erratics, stonelines, and loess capped paha formations (Cook et al. 2008; Prior, 1991). The Waverly Quadrangle is shown in relation to northeast Iowa and the landform regions described by Prior (1991) in Figure 3. The bedrock in this region is mainly Silurian (443.7-416 Ma) and Devonian (416-359.2 Ma) aged limestone and dolostone rock (Cook et al., 2008; Hallberg & Hoyer, 1982; Prior, 1991). Limestone [$Ca(CO_3)$] and dolostone [$CaMg(CO_3)_2$] will be together referred to as carbonate rock. The majority of the area has Devonian aged carbonate rock of the Middle and Upper Devonian Cedar Valley Group (Cook et al., 2008; Hallberg & Hoyer, 1982). It is this bedrock formation that contains the groundwater aquifer, the Silurian-Devonian aquifer, from which Waverly draws its public supply (City of Waverly Water Division, 2008a; Cook et al. 2008; Hallberg & Hoyer, 1982).

The Silurian-Devonian bedrock that underlies this area is also characterized by karst features (Hallberg & Hoyer, 1982). In addition to other features mentioned above, karst landscapes can be observed most noticeably at the surface in the form of sinkholes (Hallberg & Hoyer, 1982; Prior 1991; and Whitley, 1977). There are sixty-five documented sinkholes in the Waverly Quadrangle (Figure 4), many of which are located in clusters (Iowa Department of Natural Resources Geological Survey Bureau, 2008).

Figure 2: Photo overlooking the Iowan Surface from the boundary between it and the Southern Iowa Drift Plain (author's photo).

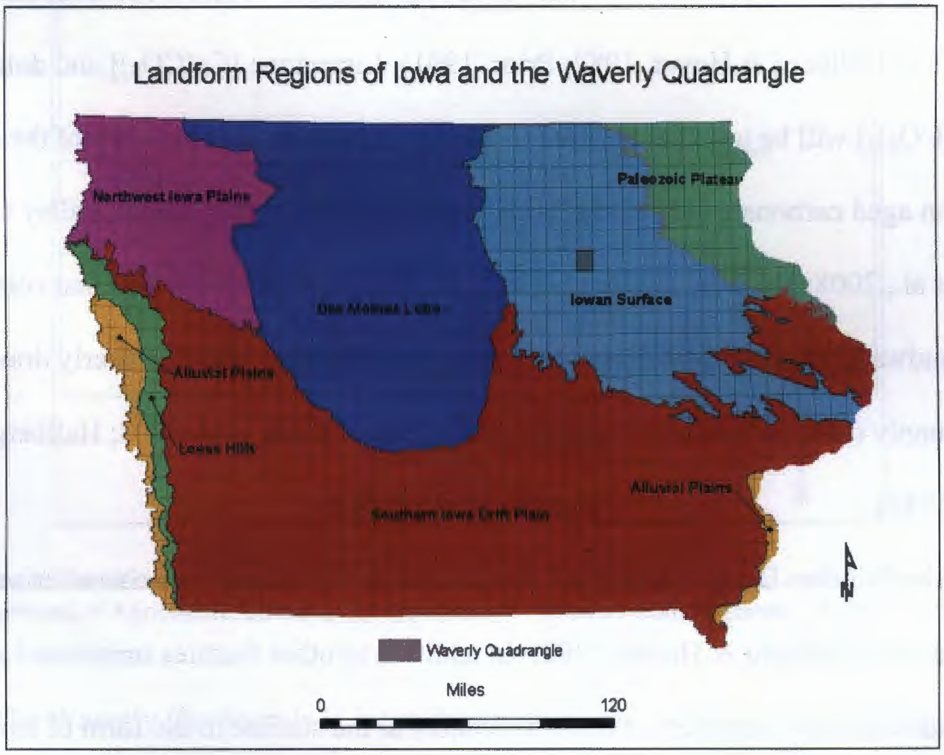

Figure 3: Location of the Waverly Quadrangle in relation to the Landforms Regions of Iowa (Landscape layer based on Prior, 1991; Landscape layer from Prior & Kohrt, 2006; County boundaries from Giglierano & Mohan, 1990; Quadrangle layer modified from Howes, Giglierano, Bunker, & Korpel)

Figure 4: Map showing the location of the sinkholes in the Waverly Quadrangle (Sinkhole layer from IGWS, 2008; Images from USDA 2008a & 2008b).

Background

The controlling factors behind the development of karst topography have been weighed and debated since the late 1960's (Mandel, 1966; Thrailkill, 1968; White, 1969). Although the order of importance of each individual factor is disputed among researchers, experts agree on several factors that contribute to karst formation. Mandel (1966) provided one of the earliest descriptions of the solution process. In it, he describes four factors that contribute to the formation of karst topography: 1) groundwater flow rate; 2) characteristics of the water; 3) characteristics of the bedrock; 4) initial presence of joints and cracks (1966). White (1969) expanded upon these ideas by incorporating basin relief and aquifer basin architecture into the karst parameters. He also expanded on Mandel's (1966) bedrock characteristic factor by observing that the pure form of limestone is more susceptible to solution and lessened as the rock moved from limestone to dolostone (1977). For carbonate rocks, Corbel (1957) found that at least 60% of the bedrock must be pure limestone for solution features to develop in it (as cited in Jennings, 1985). A simple formula for the physical solution of calcium carbonate, or limestone, is presented as follows in Jennings (1985):

$$\underset{\text{(solid)}}{CaCO_3} \leftrightarrow Ca^{2+} + CO_3^{2-}$$

Mandel (1966) concluded that groundwater flow rate was the most important factor affecting the solution of the bedrock, which is necessary in the formation of all karst features. Essentially, this means that the more water that moves through a carbonate bedrock system in a given time, the faster the bedrock will be dissolved (Mandel, 1966). The basin relief is characterized by the vertical distance from the regional base lever, i.e. a river, and the infiltration point and is necessary to calculate the hydraulic gradient

(White, 1977). The final factor that was most commonly associated with karst features the presence of joints and pores in the limestone bedrock. When water reaches the bedrock layer, it will flow along the path of least resistance. When secondary openings are present, i.e. fractures, joints and cracks, the water will move through these, causing the chemical dissolution of the rock (Hallberg & Hoyer, 1982; White, 1977).

Since sinkholes are a karst feature, the factors influencing their formation are similar to the general factors that lead to all karst features. What sets sinkholes apart is that they are a surficial expression of the karst landscape (Hallberg & Hoyer, 1982; Jennings, 1985; Prior, 1991; Whitley, 1977). Sinkholes develop when underlying bedrock is mass wasted by the process of chemical and mechanical weathering, causing the surficial material to move down into the voids, creating a depression at the surface (Hallberg & Hoyer, 1982; Jennings, 1985; Whitley, 1977). There are two common types of sinkholes; collapsed and subsidence (Jennings, 1985; Whitley, 1977).

Whitley (1977) classifies subsidence sinkholes as two separate types: subsidence and solution subsidence. The difference between subsidence and collapsed sinkholes is that subsidence sinkholes develop as voids that are continually filled, forming a gently sloped depression, and collapsed sinkholes have voids created from dissolution that grow larger and larger until the roof cannot support the ground and it falls in, resulting in steep cliff-like walls (Jennings, 1985; Whitley, 1977).

It is apparent just by looking at the sinkhole distribution in the Waverly Quadrangle that there is come clustering taking place. Furthermore, Magdalene and Alexander (1995) showed that sinkholes in Winona County in Minnesota displayed a clustered pattern. They found that when they applied the Clark-Evans (Clark & Evens,

1954) test, the ratio between expected and observed mean distances equaled 0.555 (1995). A clustered pattern would validate the presence of controlling factors for sinkhole locations.

Hallberg and Hoyer (1982) looked at the controlling factors that lead to sinkhole formation in northeast Iowa and how those factors related to the distribution of sinkholes. In it, three factors that were identified as having the greatest effect on sinkhole location: lithology and structure, erosional relief (hydraulic gradient) and a new factor not identified in previous articles, depth to the bedrock (Hallberg & Hoyer, 1982). What they found tended to coincide with the general factors for karst development. The sinkholes tended to be found in locations where the underlying bedrock was relatively pure limestone and followed known fracture features in the subsurface (Hallberg & Hoyer, 1982). One particular bedrock formation they mentioned was the Cedar Valley Limestone of the Middle Devonian aged rock (1982). They also discussed the possibility of the hydraulic gradient having an input on the formation of sinkholes, but the age of karst development on each bedrock formation is different, making it nearly impossible to correlate (1982). However, they did propose that a higher gradient would increase water flow, increasing the chance for solution and sinkhole development. Ritter, Kochel, and Miller (2002) contradict this by stating that an area of lower gradient encourages sinkhole development because it allows for a more direct infiltration of water. Finally, Hallberg and Hoyer (1982) looked at the thickness of Quaternary aged material overlying the bedrock and found a strong correlation with the presence of sinkholes and the depth to the bedrock. It turned out that 95% of the sinkholes that were mapped were in locations where the depth to bedrock was less than 25 feet (Hallberg & Hoyer, 1982). Jennings

(1971) and Whitley (1977) concluded that less dense soils, those with larger particle sizes, would allow more water to percolate to the bedrock where it would chemically erode joints and pore spaces, creating caverns for sinkholes to develop. Furthermore, Hallberg and Hoyer (1982) noted that the sinkholes found in the Silurian-Devonian aquifer, which, as noted above, the Waverly Quadrangle is in, are located alongside the Cedar River.

Aquifers in karst landscapes are typically associated with groundwater quality issues, and the Silurian-Devonian aquifer is no different. By nature, karst landscapes present a problem because the bedrocks are defined by a system of open conduits and fast recharge times through these conduits, and sinkholes are a major conduit that links the surface with the bedrock aquifer (Cook et al., 2008; Hallberg & Hoyer, 1982; White, 1969; White, 1977). White (1977) modeled this rate of recharge as the response of a conduit system to a high discharge event, such as a heavy rainfall or snowmelt. He also related this reaction to the normal diffuse response in which the water percolates through the overlying surficial geology. The conduit response of a karst landscape showed a quick, high peak following the event and then dropped back down to normal shortly after whereas the diffuse response rose slowly to a much lower peak and tapered off gradually (White, 1977). White (1969) described the diffuse response as the process of infiltrating water through the surficial geology, or what he called the epikarst, as the water makes its way down through the bedrock and into the aquifer. The diffuse response may take days or weeks to complete, whereas the conduit response may take only minutes, which presents a serious problem for the water quality in these aquifers. Water runoff from the surface may reach the aquifer in only minutes (Hallberg & Hoyer, 1982; Magdalene &

Alexander, 1995). This means that the water, and whatever it is carrying, will make its way into the groundwater with minimal filtering by the surficial geology.

Karst features, especially sinkholes, act as conduits to the groundwater from the surface. Along with the water that may flow into a sinkhole are any containments it picks up along the way. Although there are many containments that may enter the groundwater system through sinkholes, one of most common concerns for the city of Waverly is the nitrate level (Cook et al., 2008; City of Waverly Water Division, 2008b). High nitrate levels have been linked to methemoglobinemia, or blue baby syndrome (City of Waverl Water Division, 2008b; Hallberg & Hoyer, 1982). Nitrate can come from a variety of sources, both point and non-point source, including fertilizers, animal manure, septic systems and soil erosion, among other sources (City of Waverly Water Division, 2008b; Cook et al., 2008; Hallberg & Hoyer, 1982; Panno & Kelly, 2004). Increased concentrations in the groundwater have been linked to heavy rainfall events and to the late spring to early summer time period when fertilizers are being applied to the fields, but some studies contest these generalizations (2007 Annual Drinking Water Report, Boyer & Pasquarell, 1996; Cook et al., 2008; Currens, 2002; Hallberg & Hoyer, 1982; Panno & Kelly, 2004). Nitrate levels are also shown to increase with agricultural activity, but is still dependant on the regional practices of fertilizer application, tillage, and percent of land under cultivation. Iowa is known for its agriculture, particularly corn and soybeans, both of which are row crops. In the Waverly Quadrangle, the overall land use in the quadrangle is 47.4% row crops (Figure 5).The maximum containment level (MCL) for nitrate in the public water supply is 10 mg/l, and high levels of nitrate may pose a threat to newborn children (City of Waverly Water Division, 2008a; Water Quality Data

2007; 2008). Nitrate levels found in individual wells in Waverly since 2001 nitrate levels have ranged from a low of 3 mg/l from Well 6 in 2007 to 9.6 mg/l from Well 7 in 2002 (Cook et al., 2008).

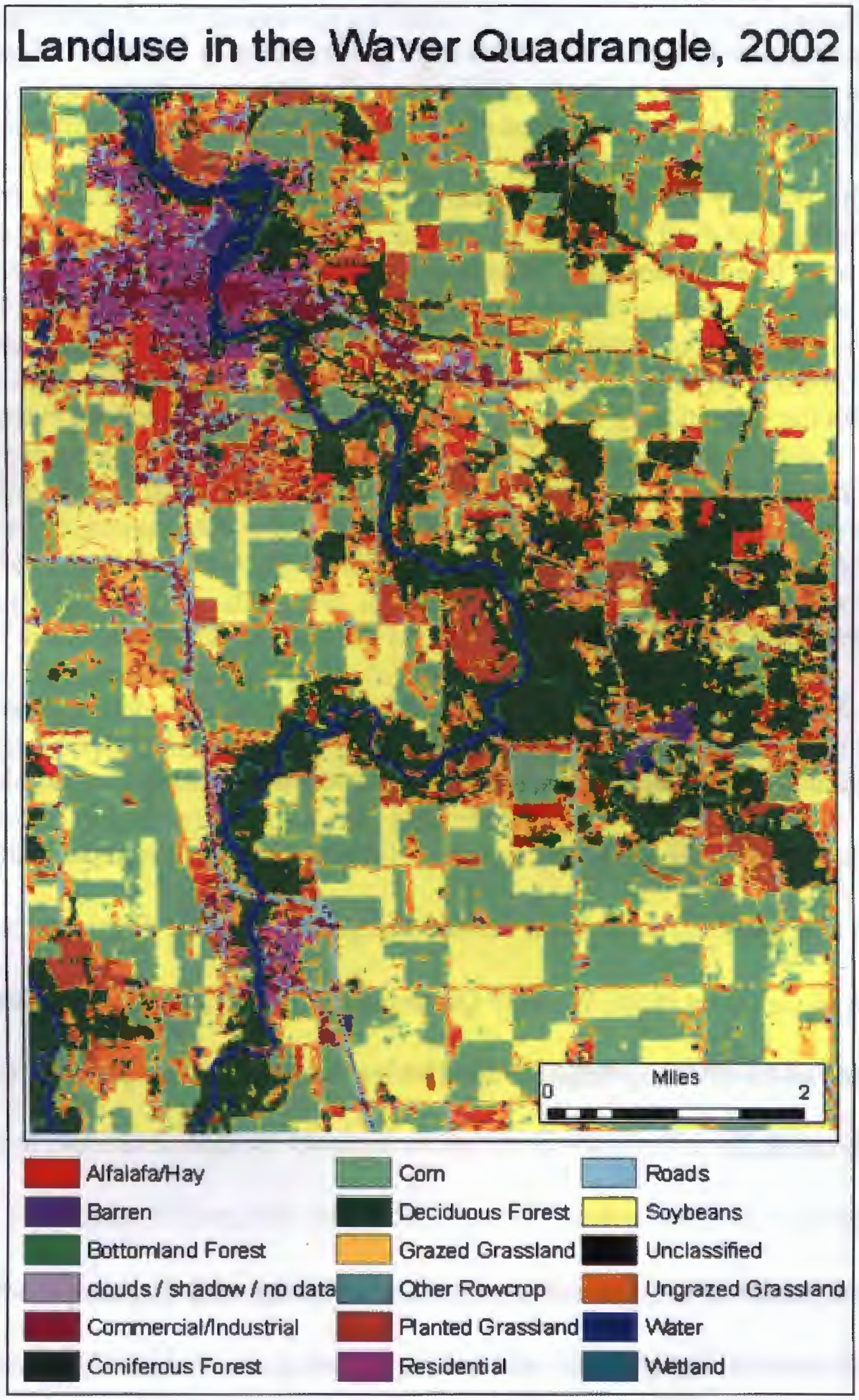

Figure 5: Land use in the Waverly Quadrangle in 2002 (Land use layer from USDA, 2004).

Purpose

Although no public water supply well in Waverly has been found to contain nitrate levels greater that 10 mg/l since 2001, the fact that levels consistently test above 6 mg/l and have reached a maximum of 9.6 mg/l is of concern to Waverly officials (Cook et al., 2008). This all leads to the question, are sinkholes of concern to groundwater quality in the Waverly Quadrangle? To answer this question, there are more fundamental issues that must be addressed first: Where are the sinkholes in the Waverly Quadrangle; What are the relationships between surficial geology composition, bedrock, and hydraulic gradient with the formation of sinkholes; What are the land use practices in the areas surrounding the sinkholes? In attempt to address these fundamental issues, this study analyzed the characteristics of sinkholes to better understand what factors lead to their development in the Waverly Quadrangle. To do this, four sinkhole sites were chosen (Figure 6). Soil samples taken for use in particle size analysis. In addition, analyses of various spatial and geological characteristics were performed using geographic information system (GIS) tools. The findings of this study will describe and discuss: 1) the particle size analysis results from the four sampled sinkholes; 2) the spatial distribution of sinkholes in the Waverly Quadrangle; 3) the results of the GIS analyses on the geologic factors affecting sinkhole distribution; and 4) land use patterns in the areas surrounding sinkholes.

Hypotheses

Based upon the background information, I hypothesized that the particle size will have a tendency to be sandy. This was based upon the ideas put forth by Jennings (1971), Whitley (1977), and Hallberg and Hoyer (1982) that were discussed earlier. Because of that, I hypothesized that the surficial composition would be largely alluvial sand.

I also anticipated that the nearest neighbor analysis will show that sinkholes in the Waverly Quadrangle exhibit a clustered pattern. It is apparent just by looking at the distribution of sinkhole on a map that there are definitely areas where there is a greater concentration of sinkholes than other areas.

In addition, my GIS analysis will confirm the ideas put forth by Hallberg and Hoyer (1982). Since their study, more sinkholes have been documented (Iowa Department of Natural Resources Geological Survey Bureau, 2008) and the boundaries for the bedrock geology and the depth to bedrock and they have been updated into GIS layers (Hoyer, Giglierano & Korpel, 1992; IGWS, 1998). To supplement their study, I believe that the hydraulic gradient data that will be extracted using GIS will confirm that there is a higher frequency of sinkholes that will have higher gradients.

Finally, I hypothesize that the land use category with the most area within 200-foot buffer of a sinkhole will be row crop agriculture.

Methods

Field methods

The field work process began by obtaining the sinkhole GIS data from the Iowa Department of Natural Resources Geological Survey Bureau's (IGWS) Natural Resources Geographic Information Systems Library to determine what sinkholes were located in the Waverly Quadrangle. The landowners on which these sinkholes were located were then identified using the Bremer County, IA Plat and Directory Book (Farm and Home Publishers, 2008). Landowners were contacted and requested permission to sample the soils from their sinkholes. A group of five landowners was selected. The sample group of five sinkholes shrank to four due to an early onset of winter conditions.

Once at the site, longitude and latitude coordinates were obtained using global positioning system (GPS) data and the surrounding vegetation was noted. Soil samples were then taken from the center of the sinkhole using a hand auger. Samples were taken near the surface and then at every point the soil color (Musell) or texture changed. Six samples were collected from the first site, which will be referred to from here on by Dix sample, seven samples from the second site, referred to as Robinson sample, and five samples each from sites three and four, referred to as Ingawanis and Christianson, respectively. The location of these sample sites are shown in Figure 6.

Laboratory methods

Particle size analysis

The method that was used to determine the particle size for the samples was the sieve and pipette method described by Singer and Janitzky (modified from Singer & Janitzky, 1986). This method is based off Stokes' Law:

$$t = 18\eta h/x^2 g(\rho_S - \rho_L)$$

where: t = time elapsed (seconds)
h = draw depth (cm)
x = particle diameter
η = fluid viscosity
g = acceleration due to gravity
ρ_S = density of particles
ρ_L = density of water.

The acceleration due to gravity (g) value used was 980.171 cm/sec^2, which was calculated for 40°N latitude by Weast (1968). Additionally, the density of particles (ρ_S) value was assumed to be 2.65 g/cm^3 (Jackson, 1969). This method does assume that the

Figure 6: The location of the four soil sample sites (USDA, 2008a; 2008b).

particles all have the same density and the particles all are spherical.

After the pretreatments were completed, the sample was wet sieved to separate the sands from the silts and clays, the sands were dried, then separated in five fractions. These five fractions ranged from very coarse (2mm>wt>1mm) sand to very fine sand (100μm>wt>50μm), based on the U.S. Department of Agriculture's classification system (USDA, 1951). The silt and clay remainder was then added to a graduated beaker and diluted to 1L. Draws were taken at the calculated times, taking in account the temperature in the room, for course silts (50μm>wt>20μm), medium to fine silts (20μm>wt>5μm) and very fine silts (5μm>wt>2μm), along with the coarse to medium clays (2μm>wt>0.5μm) and fine clays (wt<0.5μm). With the weight for each draw sample was determined, the total weight for each fraction was calculated by multiplying the draw weight by the sample factor. The sample factor is the portion of the 1L total volume that each draw represents, or:

$$SF = 1000\text{mL}/Vp$$

where: Vp = volume of the pipette
SF = sample factor.

Since Vp was found to be 25.5762, the sample factor would be 39.0988. The weights for sand could then be combined with silts and clays to calculate the percent of sand, silt and clay for each sample.

Nearest neighbor analysis

Spatial patterns in the sinkhole distribution was tested using the Clark-Evans test of spatial relationships in populations (Clark & Evans, 1954). The test is based on comparing the observed mean distance to nearest neighbor to the expected mean distance to nearest neighbor. The formula for this calculation, based on Clark and Evans (1954), is:

$$R = L_a/L_e$$

where: R = spatial index ratio
L_a = observed mean distance to nearest neighbor
L_e = expected mean distance to nearest neighbor.

L_e and L_a were calculated using the sinkhole shapefile (IGWS, 2008) and executed by the nearest neighbor tool in ESRI ArcGIS. The resulting ratio, R, may range from 0 (maximum clustering) to 1 (complete randomness) to 2.149 (maximum dispersion) (Clark & Evans, 1954; Magdalene & Alexander, 1995).

In addition, a z-score was calculated using ESRI ArcGIS to determine the confidence that the resulting R-value is not a result of chance. Confidences of 99% and 95% would result in z-score values of ±2.58 and ±1.96, respectively. Any z-score value greater than 2.58 or less than -2.58 would mean that there is a less than 1% chance that the resulting R-value was by coincidence.

Geologic distribution of sinkholes using GIS

The analyses of the geologic factors were done using ArcMap GIS tools and shapefiles from the Iowa Department of Natural Resources Geological Survey Bureau's Natural Resources Geographic Information Systems Library. The first analysis used shapefiles describing the bedrock of northeast Iowa and the other contained contours of the depth to bedrock for Iowa. The Devonian aged limestone bedrock and areas with less than 25 feet to the bedrock were selected and then intersected so that only the areas with Devonian aged limestone bedrock that was within 25 feet of the surface was left. Next, the area was clipped so that only the area of the Waverly Quadrangle was left. Finally, the documented sinkholes (IGWS, 2008) were placed over top to determine any correlation.

The method for determining the gradient was a little more tedious. Again, the shapefile for the sinkholes (IGWS, 2008) was utilized, along with an elevation GRID file (U.S. Geological Survey, 1999). Gradients were calculated with the formula:

$$G = (E_S - E_B)/D$$

where: G = gradient
E_S = elevation of the sinkhole
E_B = elevation of the river's nearest point
D = shortest distance from sinkhole to river.

This method is assuming that the flow of water as it enters the subsurface is directly to the river's closest point. In reality, the flow will be curved downstream, which is illustrated in Curren's (2002) study. However, without dye tracing, the actual flow cannot be determined.

Land use patterns surrounding sinkholes

The final analysis was also performed using ArcMap. Land use coverage for 2002 was determined by IGWS (2004) and the sinkhole shapefile was again used (IGWS, 2008). A 200-foot buffer was created to simulate the drainage area for each sinkhole. The actual drainage areas are variable and could be determined with dye tracing, but the standard 200-foot buffer established by Cook et al. (2008) was used. In addition, the overlaps of buffers for sinkholes within 200 feet of each other were dissolved so that those areas were only counted once. Finally, the land use and sinkhole buffer files were intersected so that only the land use areas inside the buffers were selected, resulting in the land use data for areas with 200 feet of a sinkhole.

Results

Field results

The Dix and Robinson sinkholes were both subsidence sinkholes that had gentle slopes. Although both sinkholes were located on farmland, the Dix sinkhole was not cultivated and grass was allowed to grow overtop, whereas the Robinson sinkhole was still cultivated and located just adjacent to a gravel road. The Ingawanis site contained a collapsed sinkhole approximately 2.5 feet in diameter. This sinkhole was located on a grass field on the Ingawanis Boy Scout property. Since a soil sample could not be taken from the center of the sinkhole, a sample was taken just next to the sinkhole.

The Christianson sinkhole, on the other hand, was somewhat of a mystery, and the results may reflect it. It was located at the north edge of Waverly in a man's backyard. The sinkhole was first identified as a subsidence sinkhole with gently sloping east side of about 2-5 degrees and a steeper west side of about 20-25 degrees. Five samples were taken at this location with the last one being at only 1.8 feet. The auger was not able to penetrate any deeper due to cobble and gravel sized rock. After leaving the site, I talked with the neighbor who had known the previous occupant of the land on which the sinkhole was located. The neighbor recalled that the previous landowner had told him that sometime before the neighbor moved in, the sinkhole was a huge pit that was filled with dump trucks full of road debris. This may be possible, for it was a common practice in the past to use sinkholes as a sort of dumping container (Hallberg & Hoyer, 1982). Pictures of all the sinkholes can be found in Appendix B.

Nearest neighbor analysis

After performing the nearest neighbor analysis in ArcMap, the observed mean distance between sinkholes in the Waverly Quadrangle was 281.63 meters. In contrast, the expected mean distance between sinkholes in an area the size of the Waverly Quadrangle would be 579.14 meter. Then, when these two values were put into to the Clark-Evans (Clark & Evan, 1954) test, we found that the ratio between the expected and actual mean distances was 0.49. That puts the spatial pattern of sinkholes in the Waverly Quadrangle in the clustered portion of the cluster-dispersion spectrum. An illustration of this data is shown in Figure 7.

In addition, the calculated z-score for this ratio equals -7.92. The significance levels of 0.01 and 0.05, which correspond to a confidence level of 99% and 95% respectively, are associated with z-scores of ±2.58 and ±1.96, respectively. With a z-score of -7.92, the probability that the sinkhole pattern that is seen in the Waverly Quadrangle is less than 1%.

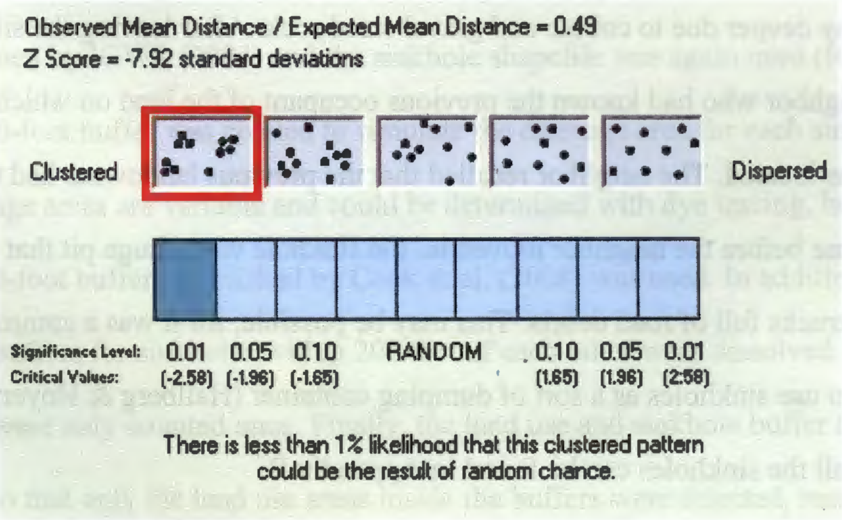

Figure 7: An illustration of the cluster data and its significance (ESRI, 2008).

Particle size analysis

After performing the particle size analysis on the four samples, three of the four samples fell close together in the loam and clay loam portion of the soil textural triangle. The outlier of the group was the Christianson sample, which was located in the sandy loam category, as can be seen in Figure 8. The actual composition of each fraction for each sample can be found in Appendix A on page 33. The average sand, silt, and clay percentage for each sample, respectively, is as follows: Dix – 34.0%, 40.0%, 25.8%; Robinson – 35.5%, 36.9%, 27.6%; Ingawanis – 42.6%, 38.0%, 19.4%; Christianson – 60.3%, 20.2%, 19.4%.

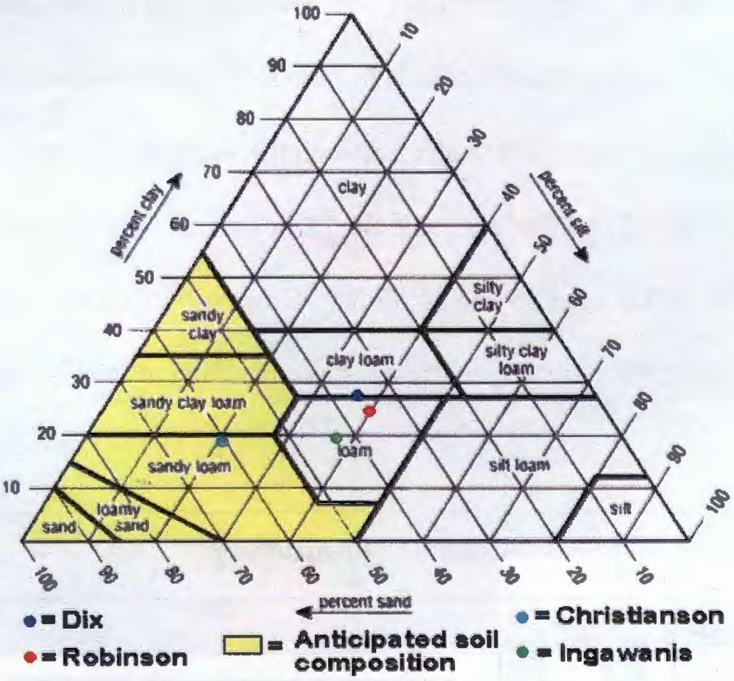

Figure 8: Textures of the four sampled soils with shaded hypothesized soil texture region (USDA, 1951).

Geologic distribution of sinkholes using GIS

GIS analysis revealed that the sinkholes exhibit other patterns as well. Overlaying shapefiles from the IGWS's Natural Resources Geographic Information Systems Library revealed that out 65 sinkholes documented in the Waverly Quadrangle, 63 were located were located where the surficial material was less than 25 feet and the underlying bedrock is Devonian aged limestone from the Cedar Valley Group. This can be seen on the map in Figure 9. The two sinkholes that did not fall in this group still were formed above the Cedar Valley limestone, but they laid just outside of the less than 25 feet to bedrock area. These can be seen in the northwest corner and east central regions of the map in Figure 9.

GIS analysis also revealed a pattern exists between the location of each sinkhole and the gradient from it and the base level's nearest point. Gradients ranged from 18 ft/mi to 361.6 ft/mi, but just over 75%, 49 out of 65, had gradients less than 130 ft/mi. Moreover, 81.5% of the sinkholes, 53 out of 65, had gradients in the lower half of the range. A frequency distribution of sinkhole to base level gradients is shown in Table 1.

The relief, or the vertical distance between the sinkhole and the base level, also had a cluster of values. The relief ranged from 18 to 86 feet, but 30 out of the 65 sinkholes had a relief between 38 and 36.99 feet. However, this data is not illustrated or expanded upon any further since no correlations or conclusions can be made from the data.

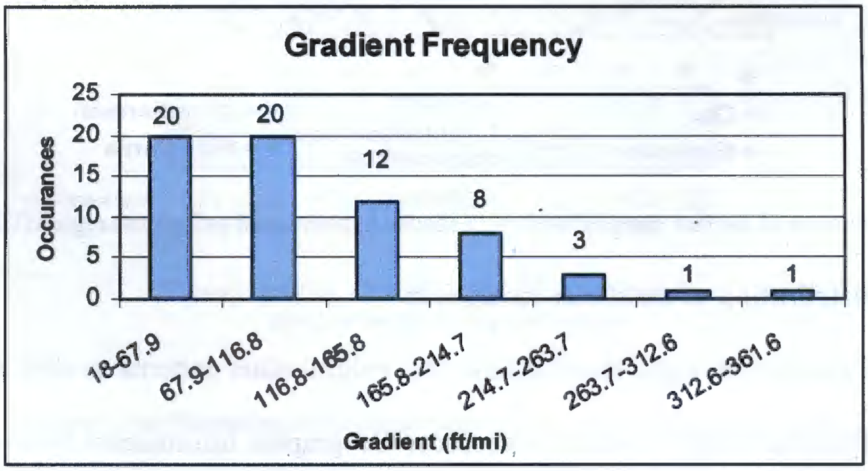

Table 1: The frequency of gradients for sinkholes in the Waverly Quadrangle.

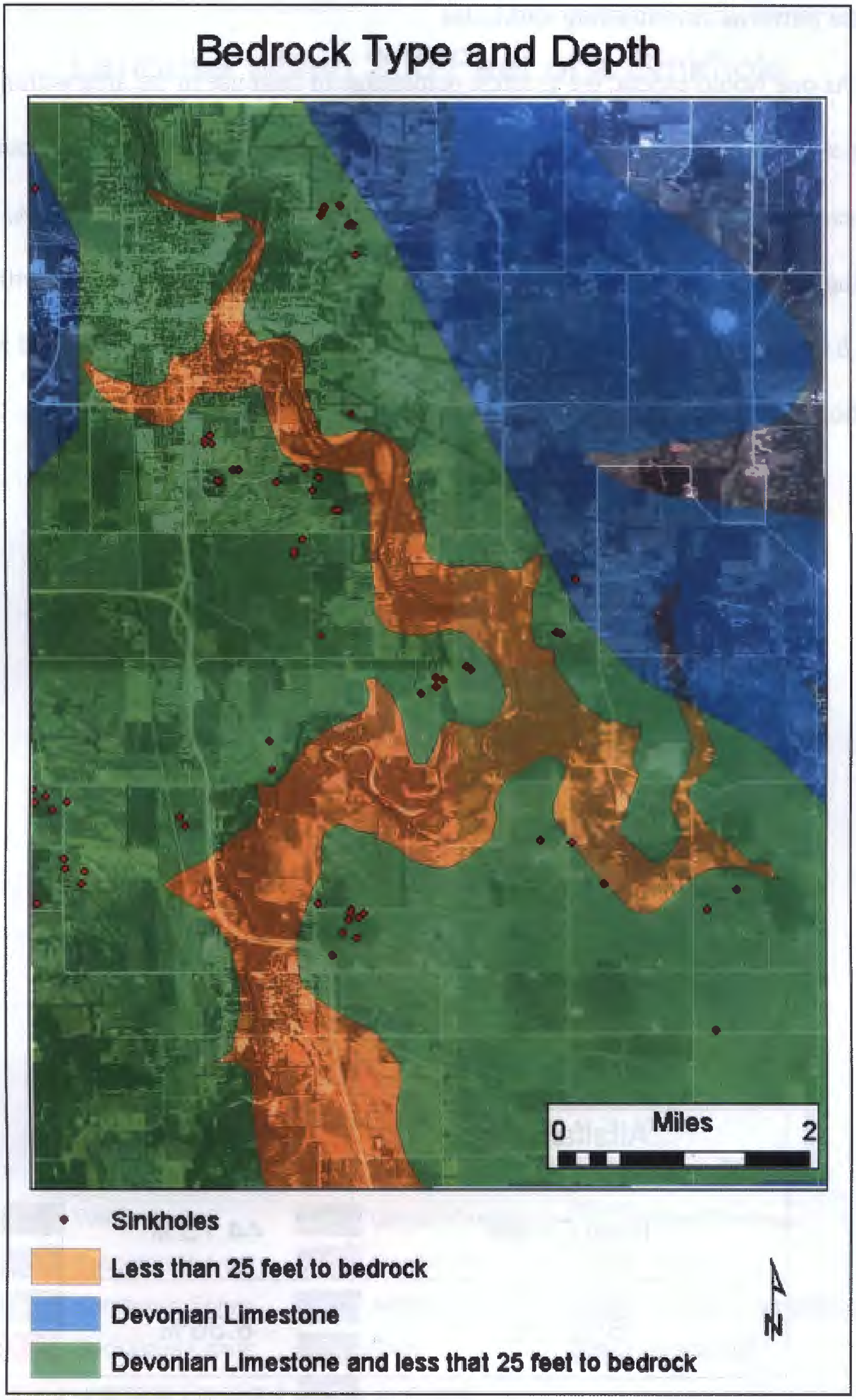

Figure 9: Sinkholes in the Waverly Quad in relation to where depth to bedrock is less than 25 feet and the bedrock is Devonian age carbonate rock from the Cedar Valley Group (Bedrock map and sinkholes from IGWS, 1998 & 2008; Depth to bedrock from Hoyer, Giglierano, & Korpel, 1992; Aerial images from USDA, 2008a & 2008b)

Land use patterns surrounding sinkholes

As one would expect, the greatest percentage of land use in the area within 200 feet of a sinkhole was row crops. Row crops comprised 44.75% of the land surrounding sinkholes. Grasslands was a distant second at 26.53% and forests third at 13.61%. The remaining land use was comprised of built of areas, alfalfa/hay, and wetlands, with 8.36%, 6.69%, and 0.07%, respectively. These values can be seen in Table 2 and an illustration of the map land use can be seen in Figure 8.

Land use surrounding sinkholes in the Waverly Quadrangle: 2002	
Wetland	0.07%
Forests	13.61%
Grasslands	26.53%
Alfalfa/Hay	6.69%
Row Crops	44.75%
Built Up	8.36%

Table 2: Land use surrounding sinkholes

Figure 10: The land use of the area within 200 feet of a sinkhole in the Waverly Quadrangle (Landuse layer from USDA, 2004; Sinkholes layer from IGWS, 2008; Aerial images from USDA, 2008a & 2008b).

Discussion

It is apparent from the tests and analyses that there are controlling that allow for the formation of sinkholes in some places and hinder the formation in other places. The first analysis performed, the nearest neighbor analysis, allowed for the assumption that there are controlling factors that determine where sinkholes develop. An R-value from the Clark-Evans (Clark & Evans, 1954) of 0.49 and a Z score of -7.92 gives us a greater than 99% confidence level that the sinkholes distribution is clustered and not a product of chance. This value is very close to the value found in Winona County, Minnesota, of 0.555 by Magdalene and Alexander (1995). This means that there is definitely one or more factors that are facilitating the formation of sinkholes.

The particle size analysis revealed that the common soil textures from sinkholes are loam and clay loam. The Christianson sample is an outlier for this sample, and this could very well be because past landowners have altered the site. Still, when these sample soil textures were compared to the soil textures assigned to that area in the soil survey, only the Ingawanis sample is the same (Iowa Cooperative Soil Survey & IGWS, 1998). The area where the Dix and Robinson samples were taken were both classified as fine sandy loam, whereas I found them to be clay loam and loam, respectively (ICSS & IGWS, 1998). The ICSS and IGWS described the Ingawanis and Christianson samples as both loam, and my analysis showed them to be respectively loam and sandy loam (1998). It is understandable that they would be different, for sinkholes are by definition a distortion of the surface. The formation of a sinkhole will mix the layers and the depression that is created will allow runoff to collect in it, altering the particle size composition. This all means that my prediction that the sinkhole soils will exhibit a sandy text was incorrect, except for the Christianson sample.

The GIS analyses also pointed out clear trends in the location of sinkholes. One of these analyses showed that nearly all, 63 out of 65, of the sinkholes were located where the Devonian aged limestone from the Cedar Valley Group was the bedrock and the depth to the bedrock was less than 25 feet. The remaining two sinkholes were still located above the Cedar Valley limestone bedrock, but they lay just beyond the 25-foot contour. This verifies my hypothesis that Hallberg and Hoyer's idea that sinkholes develop only where the depth to the bedrock is less than 35 feet would hold true.

However, my hypothesis that Hallberg and Hoyer (1982) was correct with their assumption that sinkholes would exist in greater number where the gradient was the greatest shown to be incorrect. Instead, the results favored Ritter, Kochel and Miller's conclusion that sinkhole would develop where the gradient was lower (2002). This makes sense, since a lower gradient would allow water to percolate through the surficial geology to the bedrock more directly. Additionally, since my measurements for the gradient were the shortest line from the sinkhole to the base level instead of the curved line, which the water most likely takes, the actual gradients are likely to be lower than the conservative values I calculated. The actual flow paths taken by infiltrating water may be achieved by dye analysis.

The final test showed that the dominate land use in the 200 feet surrounding a sinkhole was agriculture, primarily row crop agriculture. This was an important result, as this shows potential contamination due to non-point source pollution from sinkholes is great. Although this is just an estimation of the potential drainage area for each sinkhole, this gives us an idea of what contributes to Waverly's elevated nitrate levels. The 200-foot buffer could be replaced by doing a dye test here, as well. This test can help determine the actual drainage area for each sinkhole. In addition, if land use practices change surrounding sinkholes or best management practices (BMPs) are implemented, the effects, if any, may be monitored by water quality data from nearby wells.

Recommendations

I would recommend that further research be done in this area, particularly with dye tracing. Dye tracing would allow for better estimation of the drainage area for each sinkhole the determination of the true flow path from each sinkholes. In addition to more research, the implementation of BMPs would be a good start. Several methods are being put into use already, and although the effectiveness of some practices are contended (Currens, 2002), they are still recommended, especially grass buffers surrounding sinkholes, no-till agriculture, and the removal of land from agricultural production. The U.S. Department of Agriculture also sponsors the Water Quality Incentive Program (WQIP) to help offset the costs of the BMPs. More projects are taking place in Iowa as well, including the Allamakee County Sinkhole Project, which is looking at BMP practices in Allamakee County, and a project in Dallas County that pays for better tiling for farms in exchange for a parcel of land to create wetlands that will filter out the nitrates.

Conclusion

In conclusion, the Waverly Quadrangle is characterized by its karst landscape. Sinkholes are one of the most observed karst feature as they are the most common of all surficial karst features. Sinkholes are a threat to groundwater in the region because they act as direct conduits between the surface and the groundwater. This creates a threat of contamination of the groundwater through point and non-point sources, particularly from agricultural runoff. There are varieties of containments that can make there way into the groundwater system, but the one of most concern is nitrate. In all, there are 65 documented sinkholes in the Waverly Quadrangle. Previous research has shown that sinkhole development is influenced by several factors, including the composition of the area's underlying bedrock, the presence of joints and cracks in the bedrock, the relief and gradient of the area and the depth to the bedrock.

This study investigated the spatial characteristics of sinkholes, the geologic factors that encourage their formation, and the land use practices of the area surrounding the sinkholes. This study found that sinkholes tend to develop in clusters, especially where: the soil is a loam or fine sandy loam texture, the bedrock is of Devonian aged limestone from the Cedar Valley Group and the depth to bedrock is less than 25 feet. In addition, this study found that row crop agriculture consists of 44% of the land surrounding sinkholes. This leads me to recommend more research in the Waverly Quadrangle, especially the determination of sinkhole drainage area and water flow paths, and the implementation of best management practices.

These results illustrate the need to protect the Silurian-Devonian aquifer utilized by the city of Waverly and everyone else in the Waverly Quadrangle. It has been shown that karst topography, especially sinkholes, pose a threat to groundwater quality. White (1977) made this clear when he described the response of a conduit system to a precipitation event. This study showed that there are definitely areas that are at a higher risk for sinkhole formation. Areas fitting the parameters for sinkhole formation should be monitored and BMPs implemented to protect groundwater resources. Of special concern should be those areas fitting the parameters within the 1-mile source area for each of the four public water supply wells in Waverly.

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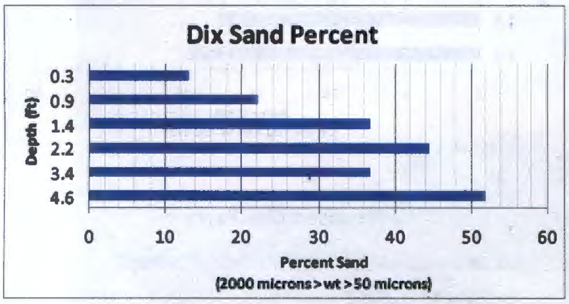
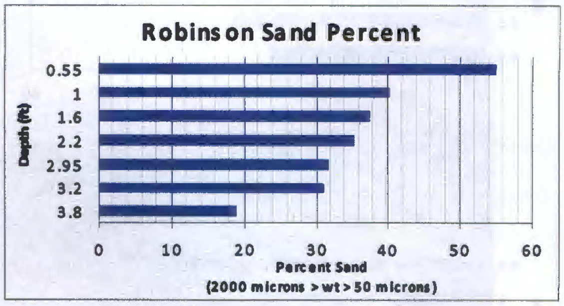
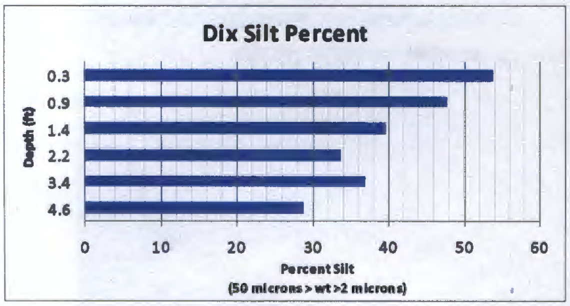
Appendix A

Complete Particle Size Results


Dix Sand Percent


Robinson Sand Percent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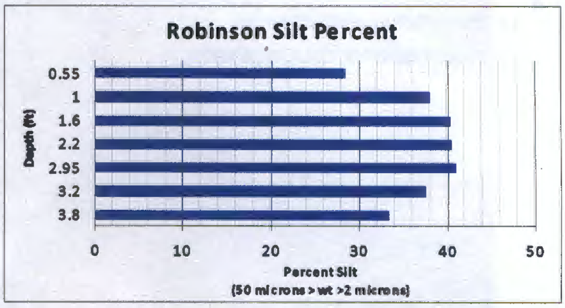
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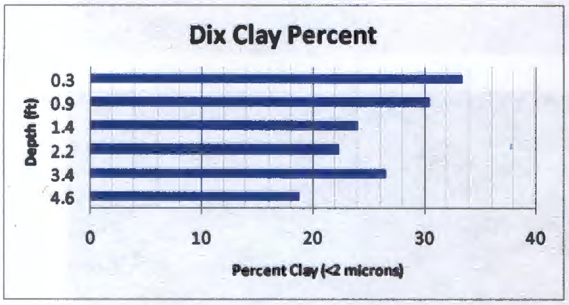
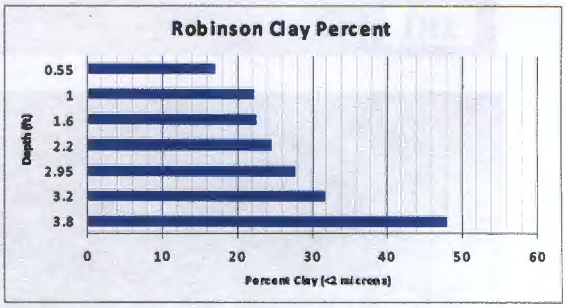

Dix Clay Percent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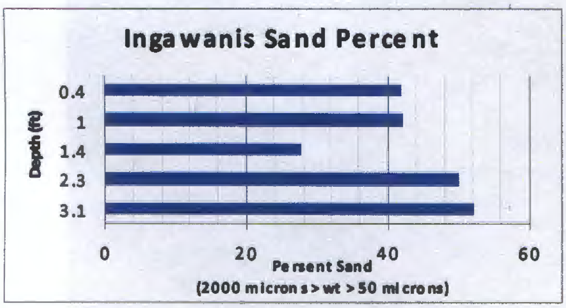
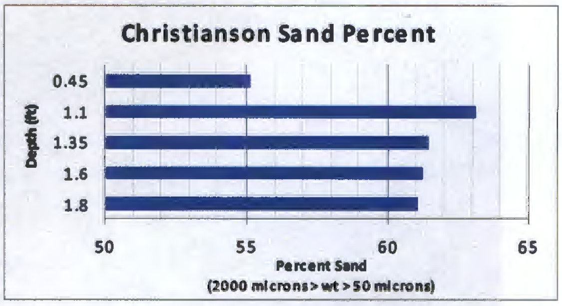
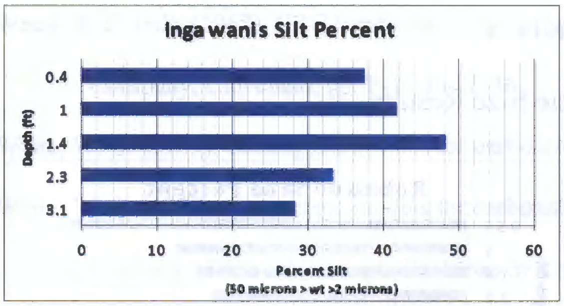
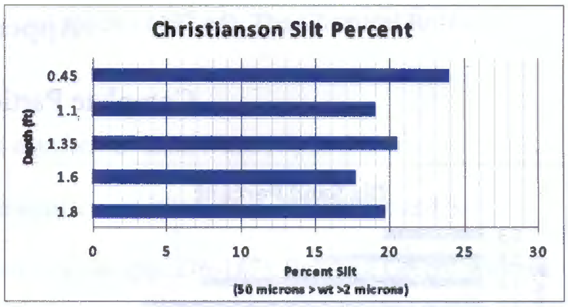
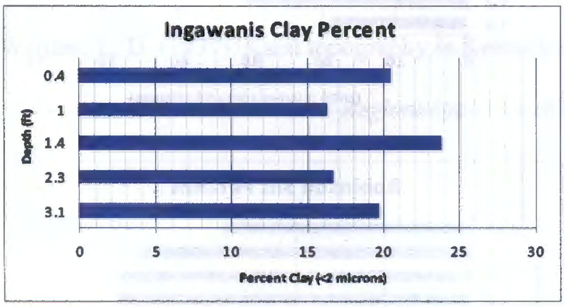
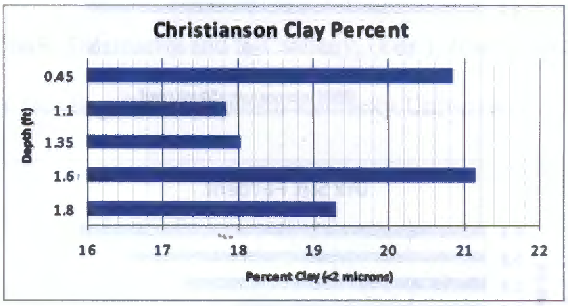

Ingawanis Sand Percent


Christianson Sand Percent


Ingawanis Silt Percent
Depth (ft)
0.4
1
1.4
2.3
3.1
0
10
20
30
40
50
60
Percent Silt
(50 microns > wt >2 microns)


Christianson Silt Percent
Depth (ft)
0.45
1.1
1.35
1.6
1.8
0
5
10
15
20
25
30
Percent Silt
(50 microns > wt >2 microns)


Ingawanis Clay Percent
Depth (ft)
0.4
1
1.4
2.3
3.1
0
5
10
15
20
25
30
Percent Clay (<2 microns)

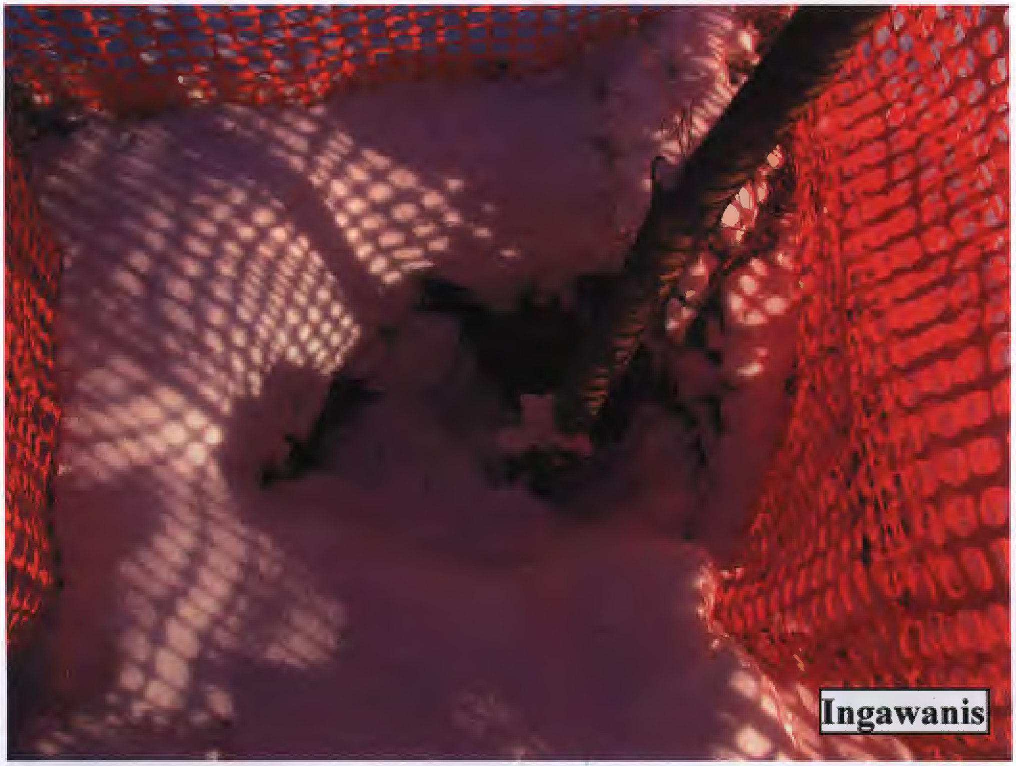

Christianson Clay Percent
Depth (ft)
0.45
1.1
1.35
1.6
1.8
16
17
18
19
20
21
22
Percent Clay (<2 microns)

Appendix B

Photos of the four sampled sinkholes

Dix

Robinson



Ingawanis

Christianson

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