Landslide Hazard Assessment of Southeastern Minnesota

A thesis submitted to the faculty of
Winona State University by

Brian Dean

In partial fulfillment of the requirements
for the degree of
Professional Science Master's

December 2018

Abstract

Landslides pose a threat to infrastructure, to the environment, and most importantly, to human lives. The goals of this research are to identify and document both recent and historical landslides that have occurred in Southeastern Minnesota (Wabasha and Goodhue counties). Ultimately, this research will be incorporated into a state-wide effort to inventory landslides and develop a predictive model of landslide hazards throughout Minnesota.

Southeastern Minnesota is especially prone to landslides because of its geologic history. It is part of the Driftless Area, a region that was largely ice-free during the Pleistocene Epoch, and because it is an older landscape than the surrounding glaciated terrain, the Driftless Area is characterized largely by deeply incised river valleys. Further, the trunk Mississippi River Valley and some tributaries were carved, in part, by glacial meltwater. Another characteristic of this area is steep bluffs where thick sequences of Paleozoic carbonate rocks cap more easily eroded sandstones and shales, creating vertical cliff faces throughout much of the region. These steep river valleys and loosely consolidated sediments and soils create prime conditions for landslides.

The steep bluff faces in the region contribute to many rock falls, while slides and debris flows appear common where there is significant soil development on slopes, primarily over sandstone and shale bedrock. Mudslides often occur during heavy precipitation events, quickly delivering water and sediment to the bottom of incised valleys. Earth slump landslides are also common in Southeastern Minnesota as a result of near-surface bedrock overlain by a layer of

loess. Modern landslides have been found most frequently in areas where slopes have been oversteepened by road-cuts and in valleys where rivers are eroding into valley walls.

Acknowledgements

I would like to thank my research advisor, Dr. Blumentritt of the Geoscience department at Winona State University. Throughout the course of my research Dr. Blumentritt has always been willing to meet with me to help sort through any issues that I’ve had with GIS, and answer any questions I’ve had about conducting field work.

I would also like to thank Andrew Williams and Sam Gardener who have been working on this research with me at Winona State University. In addition, I would like to thank Whitney DeLong, at the University of Minnesota, for taking time to help me figure out some of my GIS questions.

I also wish to thank the members of my graduate committee, Dr. Candace Kairies-Beatty, Dr. Michael Scholz, and Dr. Dylan Blumentritt, for offering their time and support throughout the course of my research.

I. Table of Contents

II. Table of Figures

Introduction

On May 22nd, 2013, two students, Haysem Sani, age 9, and Zach Mohamed Fofana, age 10, were killed in a landslide during a school field trip to Lilydale Park's East Clay Pit in Lilydale, Minnesota, where they were hunting for fossils. The tragic deaths of these two young geoscientists may have been prevented if local officials had been aware of the threat that was posed by the rain-saturated bluff above the park. Officials in St. Paul claimed they knew that erosion in the area was cause for environmental concern; however, they did not realize erosion was also a safety issue (Gottfried, 2014). Following the landslide in Lilydale, the Legislative-Citizen Commission of Minnesota Resources commissioned a plan to create a landslide hazard map for the State of Minnesota. Winona State University was given the responsibility for documenting historical and recent landslides in Wabasha, Winona, Houston, Goodhue, and Fillmore counties, which will contribute to the state-wide effort. Specifically, my research

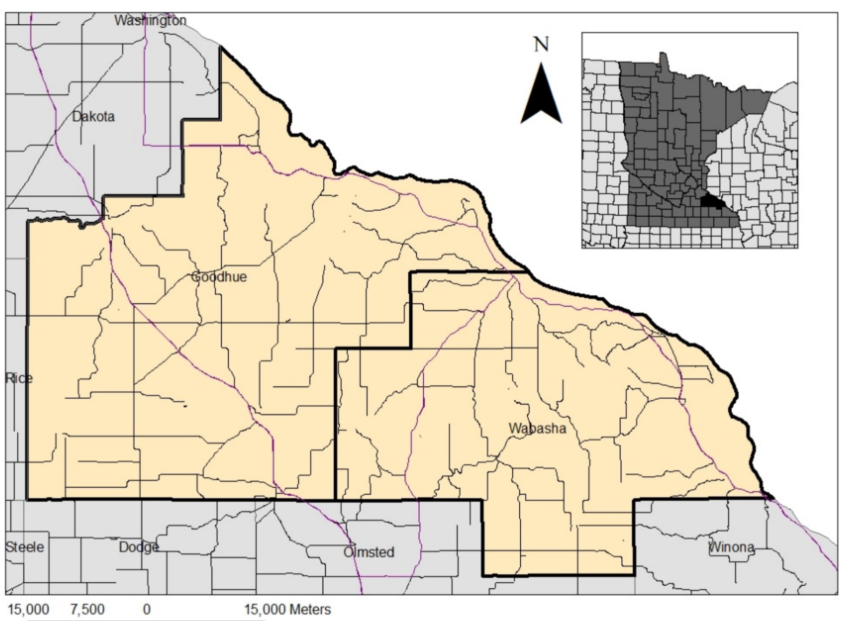


Figure 1. Map displaying Goodhue and Wabasha counties, and their location in Minnesota.

focuses on Goodhue and Wabasha counties (Figure 1).

I constructed a GIS database that documents landslides in the two counties. The specific aims of my research are stated below:

Specific Aim 1: Use a combination of historical landslide data, photo analyses, LiDAR data, and field work to classify and document landslides in Southeastern Minnesota.

Specific Aim 2: Create and manage a landslide GIS dataset for Wabasha and Goodhue counties. This database was designed and constructed according to standards set by the statewide landslide group so it may be incorporated into the larger project GIS database.

Landslide Overview

In order to properly identify landslides, it is important to be aware of the different features of a typical landslide. Figure 2 illustrates some of the more important features of a rotational landslide.

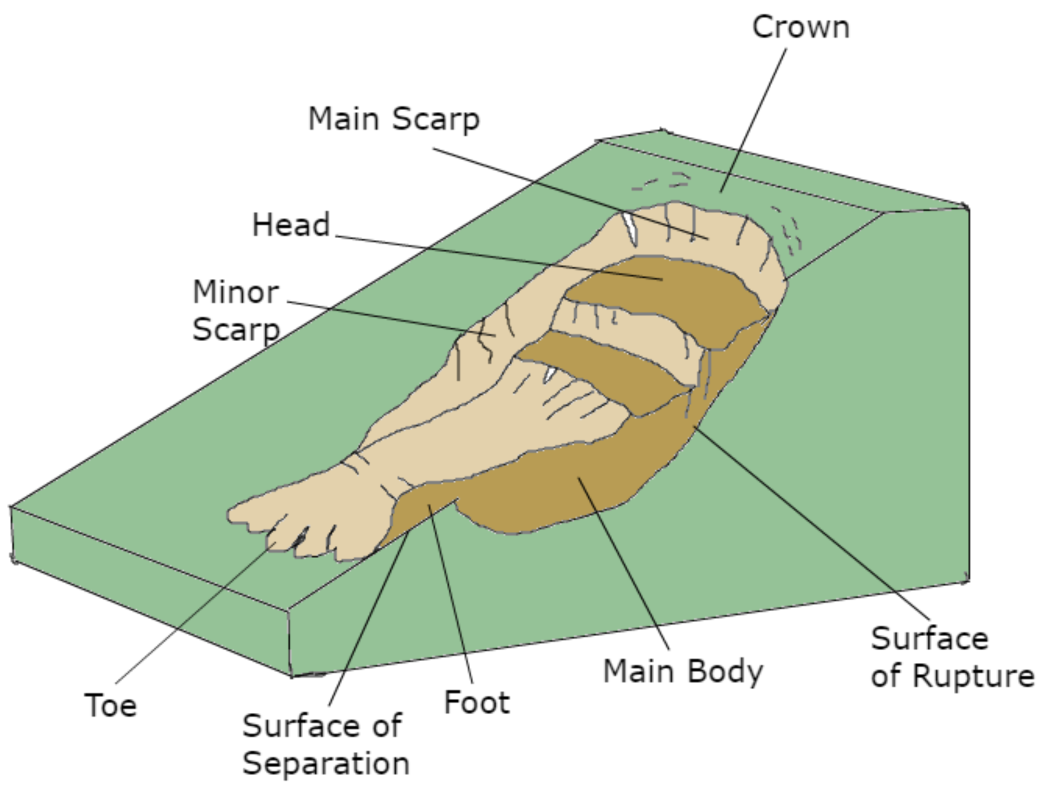


Figure 2. Diagram of a typical rotational landslide with labeling of parts.

These landslide features are defined as follows (Definitions from: Unesco and Canadian Geotechnical Society, 1993):

Crown – The practically undisplaced material still in place and adjacent to the highest parts of the main scarp.

Main Scarp – A steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the displaced material away from the undisturbed ground. It is the visible part of the surface of rupture.

Head – The upper parts of the landslide along the contact between the displaced material and the main scarp.

Minor Scarp – A steep surface on the displaced material of the landslide produced by differential movements within the displaced material.

Toe – The lower, usually curved margin of the displaced material of landslide, it is the most distant from the main scarp.

Surface of Separation – The part of the original ground surface overlain by the foot of the landslide.

Foot – The portion of the landslide along the contact between the displaced material and the main scarp.

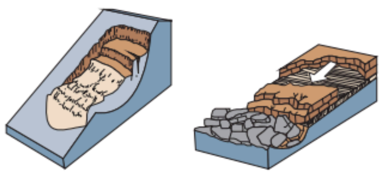
Main Body – The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface rupture.

Surface of Rupture – The surface which forms (or which has formed) the lower boundary of the displaced material below the original ground surface.

In addition to understanding the structure of a landslide, identifying the different types of landslides is critical to this research. Different landslide types may result in different types of movement, which may result in a variety of hazards. According to Burns and Madin (2009) there are six main types of landslides: falls, topples, slides, spreads, channelized debris flows, and earth flows (Figure 3). A landslide may also be a combination of two or more types; this is referred to as a complex landslide (Burns and Madin, 2009). Figure 3 depicts the various types of landslides with an additional description of each. In Southeastern Minnesota, falls and topples are both common in road cuts and other places where bedrock cliffs are exposed. Slides can be found on soil-mantled steep hillsides as well as slopes of valley walls. Channelized debris flows can also occur on the steep, incised parts of valleys, such as ravines, dry runs, or stream channels, after intense rainfalls.

Falls are near-vertical, rapid movements of masses of materials, such as rocks or boulders. The rock debris sometimes accumulates as talus at the base of a cliff.

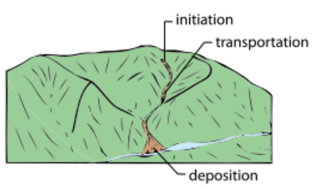
Topples are distinguished by forward rotation about some pivotal point, below or low in the mass.



Slides are downslope movement of soil or rock on a surface of rupture (failure plane or shear-zone).

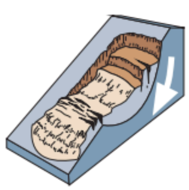
- **Rotational** slides move along a surface of rupture that is curved and concave.
- **Translational** slides displace along a planar or undulating surface of rupture, sliding out over the original ground surface.

Spreads are commonly triggered by earthquakes, which can cause liquefaction of an underlying layer and extension and subsidence of commonly cohesive materials overlying liquefied layers.



Channelized Debris Flows commonly start on a steep, concave slope as a small slide or earth flow into a channel. As this mixture of landslide debris and water flows down the channel, it pick ups more debris, water, and speed, and deposits in a fan at the outlet of the channel.

Earth Flows commonly have a characteristic "hourglass" shape. The slope material liquefies and runs out, forming a bowl or depression at the head.



Complex landslides are combinations of two or more types. A common complex landslide is a slump-earth flow, which usually exhibit slump features in the upper region and earth flow features near the toe.

Figure 3. Diagrams and descriptions of common landslide types (Burns and Madin, 2009).

Previous Landslide Inventory Efforts

Minnesota's plan to create a statewide landslide hazard map is not the first. Previous large-scale landslide inventory efforts have pioneered the way and have developed protocols and methods that are valuable to Minnesota's statewide project. Critical technological advances in computers, database development, GIS, GPS, data storage, and data input have made it possible to map the geography of the area and pinpoint landslides and potential hazards.

The following studies have contributed to the overall understanding of landslide hazard mapping, both in deducing what factors influence landslides, as well as protocol for inventorying landslides using GIS. Westen et. al. (2003) used GIS to map landslide hazards in the Italian Alps and then describe the process of creating a landslide hazard map for the Alpago area of Italy. Their work was focused specifically in the Borsoia catchment where the geomorphology has largely been shaped by the glaciers that occupied the region. Depositional and erosional landforms created by the Borsoia Glacier are the dominant features found in this area. In this study, six different maps were created, each one incorporating a different combination of factors that can influence landslides. Different factors were given weights based on evidence of how well they predicted landslides; factors included in the study were the structural geology of the area, surficial materials present, bedrock, land use, slope, distance from roads, and distance from streams. A separate set of factors was created to give weights to the different geomorphological units present in the area. For example, glacially eroded slopes related to the Borsoia glacier were given a weight of -2.618129, while denudational valleys in flysh rocks were given a weight of 1.163205. Out of the six maps created, researchers found that the two best maps for predicting landslides either took into account only geomorphological units, or took into account geomorphological units as well as structural geology, bedrock type, slope, land use, and distance from drainage (Westen et al., 2003).

Another area where a GIS based approach to predicting landslide hazards has been used is in Northeast Kansas along the Kansas and Missouri Rivers, where landslides have caused millions of dollars in property damage (Ohlmacher and Davis, 2003). To address the issue, a landslide-hazard map was made for the town of Atchison, Kansas, and the surrounding area. While identifying landslides in Northeast Kansas, rock falls, rock topples, earth flows, and earth slides were found. Ohlmacher and Davis (2003) found that bedrock units consisting of shale had the highest susceptibility to landslides, while limestone units were second highest.

Illinois, another state that lies in the Driftless Area, began a state-wide effort to create a landslide inventory in 1985. Like Kansas, Illinois was experiencing millions of dollars in property damage caused by landslides on an annual basis. In the Driftless Area of Illinois, researchers found that rock falls caused by stress relief fracturing and erosion were common (Killey et al., 1985). In addition to rock falls, researchers found rock slumps, earth slumps, rock creep, and earth flows. Factors influencing landslides in Illinois included precipitation, the freeze/thaw cycle, slope angle, vegetation, and human activity (Killey et al., 1985).

In Oregon, landslides are heavily influenced by the intense winter rain season, along with earthquakes, an influencing factor that Minnesota does not have. It is estimated that Oregon sustains an average of $10 million in damages from landslides every year. In 1996, an especially severe winter rain season led to roughly 9,500 landslides that caused $100 million in damages. After these storm events, the first statewide landslide database was created for Oregon, and in 2007 and 2008, work began to incorporate the original landslide database into a GIS. At this time, The Oregon Department of Geology and Mineral Industries (DOGOMI) developed a protocol for inventorying landslides using high resolution topographic data from LiDAR. (Burns and Madin, 2009).

Landslides in Minnesota

Throughout the history of the state, Minnesota has been affected by many landslides. In the Twin Cities area, records of landslides date back to 1879 (Jennings et al., 2016). The metro area has also suffered a number of notable recent landslides as well, like the 2013 landslide that killed two elementary school students in St. Paul's Lilydale Park that occurred when a steep bluff on the edge of the Mississippi River Valley collapsed. An investigation into the landslide found that the factors influencing the event included heavy rain events, foot traffic along the top of the bluff, and aggravation by groundwater migration.

The following year, in June of 2014, heavy rain fall events in Minneapolis caused a major mudslide that nearly forced two hospitals along the Mississippi River to have to close (Jennings et al., 2016). This mudslide also forced the closure of a major road, West River Parkway, for more than two years while crews worked to clear and repair the road and build a new retaining wall to prevent future mudslides.

Further down the Mississippi, and closer to the study area of this research, flash flooding events led to mudslides in Southeastern Minnesota and Southwest Wisconsin in August of 2007. The rainfall event, which holds the state record for 24-hour rainfall with a measurement of 383.5 mm (15.1 in), took the lives of seven people and washed away homes and infrastructure. Because Southeastern Minnesota lies in the unglaciated Driftless Area, it lacks the deep layers of glacial till that are present elsewhere in the state. Thin layers of soil are not able to retain the heavy rain waters, aiding flash flooding. Mudslides triggered by the flooding caused many homes to be swept down bluff sides (Binau, 2009).

Landslides occur on the western side of the state as well. In Crookston, Minnesota, a landslide in 2003 caused significant damage to a highway (Figure 4). Rotational landslides are common in the area around Crookston, near the Red Lake River. Landslides have been observed in the Crookston area since 1933 when a landslide destroyed a local hatchery. In order to better understand the cause of the landslides in Northwest Minnesota, automated landslide sensing instrumentation was installed to record data about the landslides. Researchers found that the landslides occurring in the Red Lake River area occurred most commonly in the fall when the water level was at its lowest because when hydrostatic pressure is lower, it causes slope creep to increase (Dasenbrock et al., 2012).

Figure 4. Highway 2 East of Crookston MN, collapsed due to rotational slumping.

Factors Influencing Landslides

Heavy rains and flooding are common occurrences in the Driftless Area, an area that stretches from Southeastern Minnesota into Southwest Wisconsin, Northeast Iowa, and Northwest Illinois (Figure 5). Such conditions in conjunction with the local geology and recent glacial history helped to form the signature bluffs for which the region is known. However, heavy precipitation events can be cause for alarm, especially in areas where steep hillsides become saturated and quickly deliver water and sediment to the bottom of incised valleys. In August of 2007, Witoka, Minnesota, received 383.5 mm (15.1 in) of rainfall in a single 24-hour event, which caused several homes and roads to be washed downhill in landslides.

Figure 5. Map of the Driftless Area – from MPR News. ("States, federal government vow to restore Driftless Area" 2006)

Killey et al. (1985), found that landslides are common where one of three particular geologic conditions exist: bedrock at ground surface, shallow bedrock overlain by unconsolidated sediments, or saturated soils at ground surface. All three of these conditions can be found in Southeast Minnesota. Exposed bedrock is very common in the Driftless Area where dolomite and sandstone from the Ordovician are exposed (Killey et al., 1985). The Driftless Area also experiences landslides caused by having bedrock overlain by a layer of loess, which often leads to "earth slump on bedrock" landslides. Saturated soils can also be a cause of landslides. Heavy precipitation, the freeze/thaw cycle, and steep slope angles that are common in Southeastern Minnesota all contribute to making this area highly susceptible to landslides (Killey et al., 1985).

In addition to soil erodibility and saturation, the presence of biomass is another factor that can influence landslide occurrence. Biomass and vegetation can be very helpful in preventing erosion; it can also be a helpful predictor of landslide hazard areas. Hwang et al. (2015) used canopy height information obtained by using LiDAR to estimate biomass; they then created a biomass map that could be used to predict landslide hazards in North Carolina (Hwang et al., 2015). Hwang et al. (2015) also mention that there are three other commonly used methods for landslide hazard prediction: slope stability analysis, event-specific forecasting that takes precipitation and other pre-existing conditions into account, and multiple regressions of climate and streamflow. In 2005, DOGAMI began working on a project with the U.S. Geological Survey to identify landslides in Oregon. DOGAMI wanted to compare different remote-sensing data sets to test effectiveness for landslide hazard identification (Burns and Madin, 2009). The data sets compared in the study were 30-m SRTM DEM, 10-m USGS DEM, 7-m City of Portland DEM, 1-m LiDAR DEM, and 1-m DEM + aerial photo to simulate stereo pair. Their study concluded that between 3 and 200 times the number of landslides were identified when LiDAR was used. DOGAMI also determined that finding the spatial extents of landslides was much easier and more accurate when using LiDAR as opposed to the other DEMs (Digital Elevation Models) (Burns and Madin, 2009).

Geology of Southeastern Minnesota

Southeastern Minnesota has several different types of sedimentary bedrock exposed at the surface: sandstone, dolostone, shale, and limestone. The Driftless Area is largely characterized by eroded plateaus and deep river valleys. The greatest amount of relief in this region occurs along the Mississippi River, in some areas as much as 600 feet (180 m).

The Driftless region was largely ice-free during the last ice age, or Pleistocene Epoch. For this reason, the region is mostly free of glacial till. One effect that the glaciers did have on Southeastern Minnesota was the release of massive amounts of melt water, which helped to carve out the deep river valleys and form the bluffs that are visible today (Runkel, 1996).

The oldest rock formations that are likely to be found exposed in Goodhue and Wabasha counties are the Ironton and Galesville Formations. The Ironton and Galesville Formations are both sandstones deposited in the Cambrian. In Illinois and Wisconsin these sandstone formations hold aquifers that are an important source of groundwater (Emrich, 1966). In the two-county focus area, there are not a lot of places where the Ironton and Galesville Formations are exposed, only on the northern edge of Goodhue County, along the Mississippi. Overlying the Ironton and Galesville Formations lies the Lone Rock Formation (Figure 6), also a siliciclastic formation deposited in the Cambrian. It is composed of fine-grained sands and silts with some minor beds of dolostone (Barry et al., 2015). On top of the Lone Rock Formation lies the St. Lawrence Formation, which consists mostly of shallow-marine deposits such as siltstone, fine-grained sandstones, and dolostones (Mossler, 1999). The St. Lawrence Formation is overlain by the Jordan Sandstone Formation, which was deposited at the end of the Cambrian, roughly 510 million years ago, and is composed of uniformly rounded quartz grains (Mossler, 1999). The uniformity and composition of the Jordan sand makes it highly sought after for sand fracking. Above the Jordan Sandstone Formation lies the Oneota Formation (Figure 6). It was deposited in the early Ordovician and usually has a tan to greyish color. Caves and cavities can be found in the Oneota Formation where mildly acidic groundwater has dissolved the dolomite over time (Runkel, 1996). Although the Oneota Formation is comprised mostly of dolostone, it does include some thin sandstone and shale layers, and some fossils can be found such as

Stromatolites (Runkel, 1996). On top of the Oneota lies the Shakopee Formation. In this region, only a thin remnant of the Shakopee Formation is usually present, although in other regions where it is better preserved it can be up to 150 feet thick. In Goodhue and Wabasha counties, the Shakopee is the most prominently exposed bedrock formation. It is similar to the Oneota Formation, but it contains more sandstone and shale (Runkel, 1996). Overlying the Shakopee Formation is the St. Peter Sandstone, also deposited in the Ordovician and composed of mostly mature quartz arenite grains (Barnes et al., 2017). It can be found exposed throughout much of Goodhue County where it is especially visible on County 25 Boulevard in Cannon Falls where tall sandstone cliffs are exposed. The Glenwood Formation overlies the St. Peter Sandstone and is a greenish-grey shale deposited in the middle Ordovician (Schutter, 1996). There are no areas in Goodhue or Wabasha counties where the Glenwood Shale is exposed. The Platteville Formation is a carbonate formation deposited on top of the Glenwood and is exposed in Central Goodhue County, especially where down cutting has occurred along the Zumbro River. The Galena Group, which consists of the Decora Shale, the Cummings Ville Formation, the Prosser Limestone, the Stewartville Formation, and the Dubuque Formation, lies atop the Platteville. The Decorah Shale is the oldest deposit in the Galena Group. Similar to the St. Peter Sandstone and the Platteville Formation, The Decorah Shale can be found exposed along the Zumbro River, as well as many other places in Goodhue County. Rich in clay, it has long been used in brick manufacturing in Minnesota. It is often gray-green or blue-green in color and can contain thin beds of limestone towards the top of the deposit (Parham and Austin, 1969). The next member of the Galena group is the Cummingsville Formation, which consists of fine-grained limestone with some interbedded shale. Because of its carbonate composition, and its proximity to the surface, the Cummingsville is home to some active karst features (Gao and Alexander, 2008).

Last, the Prosser Limestone is the youngest rock formation found in Goodhue or Wabasha counties. The Prosser Limestone can be found exposed in Southwest Goodhue County and is a fossiliferous formation deposited in the Ordovician. The Prosser is the most fossiliferous formation in the Galena group, and consists mostly of thin-bedded, fine-grained limestone, with some shale. In the northern part of its depositional extent, the Prosser is more dolomitic (Mossler, 1987).

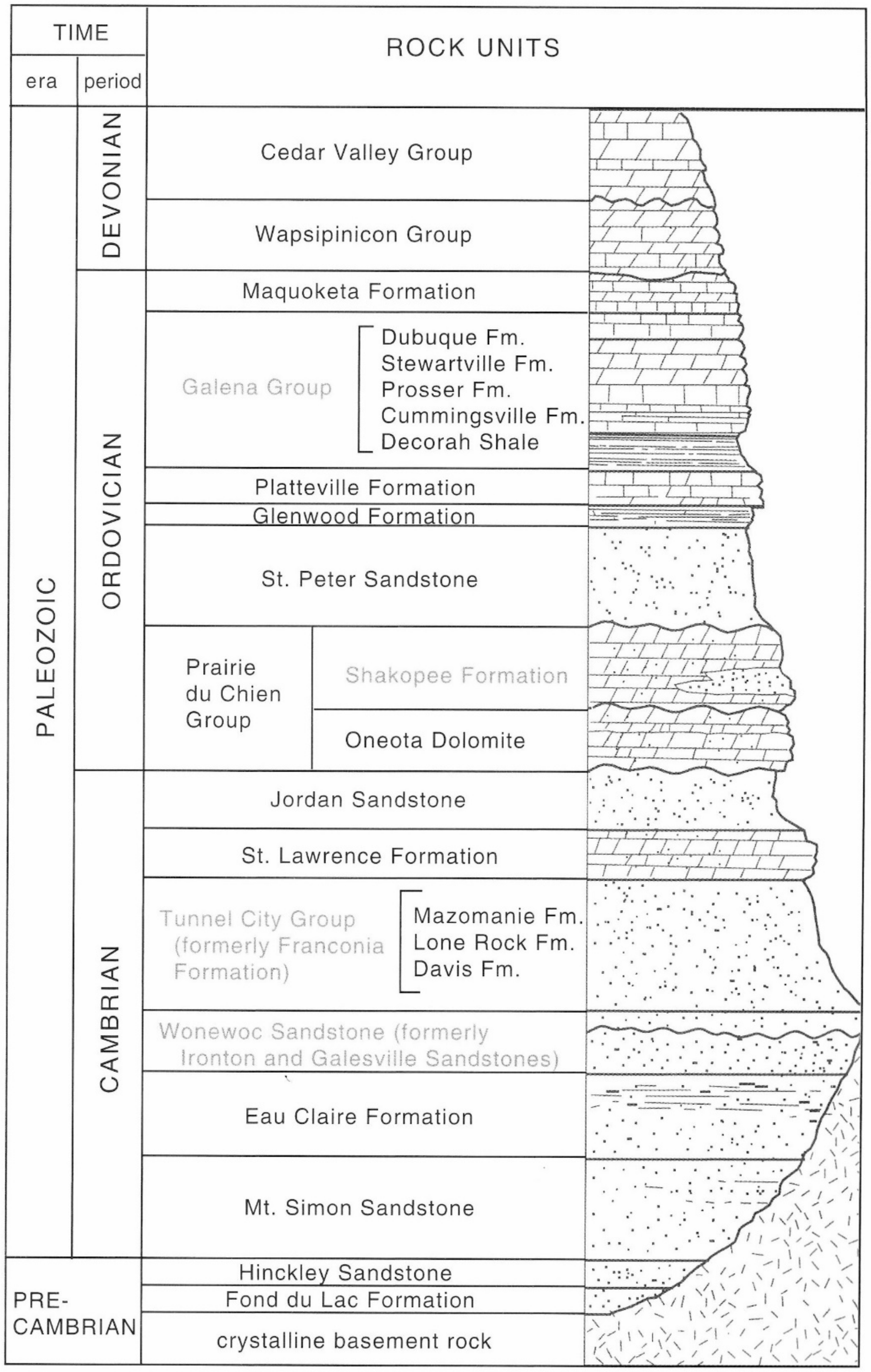


Figure 6. Stratigraphic column displaying the primary formations of Southeastern Minnesota. (Ojakangas, 2009). The primary stratigraphic formations in our study area are the Ironton and Galesville Sandstones up through the Prosser Fm.

Research Methodology

The creation of a geodatabase inventory of landslides within the borders of Goodhue and Wabasha counties was the primary objective of this study. This was done by consulting historical landslide data and recent topographic imagery derived from LiDAR data, followed up by field work. For inventorying the landslides, the protocol outlined by William J. Burns and Ian P. Madin in their paper, "Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (Lidar) Imagery" was used (Burns and Madin, 2009). In order to identify landslides using LiDAR, eight DEMs that were provided by Whitney Delong from the University of Minnesota were downloaded. These included DEMs for aspect, curvature planform, curvature profile, curvature standard, 45 degree hillshade, 315 degree hillshade, slope, and a general DEM for Southeastern Minnesota. A shapefile that contained the boundaries for county sections in Goodhue and Wabasha counties was also downloaded. The hillshade DEMs were used in conjunction with a county section layer in order to scan each county, section by section, identifying any slope that might be a landslide. A new point shapefile was created to add a point at every possible landslide location. When Wabasha County was complete, 2173 points in the shape file had been created. In Goodhue County a more discerning approach was used in identifying landslides, and only 287 points were created. Identifying landslides using only the hillshade DEMs was difficult because of high relief and a large number of slopes throughout the two counties. Much of Southeastern Minnesota is made up of bluffs and cliff faces. Determining which cliff faces might be potential rock fall areas becomes difficult, especially when deposits are not always visible on the hillshade DEM.

After potential landslide locations had been identified, field checking the points was next. Points that had been marked as potential landslides were not always found to be landslides, and many landslides were found in the field that had not been found in the hillshade data. The field work continued from mid-June to late-August. Field checking landslides involved driving to areas where a high number of points had been marked on the map, and kayaking down a segment of the Zumbro River to identify any landslides that might have resulted from down cutting by the river. While not many individual landslides were identified using the LiDAR data alone, the LiDAR data did provide a starting place, as areas where large clusters of points were marked did turn out to be areas where landslides were found. When a landslide in the field was located, a picture of it was taken using an Android App called GPS Map Camera. This application was useful as it automatically pastes an overlay onto the picture that includes a map with a point where the photo was taken, the address (if available), city, state, and county, as well as the time, date, and temperature (Figure 7).

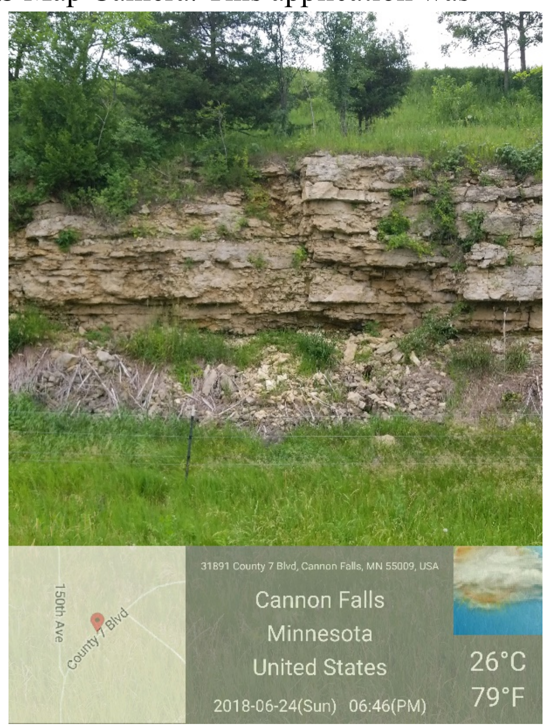


Figure 7. Example of GPS Map Camera Overlay. Rockfall in the Shakopee Formation Southeast of Cannon Falls

After landslides were identified and pictures taken in the field, points were created at each location a picture of a landslide had been taken using ArcGIS's GeoTagged Photos to Points feature. After the point shapefile had been created for all the landslide photos, a polygon shapefile was made for each landslide's head scarp and flanks, as well as a line shape file for the head scarp, and a polygon shape file for the landslide's deposit (Figure 8).

Next, the slope of each landslide was determined using a slope map that was created based on the 1 m DEM for each county. By using a shapefile created by the Minnesota Geological Survey County Geologic Atlas Program, the geologic unit in which each landslide occurred was determined (Setterholm, 1998). The location of each landslide was compared with the geologic atlas shapefile to determine which geologic unit was exposed in that location. Then the findings were checked to make sure the geologic atlas agreed with the type of rock and deposit that were noted during the field check. In addition to geologic unit and slope, the height, width, and depth of the landslide were also determined using Google Earth. A visual estimation of the azimuth of each landslide was also done in Google Earth. Each landslide was classified as a translational slide, rotational slide, or a fall. An example of a translational slide is pictured in Figure 9. It was difficult to differentiate between topples and falls, so the categories were combined into one, falls. No landslides fit into the categories of spread or channelized debris flow. The deposit of each

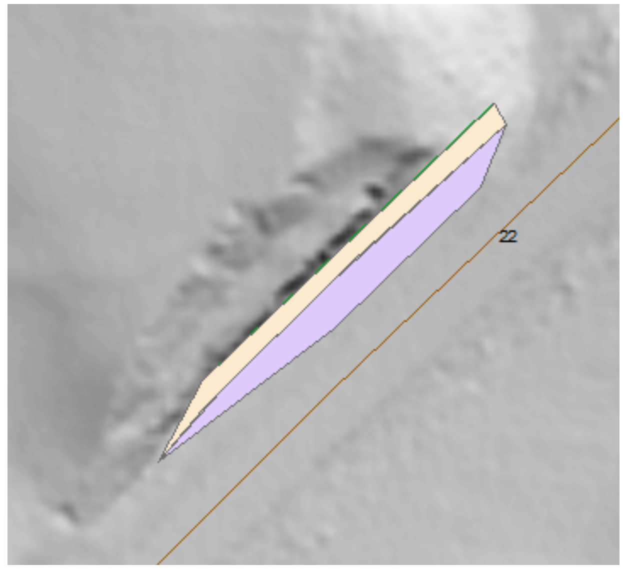


Figure 8. Hillshade LiDAR imagery of the rockfall pictured in Figure 7.

Figure 9. Translational debris slide along the Zumbro River in Wabasha County, MN

slide was categorized as rock, debris, or earth. In many cases, eroding sandstone cliff faces had a pile of sand as a deposit. Initially these were categorized as debris falls, but later it was decided that these should be considered rock falls, because technically the deposit contains only rock, and no soil.

All data collected about the landslides are stored in a geodatabase that will be submitted to the statewide effort to create a landslide hazard map.

Results

Many landslides were found throughout the northern half of Goodhue County, as well as in central Wabasha County and along Highway 61 near the Mississippi River. Figure 10 shows

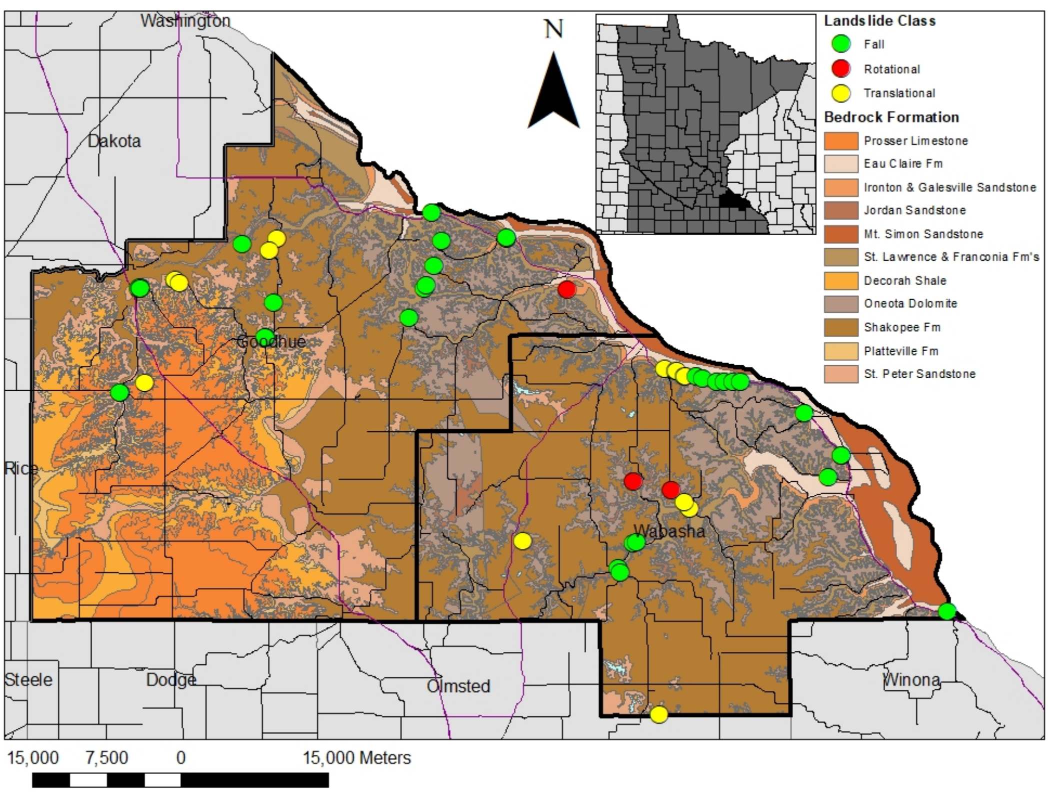


Figure 10. Landslide Locations in Goodhue and Wabasha Counties. Most landslides were found in high-relief areas, especially along the bluffs of the Mississippi River Valley and in other areas where road cuts or stream channels over-steepened hillslopes that were already prone to failure.

the distribution of landslides throughout the two counties, where landslides were more common in the areas of high relief, which often coincided with areas where the Oneota Dolomite and St. Lawrence Formations were the underlying bedrock. No landslides were found in the southern half of Goodhue County, this area of the county is primarily low-relief.

Fifty landslides were found within Wabasha and Goodhue counties, the majority of these were on road-cuts. No landslides that could be categorized as flows or spreads were found, so each slide was categorized as either a fall, a translational slide, or a rotational slide. Slides were further classified according to the type of material: rock, earth, or debris. The most common landslide type was fall, with rock being the most common deposit material (Figure 11). The bedrock unit was identified and recorded at each landslide site. A total of eight different geologic units hosted slides in our two counties: the St. Peter Sandstone Formation, the St. Lawrence Formation, the Shakopee Formation, the Platteville Formation, the Oneota Dolomite Formation, the Jordan Sandstone Formation, the Ironton-Galesville Sandstone Formation, and the Cummingsville Formation (Figure 12). The two geologic

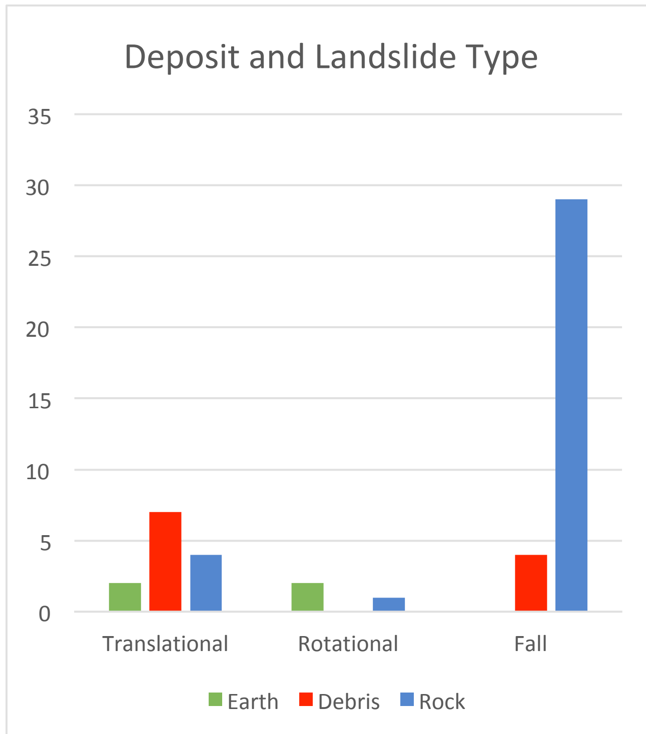


Figure 11. Chart displaying type of landslide and deposit material. Falls were the most common landslide type, while rock was the most common deposit material.

units in which the most landslides were found were the St. Lawrence Formation, where a total of

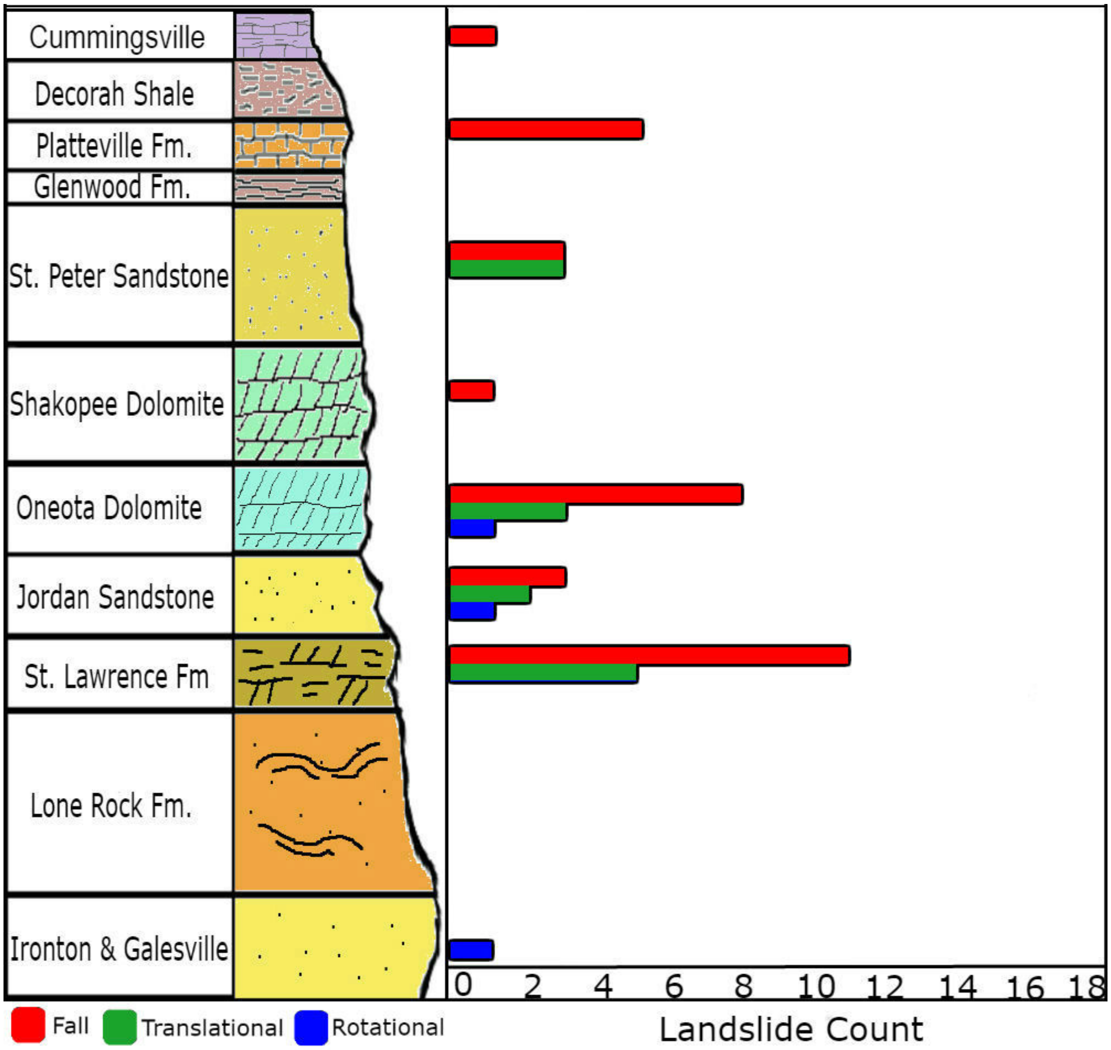


Figure 12. Chart displaying the type of landslide found in each formation. The St. Lawrence and Oneota Dolomite formations sourced the most landslides, mostly falls.

16 landslides were found, and the Oneota Formation, where a total of 12 landslides were found.

The Jordan Sandstone and the St. Peter had six landslides each

Although it is not always easy to precisely categorize a landslide, the majority that were identified were falls with rocky deposits and were located on road-cuts, many of which were on Highway 61 where the steep bluffs expose many of the formations, but notably the St. Lawrence Formation. Landslides and rock falls occurring in the St. Lawrence typically had silty shales and dolomitic rocks as the primary deposit material.

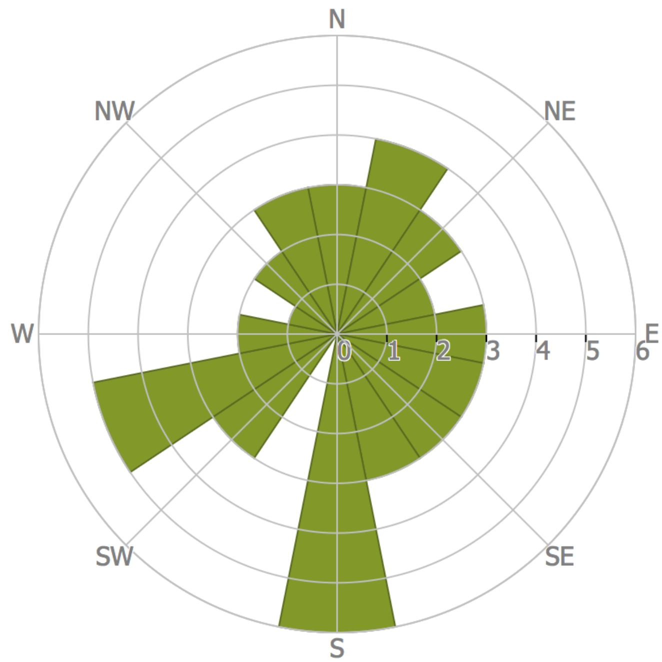


Figure 13. Rose Diagram displaying aspect of landslides. South-facing landslides were most common, followed by west-southwest-facing landslides.

Also notable is that landslides were found to be more south-facing than any other direction (See Figure 13), which could be a result of the freeze-thaw cycle. South-facing slopes receive more sunlight than north-facing slopes, and therefore are subjected to more frequent and higher-range temperature changes. This greater variation in temperature may cause more freezing and thawing, and thus, more landslides on south-facing slopes (Shan et al., 2013).

The slope of the landslide was also considered (Figure 14). Slopes were first measured in Google Earth; however, these data appeared to be inaccurate. Instead, a visual estimate of slope for each landslide was made based on the pictures of individual landslides. A slope map was then made in ArcGIS based on the 1m digital elevation model. Slope values for each landslide were recorded based on this slope map. In many cases, this slope map appeared to be inaccurate. Landslides that clearly had a slope of nearly 90 degrees appeared to have a much lower slope on the slope map. ArcGIS's spatial analyst tool uses what is known as a "neighborhood" method to determine slope where the software calculates slope by placing a three by three mask over each cell in the DEM and calculates elevation change in each direction in order to determine the

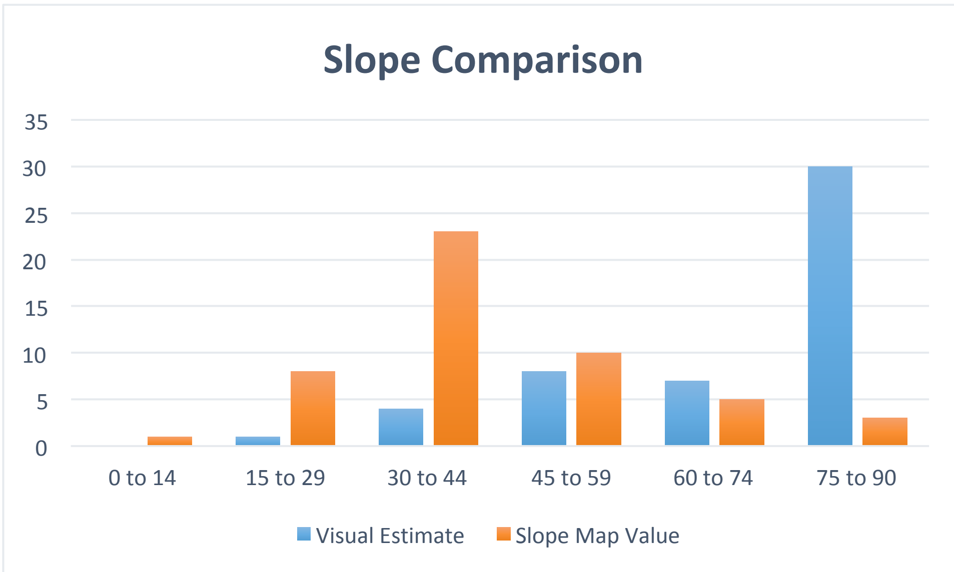


Figure 14. Bar chart comparing visual estimate of landslide slope vs. slope determined by slope map. Slope measured in degrees.

maximum slope for the center cell in the grid. Because this method does not take into account the elevation in the center of the three by three mask, it can be inaccurate when estimating slope on ridges, valleys, and small pits and peaks (Dunn and Hickey, 1998). A better way to calculate slope using the 1 m DEM may have been to use the surface slope tool in ArcGIS 3D Analyst. By first converting the DEM into a triangular irregular network (TIN), and then using this as the input for the surface slope tool, a more accurate estimation of slope can be obtained (Figure 15). TINs can be draped over irregularly shaped surfaces in order to present a higher degree of resolution ("What is a TIN surface?," 2018). This also allows the user to select a set of triangles in order to ascertain the average slope for that set. Although determining slope using this method may be more accurate, time did not allow for this method to be used for every landslide.

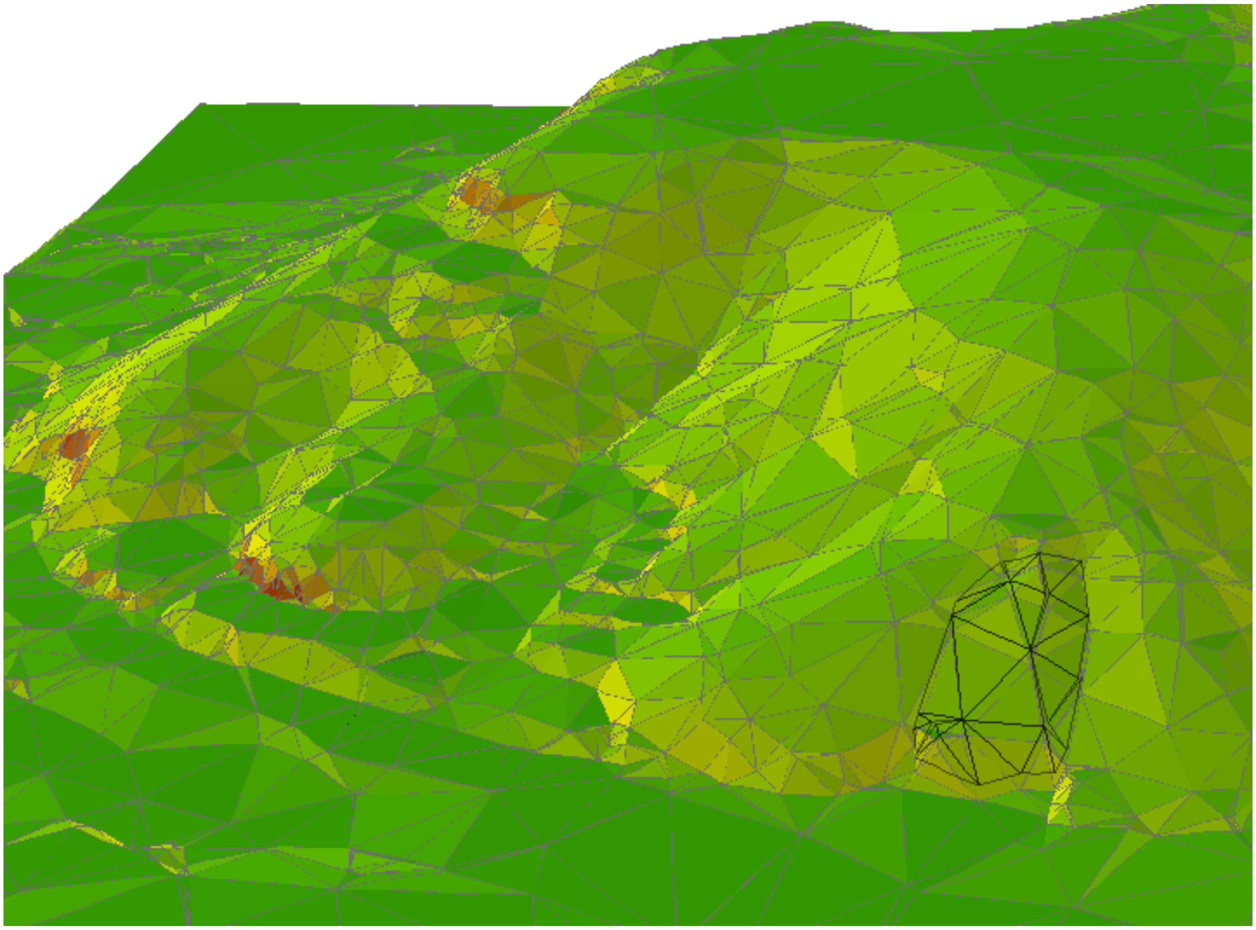


Figure 15. TIN Surface displaying slope of Barn Bluff in Redwing, MN. TINs can present a higher degree of resolution and give accurate slope calculation.

Discussion

A majority of the landslides found in Goodhue and Wabasha counties were rock falls. This was expected considering the steep bluffs and high topographic relief in the area. Because Southeastern Minnesota is the only part of the state to have steep bluffs and karst geology, the results for Southeastern Minnesota are likely to be quite different from what researchers in the rest of the state find. In Hennepin County, Jennings et al. (2018) found that there were primarily three main types of landslides occurring: rotational slides, debris flows, and rock falls and topples. Similar to our findings, Jennings et al. (2018) found topples and falls to be indistinguishable on the hillshade DEM. Also similar to our findings, Jennings et al. (2018) found many landslides occurred along the Mississippi River. Results for the rest of the state are not yet published, but Western Minnesota may have fewer landslides overall due to flatter topography.

Because nearly all of the landslides were found by either driving or kayaking around Goodhue and Wabasha counties, our findings are probably biased towards slides and falls occurring on road cuts.

Conclusions

The geodatabase created here will be added to by other students at Winona State University as they continue to document landslides in Winona, Houston, and Fillmore counties. Results from these three counties will show whether they, like Goodhue and Wabasha counties, have a significant number of landslides occurring in the Oneota and St. Lawrence Formations. A comparison can also be made for landslide aspect among the five counties to determine if south-facing landslides remain the most prominent. In the future, additional research could be done to determine why landslides occur more often in these shaley dolomitic formations. Are landslides being caused by the undercutting of underlying sandstone formations? Are they occurring in these areas simply because they exhibit the most relief? Or are they caused by the great number of road cuts through this area?

The research that was done in this project will be contributed to the statewide effort to create a landslide hazard map for Minnesota. As more research is added to this project, a more complete picture of the landslide hazards will be understood. My research, as well as the research being done on this project by the students and researchers across the state, will assist engineers and government officials to assess the landslide risk when developing infrastructure and beginning new projects. Although there are some questions that are left unanswered, this research will hopefully be valuable in preventing future tragedies such as the one that occurred in Lilydale Park in 2013.

References

Barnes, D.A., Ellett, K.M., and Rupp, J.A., 2017, Geologic-carbon-sequestration potential of the Ordovician St. Peter Sandstone, Michigan and Illinois Basins, United States: Environmental Geosciences, v. 24, p. 15–49, doi:10.1306/eg.02071716007.

Barry, J.D., Green, J.A., Steenberg, J.R., and Minnesota Geological Survey, 2015, Conduit Flow in the Cambrian Lone Rock Formation, Southeast Minnesota, U.S.A., *in* Sinkholes and the Engineering and Environmental Impacts of Karst: Proceedings of the Fourteenth Multidisciplinary Conference, Rochester, Minnesota, University of South Florida Tampa Library, p. 31–42, doi:10.5038/9780991000951.1026.

Binau, S., 2009, The Historic Flash Flood Event of 18-19 August 2007 In the Upper Mississippi River Valley: Impacts of Terrain and Societal Response: NOAA/National Weather Service, La Crosse, Wisconsin,.

Burns, W.J., and Madin, I., 2009, Protocol for inventory mapping of landslide deposits from light detection and ranging (LiDAR) imagery: Oregon Department of Geology and Mineral Industries Portland.

Dasenbrock, D., Levesque, C.L., and Danisch, L., 2012, Long-term rate behavior monitoring using automated MEMS-based sensing arrays in an urban landslide environment, *in* Proceedings of the 11th international and 2nd north american symposium on landslides, Banff, Alberta, Canada, p. 3–8.

Dunn, M., and Hickey, R., 1998, The effect of slope algorithms on slope estimates within a GIS: Cartography, v. 27, p. 9–15, doi:10.1080/00690805.1998.9714086.

Emrich, G.H., 1966, Ironton and Galesville (Cambrian) sandstones in Illinois and adjacent areas: Urbana : Illinois State Geological Survey, 62 p., http://archive.org/details/irontongalesvill403emri (accessed November 2018).

Hwang, T., Lawrence E. Band, T. C. Hales, Chelcy F. Miniat**;** James M. Vose, Paul V. Bolstad, Brian Miles, Katie Price., 2015, Simulating vegetation controls on hurricane-induced shallow landslides with a distributed ecohydrological model: Journal of Geophysical Research: Biogeosciences. 18 p., v. 2015, p. 361–378, doi:10.1002/2014JG002824.

Jennings, C., Kurak, E., and Anonymous, 2018, Landslide inventory and categorization for Hennepin County, Minnesota: Abstracts with Programs - Geological Society of America, v. 50, p. Abstract no. 42-4.

Jennings, C.E., Presnail, M., Kurak, E., Meier, R., Schmidt, C., Palazzolo, J., Jiwani, S., Waage, E., and Feinber, J.M., 2016, Historical Landslide Inventory for the Twin Cities Metropolitan Area: Minnesota Department of Natural Resources, Division of Ecological and Water Resources., p. 34.

Killey, M.M., Hines, J., and DuMontelle, P.B., 1985, Landslide inventory of Illinois: Illinois State Geologic Survey, v. Circular.

Gottfried, M.H., 2014, Lilydale park landslide, a year later – Twin Cities: Pioneer Press, https://www.twincities.com/2014/05/20/lilydale-park-landslide-a-year-later/ (accessed December 2018).

Mossler, J.H., 1999, Educational Series 10. Geology of the Root River State Trail Area, Southeastern Minnesota: Minnesota Geological Survey Map, http://conservancy.umn.edu/handle/11299/57294 (accessed November 2017).

Mossler, J.H., 1987, Paleozoic lithostratigraphic nomenclature for Minnesota: Minnesota Geological Survey Report of Investigations, v. 36.

Ohlmacher, G.C., and Davis, J.C., 2003, Using multiple logistic regression and GIS technology to predict landslide hazard in northeast Kansas, USA: Engineering Geology, v. 69, p. 331–343, doi:10.1016/S0013-7952(03)00069-3.

Parham, W.E., and Austin, G.S., 1969, Clay Mineralogy, Fabric, and Industrial Uses of the Shale of the Decorah Formation, Southeastern Minnesota: Minn. Geol. Survey Rept. Inv, v. 10.

Runkel, A.C., 1996, Educational Series 9. The Geology of Whitewater State Park: Minnesota Geological Survey Report, http://conservancy.umn.edu/handle/11299/57274 (accessed January 2018).

Schutter, S.R., 1996, The Glenwood Shale as an example of a Middle Ordovician condensed section, *in* Special Paper 306: Paleozoic sequence stratigraphy; views from the North American Craton, Geological Society of America, v. 306, p. 55–65, doi:10.1130/0-8137-2306-X.55.

Setterholm, D.R., 1998, C-12 Geologic atlas of Goodhue County, Minnesota [Part A]: Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/58551. (accessed November 2018).

Shan, W., Guo, Y., Wang, F., Marui, H., and Strom, A., 2013, Landslides in Cold Regions in the Context of Climate Change: Springer Science & Business Media, 310 p.

Unesco, and Canadian Geotechnical Society (Eds.), 1993, Multilingual landslide glossary: Richmond, B.C., Canada, BiTech Publ, 100 p.

Westen, C.J. van, Rengers, N., and Soeters, R., 2003, Use of geomorphological information in indirect landslide susceptibility assessment: Natural hazards, v. 30, p. 399–419.

What is a TIN surface?, 2018, ArcGIS Desktop - Help - ArcMap 10.6, http://desktop.arcgis.com/en/arcmap/latest/manage-data/tin/fundamentals-of-tin-surfaces.htm (accessed December 2018).