MnDOT Slope Vulnerability Assessments

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16. Abstract (Limit: 250 words)

Transportation infrastructure intersects challenging terrain that can negatively impact integrity. Minnesota's climate, geomorphology, and steep terrain along rivers increase the incidence of slope failures such as rockfalls and landslides. WSB was contracted by MnDOT to determine the risk of slope failure along state highways in districts 6, 7, and the Metro. This report outlines the methods and results of the MnDOT Slope Vulnerability project including a new Geographic Information Systems (GIS) model that can be implemented anywhere in the state.

The model contains three main parts: 1.) identify past slope failures, 2.) model the causative factors of past slope failures and how they vary locally, 3.) model the risk of new slope failures. Vulnerability factors including slope, terrain curvature, proximity to rivers, and proximity to bedrock outcrops were statistically tested to determine their capabilities in causing slope failure. Field verification results validate the model's capability of identifying risk in regions with different geology, geomorphology, and hydrology.

Model results were ranked into four risk management categories: action recommended, further evaluation, monitoring, and no action recommended. Risk incorporates the model outputs with consequence to infrastructure including distance to roads and populated areas. Results indicate that 826 of the 35,000 "management areas" delineated and ranked in GIS are recommended for mitigation. Next steps include field visits and a site-specific mitigation program. The results of this study are intended as the first step of actions required in minimizing the effects of slope failure including expensive mitigation and maintenance repairs and threats to public safety.

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MNDOT SLOPE VULNERABILITY ASSESSMENTS

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EXECUTIVE SUMMARY

Introduction

Geohazards are environmental risks to infrastructure. Unstable slopes, floods, excessive precipitation, and frost action are examples of environmental risks that damage state transportation assets and cause injury or even loss of life. Geohazards are managed through the implementation of geohazard risk assessments which quantify risk factors and incorporate them into transportation asset management plans (TAMPs).

WSB was contracted by MnDOT to determine the risk of slope failure along state highways in districts 6, 7, and Metro. This project outlines the methods and results of the slope vulnerability study including a new Geographic Information Systems (GIS) model that can be implemented anywhere in the state. The results of this study are intended as the first step of actions required in minimizing the effects of slope failure including expensive mitigation actions and threats to public safety.

Literature Review and GIS Model Design

WSB incorporates a combination of geomorphology and GIS to identify the risk of slope failures along state trunk highways. This combination permits a powerful approach that identifies and statistically tests the specific causes of slopes failures with minimal data input, while covering more ground than previous research methods.

Geomorphology

Slope failures are one of the most expensive geohazards to infrastructure. Slope failures are mass wasting processes including landslides, rockfalls, surface erosion, avalanches and debris flows that occur when a slope weakens and collapses. The natural processes that result in slope failures are understood through geomorphology, the science of landscape evolution and function. Geomorphology is a multidisciplinary science incorporating terrain attributes, geology, hydrology, soil science, and climate science. Geomorphology provides a specific framework for understanding why a slope failure is occurring in a given location. A geomorphic approach allows for a much more thorough risk assessment evaluation than a single disciplinary approach in that it accounts for the local variation of causative factors, how these factors change over time, and how they exacerbate one another.

GIS Model

WSB researched previous efforts that categorized the risk of slope failures with emphasis on GIS models. WSB determined that GIS models that incorporates the causative factors of past slope failures enhance the predictive modeling of new slope failures. Geostatistical models identify these causative factors and how they vary locally. WSB determined that a geostatistical model is most appropriate for Minnesota state highways, allowing for any vulnerability factor to be statically tested.

WSB designed a new GIS-based model with three main parts: 1.) identify past slope failures, 2.) model the causative factors of past slope failures and how they vary locally, 3.) model the risk of new slope failures. The first step is to identify the locations of past slope failures in order to determine the causative factors. WSB created a method for detecting past slope failures using geomorphology and elevation data. Geomorphology is used to analyze terrain and landforms associated with slope failures; almost all types of slope failures have unique terrain in comparison to their surrounding environment. GIS and elevation data were used to highlight the areas that have geomorphic features resembling slope failures along the state highways. Once the locations were identified several vulnerability factors were tested as causative factors. These factors can vary locally from place to place. The vulnerability factors tested for the study area of this project, districts 6, 7, and Metro include:

- Slope angle,
- Stream power / gullying index,
- Terrain curvature,
- Topographic wetness index (pore water pressure),
- Proximity to rivers,
- Proximity to bedrock outcrops,
- Karst features,
- Lakes,
- Bedrock geology,
- Soil texture and erodibility characteristics

The final step in designing the model was identifying the risk of slope failure along the entire right of way. The results from part 2, modeling the causative factors, were incorporated into a logistic regression equation which calculates the probability of an event occurring (i.e. any type of slope failure). The final output includes maps that allow users to determine the areas that are most at risk of slope failure by categorizing slopes as either having a higher risk, moderate risk, or lower risk.

Data was collected for each of the vulnerability factors of this study. The data collected and assembled for this project includes a combination of DEM-derived data and data from publicly available sources including the Minnesota Geological Survey, NRCS, and DNR.

Sensitivity Analysis

Once the GIS model was designed, a series of tests, collectively called a sensitivity analysis, were conducted to determine how well the model performs. The sensitivity analysis for this study tested 5 important parameters: elevation data resolution, size of the right of way, capability of identifying past slope failures, capability of identifying causative factors, and site selection. The results from the sensitivity revealed that:

- 10-meter elevation data resolution is most appropriate,
- A right-of-way size of 0.5-mile buffer is sufficient,
- The geomorphic index model for identifying past failures can detect known failures and thousands of unrecorded ones,
- A combination of seven vulnerability factors predict most failures, and
- The most important factor in site selection is including locations from both failed and non-failed areas.

Once the sensitivity analysis was complete, the model was refined, scripted, and executed for 12 counties in 3 districts: Blue Earth, Le Sueur, and Nicollet, (District 7); Dakota, Hennepin, Ramsey, Scott, and Washington (Metro); and Goodhue, Houston, Wabasha, and Winona (District 6). These counties were chosen primarily on three factors: higher risk, larger populations, and more infrastructure. Draft PDF maps of preliminary model results were completed for these 12 counties. The draft maps were taken out into the field for further model refinement/ verification.

Field Verification

The objective of this phase was to field verify the model developed in previous phases. This phase included a total of three site visits, one for each district- Metro, 6, and 7. Site visit locations were chosen collaboratively by TAP committee members. WSB and MnDOT visited the sites together to discuss model improvements, model strengths, and future work. The activities in this phase served to validate the model and indicates it performs well for identifying different types of slope failures in regions with different geology, geomorphology, and hydrology. Three main catastrophic slope failures were observed—rotational slides, translational slides, and rockfalls. Other types of slope failures observed included gullying, surface erosion, and surface tension cracks.

Risk Estimation

The risk of slope failure was estimated after field verification. Risk estimation involves two main components: the likelihood of failure (estimated from the model) and consequence to infrastructure (e.g. densely populated areas, and proximity to road centerlines). Risk is the product of these components and can be calculated using a risk matrix. To be most effective, risk matrices must have robust probability and consequence definitions. The outcome of risk matrices is defined levels of management. The matrix in this study has 4 categories of risk management:

1. Site visit / action recommended
2. Further evaluation,
3. Monitoring, and
4. No further action recommended.

Risk ranking was conducted at the “management area” level for this study. A management area is defined as local regions consisting of one or more slopes with similar geomorphic, geologic, or hydrologic settings. Over 35,000 polygons, or management areas were delineated in GIS and then ranked using the risk matrix. Delineation took place at a scale that balanced efficiency and accuracy. The results from the risk ranking determine:

- 826 management areas for site visit / action recommended,
- 1189 further evaluation,
- 4532 monitoring, and
- 28902 are no further action.

Recommended Next Steps

The results of this study are intended as the first step of actions required in minimizing the effects of slope failure including expensive mitigation actions and threats to public safety. In this study, a new GIS model was designed and implemented to identify slope vulnerability along state trunk highways. The model's capability of identifying slope vulnerability anywhere in the State with minimal data input was field verified. Final maps depicting slope vulnerability for 12 counties in three districts were produced and management areas were ranked based on risk that can provide useful information for district, county, or city engineers, planners, project managers, and maintenance staff. Several steps should be taken to maximize the value and usefulness of the model:

- Field verification of the 826 sites with mitigation recommended.
- Incorporate the Risk Factors determined in this project into MnDOT's TAMP.
- Design and implement mitigation and monitoring programs including severe weather investigations.
- Model and produce results for other Districts within the State.
- Model the cascading effects of slope vulnerability including ne hazards caused by the effects of slope failures such as interruption of power or water supply, closed roads, and commercial or residential damage.

CHAPTER 1: INTRODUCTION

Transportation infrastructure intersects challenging terrain that can negatively impact integrity. Minnesota's climate, geomorphology, and steep terrain along rivers increase the incidence of slope failures such as rockfalls and landslides. Slope failures result in costly repairs, service disruptions, and jeopardizes public safety. The Minnesota Department of Transportation (MnDOT) is interested in determining slope vulnerability risk in a systematic and comprehensive manner that will allow the agency to proactively manage slope failures, saving mitigation and maintenance dollars while decreasing risks to public safety and the environment.

WSB was contracted by MnDOT to determine the risk of slope failure along state highways in districts 6, 7, and the Metro. This report outlines the methods and results of the MnDOT Slope Vulnerability project including a new Geographic Information Systems (GIS) model that can be implemented anywhere in the state. The following sections outline each phase of this project and recommended next steps. Below are the following Phases discussed in this report:

- Phase 2 – Literature Review
- Phase 3 – GIS Model Design
- Phase 4 – Data Collection
- Phase 5 – Sensitivity Analysis
- Phase 6 – Draft PDF Maps
- Phase 7 – Field Verification
- Phase 8 – Final Report, Final Maps, GIS Model and Documentation

CHAPTER 2: PHASE 2 LITERATURE REVIEW

WSB conducted a literature review of previous efforts that categorized the risk of slope failures including the pilot study, other state DOT efforts, work in Duluth and in the metro. Different modeling approaches were reviewed with emphasis on models incorporated in GIS software programs. This phase also included research on the geomorphology of Minnesota and the conditions that make Minnesota vulnerable to failures.

2.1 REVIEW OF MODELING METHODS

Four types of models are used for determining slope vulnerability: inventory, heuristics, statistical, and deterministic (Appendix A: Table 1):

- Inventory is the most straight-forward model type because shows the locations of existing slope failures on a map. There is no predictive capabilities or analysis of what causes slope failures (Ohio DOT).
- Heuristic models use algorithms to identify the risk of slope failure, however, they incorporate expert opinion and can be highly subjective when assign weights or ratings (Colorado DOT).
- Statistical models incorporate variables that caused past failures to predict new failures, providing more objective and data-driven results (Vermont DOT). However, they can become too complex with large numbers of causative factors.
- Deterministic models use limit equilibrium methods to calculate factor of safety (Massachusetts DOT). An example of this is the infinite slope model. These types of models determine the level of failure based on soil or rainfall conditions with no regard to other causative factors or past failures.

Few states have created their own slope vulnerability models. Most states have slope design requirements or protection and stabilization protocols, but do not model for slope failures. For the few states that do model for slope failures, most fall under the inventory / rating system category that do not model for new slope failures or determine causative factors. Other disadvantages of inventory or rating system models are that they are qualitative, use non-spatial data, and rank important parameters with no analysis.

Because MnDOT was interested in GIS-based models, research efforts were focused on heuristic, statistical and deterministic model types. GIS models by non-state DOT organizations were compared to state DOTs. The literature review indicated that non-state DOT organizations had several variations of heuristic, statistical, and deterministic models. Non-state DOTs also had a wider range of complexity (i.e. external software and add-ins) than state DOT efforts, as well as a wider range of objectivity and subjectivity (i.e. automatic detection).

The literature review indicated that the most powerful slope failure models account for past slope failures, because new failures are likely to happen where they have occurred in the past or in new places under similar environmental conditions. Therefore, WSB determined that a statistical model is most appropriate model type for Minnesota due to its powerful capabilities that include incorporating past slope failures and causative factors in a statistical, non-biased, objective manner.

The most challenging aspect of designing a statistical model is incorporating data on past failures if there is no inventory for the study area. Therefore, WSB reviewed methods of incorporating locations and characteristics of past slope failures.

This review revealed three ways to account for past slope failures: collect data on documented historical landslides, digital elevation model (DEM) methods, and a combination of the two. WSB conducted an extensive review on any available documented historical landslides along MnDOT roads online and in historical archives. Historical archives revealed a survey on roadside erosion in the 1970s – 1980s organized by the MN Chapter of Soil Conservation. However, these archives do not record specific locations; rather, they include a description of the general area (i.e. town), limiting the usefulness of this dataset.

WSB further reviewed using DEM methods in identifying locations of past slope failures. Identifying past slope failures in GIS with elevation data has several advantages including efficiency, objectivity allows the incorporation of causative factors, and strengthens the predictive capabilities for modeling future slope failures. Several models use elevation data to determine past slope failures, however, very few use geomorphology to identify the specific landforms and terrain features in locating or causing slope failures. WSB determined that using geomorphology will locate more slope failures than previously recorded, therefore enhancing the model's predictive capabilities for future failures. Geomorphology locates more slope failures by analyzing the specific terrain attributes and hydrological characteristics that trigger slope failures. GIS determines these geomorphic thresholds and how they vary locally.

2.2 GEOMORPHOLOGY AND VULNERABLE CONDITIONS

WSB researched the geomorphology of Minnesota, the conditions that increase the incidence of slope failures, and expected failure types. The following section describes the results of this research.

2.2.1 MINNESOTA'S GEOMORPHIC SETTING

In general, the last glaciation did not extend over southeast Minnesota, resulting in thin soils and frequent bedrock exposures susceptible to rockfalls. Other parts of the state have deeper soils, less bedrock exposure, and higher risk of landslides rather than rockfalls. The vulnerability factors that increase the risk of landslides include naturally steep slopes, proximity to rivers, and terrain curvature. These vulnerability factors and how they increase the incidence of slope failures are explained in more detail below.

The soils geomorphology of SE Minnesota is characterized by smaller particles sizes in the southern half of the state and larger sizes further north. Glacial silts and clay are more common in the southern half of the state, specifically Districts 6, 7, and the Metro. Larger particle sizes such as sandier glacial soils occur further north (i.e. Districts 1 and 3). Soil size is important in the context of slope failures because it can influence the types of slope failures that are expected to occur. For example, smaller silts and clay are more porous and poorly drained, leading to deeper rotational failures, even in gradual terrain. Slopes with larger particle sizes have higher angle of repose, leading to translation slides where the failure will slide down slope as a cohesive mass.

Bedrock exposure is often associated with areas that have very thin soils and is an important vulnerability factor for the state. Bedrock exposure is more common in southeast Minnesota, but also occurs in other parts of the state along river bluffs, lake shores, and road cuts. Bedrock exposure increases the risk of slope failures because they are prone to weathering that induces rock falls and rock topples. Bedrock exposures in karst environments have higher risk of slope failures because limestone and dolomite rock types are easily eroded and weathered by rainfall and flood events compared to less resistant rock types.

Slope angle is another important vulnerability or causative factor of slope failures. In general, higher slope angles increase the risk of slope failure. However, because slope failures are influenced by local geomorphic variations, no single slope angle constitutes a minimum threshold in causing failures. Instead, certain areas of the state experience slope failures at angles such as 20-30 degrees where failure types are characterized by deep-seated rotational slides. For example, higher water tables along floodplains saturate soils and reduce the angle at which slopes are stable. In contrast, translational slides are more common in other terrains characterized by well drained soils. In these areas, heavy rainfall causes slides to occur on slopes with angles between 30-45 degrees.

Proximity to streams is also an important causative factor of slope failures. In general, the closer to the stream centerline an area, the higher the risk of slope failure. Not all streams have the same risk of failure, since geomorphic conditions vary locally. Channel cut banks, the outside bank of a stream, and channel beds are the types of landforms in river environments that have the highest risk of slope failure.

Terrain curvature, or the shape of the slope, is another important vulnerability factor for the state. Concave slopes are landforms where the slope curves inward, allowing for more water, soil, and sediment to concentrate, increasing the amount of erosivity and risk of failure. Concave curvature is an important vulnerability factor for deeper rotational slides, sinkholes, and subsidence or vertical soil collapse from heavy rainfall.

Construction site conditions often influence slope vulnerability in Minnesota. For example, roads often have contrasting permeabilities where the top soil is removed or replaced to fill road designs. This type of contrast can increase the risk of translational slides and gullying. Additionally, construction sites have high risk of surface erosion due to lack of vegetation cover. Surface erosion can cause damage to infrastructure or form the pre-cursors for catastrophic slope failures.

In summary, Minnesota has a unique geomorphic history that includes both glaciated and unglaciated terrain. These environments have differing slope failure vulnerabilities influenced by their specific geomorphology. In Districts 6, 7, and the Metro rockfalls/topples, translational slides, and rotational slides are the most common failure types. GIS-based statistical modeling methods provide a means of capturing slope failure risks across geomorphic differences and can be tailored for use across the state.

CHAPTER 3: PHASE 3 GIS MODEL DESIGN

WSB incorporated the information from Phase 2 and feedback from the Technical Advisory Panel Committee (TAP) to design a new GIS-based model with three main parts: 1.) identify past slope failures, 2.) model the causative factors of past slope failures and how they vary locally, 3.) model the risk of new slope failures (Appendix A: Figure 1).

3.1 IDENTIFY PAST SLOPE FAILURES

WSB created a method for detecting past slope failures using geomorphology and elevation data. Geomorphology is used to analyze terrain and landforms associated with slope failures; almost all types of slope failures have unique terrain in comparison to their surrounding environment (Appendix A: Figure 2). GIS and elevation data were used to highlight the areas that have geomorphic features resembling slope failures along the state highways. These areas reveal thousands of slope failures including slides, rockfalls, failures along karst features, lake shores, river banks, and surface erosion (Appendix A: Figure 3).

3.2 MODEL THE CAUSATIVE FACTORS OF PAST SLOPE FAILURES

After the locations of past failures are identified, the next step is to determine the causative factors. The factors that cause slope failures can vary from place to place. For example, in one district, the amount of water draining through a slope may be the most important factor, but in another district, slope angle may be the most important factor. This information will ultimately assign appropriate weight to each variable so that the model can account for the local variations of the vulnerability factors.

WSB designed a model that allows for any variable to be tested as a probable causative factor. Probable causative factors are tested with a geographic weighted regression (GWR). GWR is a statistical analysis that compares a dependent variable with the independent variables. For this project, the dependent variable are the slope failures, and the independent variables are the vulnerability factors such as slope angle. These factors are tested statistically by evaluating r-square values, values that determine the statistical strength of how well the variation of a causative factor correlates with the variation of the geomorphic index at the past failure locations. For example, if there is no correlation with slope angle at past slope failures for an area, then slope angle is not a strong predictor of future slope failures for that area. The model does not require the locations of every past slope failure to determine which vulnerability factors are the most important; rather, a sampling of locations that produce statistically significant results is sufficient.

Several slope vulnerability factors were tested in the model, including:

- Slope angle,
- Stream power / gullying index,
- Terrain curvature,
- Topographic wetness index (pore water pressure),
- Proximity to rivers,

- Proximity to bedrock outcrops,
- Karst features,
- Lakes,
- Geology,
- Soil characteristics.

3.3 MODEL SLOPE FAILURES PROBABILITY

The final step in designing the model was determining slope failure probability along the entire right of way. The results from part 2 of this phase, modeling the causative factors, were incorporated into a logistic regression equation which calculates the probability of an event occurring (i.e. any type of slope failure). Logistic regression values range from 0 to 1, where 1 equals a 100% chance of occurring. Probability is calculated by using data on each of the vulnerability factors along with the local weight or level of importance of each vulnerability factor in causing failures. For example, a 45-degree slope will have a higher probability of failing in one district than another if slope angle is a more important causative factor in that area.

The final output includes maps that allow users to determine the areas that are most at risk of slope failure by categorizing slopes as either having a higher risk, moderate risk, or lower risk.

CHAPTER 4: PHASE 4 DATA COLLECTION

Phase 4 of this project included data collection for the GIS model. The data collected and assembled for this project includes the following slope vulnerability factors and their sources:

- Digital Elevation Models: United States Geological Services (USGS)
- Slope angle (DEM-derived)
- Stream power / gullying index (DEM-derived)
- Terrain curvature (DEM-derived)
- Topographic wetness index for pore water pressure (DEM-derived)
- Proximity to rivers: Department of Natural Resources (DNR) rivers and streams shapefile
- Proximity to bedrock outcrops: MN Geological Survey (MGS)
- Proximity to karst features: MGS
- Proximity to lakes: DNR hydrology shapefile
- Bedrock Geology – MGS S-21 Geologic Map of Minnesota Bedrock Geology – state-wide 1:500,000 - https://conservancy.umn.edu/handle/11299/101466 and http://www.mngeo.state.mn.us/chouse/geology/statewide.html - Accessed February 13, 2018
- Soil characteristics including soil texture in rooting zone and substratum (just below rooting zone), surface erodibility factor (K in the Universal Soil Loss Equation), surface and substratum shrink-swell capacity – state-wide 1:250,000 – Minnesota Soil Atlas by University of Minnesota Dept. of Soil, Water, and Climate and NRCS - http://www.mngeo.state.mn.us/chouse/metadata/soil_atlas.html and http://www.mngeo.state.mn.us/chouse/soil.html#general - Accessed February 13, 2018

The stream power / gullying index (SPI) and the topographic wetness index (TWI) were calculated using equations from a paper by Clift and Springston (2012) for the Vermont Geological Survey.

- $SPI = a * \tan B$,
- $TWI = \ln (a / \tan B)$,

Whereas a is the drainage area above the slope failure and B is the slope angle for both of those equations.

CHAPTER 5: PHASE 5 SENSITIVITY ANALYSIS

Phase 5 of the slope vulnerability project included a series of tests collectively called the Sensitivity Analysis. A sensitivity analysis determines how well the GIS model predicts slope failures and how the model responds to changes in testing parameters. The sensitivity analysis tested five factors:

- elevation data resolution,
- appropriate size of the right-of-way (i.e. study area),
- ability of the geomorphic index to detect past failures,
- testing various vulnerability factors in the model,
- testing site selection for the model.

The following sections describe each of these five tests along with some of the statistical measures that supported model refinement.

5.1 ELEVATION DATA RESOLUTION

Spatial data resolution is an important quality control measure that affects the predictive accuracy of the model. An optimum level of resolution depends on the specific project objectives and scale of study. The model objectives in this study are to locate past slope failures, determine the causative factors, and determine the risk of new slope failures. Elevation data at 1-meter, 3-meter, and 10-meter were tested to determine the most efficient resolution in locating and predicting slope failures at the district level. Results indicate:

- 1-meter resolution spatial data is results in ineffective GIS processing. For example, slope angle calculations, a key vulnerability factor, cannot process at the county level because the resolution includes too much detail.
- 3-meter resolution can process slope angle at the county level but is very time consuming.
- 10-meter resolution detects both small and large failures. Relatively small slope failures like gullying, failures at slope crests, failures along small streams (2-feet), and small-scaled channel head-cutting are detected using 10-meter spatial data. Relatively large slope failures over hundreds of feet long are also detected (Appendix A: Figure 1).
- 10-meter resolution is a standard resolution used for hydrologic analyses, an important component of this study.
- Smaller resolutions are time consuming, data intensive, and may be less accurate. They may detect too much detail not required to meet project objectives and therefore do not improve model predictions. For example, artificial slopes like landscaped hills are detected using 1 and 2-meter resolution data. These “slopes” would need to be manually deleted from results.

5.2 SIZE OF THE RIGHT-OF-WAY

Selecting an appropriately sized right-of-way underpins the predictive accuracy of the model. The area incorporated into the model must balance the amount of data incorporated into the model with ensuring that the maximum number of slope failures are detected. Three options were analyzed: sub-watersheds that intersect the highways, a uniform buffer of 0.5 miles on each side of the highway, and a combination of the two (Appendix A: Figure 2).

Testing results indicated a combination of a 0.5-mile buffer and sub-watershed boundaries would be the most appropriate sized right-of-way for this study, since they capture slopes failures most likely to occur in Minnesota. This combination results in a minimum buffer of 0.5 miles, with many highways having a larger buffer where the sub-watershed is larger. Testing indicates both will be sufficient for predicting slope failures.

5.3 DETECTING PAST SLOPE FAILURES

WSB created a method for detecting past slope failures by calculating for geomorphic features with elevation data as its only input. The accuracy of this measure was compared to known slope failure sites from other work and verified with aerial photos and hillshade data. Over 2,000 slopes in every county in the study areas were identified as having the highest risk of past failure and verified with aerial photos and hillshade data (Figures 3 and 6). Only verified slope failure sites were used in the model to ensure quality. The geomorphic index detected over 90% of the 142 known sites provided by MnDOT, almost all known sites from other work, and thousands of others that were previously unrecorded. The index was also verified the known slope failures field verified in Burnsville by WSB (separate project), including small slides and river bank failures.

5.4 TESTING DIFFERENT VULNERABILITY FACTORS

The sensitivity analysis also tested several vulnerability factors:

- Slope angle
- Stream power index
- Topographic wetness index
- Distance to streams, bedrock outcrops, large lakes, urban areas, and karst
- Terrain curvature
- Geomorphology (DNR landform classification)
- Soil characteristics

Testing these variables in the model included two main parts: 1) ensuring the data processes correctly for the model tools, and 2) determining which variables are most important for detecting and predicting slope failures. The main purpose of testing vulnerability factors in the model is to find the fewest number of variables that have the largest effect on causing slope failures to improve accuracy and eliminate any unnecessary data. The process of deciding which factors should be eliminated or kept in the model is driven by the statistical significance results from the geographic weighted regression (GWR) component of the model. GWR determines the correlations that the dependent variable (geomorphic index) has with any independent variable (vulnerability factors). The r-square values from the GWR statistically test these correlations and the model's predictive capabilities.

Each of the vulnerability factors were tested in the model individually, to test the accuracy of each variable in predicting or causing slope failures. Once the variables were tested separately, different combinations of the variables were tested with the aim of determining the combination of variables that produces the highest, statistically significant r-square value. The process of testing variables includes the following considerations:

- Low r-square values indicate that significant vulnerability factor(s) are not in the combination of variables currently tested.
- To determine if a vulnerability factor is the missing factor(s) in causing slope failures, it is added into the model.
- From this type of analysis, the most important vulnerability factors can be kept in the model, and the ones that have no correlation or do not add much improvement in the model's predictive capabilities can be eliminated.
- When all the vulnerability factors are tested independently in the model, the following results emerge:
- Slope angle is the most important causative factor overall at the study area scale
- The second most important causative factor at the study area scale is proximity to streams.
- A combination of three variables, slope angle, stream proximity, and bedrock proximity result in over 1000 (72%) of sites with r-square values greater than 0.5 (Appendix A: Table 2).

Including concave curvature, lake proximity, topographic wetness index, and stream power index with the previous three variables results in 99% of sites having r-square values greater than 0.5.

5.5 TESTING SITE SELECTION

Determining the number of testing sites for incorporation into the model was the final step of the sensitivity analysis. Testing sites are a combination of verified past slope failures and randomly generated locations in GIS used to test the results of the sensitivity analysis and run the model. Typically, a minimum of 30 sites are recommended for statistical analyses. WSB verified and included over 1500 sites for incorporation into the model. Testing indicates that the most important factor in site selection is including locations from both failed and non-failed areas rather than the sheer number of sites because the results of GWR will be interpolated for all areas in the right-of-way. If only failed areas were included in the model, the interpolated surfaces will inaccurately have high probabilities of failure.

5.6 SUMMARY

WSB tested five components of the model: resolution of spatial data, size of right-of-way, historic slope failure detection, variable combinations, and the number of sites incorporated into the model. The sensitivity analysis reveals that:

- 10-meter elevation data resolution is most appropriate (Appendix A: Figure 4),
- A right-of-way size of 0.5-mile buffer is sufficient (Appendix A: Figure 5),
- The geomorphic index model for identifying past failures can detect known failures and thousands of unrecorded ones (Appendix A: Figures 6 and 7),
- A combination of seven vulnerability factors predict most failures (Appendix A: Table 2),
- The most important factor in site selection is including locations from both failed and non-failed areas.

CHAPTER 6: PHASE 6 DRAFT PDF MAPS

Phase 6, Produce Draft Maps was completed for 12 counties in 3 districts. In this Phase, the model was refined, scripted, and executed for the following counties: Blue Earth, Le Sueur, and Nicollet, (District 7); Dakota, Hennepin, Ramsey, Scott, and Washington (Metro); and Goodhue, Houston, Wabasha, and Winona (District 6). These counties were chosen primarily on three factors: higher risk, larger populations, and more infrastructure.

CHAPTER 7: PHASE 7 FIELD VERIFICATION

The objective of Phase 7 was to field verify the model developed in previous phases. This phase included a total of three site visits, one for each district- Metro, 6, and 7. Site visit locations were chosen collaboratively by TAP committee members. WSB and MnDOT visited the sites together to discuss model improvements, model strengths, and future work. The following sections outline the methods, results, and conclusions of this phase.

7.1 METHODS

The objectives of this phase were to verify the model's input parameters, symbology, and results, with field observations, as well as provide additional information including cause of failure or potential precursors of failure, type of failure, and site-specific mitigation / management solutions. The methods for this phase along with equipment used are listed below:

- Navigation from site to site (ESRI mobile apps and printed maps)
- Quantifying slope angles using a laser range finder (TruPulse 360)
- Geomorphic, geologic, and hydrologic observations (field forms on iPad and photos)

The three site visits included TH13 near Lilydale Park in Dakota County (Metro), TH22 along the Le Sueur River in Blue Earth County (District 7), and TH61 in Wabasha County (District 6).

7.2 RESULTS

The model's input parameters, symbology, and results were validated in the field. In previous phases, the four input parameters- slope, terrain curvature (slope shape), distance to bedrock, and streams went through a series of geostatistical analyses to verify that these parameters can accurately indicate the risk of slope failure anywhere in the study area. Field observations verified that these parameters indicate the risk of failure at three sites with different hydrologic, geomorphic, soil, and geologic backgrounds. The following sections discuss the results of each site visit in more detail.

7.2.1 Site 1 – TH13 Lilydale Park, Dakota County, Metro District (June 5, 2018)

Site 1 is located along TH13 near Lilydale Park in Dakota County and runs parallel to the Mississippi River. This slope was selected for field verification by MnDOT due to model results suggested higher slope vulnerability risk; additionally, the slope has a relatively large surface area.

Model results suggested the slope was already experiencing catastrophic landslides or surface erosion, and field verification validated this assessment (Appendix A: Figure 10). Several landslides are occurring along this slope primarily due to steep slopes, soil type, shallow bedrock, and hydrology. The slope angles in this area ranged from 70-85 degrees, and some of the headwalls of the slides were even steeper. The soil in this area consisted primarily of glacial till deposits. Alluvium occurs off the slope, further down the valley along the Mississippi River. The silty and sandy till exacerbates the slope failures in this region. Shallow bedrock and a spring with steady flow in the center of the slide also exacerbate the slope failures. Exposed bedrock and several springs were observed along several slopes in this area and were often associated with a slide. An inadequately placed culvert does not properly drain the toe of a slope in one area, incising the walking path in the park. TH13 is at risk as the slope is retreating, as well as residential homes, local roads, and residents enjoying the park.

7.2.2 Site 2 – TH22 Le Sueur River, Blue Earth County, District 7

Site 2 was selected by MnDOT for field verification to determine how well the model identifies for slope failure in a different geologic and geomorphic setting with minimal input parameters (Appendix A: Figure 11). Field verification reveals that the slope along the Le Sueur River near TH22 in Blue Earth County also experienced past catastrophic slope failures. The rotational landslides in this area occur mainly along river channel banks. The soil particle sizes are smaller and less sandy compared to Site 1. The river is currently eroding the cut banks, exposing deeper depths of the alluvial soil and increasing the risk of future slides. A bridge over the Le Sueur River is currently experiencing erosion mainly caused by a spring with steady flow and from major flood events. The slopes in this area are less steep than Site 1, ranging from 60-80 degrees. This lower slope angle threshold for slope failure, validates the model's capabilities of automatically accommodating for local changes in geology and soil; minimum slope thresholds for failure change locally, and are detected by the model. TH22 is at risk as slopes along the river to fail during rain and flood events, as well as residential homes in the area.

7.2.3 Site 3 – TH61 RP 68.7 Wabasha County, District 6

Site 3 was selected by MnDOT to validate the model's risk assessment capabilities for a third region with different geologic and geomorphic background (steep rock slopes) and road design (Appendix A: Figure 12).

Field verification reveals that Site 3 along TH61 RP 68.7 has a history of past slope failures as well as high risk for future failures. A relatively large boulder recently fell out of the exposed colluvium (soil on hillslopes), indicating that the slope is currently eroding. Naturally steep slopes over 70 degrees form the valley wall for the Mississippi River in this area and are even higher where the road is cut into the slope. Geologically, the steep slopes along TH61 form either along exposed bedrock or in varying types of colluvium. The site that was verified contains colluvium. The colluvium and shallow depths to bedrock exacerbated the translational slides observed in this area. Rockfalls are observed slightly further from the site where there is exposed bedrock instead of colluvium. As rainfall and runoff erode the colluvium on the slope, large angular boulders and cobbles naturally found in this soil type are exposed and eventually fall out toward the highway. Rock slides can occur in areas where there is currently colluvium, if the colluvium is eroded down to the shallow depths of bedrock. This is an example of how the type of slope failure can change temporally at a given site over time. The model's capabilities for identifying different types of slope failures is validated. TH61 is at risk, as well as residential homes and private companies.

7.3 CONCLUSIONS

The activities in phase 7 served to validate the model and indicates it performs well for identifying different types of slope failures in regions with different geology, geomorphology, and hydrology. Three main catastrophic slope failures were observed—rotational slides, translational slides, and rockfalls. Other types of slope failures observed included gullying, surface erosion, and surface tension cracks.

Improvements for the model and final maps discussed during field activities included:

- Revising the risk symbology
- Including more reference points like road markers and aerial photos
- Using management areas for risk ranking as opposed to individual slopes
- Reducing the right-of-way to a uniform half-mile buffer instead of watershed boundaries. Field results indicated a uniform buffer was sufficient to capture slope failures in this study area, since the slope failures in these districts travel less than 2000 feet horizontally. Therefore, watershed boundaries were eventually eliminated in forming the boundaries of the right-of-way, and finals maps and outputs for this study will have a right-of-way of 0.5 miles on either side of trunk highways.

CHAPTER 8: PHASE 8 FINAL REPORT, PDF MAPS, GIS MODEL AND DOCUMENTATION

The deliverables in this phase include the following: draft report, final report, final PDF maps, vulnerability raster files, the GIS model and model documentation, and the management areas ranked by risk for efficient use of project results.

8.1 FINAL PDF MAPS

WSB completed final PDF maps for the following counties: Blue Earth, Le Sueur, and Nicollet, (District 7); Dakota, Hennepin, Ramsey, Scott, and Washington (Metro); and Goodhue, Houston, Wabasha, and Winona (District 6). Field verification results from Phase 7 were incorporated into the final maps. The improvements following Phase 7 focused on cartographic improvements and the size of the right-of-way (discussed above). The most important cartographic improvement included adjusting the symbology to accurately reflect the relative vulnerability between slopes. The appropriate symbology classification for determining the minimal threshold constituting higher vulnerability, was driven by field verification results. Other cartographic improvements included adding more reference points and an aerial photo background. Lastly, an updated roads layer from MnDOT with the most recent jurisdiction was used for the final maps for accuracy. Figure 13, shows an example of the final maps and Figure 14 shows a zoomed in example of the vulnerability output (Appendix A).

8.2 VULNERABILITY RASTER FILES

WSB combined the vulnerability final outputs from each of the 12 counties into one raster file that has the appropriate symbology, correct size right-of-way, and most updated roads jurisdiction. The file is readily available for use in any ArcGIS platform.

8.3 GIS MODEL AND DOCUMENTATION

WSB provided MnDOT the GIS model along with appropriate scripts and documentation for running the model. Final scripting edits included clipping the final outputs to a half mile buffer and ensuring every cell within the right-of-way had a value. When running the model, MnDOT will be prompted with instructions on how to use the model.

8.4 RISK RANKING OF MANAGEMENT AREAS

Risk is the product of probability and consequence (Probability x Consequence = Risk); risk matrices provide a framework for determining probability and consequence. To be most effective, risk matrices must have robust probability and consequence definitions. The Slope Vulnerability Risk Matrix with the definitions is presented in Appendix A Table 3.

The matrix has 4 categories of risk management:

1. Site visit / action recommended
2. Further evaluation,
3. Monitoring, and
4. No further action recommended

Risk ranking of the vulnerability outputs was conducted at the Management Area scale. In this project, Management Areas are defined as local regions consisting of one or more slopes with similar geomorphic, geologic, or hydrologic settings.

Over 35,000 polygons, or Management Areas were delineated in GIS and then ranked using the risk matrix. Delineation took place at a scale that balanced efficiency and accuracy. Figure 15 shows an example of the ranked Management Areas at the Blue Earth County scale, and Figure 16 shows a closer look at examples of Management Areas (Appendix A). The results from the risk ranking determine:

- 826 Management Areas for site visit / action recommended,
- 1189 further evaluation,
- 4532 monitoring, and
- 28902 are no further action

8.5 RECOMMENDED NEXT STEPS

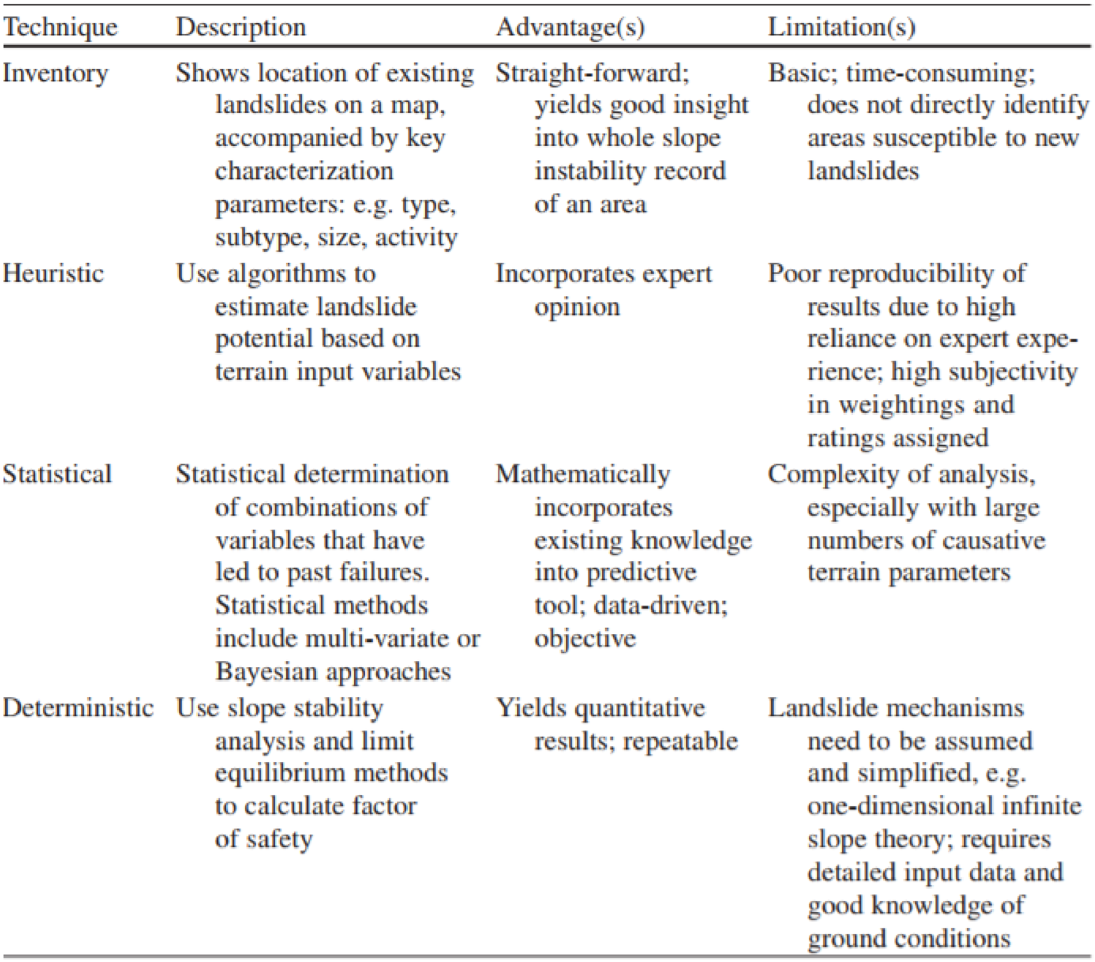
The results of this study are intended as the first step of actions required in minimizing the effects of slope failure including expensive mitigation actions and threats to public safety. In this study, a new GIS model was designed and implemented to identify slope vulnerability along state trunk highways. The model's capability of identifying slope vulnerability anywhere in the State with minimal data input was field verified. Final maps depicting slope vulnerability for 12 counties in three districts were produced and Management Areas were ranked based on risk that can provide useful information for district, county, or city engineers, planners, project managers, and maintenance staff. Several steps should be taken to maximize the value and usefulness of the model:

- Field verification of the 826 sites with mitigation recommended.
- Incorporate the Risk Factors determined in this project into MnDOT's Transportation Asset Management Plan (TAMP).
- Design and implement mitigation programs for the Management Areas with mitigation recommended.
- Design and implement an ongoing monitoring program for MnDOT maintenance staff to utilize. This schedule will incorporate periodic monitoring as well as severe weather investigations.
- Model and produce results for state trunk highways in other counties within Districts 6, 7, and Metro.
- Model and produce results for other Districts within the State.

- Model the cascading effects of slope vulnerability including new hazards caused by the effects of slope failures such as interruption of power or water supply, closed roads, and commercial or residential damage.
- Use the preliminary sinkhole risk results identified in this study to model for the locations that have actively forming sinkholes directly under state trunk highways.

APPENDIX A: FIGURES AND MAPS

Table 1 . Slope Failure Models.



Technique	Description	Advantage(s)	Limitation(s)
Inventory	Shows location of existing landslides on a map, accompanied by key characterization parameters: e.g. type, subtype, size, activity	Straight-forward; yields good insight into whole slope instability record of an area	Basic; time-consuming; does not directly identify areas susceptible to new landslides
Heuristic	Use algorithms to estimate landslide potential based on terrain input variables	Incorporates expert opinion	Poor reproducibility of results due to high reliance on expert experience; high subjectivity in weightings and ratings assigned
Statistical	Statistical determination of combinations of variables that have led to past failures. Statistical methods include multi-variate or Bayesian approaches	Mathematically incorporates existing knowledge into predictive tool; data-driven; objective	Complexity of analysis, especially with large numbers of causative terrain parameters
Deterministic	Use slope stability analysis and limit equilibrium methods to calculate factor of safety	Yields quantitative results; repeatable	Landslide mechanisms need to be assumed and simplified, e.g. one-dimensional infinite slope theory; requires detailed input data and good knowledge of ground conditions

Figure 1. WSB’s GIS Model.

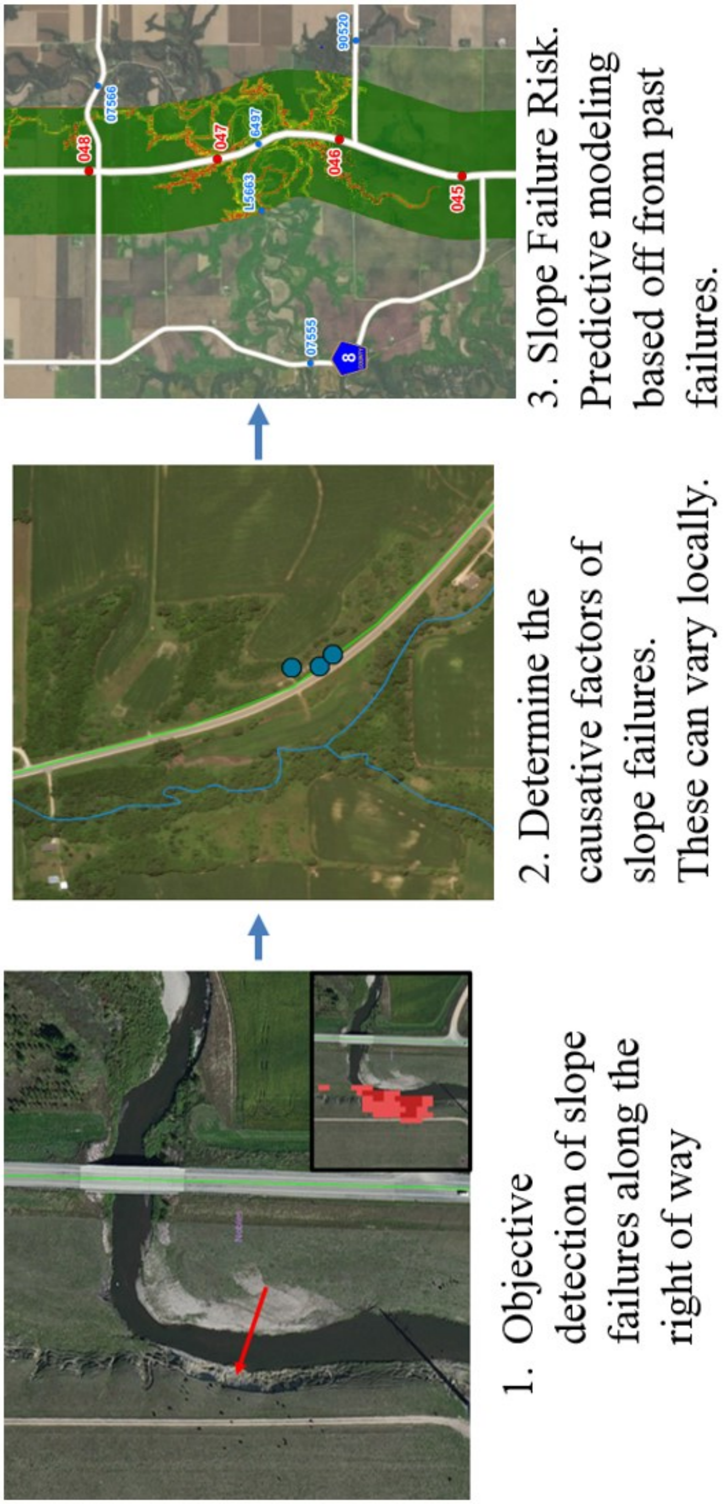
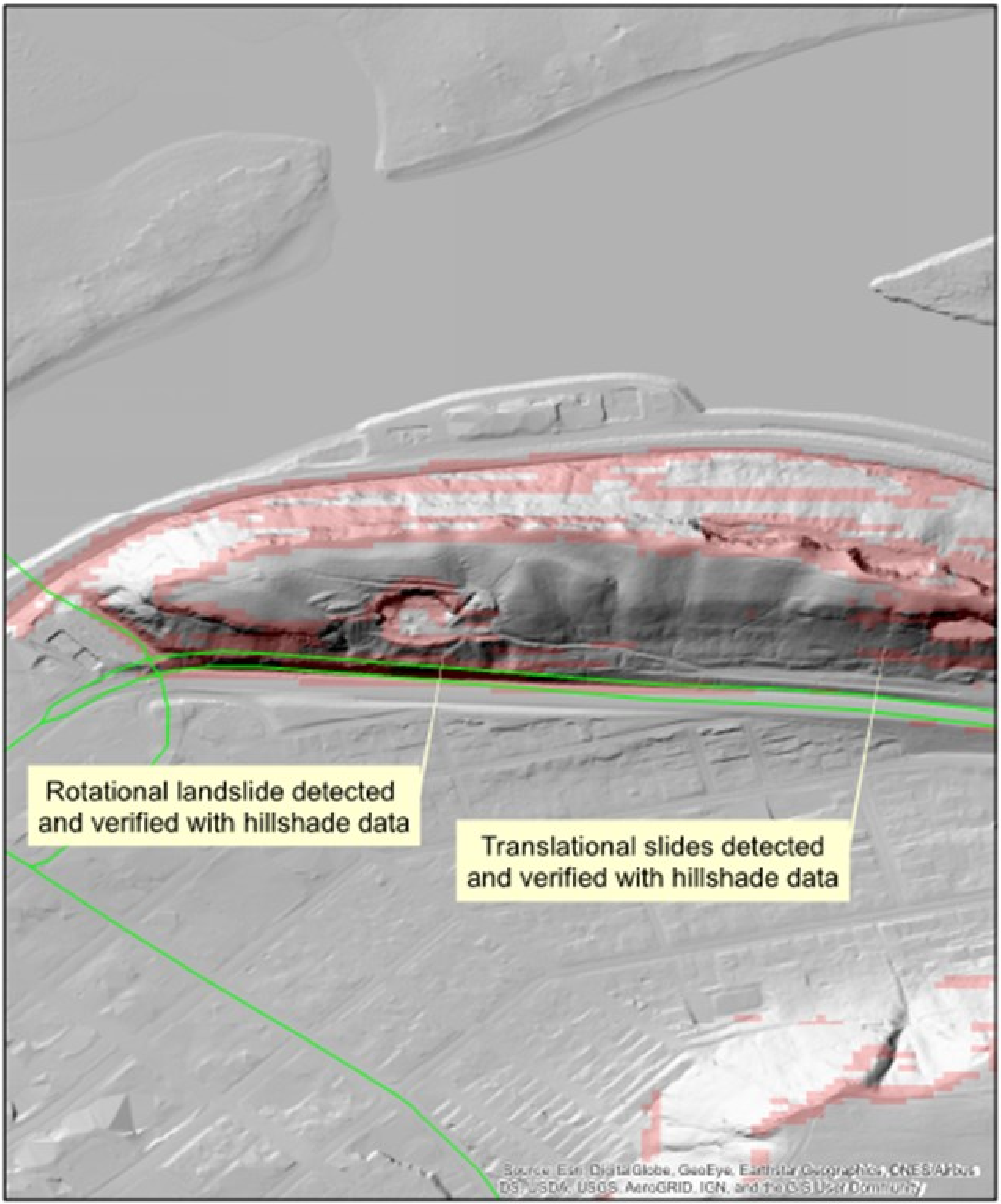


Figure 2. Slope Failures and Distinct Terrain Attributes.



Rotational landslide detected and verified with hillshade data

Translational slides detected and verified with hillshade data

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3. GIS Model Part 1

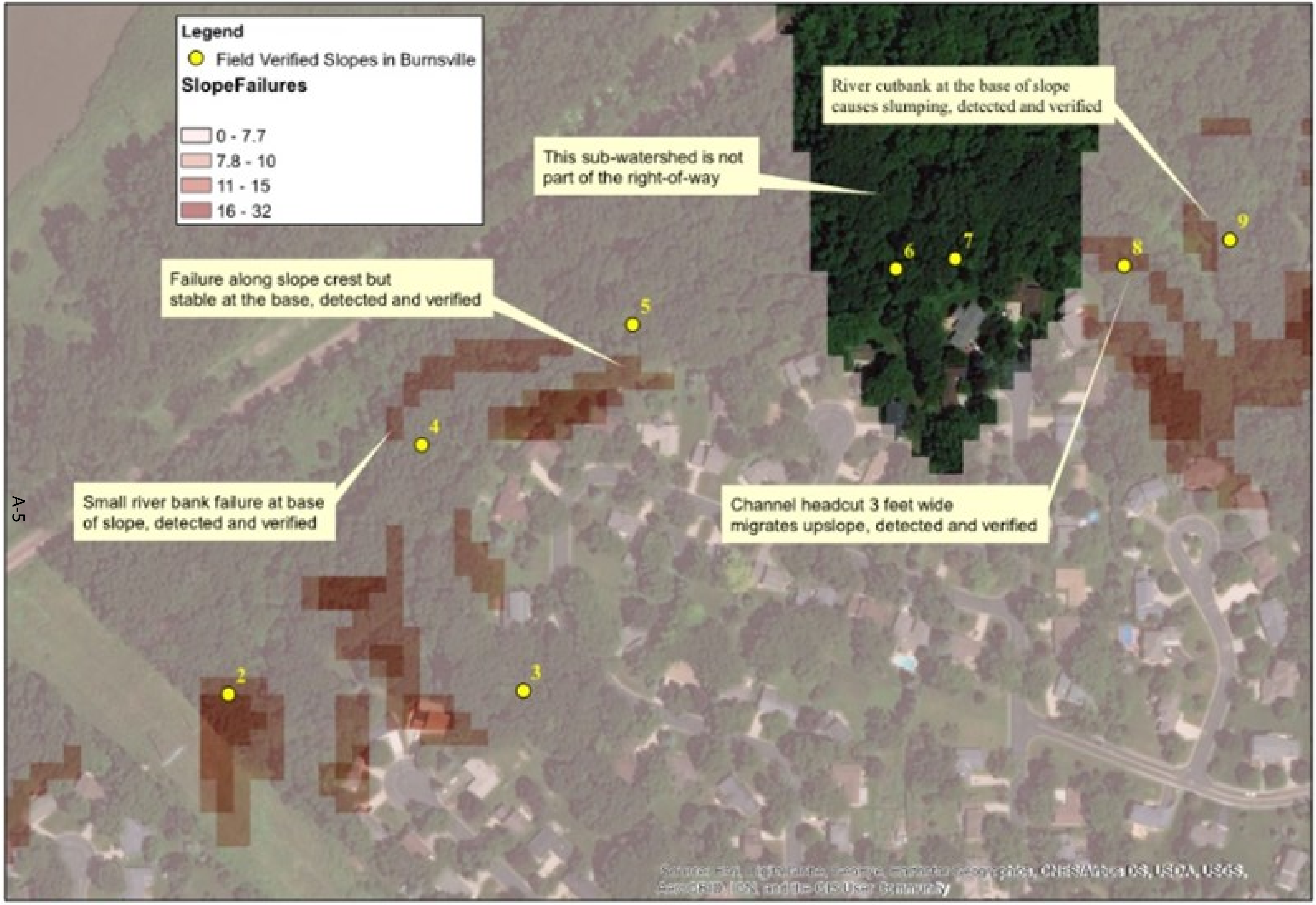
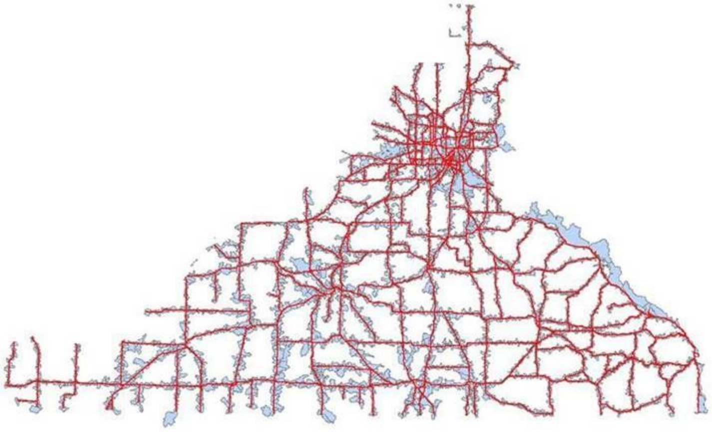


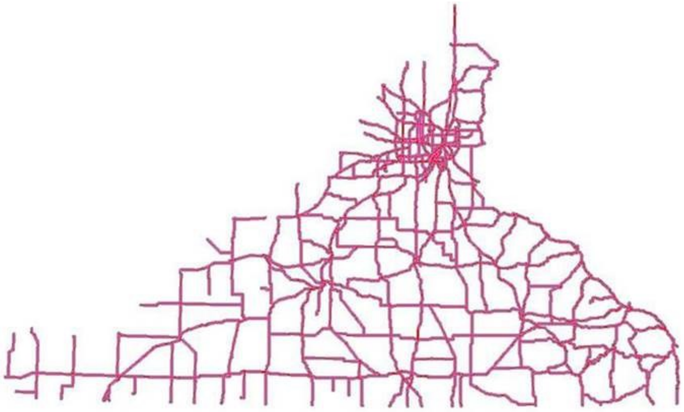
Figure 4. Elevation Resolution

Figure 5. Size of the Right-of-Way.

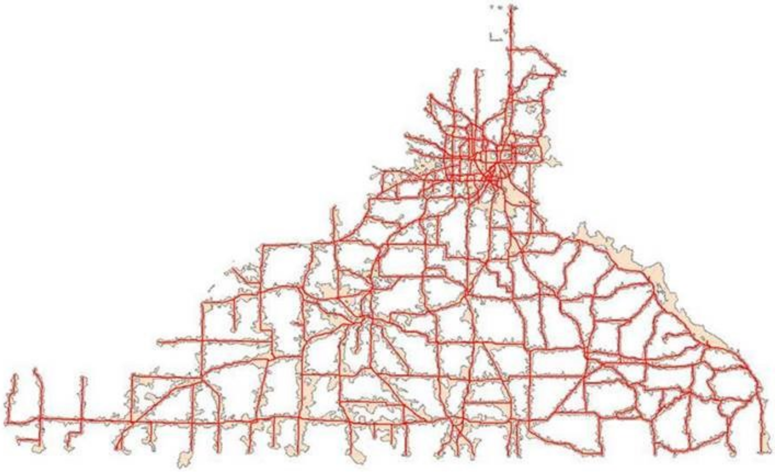
A.) Sub-watersheds.



B.) 0.5-mile Buffer.



C.) Combination



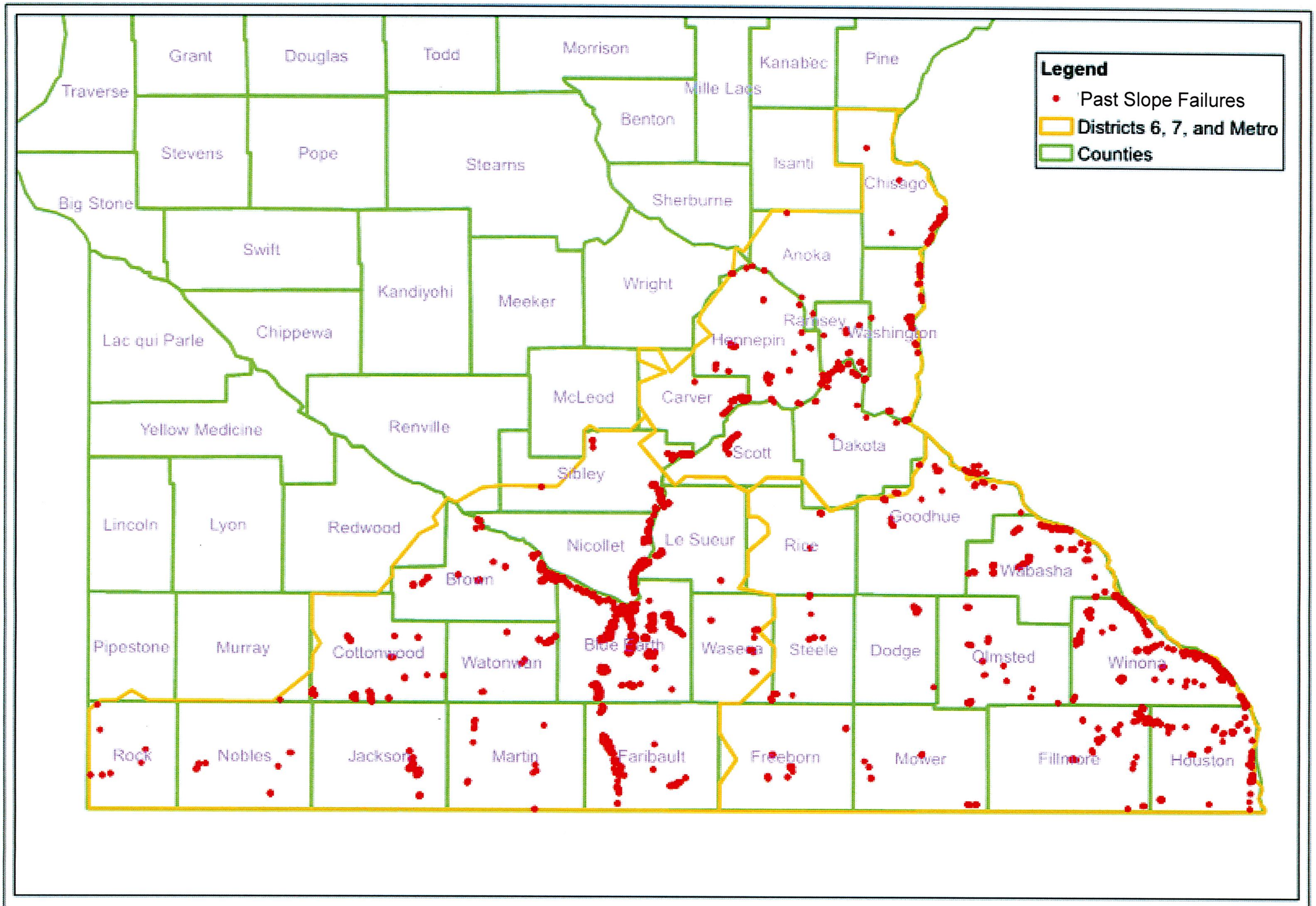


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Figure 6. Identified Slope Failures

N

0 5 10 20 30 40 Miles

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Table 2. Sensitivity Analysis.

	Variable(s)	Sites with r-square values greater than 0.5
Single	1. Slope	524
	2. Distance to streams	168
	3. Geomorphology (DNR landform classification)	131
	4. Distance to bedrock	125
	5. Soil type	91
	6. Distance to large lakes	36
	7. Distance to karst	30
	8. Concave curvature	26
	9. Stream power / gullying index (SPI)	18
	10. Topographic wetness index (TWI)	2
Combinations	11. Slope and streams	828
	12. Slope, streams, bedrock	1044
	13. Slope, streams, bedrock, concave curvature, lakes	1329
	14. Slope, streams, bedrock, concave curvature, lakes, SPI, TWI	1437 (99% of the sites)

Figure 7. Examples of Detected Slope Failures

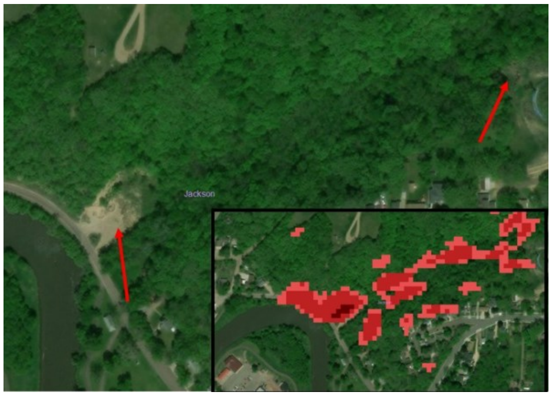
A.) River cut bank

B.) Translational slides

C.) Rockfall

D.) Lake shoreline failure

E.) Large rotational slide



F.) River cut bank between highways

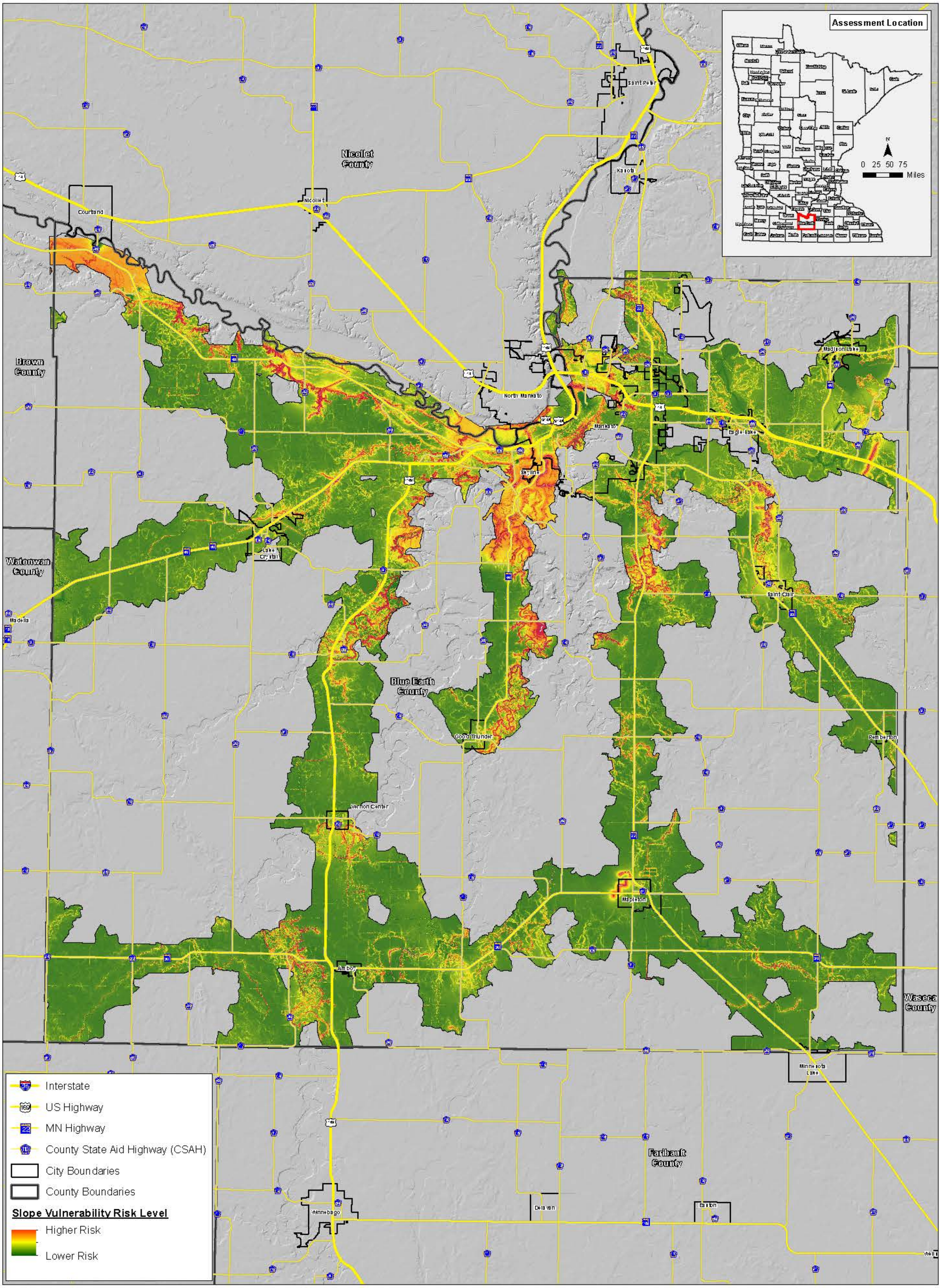


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Figure 8. Slope Vulnerability Assessment Blue Earth County

Date Created: 9/5/2018
Created By: Andrew Shinnefield, Nick Bradley, Jen Holmstadt, and Bruce Holdenhusen
Basemap Source: MN Geospatial Information Office, LiDAR Data
Disclaimer: MnDOT is not responsible for implication from data provided by this map

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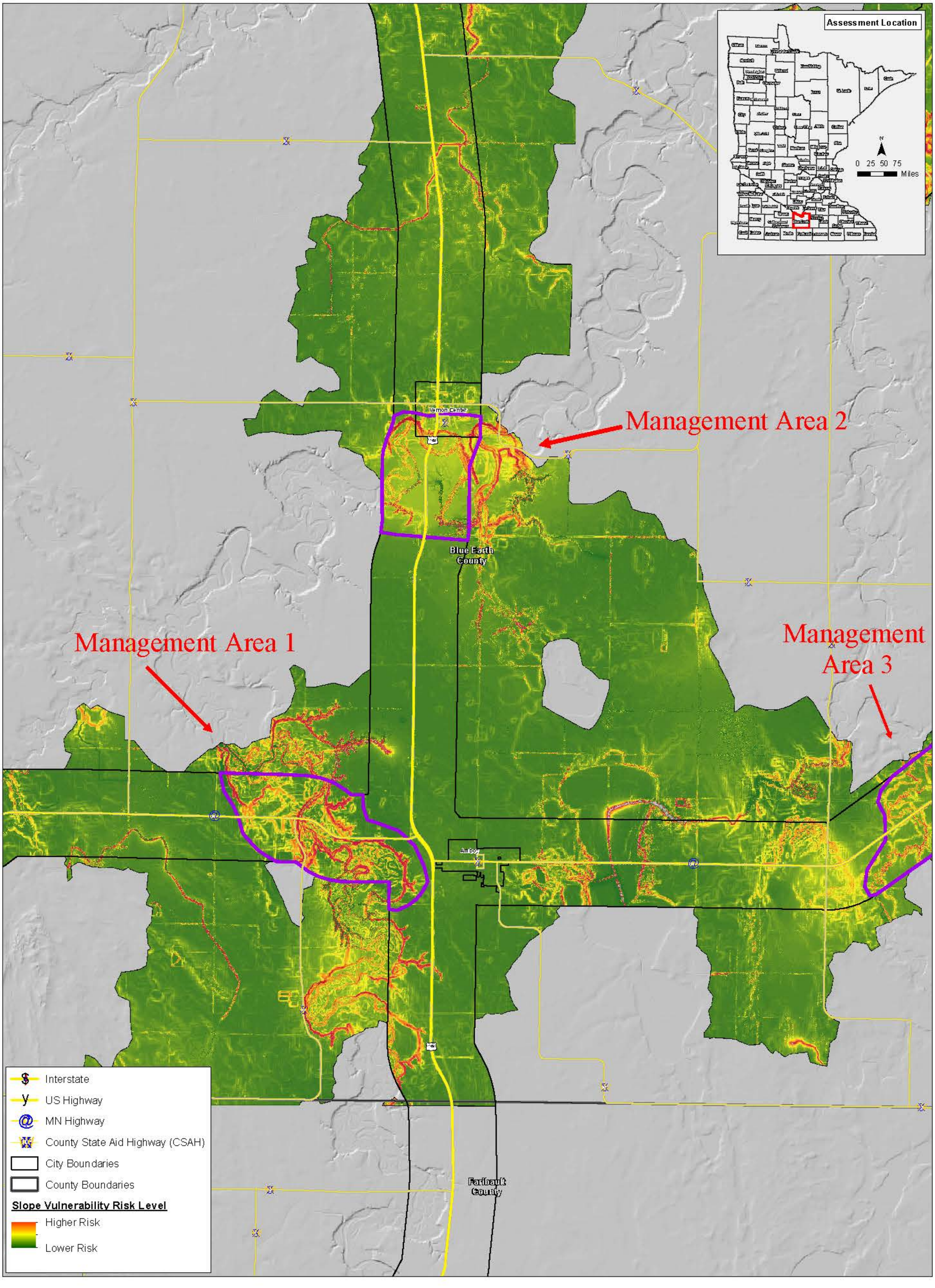

Figure 9. Slope Vulnerability Management Area Proposal
Blue Earth County

N
0 0.25 0.5 1 1.5 2 Miles
0 1,125 2,250 4,500 6,750 9,000 Feet

Date Created: 4/26/2018
Created By: Andrew Shinnefield, Nick Bradley, Jen Holmstadt, and Bruce Holdenhusen
Basemap Source: MN Geospatial Information Office, LiDAR Data
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Figure 10. Field Site 1 – TH13 Lilydale Park.

The model was verified at the first site visit. Field verification results validate the model's indication that there is a high risk of slope failure at this site. The image to the right is from a draft map of Dakota County Slope Vulnerability Assessment where high risk of failure is displayed in red.

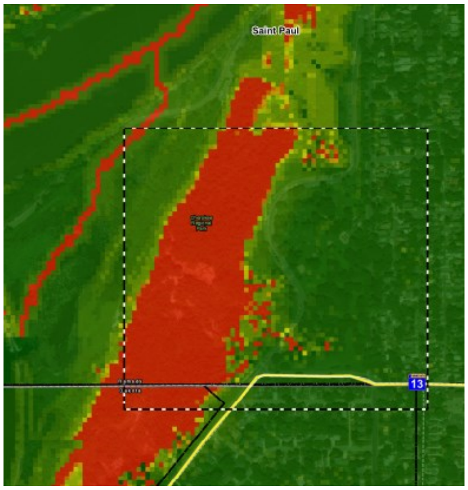


Figure 11. Field Site 2 – TH22 Le Sueur River.

As seen in the clipped image from the draft Blue Earth County Slope Vulnerability Assessment map, the red areas identify the slopes vulnerable to failure. The tall cut bank slopes along the Le Sueur River valley show clearly that the slope is in constant failure of various degrees as indicated by the dark intense red color on the vulnerability map.

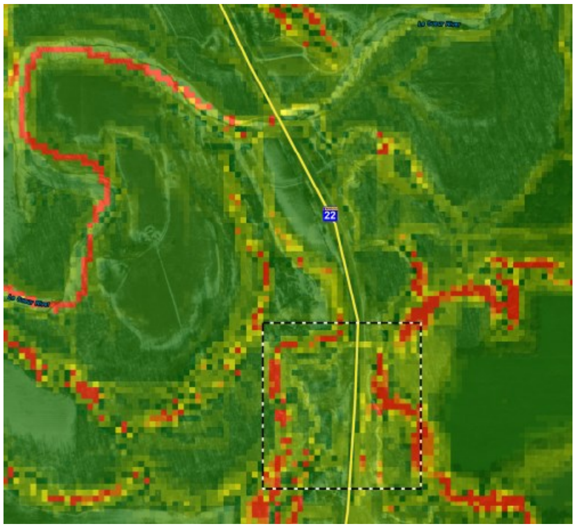
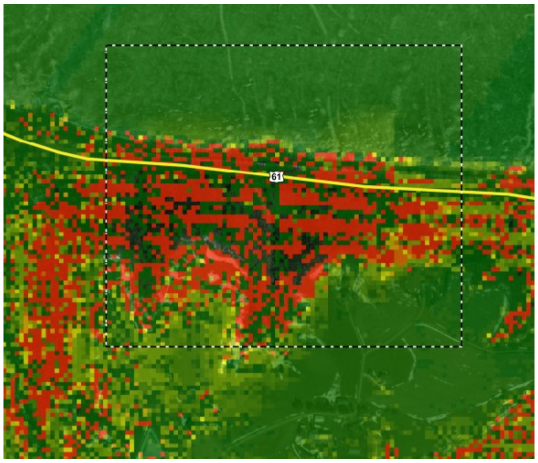


Figure 12. Field Site 3 – TH61 RP 68.7.

The model was validated for a third time at the third site visit. The field results verify the model’s ability to indicate the risk of failure in different environments and for different slope failure types. The image to the right from a draft map of Wabasha County Slope Vulnerability Assessment.



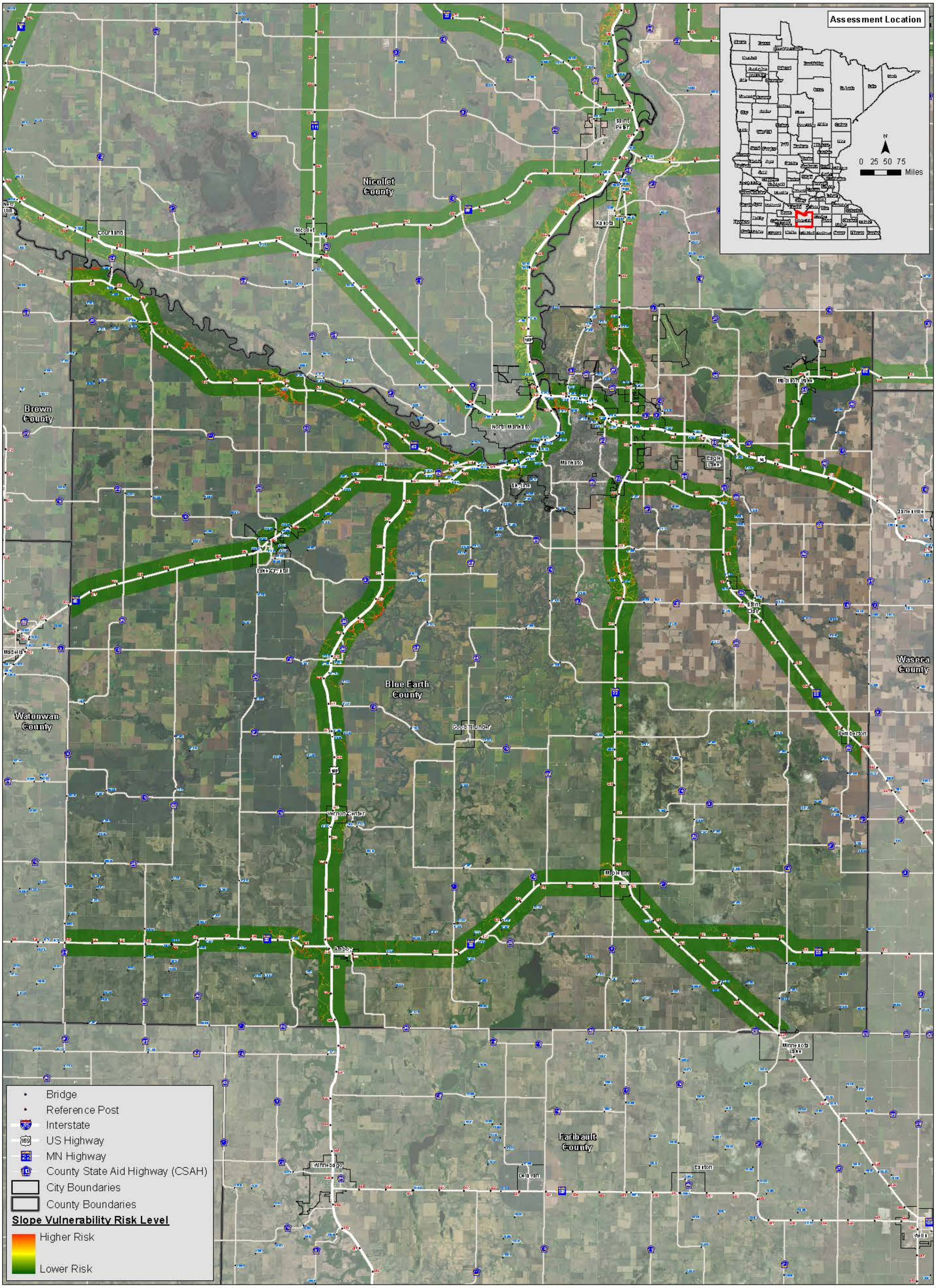


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Figure 13. Blue Earth County Slope Vulnerability

Date Created: 8/20/2018
Created By: Andrew Shinnefield, Nick Bradley, Jen Holmstadt, and Bruce Holdenhusen
Basemap Source: MN Geospatial Information Office, LiDAR Data / ESRI World Imagery WMS
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Figure 14. Example of Blue Earth County Slope Vulnerability.

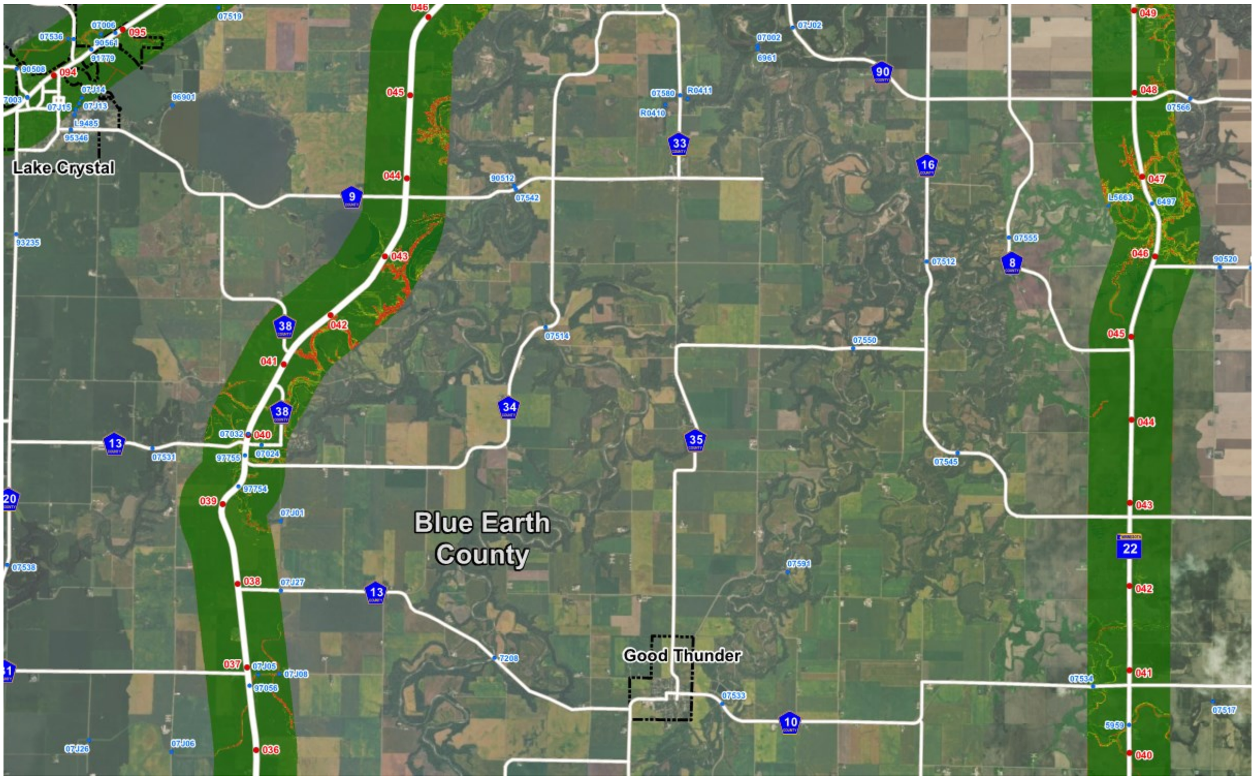

Table 3. Risk Matrix.

				Consequence		
				Intersects Trunk Highways	Within 500 feet of Trunk Highways	More than 500 feet of Trunk Highways
				Within Metro or Incorporated Town	Rural	
	Slope Stability	Rational		Critical (5)	Serious (3)	Marginal (2)
LIKELIHOOD	Low	Slope is likely already experiencing mass failure or has the highest risk of failure.	Likely (4)	20 Site Visit / Action Recommended	12 Further Evaluation	8 Monitoring
	Medium	Surface erosion and other pre-cursors for catastrophic failure.	Possible (3)	15 Further Evaluation	9 Monitoring	6 No Action Recommended
	High	Slope has been repaired, recovered, or shows no signs of imminent future.	Unlikely (2)	10 Monitoring	6 No Action Recommended	4 No Action Recommended

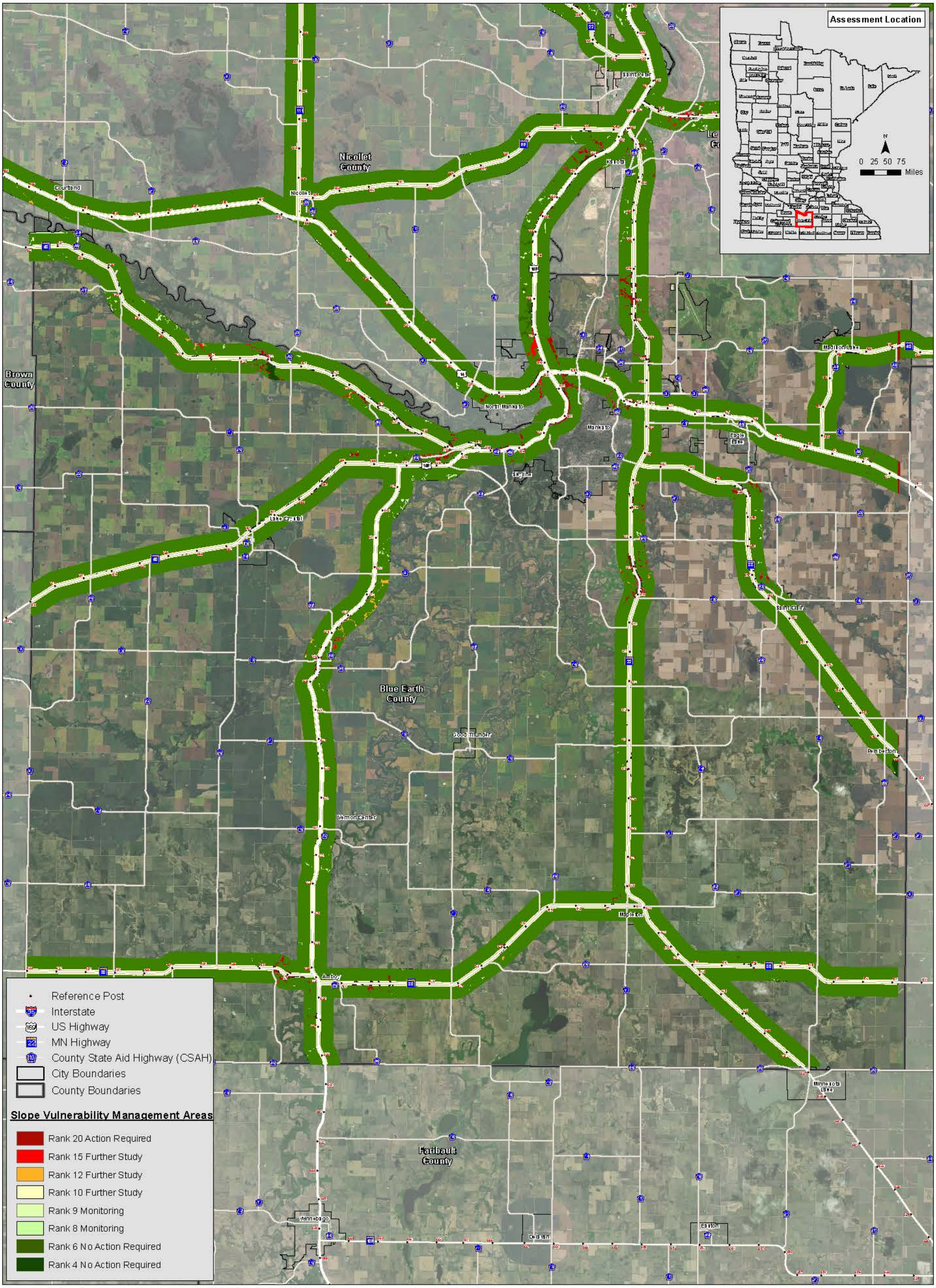

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Figure 15. Ranked Management Areas

Date Created: 9/5/2018
Created By: Andrew Shinnefield, Nick Bradley, Jen Holmstadt, and Bruce Holdenhusen
Basemap Source: MN Geospatial Information Office, LiDAR Data / ESRI World Imagery WMS
Disclaimer: MnDOT is not responsible for implication from data provided by this map

N
0 1 2 3 4 Miles
0 11,000 22,000 Feet

WSB

Figure 16. Example of Ranked Management Areas.