

Phase 3 MnDOT Slope Vulnerability Assessments

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July 2020

Research Project
Final Report 2020-21

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Technical Report Documentation Page

1. Report No. MN 2020-21	2.	3. Recipients Accession No.	
4. Title and Subtitle Phase 3 MnDOT Slope Vulnerability Assessments		5. Report Date July 2020	
		6.	
7. Author(s) Jen Holmstadt, Nick Bradley, Nick Rodgers		8. Performing Organization Report No.	
9. Performing Organization Name and Address WSB & Associates, Inc. 701 Xenia Ave South, Suite 300 Golden Valley, MN 55416		10. Project/Task/Work Unit No.	
		11. Contract (C) or Grant (G) No. (C) 1035395	
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Office of Research & Innovation 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes http://mndot.gov/research/reports/2020/202021.pdf			
16. Abstract (Limit: 250 words) Phase 3 Slope Vulnerability Assessments is a continuation of Phases 1 and 2 previously conducted by WSB and MnDOT to determine the risk of slope failure along state highways. This phase includes 27 counties located in MnDOT districts 1, 2, 3, and 4. The three main components of the model are 1) identify past slope failures, 2) model the causative factors of past slope failures and how they vary locally, and 3) model the risk of new slope failures. Vulnerability factors, failure types, and model results reflect the geomorphology of this region. Vulnerability factors for the new study area include slope angle, terrain curvature, and water table depth. Field verification validates the model's capability of identifying risk in regions with different geology, geomorphology, and hydrology including deep-seated slides. Model results were ranked into four proposed risk management categories: action recommended, further evaluation, monitoring, and no action recommended. The risk estimation process for this phase is considered preliminary; further consideration of risk tolerance and consequence definitions should be conducted. Preliminary risk results indicate that 370 management areas, and 3% of the total area falls into the action recommended category under the proposed risk matrix. The results of this study are intended to be the first step of actions required in minimizing the effects of slope failure including expensive mitigation and maintenance repairs and threats to public safety.			
17. Document Analysis/Descriptors Slopes, Risk assessments, landslides, erosion, geotechnical engineering, geomorphology, geographic information systems, mathematical models		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 36	22. Price

PHASE 3 MNDOT SLOPE VULNERABILITY ASSESSMENTS

FINAL REPORT

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JULY 2020

Published by:

Minnesota Department of Transportation
Office of Research & Innovation
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

This report represents the results of research conducted by the authors and does not necessarily represent the views or policies of the Minnesota Department of Transportation or WSB & Associates, Inc. This report does not contain a standard or specified technique.

The authors, the Minnesota Department of Transportation, and WSB & Associates, Inc. do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to this report.

ACKNOWLEDGMENTS

WSB would like to acknowledge Raul Velasquez and Katie Fleming. Their contributions and guidance were invaluable. WSB would also like to acknowledge members of the Technical Advisory Panel for their time, ideas, and positive contributions to the final project: Nathan Bausman, James Bittmann, Chris Dulian, Shannon Foss, Bernard Izevbehai, Sara Johnson, Blake Nelson, Tony Runkel, Andrew Shinnfield, Amy Thorson, and Jennifer Wiltgen.

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EXECUTIVE SUMMARY

Introduction

Geohazards are environmental risks to infrastructure. Unstable slopes, floods, excessive precipitation, karst, and seismic events 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 that quantify risk factors and incorporate them into transportation asset management plans (TAMPs).

Phase 3 Slope Vulnerability Assessments is a continuation of Phases 1 and 2 previously completed by WSB and MnDOT to determine the risk of slope failure along state trunk highways. The results from previous phases objectively identified risk and prioritized areas recommended for management using a new Geographic Information Systems (GIS) model that can be implemented anywhere in the state. This model was refined for the Phase 3 study area to reflect the geomorphology in this part of the state. The results of this study are intended to be the first step of actions required in minimizing the effects of slope failure including expensive mitigation actions and public safety hazards.

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 provides 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

The Phase 3 study area has two major types of geomorphology: low relief and gradual slopes formed in the bed of Glacial Lake Agassiz in the northwest and far northern part of the state, and glacially eroded and deposited landforms such as hummocky terrain formed by receding glaciers in the northcentral part of the state. The area within the bounds of Glacial Lake Agassiz has relatively gradual relief, gentle slopes and an abundance of clay soil particles typically associated with lake beds. Parts of the study area outside of Glacial Lake Agassiz have higher relief, slope, and larger soil particle sizes.

GIS Model

The purpose of Task 3 was to refine the model developed in previous phases. Results from Phases 1 and 2 indicated that the most powerful slope failure models account for past slope failures. Therefore, WSB created a method for detecting past slope failures using geomorphology and elevation data.

Geomorphology was used to analyze terrain and landforms associated with slope failures; almost all 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 state highways. These areas reveal thousands of slope failures including, slides, lake shores, riverbanks, and surface erosion.

The past slope failures model was applied to the study area to ensure the same types of slope failures identified in Phases 1 and 2 were accounted for, as well as 1 additional type—deep-seated slides. Results from Phase 3 indicated that the same types of slope failures identified in Phases 1 and 2 were accounted for as well as hundreds of previously unrecorded deep-seated slides. Unlike Phases 1 and 2, most historical slope failures in the study were low-relief deep-seated rotational slides with low slope angles. Historical rotational slides were also common along river valleys with steeper slopes; these slides likely occurred at shallower depths and were also present in other regions of the state previously modeled. To a lesser extent, rotational slides were also present on the steep hummocky terrain in the central part of the study area and along lake shorelines.

Data on past slope failures were then incorporated into the second part of the model — model for causative factors. Slope failure models that incorporate data on potential causative factors provide for a much more powerful approach to identifying risk. WSB designed a GIS model that permits any vulnerability factor (potential causative factor) to be tested. This process is important for providing a non-biased study and results that are driven by data. Furthermore, this design recognizes that slope angle is not always the best indication of slope failure in every region and that other factors may be at play. For the Phase 3 study area, WSB designed new datasets derived from elevation data and post-processed them — distance from lakes and water table depth.

The final step of the model — model for new slope failures — was revised using the new input parameters statistically tested for the new study area. These input parameters were tested as part of the sensitivity analysis described in the next section. Once the input parameters were determined, the model computed a logistic regression, like Phases 1 and 2, to identify the risk of slope failure for the entire study area.

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 study area, capability of identifying past slope failures, site selection, and capability of identifying causative factors. The results from the sensitivity analysis revealed that:

- 10-meter elevation data resolution is most appropriate.
- A 0.5-mile buffer study area is sufficient.
- The geomorphic index model for identifying past failures initially overestimated the number and size of historic failures and was adjusted.
- The most important factor in site selection is including locations from both failed and non-failed areas.
- 3 vulnerability factors with greatest statistical strength were selected as model input parameters (slope, terrain curvature, and water table depth).

Once the sensitivity analysis was complete, the model was scripted and executed for 27 counties in 4 districts: Koochiching (District 1); Beltrami, Clearwater, Hubbard, Kittson, Lake of the Woods, Marshall, Norman, Pennington, Polk, Red Lake, and Roseau (District 2); Sherburne, Stearns, Todd, Wadena, and

Wright (District 3); and Becker, Clay, Douglas, Grant, Mahnommen, Otter Tail, Pope, Stevens, Traverse, and Wilkin (District 4). Draft PDF maps of preliminary model results were completed for these 27 counties.

Field Verification

The objective of this task was to field verify the model developed in previous tasks. This task included 5 site visits—one in District 3, two in District 2, and two in District 4. WSB chose these sites to determine the model’s capability of identifying slope failures in different regions of the state. The activities in this task served to validate the model and indicated it performs well for identifying different types of slope failures in regions with different geology, geomorphology, and hydrology.

Risk Estimation

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 proposed categories of risk management:

1. Site visit/action recommended* (A site specific study is recommended to determine the best mitigation strategy for the slope.)
2. Further evaluation* (A site specific study is recommended to more accurately classify and prioritize the slope.)
3. Monitoring* (Periodic checks on the slope are recommended.)
4. No further action recommended* (The risk is at an acceptable level and no action is necessary for this slope at this time.)

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. Proposed 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:

- Action Recommended*: 370 areas (3% of total study area)
- Further Evaluation*: 388 areas (1.5%)
- Monitoring*: 456 areas (8%)
- No Action*: the rest of the area of interest (87.5%)

NOTE: * Denotes preliminary terminology

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 dangers to public safety. In this study, the GIS model developed in previous phases was refined and implemented to identify slope vulnerability along

state trunk highways for 27 more counties. 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 27 counties in 4 districts were produced and proposed 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:

- Complete a robust risk estimation that incorporates the geomorphic vulnerabilities evaluated in this study with consequence definitions that will guide further action
- Field verification of the 370 sites with action 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 (Phase 4)

CHAPTER 1: INTRODUCTION

Phase 3 Slope Vulnerability Assessments is a continuation of Phases 1 and 2 previously completed by WSB and MnDOT to determine the risk of slope failure along state trunk highways. In previous phases, a new Geographic Information Systems (GIS) model was developed that can be implemented anywhere in the state. This model was refined to reflect the geomorphology of the Phase 3 study area. The model identifies risk and prioritizes areas recommended for management for 27 additional counties. Through completion of this project, 71 counties have been modeled across the southern half and northwestern part of the state.

This report outlines the methods and results of each task of this project as well as the recommended next steps. The results of this study are intended to be the first step of actions required in minimizing the effects of slope failure including expensive mitigation actions and threats to public safety. Below are the following tasks discussed in this report:

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

1.1 PHASES 1 AND 2 SUMMARY

Phases 1 and 2 were conducted from 2017 to 2019. In this study, a new GIS model was designed and implemented to identify slope vulnerability along trunk highways (Appendix A; Figure 1). The model provides an innovative, objective, and systematic approach to further understand geohazard risk to the state's transportation infrastructure. The model's capability of identifying slope vulnerability anywhere in the state with minimal data input was field verified. Final maps depicting slope vulnerability were produced for 44 counties and proposed management areas were ranked based on preliminary risk categories that provide useful information for district, county or city engineers, planners, project managers, and maintenance staff. The results can be incorporated into MnDOT's Transportation Asset Management Plan (TAMP) or as part of Georilla (MnDOT's internal GIS platform).

CHAPTER 2: TASK 2 LITERATURE REVIEW

The main objective of the literature review was to understand how the model designed in Phases 1 and 2 should be revised for the Phase 3 study area (Appendix A; Figure 2). Phases 1 and 2 methodologies, data requirements, and vulnerability factors were reviewed as well as documentation on historical landslides. The model designed in Phase 1 and 2 uses a combination of geomorphology and GIS. This combination provides a powerful approach that identifies and statistically tests the specific causes of slope failures with minimal data input. However, the geomorphology of Minnesota varies across the state, requiring that the model be redesigned to capture the most important vulnerability factors and expected failure types for each region.

2.1 GEOMORPHOLOGY

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 more thorough risk assessment evaluation than a single disciplinary approach because it accounts for the local variation of causative factors, how these factors change over time, and how they exacerbate one another.

The geomorphology of Phases 1 and 2 is different from the Phase 3 study area. Phase 1 included steep terrain and bedrock exposures characteristic of the Driftless Area (not affected by the last glaciation) in the southeastern part of the state. Phase 2 included a significant portion of the Minnesota River Valley in the southwestern and southcentral part of the state that contains steep slopes along river tributaries formed by the catastrophic drainage of Glacial Lake Minnesota. Phase 3 has two major types of geomorphology: low relief and gradual slopes formed in the bed of Glacial Lake Agassiz in the northwest and far north part of the state, and glacially eroded and deposited landforms such as hummocky terrain formed by receding glaciers in the northcentral part of the state.

The geomorphology of the Phase 3 study area is expected to form the basis of the model design. Therefore, review efforts began with understanding the geomorphology of this study area and how it compares to Phases 1 and 2. Review of the geomorphology provides valuable information for the vulnerable conditions, expected failure types, and new data requirements for the model.

2.1.1 Geomorphic History of Low Relief Glacial Lake Agassiz in Northwest Minnesota

Most of the Phase 3 study area is in the bed of Glacial Lake Agassiz (Appendix A; Figure 3). Glacial Lake Agassiz was a large glacial lake that formed during the onset of the last deglaciation (melting period) about 12,000 years ago (Teller et al., 2002). The weight of the glacier and the meltwater drainage caused water to flow north. Over time, the lake expanded toward the ice margin further north (Leverington et al., 2000). Eventually the lake overtopped its banks and meltwater flowed in several directions including carving an ancient riverbed through a topographic divide in what's now called Lake

Traverse. As the lake drained and water levels dropped, the main outlet switched back to flow toward the north along what is the present-day Red River of the North. As a result, Glacial Lake Agassiz left behind very gradual terrain with low topography.

This brief geomorphic history explains 1) the specific slope failure types expected in this region, 2) the relatively low elevation in this region, 3) the relatively gradual relief and slope and 4) the abundance of clay soil particle soils typically associated with lake beds. Expected failure types in this region include low relief deep-seated rotational slides that primarily occur along riverbanks. This type of failure is not as easily identifiable in the field as other types of slope failures such as mudslides and rockfalls with large deposits and well-formed scarps. Deep-seated slides have lower slope angle thresholds for failure compared to other types of failures that occur on steeper terrain. Certain conditions exacerbate the risk of these deep-seated slope failures including flooding, heavy rainfall, and human modifications to the landscape. Flooding in this region extends relatively far laterally since floodplains are not well defined in this low topographic environment. As a result, the flood waters have longer residence times causing soil saturation. The Glacial Lake Agassiz clay type in this region exacerbates the problem because it becomes particularly weak when saturated and has difficulty draining. This process is likely the primary cause of deep-seated failures in this region. Other vulnerable conditions include human modifications to the landscape, especially alterations that affect the water table. Groundwater extraction, irrigation, and changes to surface drainage also increase the risk of failure in this region.

2.1.2 Geomorphic History of Hummocky Terrain in Northcentral Minnesota

The rest of the Phase 3 study area not formed in the bed of Glacial Lake Agassiz occurs in the northcentral part of the state and has more variable topography. The northcentral part of the state has landforms associated with the retreat of the last glacial maximum (Carney and Mooers, 1998). As the glacier advanced, it eroded material in its path including boulders, rock, sand, and trees that become entrapped, ground up and mixed into the bottom of the ice (Lusardi and Dengler, 2017). When the ice melted and retreated, the debris entrapped in the glacier was deposited in several different ways. The deposition of this sediment and debris is responsible for forming the present-day gently rolling topography of this region. The low-lying depressions between these hills filled in with water and formed several lakes. As a result, this region has several hills and topographic highs.

This geomorphic history explains why several landforms are characteristic to this part of the study area only. Furthermore, this history explains why this region has higher elevation, relief, slope, and larger particle sizes including sand, silt, gravel, and boulders compared to other parts of the study area. Expected failure types in this region include rotational slides that may not be as deep-seated compared to other regions described above. Rotational slides are likely to occur along the steep but rolling hills of the hummocky terrain as well as lake shorelines. Translational slides may occur in areas with sandier soils. Heavy rainfall in this region may exacerbate the risk of slope failures by causing higher water levels in lakes and more frequent flooding.

CHAPTER 3: TASK 3 MODEL DESIGN

The purpose of Task 3 was to refine the model developed in Phases 1 and 2. This section describes the 3 main components of the model and how each will be refined to apply to the Phase 3 study area. Specifically, this section will discuss the methods used to design the new datasets required for the model.

3.1 HISTORICAL SLOPE FAILURES MODEL

Results from Phases 1 and 2 indicated that the most powerful slope failure models account for past slope failures. Therefore, WSB created a method for detecting past slope failures using geomorphology and elevation data. Geomorphology was used to analyze terrain and landforms associated with slope failures; almost all 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. These areas reveal thousands of slope failures including, slides, rockfalls, lake shores, riverbanks, and surface erosion.

The past slope failures model was applied to the study area to ensure that not only the same types of slope failures identified in Phases 1 and 2 were accounted for, but 1 additional type—deep-seated slides. Results from Phase 3 indicated that the same types of slope failures identified in Phases 1 and 2 are accounted for as well as hundreds of previously unrecorded deep-seated slides. Unlike Phases 1 and 2, most historical slope failures in the study were low-relief deep-seated rotational slides with low slope angles. Historical rotational slides were also common along river valleys with steeper slopes; these slides likely occurred at shallower depths and were also present in other regions of the state previously modeled. To a lesser extent, rotational slides were also present on the steep hummocky terrain in the central part of the study area and along lake shorelines. Historical translational slides were not as common in this region of the state; southern and eastern parts of the state are more prone to this failure type with longer and steeper slopes. Rockfalls were also not very common; generally, this part of the state has the least amount of bedrock exposure.

3.1.1 Deep-Seated Slides in Lake Agassiz Clay

The historical failures modeled for Phase 3 primarily consisted of rotational slides in different environments. The GIS algorithm designed to identify past slope failure was altered twice to accommodate for the slope failures in regions with different geomorphology. The algorithm designed for high relief hummocky terrain failures was only altered slightly since many of the slope failures in that region were similar to those previously modeled. Alterations had to account for the steep but relatively stable circular and elongated shaped rolling hills that had relatively high thresholds for failure compared to other areas of the state. However, the algorithm designed for the low relief Glacial Lake Agassiz area was altered in order to detect the subtle topographic signatures characteristic of deep-seated slope movement. Historical deep-seated slides with failure planes of 100 feet deep or more did not have obvious earth displacement characteristics on the surface compared to other failure types. For example,

these types of slope failures rarely had deposits at the toe of the slope or well-formed scarps. These failure types were also larger in size and did not have well-formed boundaries compared to rockfalls, translation slides, and rotational slides in steeper terrain. Verification of the model's ability to identify past slope failures are conducted in Task 5 (Sensitivity Analysis), where these results are checked with aerial photos, hillshade data, and historical known slope failures provided by previous studies.

3.2 CAUSATIVE FACTORS

Slope failure models provide a powerful approach to risk identification when they incorporate data on potential causative factors. WSB designed a GIS model that permits any vulnerability factor (potential causative factor) to be tested. This process is important for providing a non-biased study and results that are driven by data. Furthermore, this design recognizes that slope angle is not always the best indication of slope failure in every region and that other factors may be important.

WSB's model not only permits for any factor to be tested but is designed to incorporate how these factors vary locally. This design recognizes that a factor likely contributing to slope failure in one part of the state may not necessarily contribute to slope failures in another part. WSB's model for causative factors allows for multiple causative factors to be included in the model at once, and for each one to weigh appropriately according to its likely influence in causing slope failures.

In Phases 1 and 2, causative factors were modeled by a geostatistical process called Geographic Weighted Regression (GWR). GWR works by comparing a dependent variable with independent variables. In our study, the dependent variable is the geomorphic index for past slope failures which can be described as the surface roughness of a slope failure compared to its adjacent un-failed terrain and the independent variables are the causative factors. Specifically, GWR works by determining the relationships that dependent and independent variables have with one another. GWR accounts for failed and unfailed test sites. This removes an overemphasis of failed slopes that may have a specific set of attributes, providing a more accurate representation of the landscape and a control for the test. For example, if there is no relationship between terrain curvature and past slope failure data, then terrain curvature is probably not the most important parameter influencing slope failures for that specific area. In other words, terrain curvature is statistically similar in failed and unfailed locations and therefore not a strong local causative factor. If there is a correlation between these variables, then the independent variable is considered a local causative factor. If a vulnerability factor has no relationship to the dependent variable across the whole study area that factor will not be included as an input parameter in the final model. GWR is tested through trial and error, running through the process multiple times until the best results are produced (highest statistical strength). This process is executed in Task 5 (Sensitivity Analysis).

For the Phase 3 study area, WSB anticipated that some of the vulnerability factors passed through GWR will be different than those in Phases 1 and 2. The geology and geomorphology of the area suggest that saturation is a key factor in unstable slopes. To account for this, two new vulnerability factors were developed – water table depth and distance to lakes.

3.2.1 Water Table Depth

In this project, water table depth is defined as the difference in the ground elevation and the water table elevation. Water table depth was modeled using a hydrological spatial interpolation. A spatial interpolation is a process that estimates the values of an attribute from few known points. A hydrological spatial interpolation is a specific type of spatial interpolation used to estimate the values of a hydrological feature such as water table height. For this project, a spatial hydrological interpolation was conducted to estimate the water table height from few known points within the landscape where the water table is naturally at 0 depth (rivers and lakes). Water table elevation was computed first and then subtracted from the land elevation to calculate water table height (MN Department of Natural Resources, 2016). The model inputs include hydrography data on water bodies and rivers and elevation data (USGS). Known points comprised of land elevation data along the perimeters of water bodies and along rivers. The output of the model is water table height at 10-meter resolution where lower values are closer to the ground surface. Water table depth is important in slope processes because pore water acts as a driving force for failure. Slopes are stabilized by the friction between grains, water between grains reduces that friction, destabilizing the slope. The water table is directly related to the pore water pressure present in the slope and therefore the amount of destabilization.

3.2.2 Distance to Lakes

In this project, distance to lakes is defined as the Euclidian, or “straight line” distance from the nearest lakeshore. The Phase 3 study area has more lakes than Phase 1 and 2 studies areas. The areas immediately surrounding lakes tend to have saturated soils which can cause slope failure, as previously discussed. Furthermore, waves form on larger lakes and remove sediment from toes of slopes, increasing slope angle and destabilizing the slope.

3.2.3 Slope, Terrain Curvature, and Distance to Streams

Other vulnerability factors used in Phases 1 and 2 are likely to stay and include: slope angle, terrain curvature, and distance to streams. Distance to streams is the horizontal distance to the nearest channel bank. This factor accounts for channel bank slope failures that are common statewide. These datasets are expected to have no overlap and enhance the model’s predictive capability when they are all included in the model at once. Task 5 (Sensitivity Analysis) will test that prediction.

3.3 MODEL SLOPE FAILURE PROBABILITY

The final step in designing the model was determining the probability of slope failure for the entire study area. This includes the same logistic regression computation used in Phases 1 and 2:

$$p = \frac{e^z}{1 + e^z}$$

where p is the probability of a landslide and ranges from 0 to 1. Z is defined by the following:

$$z = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n$$

where $X_{1,2,\dots,n}$ are the independent variables, $\beta_{1,2,\dots,n}$ are the coefficient outputs from GWR, and β_0 is the intercept from GWR. The input parameters, test sites, and counties will change for Phase 3. This final stage of the model incorporates data from Parts 1 and 2 – Historical Slope Failures and Causative Factors.

CHAPTER 4: TASK 4 DATA COLLECTION

Task 4 of this project included data collection of the slope vulnerability factors. The data includes a combination of publicly available data and data derived from elevation data. This project includes the following slope vulnerability factors and their sources:

- Digital Elevation Models (DEM): United States Geological Survey (USGS)
- Slope angle (DEM-derived)
- Terrain curvature (DEM-derived)
- Proximity to streams: (Derived from DNR rivers and streams shapefile)
- Distance to lakes: (Derived from DNR lakes shapefile)
- Water table depth: (Derived from DNR lakes and streams shapefile and DEM)

It is important to note that in this project, vulnerability factors are all potential causative factors, whereas input parameters are statistically tested causative factors determined in later Tasks.

CHAPTER 5: TASK 5 SENSITIVITY ANALYSIS

Task 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.

5.1 PHASE 1 RECAP

The sensitivity analysis tested five factors:

- elevation data resolution,
- appropriate size of the study area (distance from road centerline),
- ability of the geomorphic index to detect past failures,
- testing various vulnerability factors in the model,
- testing site selection for the model.

Three of these factors — elevation resolution, size of the study area, and site selection methods were not adjusted for the Phase 3 study area and did not require further testing. However, they required different data collection and model preparation than for Phases 1 and 2. Recap of the Phase 1 and 2 results for these factors are described below in further detail.

5.1.1 Elevation Data Resolution

Spatial data resolution is an important quality control measure that affects the predictive accuracy of the model. The optimum level of resolution depends on the specific project objectives and scale of study. The model objectives in this study are to locate historic slope failures, determine the causative factors, and determine the risk of new slope failures. Elevation data at 1-meter, 3-meter, and 10-meter resolutions were tested to determine the most efficient resolution in locating and predicting slope failures at the district level (Holmstadt, Bradley, & Muehlbach, 2019).

In summary, the results indicated that 10-meter elevation resolution is most appropriate for the scale of the study. Smaller resolutions are time consuming, data intensive, and may be less accurate. They 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 3-meter resolution data. These “slopes” would need to be manually deleted from results. More information about the elevation resolution process please see Phase 1 Slope Vulnerability final report (Holmstadt et al., 2019).

Elevation data at 10-meter resolution was applied for the Phase 3 study area as well.

5.1.2 Appropriate Size of the Study Area

Selecting an appropriately sized study area (distance from road centerline) 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. In Phase 1, 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.

In summary, testing results indicated a 0.5-mile buffer is the most appropriately sized study area for this project, since it captures slope failures most likely to occur in Minnesota (Holmstadt et al., 2019).

A 0.5-mile study area was applied for the Phase 3 counties as well.

5.1.3 Testing Site Selection

Determining the number of testing sites for incorporation into the model was one of the final steps of the Phase 1 sensitivity analysis. Testing sites are a combination of verified historic 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. For Phase 1, WSB included over 30,000 sites (combination of verified and random) for incorporation into the model (Holmstadt et al., 2019).

In summary, testing results indicated 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 study area. If only failed areas were included in the model, the interpolated surfaces will inaccurately have high probabilities of failure.

Site selection for Phase 3 included similar methods—combination of verified and randomly generated sites, and a combination of failed and non-failed sites. The sites are single 10 by 10-meter grid cells and the total number of sites for Phase 3 is over 200,000, due to the larger scale of the study area. However, the number of sites per county is roughly the same as previous phases.

5.2 PHASE 3 TESTING HISTORIC FAILURE GEOMORPHIC INDEX

5.2.1 Phase 1 and 2 Recap

WSB created a method for detecting historic slope failures by searching for geomorphic features that resemble failed slopes using elevation data as the only input (Phases 1 and 2 Final Report). The accuracy of this measure was compared to known slope failure sites from other work and verified with aerial photos and hillshade data for Phases 1 and 2. In summary, thousands of slopes from Phases 1 and 2 study areas were identified as having high risk of historic slope failures. This historic slope failure model is powerful because it accounts for over a dozen slope failure types while identifying the most common failure type occurring in each region. For example, rockslides and falls were more common in southeastern Minnesota, but slides along tributary ravines were more common in southwestern Minnesota. Both slope failure types were objectively detected using the same historic slope failures algorithm. The objective of the Phase 3 historic slope failures sensitivity analysis was to determine if the algorithm from Phases 1 and 2 should be adjusted for the new study area.

5.2.2 Phase 3 Adjustments

The results from the previous Tasks of this project indicated that the historic slope failures model may need to be adjusted in order to account for the new geomorphology and expected failure types in the Phase 3 study area (Phase 3 Tasks 2-4 Report). The literature review identified that much of the study area is within Glacial Lake Agassiz, which has very low relief and gradual terrain with slope failures likely characterized by deep-seated slides. These deep-seated slides occurring beneath the land surface have subtle topographic signatures compared to other failure types that have more obvious signs of slope displacement on the surface (Appendix A; Figure 4). Other parts of the study area consisted of hummocky terrain characteristic of rolling hills with more relief than Glacial Lake Agassiz, but relatively stable slopes with shorter lengths and heights. The characteristics of these regions do not have obvious terrain features indicating historic failures have occurred. Therefore, the geomorphic index used to quantify topographic signatures such as past slope failures was adjusted to account for these more subtle slope failures while also ensuring that the same failure types in Phases 1 and 2 were also accounted.

The sensitivity analysis tested the accuracy of this adjusted historic slope failures model. As a control, the same algorithm developed in Phases 1 and 2 was implemented for the new study area but was expected to not fully capture the new failure types. The results show that the same algorithm underestimated the amount of slope failures in the Glacial Lake Agassiz region and overestimated the amount of slope failures in the region with hummocky terrain. It underestimated the slope failures in the Glacial Lake Agassiz region because it did not detect the subtle deep-seated slope failures known to occur along the cut banks of the Red River and its tributaries. Deep-seated slope failures in this river valley were characteristic of having short head scarps and very little to no slide deposits or other definite characteristics. The failures were also larger in area than typical translational or rotational slides. Some deep-seated slides also had what appeared to look like gradual waves in the mid-section of the slides instead of a bowl-shaped circular plane of failure. This feature is likely caused by slope movement occurring in series perpendicular to the river's flow. The model was adjusted to detect these subtle scarp features associated with deep-seated slides. For example, one changed parameter was lowering the size of the area used in detecting slope failures at any given location to more accurately pinpoint the smaller scarps.

Conversely, the model initially overestimated the slope failures occurring in the region with hummocky terrain because there were more features that falsely resembled slope failures. These features are part of the natural glacial terrain and constitute the types of depositional environments left behind by glaciers. The model was adjusted to correct for this error and to differentiate between glacially deposited landforms and slope failure deposits. This first part of the sensitivity analysis confirmed that the adjusted historic slope failures model was more accurate than the algorithm applied in Phases 1 and 2.

After the historic slope failure models were tested against the control, they were further tested to determine if they accurately identified locations with known slope failures from other reports and historic failures visible in aerial photos and hillshade data. The results from this part of the sensitivity

analysis indicated that the historic slope failure models accurately identified these locations with known failures. In general, there were less slope failures recorded from other reports in this region of the state compared to previously modeled regions. However, for the few that were previously reported, the model accurately identified these locations as historic failures. For example, one known failure was previously reported along a channel bank in Crookston, MN and the historic failures model accurately identified this location. Furthermore, less slope failures were visible in aerial photos compared to hillshade data due to the subtle nature of the failure types. Hillshade data therefore proved to be a better check on the historic slope failures model overall for the Phase 3 study area.

5.3 PHASE 3 TESTING VULNERABILITY FACTORS

The process of statistically testing all potential causative factors of slope failures was completed in this Task. Task 4 defined vulnerability factors as all potential causative factors, whereas input parameters are causative factors with the greatest statistical strength. Vulnerability factors are discarded as input parameters through a process of elimination based on statistical strength. This statistical indicator is the r-squared value results of geographic weighted regressions (GWR) (Tasks 2-4 Report). The following sections outline the results of this process in more detail.

5.3.1 Phase 1 Final Input Parameters

The sensitivity analysis results from Phase 1 narrowed down the number of vulnerability factors to just 4 final input parameters:

- Slope angle,
- Distance to streams,
- Distance to bedrock outcrops, and
- Terrain curvature

5.3.2 Phase 2 Final Input Parameters

The sensitivity analysis results from Phase 2 had two similar input parameters as Phase 1, but also two new ones to account for the new geomorphology of the study area:

- Slope angle
- Local relief
- Incision potential
- Terrain curvature

5.3.3 Phase 3 Vulnerability Factors

Data on the following vulnerability factors were collected/ derived and then processed for GWR:

- Slope angle – steepness of the hill

- Terrain curvature – shape of the slope (e.g. convex or concave)
- Distance to streams – horizontal distance to nearest stream bank
- Distance to lakes – horizontal distance to nearest lake
- Water table depth – depth to groundwater from land surface

Some datasets previously tested in Phases 1 and 2 were excluded from the sensitivity analysis of this phase. These datasets include bedrock outcrops, stream power index, topographic wetness index, incision potential, and local relief. They were excluded due to the model's ability to account for the spatial variance in these factors more efficiently with other datasets (e.g. terrain curvature and distance to streams) or because of the absence of certain datasets in the study area (bedrock outcrops and steep local relief).

5.3.4 Geographic Weighted Regression

As discussed in previous tasks, the execution of GWR is efficient because it not only permits more than one causative factor to be in the model at once, but it statistically tests how these causative factors vary locally. Furthermore, the trial and error process of GWR effectively eliminates potential causative factors that are either weak statistically or do not enhance the model.

GWR was computed with the vulnerability factors outlined above. First, each of the vulnerability factors were tested in the model individually, to test the accuracy of each variable in causing slope failures. Once the variables were tested separately, different combinations of the variables were tested with the aim of determining the best possible combination of variables that generates the greatest statistical strength.

When the vulnerability factors are tested independently in the model the following results emerge:

- Slope angle is the most important vulnerability factor with an average adjusted r-squared value of 0.650 for all 200,000 plus points across the study area (Appendix A; Table 1)
- Terrain curvature is second with an average adjusted r-squared value of 0.406
- Distance to streams had an average adjusted r-squared of 0.325
- Water table depth had an average adjusted r-squared value of 0.312
- Distance to lakes had an average adjusted r-squared value of 0.279

Water table depth had a higher than expected r-squared value, confirming that it will be incorporated as a model input parameter. Distance to streams had a lower than expected r-squared value, indicating that it is not the strongest predictor of slope failures. Water table elevation acts as a proxy for distance to streams because the water table will be high close to streams. The same result occurred for distance to lakes. Distance to lakes was expected to play a larger role in causing slope failures due to the high prevalence of lakes in this region of the state. One possible explanation for why it does not is that failures along lake shorelines may be better correlated with water table depth and not necessarily the fact that a lake is nearby.

When different combinations of the vulnerability factors are tested in the model the following results emerge:

- Slope and terrain curvature together had an average adjusted r-squared value of 0.714
- Slope and water table depth had an average adjusted r-squared value of 0.699
- Slope, terrain curvature, water table depth had an average adjusted r-squared of 0.734
- Slope, terrain curvature, water table depth, distance to streams had an average adjusted r-squared of 0.742
- Slope, terrain curvature, water table depth, distance to streams, distance to lakes had an average adjusted r-squared of 0.739

These results highlight an important benefit of GWR — more data is not necessarily better. Additions to the model may not enhance the results, in fact, sometimes they slightly weaken the results. This feature minimizes the amount of data in the model and facilitates a data-driven approach for identifying causative factors. For example, when distance to lakes is added as a fifth vulnerability factor to the model, it lowers the average adjusted r-squared value from 0.742 to 0.739. Furthermore, other additional vulnerability factors may slightly increase the average adjusted r-squared value only marginally, such as distance to streams.

5.3.5 Phase 3 Final Input Parameters

The sensitivity analysis results from Phase 3 narrowed down the number of vulnerability factors to just 3 final input parameters:

- Slope angle
- Water table depth
- Terrain curvature

The two input parameters from Phases 1 and 2—slope angle and terrain curvature—will remain in the model. The new input parameter, water table depth, is included because it captures landforms important for the Phase 3 study area—riverbanks, floodplains, and lake shorelines susceptible to deep-seated failures (Appendix A; Figures 5-6).

5.4 SUMMARY

WSB tested five components of the model: resolution of spatial data, size of the study area, historic slope failure detection, methods of site selection, and variable combinations. The sensitivity analysis reveals that:

- The geomorphic index for identifying historic failures was altered and tested to account for one additional failure type— deep-seated failures with subtle topographic features
- The most important factor in site selection is including locations from both failed and non-failed areas

- Statistical tests identified water table depth as the new model input parameter for Phase 3 Counties.

CHAPTER 6: TASK 6 DRAFT PDF MAPS AND RISK RANKING

Task 6, Produce Maps and Rank Lists was completed for 27 counties in 3 districts. In this Task, the model was refined, scripted, and executed for the following counties: Beltrami, Clearwater, Hubbard, Kittson, Koochiching, Lake of the Woods, Marshall, Norman, Pennington, Polk, Red Lake, Roseau (District 2); Sherburne, Stearns, Todd, Wadena, Wright (District 3); Becker, Clay, Douglas, Grant, Mahnomen, Otter Tail, Pope, Stevens, Traverse, and Wilkin (District 4). The deliverables include draft maps of the 27 counties, draft shapefiles, and rasters. The following sections describe the methodology and results of this Task.

6.1 DRAFT PDF MAPS

WSB executed the model to produce slope vulnerability results. For this project, vulnerability is defined as likelihood of failure, and risk is defined as likelihood multiplied by consequence. Figure 7 shows an example of the draft maps and Figure 8 shows a zoomed in example of the vulnerability output (Appendix A). The vulnerability results were then utilized in a risk ranking procedure, described in the next section.

6.2 RISK RANKING

6.2.1 Methodology

Risk is the product of probability and consequence ($\text{Probability} \times \text{Consequence} = \text{Risk}$); 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 2.

The matrix has 4 proposed categories of risk management:

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

*Preliminary terminology for proposed risk management categories.

Definitions for the preliminary terminology are presented below:

1. Site visit / action recommended – A site specific study is recommended to determine the best mitigation strategy for the slope.
2. Further evaluation – A site specific study is recommended to more accurately classify and prioritize the slope.
3. Monitoring – Periodic checks on the slope are recommended.

4. No further action recommended – The risk is at an acceptable level and no action is necessary for this slope at this time.

Risk ranking was conducted at the Management Area scale. Management areas are regions with similar risk scores. This aggregates the large number of individual slopes into a workable number.

Management areas were delineated in GIS. Probability was delineated based on separating the slope vulnerability results into 3 categories: high ($p > 0.9999$), medium ($0.9995 < p < 0.9999$), and low ($p < 0.9995$) likelihood of failure. Consequence was delineated based on proximity to roads and urban vs. non-urban areas. Future field verification can further refine how to define vulnerability and consequence.

6.2.2 Results

The draft risk rankings successfully transformed tens of thousands of slopes into hundreds of management areas. The full list of management areas ranked by risk is presented in Table 3 of the Appendix. The total number of areas and their total areas in square miles for each of the different rankings are as follows:

- Action Recommended*: 370 areas (110 mi²)
- Further Evaluation*: 388 areas (56 mi²)
- Monitoring*: 456 areas (294 mi²)
- No Action*: the rest of the area of interest (3164 mi²)

The management areas range in size from a few thousand square feet to over one million square feet. The percent of the entire domain area that each risk ranking covers is below:

- Action Recommended*: 3%
- Further Evaluation*: 1.5%
- Monitoring*: 8%
- No Action*: 87.5%

Although draft results include many management areas, the majority of the study area falls into the No Action category.

CHAPTER 7: TASK 7 FIELD VERIFICATION

WSB completed Task 7 of this project—Field Verification. The objective of Task 7 was to field verify the historic slope failure model developed in previous tasks and investigate what causative factors are creating slope failure in the area. This task included 5 site visits—one in District 3, two in District 2, and two in District 4. WSB chose these sites to determine the model’s capability of identifying slope failures in different regions of the state. The following sections outline the methods, results, and conclusions of this task.

7.1 METHODS

This section outlines the model’s progress prior to the field visits, rationale for site selection, and the methods and equipment used during the visits.

7.1.1 Model Progress Prior to Visit

Task 7 was completed between tasks 4 and 5, in case that the model needed to be redesigned or adjusted. Prior to the field visits, only the first part of the model was executed— Part 1 (Model Historical Failures). Model Part 1 objectively identifies all areas of past slope failures, both where slopes are actively failing and where slopes have previously failed but are currently more stable. Data on past slope failures enhances predictive modeling. Predictive modeling was completed in Task 6 (Final Risk Maps).

7.1.2 Rationale for Site Selection

These sites not only had a high likelihood of past failure but are in different districts to ensure the entire area of Phase 3 is considered in model development.

Site 1 – MN241 St. Michael, Wright County, District 3

Site 1 is located east of St. Michael, Minnesota in District 3 (Appendix A; Figure 9). It is within the Mississippi River basin along the north side of the Crow River where a cut bank is between the river and the road. Elevation data reveal ravines cutting up from the river to near the road.

Site 2 – MN32 Red Lake Falls, Red Lake County, District 2

Site 2 is located east of Red Lake Falls, Minnesota in District 2 (Appendix A; Figure 10). It is within the Red River basin along the north side of the Red Lake River where the road crosses the river at a cut bank. Lidar data show slides cutting up from the river to previously undisturbed land.

Site 3 – MN32 Red Lake Falls, Red Lake County, District 2

Site 3 is located east of Red Lake Falls, Minnesota in District 2 (Appendix A; Figure 11). It is 1.5 miles west on MN32 from Site 2. This site was chosen because aerial photos reveal a slide on the bank of the river, near the road.

Site 4 – I-94 Fergus Falls, Otter Tail County, District 4

Site 4 is located north of Fergus Falls, Minnesota in District 4 (Appendix A; Figure 12). It is within the Red River basin where the Pelican River exits a culvert under I-94. This site was not selected beforehand, rather the team saw a distinct headscarp from the road and decided to make an additional stop.

Site 5 – I-94 Fergus Falls, Otter Tail County, District 4

Site 5 is located west of Fergus Falls, Minnesota in District 4 (Appendix A; Figure 13). It is within the Red River basin along the east side of the Otter Tail River where multiple cut banks near the road.

7.1.3 Equipment

The methods for this task 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 (Halo XL 450)
- Geomorphic, geologic, and hydrologic observations (field forms and photos with Datafi web service and iPad)

The 5 site visits were completed on November 19th and 20th, 2019.

7.2 RESULTS

The model's capability of identifying areas at risk was validated in the field. All sites are active and are supported with evidence from the field. The following sub-sections describe the field results in more detail.

7.2.1 Site 1 – MN241 St. Michael, Wright County, District 3

The field results confirm that Site 1 is an active river cut bank and ravine caused by a culvert passing below MN241 (Appendix A; Figures 14-17). The ravine has very steep walls near the river but as it approaches the road, the slopes become less extreme. The nearest active erosion to the road is around 50 feet away. The slopes immediately adjacent to the road are gently sloping and highly vegetated.

Evidence of active erosion includes the following:

- Headscarps along both riverbank and ravine walls
- Exposed roots from soil removal
- Recently fallen trees

7.2.2 Site 2 – MN32 Red Lake Falls, Red Lake County, District 2

The field results confirm that Site 2 is an active river cut bank and near where MN32 crosses the Red Lake River (Appendix A; Figures 18-20). The riverbank has very steep walls on either side of the bridge,

but vegetation and human placed roughness have reduced erosion under the bridge and have kept the slopes shallower.

Evidence of active erosion includes the following:

- Steep slopes on riverbanks
- Recently fallen trees

7.2.3 Site 3 – MN32 Red Lake Falls, Red Lake County, District 3

The field results confirm that Site 3 is an active river cut bank and near where MN32 crosses the Red Lake River (Appendix A; Figures 21-22). Like Site 2, there are very steep slopes along the river on either side of the bridge. This site has vegetation and added roughness under the bridge as well, however there are small headscarps forming to the north side of the bridge.

Evidence of active erosion includes the following:

- Headscarps along riverbank
- Exposed roots from soil removal
- Recently fallen trees

7.2.4 Site 4 – I-94 Fergus Falls, Otter Tail County, District 4

The field results confirm that Site 4 is an active valley wall with erosion caused by a culvert passing below I-94 (Appendix A; Figures 23-25). South of the culvert exit is a very steep wall with evidence of recent failure. The culvert structure is concrete, but a gully is actively forming on the southern side of it, expanding toward the road.

Evidence of active erosion includes the following:

- Headscarps along valley wall
- Exposed roots from soil removal
- Recently fallen trees
- Exposed soil

7.2.5 Site 5 – I-94 Fergus Falls, Otter Tail County, District 4

The field results confirm multiple active river cut banks at Site 5 (Appendix A; Figures 26-28). The northern cut bank (Site 5a) has both headscarps along it and gullies growing from the river towards the road. The southern cut bank (Site 5b) has multiple headscarps along it and is closer to the road than the northern cut bank. The area is highly vegetated; however, erosion is still occurring.

Evidence of active erosion includes the following:

- Headscarps along both riverbank and ravine walls
- Exposed roots from soil removal

- Recently fallen trees
- Gully formation

7.3 CONCLUSIONS

Field verification results suggested that the historic failures model was overestimating the number and scale of the slope failures in the Phase 3 study area. Therefore, the model was updated by increasing the threshold on the past failure geomorphic index and decreasing the aggregation distance for slopes. Increasing the roughness threshold means that only areas with the highest likelihood of past failure are considered historic slope failures. Decreasing the aggregation distance prevents separate slope failures from being grouped together as one failure. The results of these two changes are more representative of what was observed in the field (Appendix A; Figure 29).

CHAPTER 8: TASK 8 FINAL REPORT, FINAL 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 proposed 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: Beltrami, Clearwater, Hubbard, Kittson, Koochiching, Lake of the Woods, Marshall, Norman, Pennington, Polk, Red Lake, and Roseau (District 2); Sherburne, Stearns, Todd, Wadena, and Wright (District 3); and Becker, Clay, Douglas, Grant, Mahnomon, Otter Tail, Pope, Stevens, Traverse, and Wilkin (District 4). In Phase 2, the naming conventions of the management areas were modified. In Phase 2, management areas were labeled as “proposed management areas” and the titles of the four categories of risk management were marked as preliminary titles. These changes are to reflect the preliminary nature of the consequence definition and are continued into Phase 3.

8.2 VULNERABILITY RASTER FILES

WSB combined the vulnerability final outputs from each of the 27 counties into one raster file that has the appropriate symbology, correct size study area, and most updated roads jurisdiction. The file is readily available for use in any ArcGIS platform.

8.3 PROPOSED MANAGEMENT AREAS SHAPEFILES

WSB combined the proposed management areas final outputs from each of the 27 counties into one shapefile that has the appropriate symbology, correct size of study area, and most updated roads jurisdiction. The file is readily available for use in any ArcGIS platform.

8.4 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 study area had a value. When running the model, MnDOT will be prompted with instructions on how to use it.

8.5 RECOMMENDED NEXT STEPS

The results of this study are intended to be 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, the GIS model developed in previous phases was refined and implemented to identify slope vulnerability along state trunk highways for 27 more counties. The model’s capability of identifying slope vulnerability

anywhere in the Phase 3 study area with minimal data input was field verified. Final maps depicting slope vulnerability for 27 counties in 4 districts were produced and proposed 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:

- Complete a robust risk estimation that incorporates the geomorphic vulnerabilities evaluated in this study with consequence definitions that will guide further action
- Field verification of the 370 sites with action 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 (Phase 4)

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