# DEVELOPMENT OF A GIS-BASED LANDSLIDE MANAGEMENT SYSTEM FOR WESTERN MANITOBA'S HIGHWAY NETWORK

BY

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A Thesis Submitted to
the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements for the Degree of

**MASTER OF SCIENCE**

**Department of Civil Engineering**
University of Manitoba,
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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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# DEVELOPMENT OF A GIS-BASED LANDSLIDE MANAGEMENT SYSTEM FOR WESTERN MANITOBA'S HIGHWAY NETWORK

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

MASTER OF SCIENCE

# Abstract

Slope failures are a significant issue in the sedimentary clay shales of western Manitoba. Fluvial induced erosion by under fit rivers of the glacial Lake Agassiz have carved into the Odanah and Millwood clay shales in many regions, exposing them along valley walls in many areas of Western Manitoba. Manitoba's highways and surrounding infrastructure are at risk in these areas, where significant damage and hazards to the public due to landslides are a large concern. In today's age of proactive risk assessment it has become necessary to develop a management approach to optimize allocation of resources to highway infrastructure maintenance and rehabilitation in these areas.

Four previously investigated and documented failures are the focus for developing a predictive model of which environmental and geological attributes tend to lead to failure. In the fall of 2006, six sites were visited where the Saskatchewan risk assessment system (Kelly *et al.* 2004) was applied to establish probability, consequence and risk factors for each site. Results from the tour were used as the basis for developing a Geographic Information System (GIS) model to predict risk of failure.

Development of the Manitoba Infrastructure and Transportation Risk Management System (MITRMS) includes mathematical processing of digital elevation models (DEMs), allocating buffer distances around water bodies and highway infrastructure, selection of a representative statistical distribution to describe the occurrence level of grade in spatially selected regions, and reviewing highway designation and their public dependency. By combining a GIS and manually observed site specific information, a prioritized list of potentially hazardous landslide sites is created along western Manitoba's highway network.

# Acknowledgements

First are foremost I would like to thank my advisor, Dr. James Blatz. His guidance and overwhelming confidence in my efforts helped me to take this research to unforeseen levels. Quick feedback and thought provoking discussions kept me on track and always in pursuit of the best solution.

Secondly I'd like to thank all those who helped during site assessment tours. James Blatz, Tony Ng, Said Kass, Jeff Tutkaluk, Jorge Antunes, and Allen Kelly who formed the spring assessment committee and MIT regional staff Chuck Lund, Doug Struthers, Scott Lawrence, and Stacy McBride who also played a significant role. Additional appreciation goes to Scott Lawrence who also aided during the verification trip. Without their efforts, this research could not have began and concluded as it did.

I'd also like to acknowledge the Department of Civil Engineering and Intergraph support staff. A countless number of times they helped avert potential software disasters. Their timely efforts and technical product knowledge proved extremely valuable.

Lastly, I'd like to thank my close friends and family. Between mood swings, absences, relapses, compulsive napping, stress induced ridiculousness, and all around good times, they were always there to support me in one form or another. Advice and a lent ear during occasional difficult times helped to indefinable levels; you know exactly who you are.

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# List of Symbols and Abbreviations

| | |
|---|---|
| ASI | After Site Investigation |
| AADT | Annual Average Daily Traffic |
| BSI | Before Site Investigation |
| CF | Consequence Factor |
| DEM | Digital Elevation Model |
| ESC | Eroded Slope Complex |
| FS | Factor of Safety |
| FC | Functional Classification |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| ITS | Intelligent Transportation Systems |
| MIT | Manitoba Infrastructure and Transportation |
| MITRMS | Manitoba Infrastructure and Transportation Risk Management System |
| MCS | Monte Carlo Simulation |
| *pdf* | Probability Density Function |
| PF | Probability Factor |
| PR | Provincial Roadway |
| PTH | Provincial Trunk Highway |
| QRS | Quantitative Risk Assessment |
| RMF | Riding Mountain Formation |
| RF | Risk Factor |
| SDHT | Saskatchewan Highways and Transportation |
| SDHTRMS | Saskatchewan Highways and Transportation Risk Management System |
| SPT | Standard Penetration Test |
| UM | University of Manitoba |
| WC | Weight Classification |
| $\Gamma(k)$ | Gamma Function (gamma *pdf*) |
| $\theta$ | Scale Parameter (gamma *pdf*) |
| $k$ | Shape Parameter (gamma *pdf*) |
| $\mu$ | Mean (normal *pdf*) |
| $\sigma$ | Standard Deviation (normal *pdf*) |
| X | Random Variable |
| Z | Normalized Random Variable |

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Chapter Two – Literature Review

# 1 Introduction

## 1.1 General Overview

Long term performance of infrastructure is a rising concern for many engineers and governments, where neglect of our current infrastructure is causing concerns regarding public safety. Design lifespan can be reduced by decreasing capital expenditure, which in turn increases long term maintenance and potential for costly future rehabilitation. Life expectancy of infrastructure follows suit; it is sometimes more economical to decrease the design life and increase periodic maintenance thereafter due to restrictions in initial capital budget. Geotechnical considerations are a subsection of civil engineering where design life is largely dictated by numerous material uncertainties and varying stratigraphic conditions between sites. Roadway foundations require further consideration since they span many kilometers through highly variable geological conditions.

Construction of roadways have become routine; excavate native material, install drainage, apply base and sub-base in lifts, and apply concrete and asphalt overlay at a two to four percent transverse grade. In hummocky terrain and areas of moderate to high relief, embankments are necessary to ensure proper drainage requirements are met for hydraulic, freeze/thaw, and stability concerns. In areas of dense fluvial waterways, crossings are necessary but sparse due to costs, placing substantial importance on the integrity of roadway and bridge structures. Importance increases exponentially with increasing valley size and relief as these areas are more hazardous for slope instabilities and ground movements.

The sedimentary basin of western Manitoba contains several slope stability concerns in proximity to highway and public infrastructure. Four major sites include: PR259 & Assiniboine River, PTH41 & Assiniboine River, PR478 & Assiniboine River, and PTH83 & Shell River, shown in Figure 1.1. Methods of rehabilitation are reactionary, that is, only when noticeable slope movements are observed is a study group dispatched to investigate. These groups generally require a large amount of available resources to properly investigate and recommend desirable rehabilitative methods and are subject to untimely bureaucracy, lengthening the period at which mitigative measures can be implemented.

Several components are necessary to investigate and quantify isolated slope failures. Detailed site investigations are required to assess stability of naturally occurring slopes or engineered embankments by drilling boreholes, conducting numerous field and lab tests, and installing field monitoring instruments such as slope inclinometers and piezometers. These measures generally lead to the development of numerical models containing spatially averaged soil strength characteristics. Outputs from these models include factors of safety (FS) that numerically quantify instability. By varying boundary and initial conditions such as piezometric water surface and mitigative measures, the cause of instability can be identified accompanied by determination of a preferred response method. Although site investigations are invaluable in repairing slope instabilities, they take a considerable amount of time to plan and carry out, and can range in completion from several months to years following initial mass slide movements.

The Manitoba Infrastructure and Transportation (MIT) materials branch is responsible for overseeing geotechnical considerations for all provincial trunk highway (PTH) and provincial roadway (PR) construction, maintenance and rehabilitation, which includes short- and long-term stability of their embankments. With several precarious slope instability locations in the sedimentary basin of western Manitoba it has become necessary to develop a risk management system to categorize and prioritize potential landslide instabilities. MIT has enlisted the University of Manitoba (UM) Department of Civil Engineering to undertake research to develop a predictive risk management tool using a Geographic Information System (GIS), modeled after the Saskatchewan Highways and Transportation (SDHT) risk management system (Kelly *et. al.* 2004).

Risk management is quickly becoming an expected planning tool for government agencies. In the broadest sense risk management takes several inputs that aid in determining the risk of a particular consequence, providing a prioritized output where resources can be allocated in a much simpler and systematic fashion. Inclusion of GIS provides for investigation where a preliminary list of sites can be developed for personnel to assess them manually. GIS provides a modern and innovative tool that can be extrapolated across an entire region, and eventually the entire province, to begin prioritizing resources by incorporating qualitative and quantitative analysis of geospatial systems and engineering judgment.

## 1.2 Hypothesis and Objectives

Hypothesis:

"Geographic Information Systems can be used as a predictive tool for assessing, ranking and prioritizing landslide risk along highway embankments in western Manitoba using available geospatial data"

In general, risk is the combination of probability and consequence where for these purposes probability and consequence are numerically meaningful values selected from a predetermined scale indicating the probability of an embankment failing and the consequence should such a failure occur. Consequence can be further divided into exposure and elements at risk, where exposure reflects the vulnerability of the designed user to a series of particular elements.

It is difficult to pinpoint what environmental conditions are specifically required to induce slope failure, and development of an exact criterion is near impossible. Geospatial information manipulated and observed through GIS software can instead provide insight and develop a statistical expectancy of what is required for slope failures to occur. Through this model, a system can be developed to compare an unlimited number of sites against it, and within some variance, quantify failure probability. A consequence factor determined by spatially observable attributes such as average annual daily traffic (AADT), length of shortest detour, and roadway classification, places significance on areas subject to higher consequence. The resulting product is a prioritized list of sites for assessment and remediation at crossings in the western Manitoba sedimentary basin.

The objectives of this research are:

a) Manually assess four known failure sites in the sedimentary basin of western Manitoba using a risk management system (Kelly *et al.* 2004).

b) Use the four assessed sites to qualitatively develop a failure model using GIS software and available geospatial information.

c) Refine and advance existing risk management approaches to suit and encompass further complexities observed in the sedimentary basin of western Manitoba.

d) Develop a preliminary list of crossings in western Manitoba's sedimentary basin using a proactive GIS risk management tool.

Results of this research will provide a risk management system for assessing crossings in the sedimentary basin of western Manitoba and will also provide essential tools for expanding this system to further geological regions. This research is meant to further advance risk management of geotechnical phenomena using transportation engineering and GIS-based techniques. It is no way meant to claim to advance or refine either of these fields.

## 1.3 General Description of Testing and Verification

It is critical to understand that management of geotechnical phenomena only provides a tool for assessing and prioritizing mobilization of resources and remediation. When applying this tool it will be necessary to assess higher risk sites individually by visiting the sites to improve the data and information for a specific site.

A significant portion of this project relies on GIS experimentation and verification. GeoMedia Professional has been selected as the GIS processing software because it is currently being used by MIT. Computational requirements dictate that two software expansions are required for the analytical methods developed in this work: GeoMedia Grid for processing large amounts of point data and developing raster images and GeoMedia Transportation Manager for automated network analysis of detour lengths, shortest direct distances, and attribute manipulations.

The first phase of this project consisted of gathering site information on four known failure sites and compiling four project binders. Time was spent at the MIT head office gathering site specific information including: borehole logs, instrumentation results, documentation, and images. Each binder begins with an executive summary discussing the most up-to-date knowledge of each site and provides preliminary insight into each site's probability and consequence factors. This phase was completed with a group of qualified personnel assessing each site with the SDHT model.

Development of the GIS system began with gathering data for several geospatial layers: bedrock geology, soils geology, digital elevation models (DEMs), land use, roadways, water bodies, and 2m resolution aerial photos. These layers were supplied in varying GIS based extensions. Phase two of the project included spending time cross-referencing data points and geometries for layer alignment within GeoMedia.

Phase three of the project consisted of a slope hazards tour in the fall of 2006. A team of individuals were gathered to form a core assessment committee and were instructed to assess each of the four selected failure sites visited. These assessments would form the basis for calibrating the GIS model. A handheld Global Positioning System (GPS) unit was used at each site to draw a cross-section for comparison with that of the DEM. Completion of the fall slope hazards was the final step to complete the four project binders.

Phase four consisted of design and conceptualization of probability and consequence factors. This included updating the SDHT model to consist of additional qualitative factors, including: outcropping of clay shale bedrock, past mitigative measures, and continued slope movements in the case of probability, and shortest detour length, functional highway classification, roadway weight classification, AADT, and proximity to infrastructure, in the case of consequences. Failure model development was done by overlapping geospatial layers at known failure sites, and developing a probability density function of maximum slope over the region. This formed the basis for all future queries pertaining to a site's probability of failing.

The final phase of the project included implementation of the GIS model. The GIS based risk management model was applied over the sedimentary basin of western Manitoba to output a list of sites according to risk level and appropriate response. Three sites were visited and assessed by a smaller committee using the hands-on portion of the risk management model to compare and verify results.

## 1.4 Organization of Thesis

This thesis is organized as follows: Chapter 2 presents a background of risk management applications in geotechnical engineering and a literature review of relevant research and theories in the field of GIS based geotechnical risk assessment. Chapter 3 is a review of the Saskatchewan Highways and Transportation Risk Management System (SDHTRMS) which is used as a basis for this work, discussing its value in geotechnical risk management and its potential for expansion to other regions and advancing its applicability. Chapter 4 is a summary of the fall 2006 slope hazards tour; discussing results and potential for real-time inclusion in the probability and consequence factor development. Chapter 5 discusses conceptualization of the GIS based failure model and theory behind using GIS for accurate probability and consequence factor analysis. Chapter 6 is a description of how to use and apply the GIS risk management model and results of its application over the research extents. Chapter

7 presents verification during a spring assessment trip, and finally Chapter 8 presents conclusions and recommendations for future work.

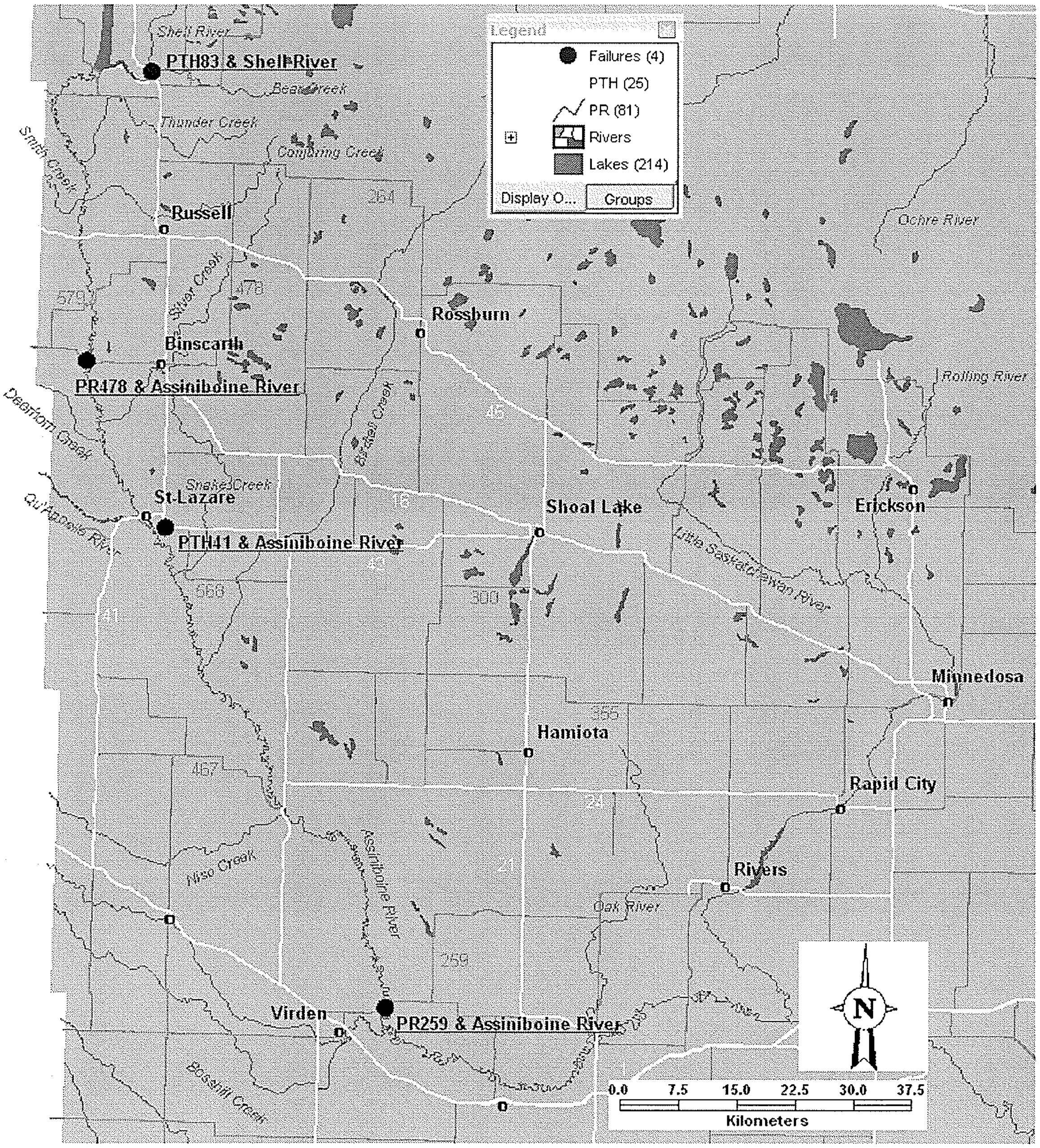

Figure 1.1 - Map view of western Manitoba

# 2 Literature Review

## 2.1 Introduction

GIS was originally used to compile roadway and geological maps and to calculate spatial properties such as distances and areas. By introducing GPS, real-time spatial data and aerial images could be imported and overlapped. Recent advancement in computational capacity of personal computers has allowed GIS software developers to enhance capability, permitting comprehensive query based calculations. Users can manipulate, summarize, and isolate data or geospatial features in order to segregate areas of relevance or importance for any application. Additions such as spatial analysis and functional attributes allow for quick computations of varying complexity that permits users to integrate risk management algorithms into GIS software.

A review of existing literature has been conducted in order to present previous research that is relevant to the use of GIS in risk management of geotechnical engineering phenomena. The review is divided into sections including: Application of Risk Management in Geotechnical Engineering, Application of Geographic Information Systems as Tools in Geotechnical Engineering, Probabilistic Quantification of Slope Failure, Integration of Slope Failure Models and Geographic Information Systems, and Geographic Information Systems as Proactive Risk Management Tools.

### 2.1.1 The Millwood and Odanah Clay Shales

The bedrock in western Manitoba is largely comprised of the Riding Mountain and Turtle Mountain Formations. Concentration is placed on the Riding Mountain Formation (RMF) that includes the soft cretaceous Millwood and Odanah clay shale members and have been defined as the geological extents of this research. Any information stated about the Millwood and Odanah Members are available in Bannatyne (1970).

The Millwood Member consists of bentonitic shale composed largely of partly swelling montmorillonite. Thickness varies between 25m in the Pembina Mountain region to over 150m in the St. Lazare-Roblin areas. The member outcrops along the Manitoba Escarpment and Souris, Pembina and Assiniboine River valleys, generally under a cover of hard Odanah shale as shown in Figures 2.1 and 2.3. Near the contact with the overlying Odanah Member, olive-green waxy bentonite occurs in thin bands, ranging between 20 and 25cm thick with few on the order of 60 cm. These bands are highly susceptible to shearing during periods of higher precipitation and infiltration.

The Odanah Member consists of light, hard siliceous shale and occurs as both fissile and thick massive beds that are brittle and break with a subconchoidal fracture. Thin interbeds of bentonite and bentonitic shale are present; mostly within the lower 30m. Outcrops of the Odanah shale are frequent in southwest Manitoba wherever the glacial drift is moderately thin, along the Manitoba Escarpment, and in river valleys as shown in Figures 2.2 and 2.3. In the lower part of the member in the eastern RMF area, precise determination of the Millwood-Odanah contact is difficult, likely due to higher illite-montmorillonite content. An increase in montmorillonite content is also present at higher elevations within the member near Onanole, this results in an increase of softer shale, somewhat resembling parts of the Millwood Member when wet.

### 2.1.2 Slope Instability and the Weather and Geology of Western Manitoba

Slope instabilities of varying magnitudes are common in any region and are a function of geological evolution. Observable environmental triggers of slope instability include: toe erosion, scour, piezometric conditions, earthquakes, crest loading, tension cracks, compression ridges, headscarp, seepage out the face of a slope, and damage to vegetation and can be quantified by a variety of means (Ferris 2003).

The geology of western Manitoba is dominated by glacial deposition, alluvial deposits, and cretaceous and tertiary sedimentary bedrock, subsequently carved by fluvial erosion by the receding Lake Agassiz. Vegetative cover is abundant except in areas of outcropping Odanah and Millwood clay shales, where plant growth is limited. Large areas of flat fertile land characterize this area as a portion of the Canadian prairies, where agriculture flourishes because of warm summers and high amounts of precipitation. High precipitation is the most common trigger of instability. In August of 1999 following a record setting precipitation event, several damaging failures took place; four yielded immediate response measures. The Millwood and Odanah clay shales have also been attributed to several failures in areas of outcropping. During rainfall events in these areas, where vegetative cover is sparse, infiltration causes fluctuation in piezometric pressures, where soft bentonitic layers begin swelling, encouraging well defined shear planes and decreasing resistive forces against slope failure. Also, higher montmorillonite content within the Odanah Member lower inter-particle molecular forces, leading to further instabilities.

Many years of fluvial erosion by major rivers and medium sized ravines and creeks have deposited complex clayey soils along their banks and valley walls, creating highly variant underlying stratigraphy across relatively small regions. Manitoba Mines has characterized portions of the valley floor and walls where soil disturbance caused by fluvial erosion as Eroded Slope Complex (ESC) in their surficial soils terrain map, as seen in Figure 2.4. Though these areas by themselves are not indicative of instability, when coupled with removed toe material or higher slope angles, they have an increased susceptibility to failure.

### 2.1.3 History of Slope Instability in Western Manitoba

During the last ice age, glacial Lake Agassiz covered a significant portion of Manitoba and Saskatchewan, and parts of Ontario as shown in Figure 2.5. As the Laurentide Ice Sheet receded to the north, several valleys were cut by fluvial erosion through glacially deposited clays and tills and into cretaceous and tertiary sediments and bedrock. The Assiniboine, Souris, Pembina, Qu'Appelle, and Shell River valleys are remnants of these once large rivers and are now underfit. That is, the rivers that currently reside within the walls were once significantly larger. These river valley walls have been the location of recurring slope instabilities and although this is a natural process, near major infrastructure it poses severe hazards.

In terms of the four assessed failure sites, instabilities have been documented since their construction[1]. Reports obtained from MIT suggest that most slope movements are deep and retrogressive in nature. Site investigations have identified various causes of slope movements and have recommended rehabilitative measures that have been implemented at select sites. Instrumentation is monitored on a semi-regular basis with

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[1] Documentation of these instabilities is available in several internal reports at Manitoba Infrastructure and Transportation

frequent abandonment due to continued movements leading to instrumentation failure. Surrounding environmental conditions vary across the region, making it difficult to quantify which of those lead to higher risks of instability. The summer of 1999 yielded insight into this issue with higher than normal precipitation that resulted in significant movements at the four assessed sites.

A primary contributor to slope instability is grade. A slope with a mild grade generally has a lower risk of instability under similar environmental conditions as a slope with higher grades in the same material. This holds true with the outcropping Millwood and Odanah clay shales. Naturally occurring slope angles have been found to be in excess of 12 degrees, approximately 4.5:1 (H:V), over the entire valley wall length. These slopes increase when roadway construction force cuts in valley walls for smooth transition from prairie to valley floor level. Crossings between the Assiniboine River and PR259 and PTH41 are examples of these, where the upper slopes have higher instances of slope movements than lower slopes as shown in Figures 2.6 and 2.7. The sites noted are also areas of outcropping Odanah clay shales, where that of PR259 is substantially more visible. At PTH83 and the Shell River, a lack of outcropping bedrock is made up by relief of over 100m and slope angles in excess of 16 degrees (3.5:1). Outcropping bedrock and moderate to high slope angles also lead to instabilities at the intersection of PR478 and Assiniboine River. Several additional sites have also been identified such as at PR568 near the Assiniboine River, where reoccurring instabilities have led to continued movements.

#### 2.1.3.1 PR259 and the Assiniboine River

Several site investigations have led to numerous remedial measures at this site. Most recently, AMEC was hired to provide alternatives to remediate two failures sites; one on each side of the Assiniboine River valley. The underlying bedrock is the Millwood Member with outcropping of the Odanah Member along valley walls as shown in Figure 2.6. In general, shattered shale rubble overlies hard clay shale with intermittent layers of glacially deposited silts, sands, and gravels. The groundwater level is generally 4 to 5m below grade with several recharge and artesian pressure zones. In some areas, artesian pressures are known to reach 8m above grade.

Several characteristics of the area have been quantified as a result of years of observation and testing. Detailed borehole logs and soil property summaries are available through MIT and AMEC[2]. Detailed soil property summary tables are also provided containing liquid and plastic limits, water contents, grain size distributions (if applicable) and SPT results. On average, the surficial clay layer yields a plastic and liquid limit of approximately 20 to 30 percent and 55 to 70 percent, respectively. Moisture content generally resides near the plastic limit.

### 2.1.3.2 PTH41 and the Assiniboine River

Two failures have been observed on the east side of St. Lazare, sliding southwards towards the Assiniboine River. Borehole logs from a section of land nearby show a dominant clay layer that exhibits a plastic and liquid limit of approximately 20 to 25 percent and 45 to 55 percent, respectively. A similar soil layer near Binscarth yielded a unit weight of approximately 18 kN/m$^3$.

The Millwood Member is dominant in the area, located between 17 and 19m below grade, with the Odanah Member outcropping along valley walls as shown in Figure 2.7.

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[2] Geotechnical site investigation final report dated March 13, 2006. Submitted by AMEC to Manitoba Infrastructure and Transportation

Surficial geology is mainly composed of clay shales and clay tills, with outcropping glaciofluvial sands and gravels. The water table is located between approximately 5 and 8m below ground surface with levels reaching 2 to 3m after large rainfall events. Artesian pressures are encountered near 14 to 16m below grade, generally leveling at 1.5m above grade.

#### 2.1.3.3 PR478 and the Assiniboine River

Failure in 1995 resulted in the installation of engineered sand drains. Movements continued resulting in new tension cracks and in 1999, rates of movement reached 30mm per day. The Millwood Member is the underlying bedrock, and is exposed sporadically as shown in Figure 2.8. Contact with the overlying Odanah Member is located at a higher elevation and so is of no concern in this area. The soil profile, in general, is comprised of disturbed and undisturbed clays. The disturbed clay is a soft to stiff, highly plastic, non calcareous clay with blocky structure; plastic limit ranging between 24 and 34 percent and liquid limit ranging between 66 and 97 percent. The water content generally lies above the plastic limit and the unit weight ranges from 18.3 to 19.7 kN/m$^3$. The undisturbed clay layer is a hard, highly plastic, non-calcareous clay with similar plastic and liquid limits as the disturbed clay layer. Water content on average is less than the plastic limit and unit weight ranges from 19.5 to 20.8 kN/m$^3$.

A high local groundwater table, 1 to 2m below grade, discharges into a ravine that further flows into the Assiniboine River. Slope inclinometer results measured in 1999 show movements on the order of 30mm per month near the toe and 4mm per month near the crest of the failure. These values, in conjunction with several observed depths of movement (3, 6 and 11m), are characteristic of retrogressive type slope failures[3].

#### 2.1.2.4 PTH83 and the Shell River

Most recently a French Drain was installed in 1999 by KGS Group on the east side of PTH83 adjacent to a lookout area. This was a result of increased slope movements, upwards of 100 mm per day, triggered by several high intensity rainfall events. Movements continue to take place though at a substantially slower rate, 140 mm per year. Detailed review of the surficial geology, provided by KGS[4], shows three distinct till units and one intermittent, interglacial lacustrine clay unit. The Minnedosa formation is an outcrop of the RMF; thickness ranges from 3 to 30m and is most widespread on the Assiniboine River plain. It is generally overlain by the Lennard Formation, a thick till unit found over the lookout area. This formation is more susceptible to minor earth flows than other till formations because of its highly jointed nature and fine grain size. The Shell Formation is present in outcrops along the lower Shell River valley. The Shell River valley is entirely in drift and the Millwood Shale contact lies well below the valley bottom. In general the soil profile consists of variable depths of fill overlying clay tills. A simplified aerial image is shown in Figure 2.9.

Groundwater level, on average, is observed between 3 and 5m below ground level near the roadway, and is assumed to coincide with the valley surface. It should also be noted that some intermittent sand layers were observed to contain artesian pressures. Several methods of testing, as well as back analysis through slope stability, yielded cohesion

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[3] Soil characteristics and site stratigraphy for the crossings of PTH41 and PR 478 with Assiniboine River is reproduced from documentation available in Manitoba Infrastructure and Transportation archives

[4] Geotechnical site investigation draft report dated November, 2005. Submitted by KGS Group to Manitoba Infrastructure and Transportation

values of 1 to 1.5 kPa and internal friction angles of 20 to 30 degrees. The slope failure mechanism is likely that of a sliding block geometry.

### 2.1.4 Current Slope Instability Management in Manitoba

Current slope instability management in Manitoba is reactionary and subject to lengthy bureaucracy in the event remediation is complex and requires extensive investigation. Assessments begin with regular roadway maintenance personnel; weekly passes become the first line of defense against roadway hazards. In most cases, instabilities are small and are considered nuisances. In these cases, maintenance personnel have the ability and resources to repair any hazard as continued maintenance operations. Typical scenarios include small slumps, ditch grading, and small drainage applications.

In the event that hazards are deemed beyond the scope of regular maintenance duties, they are reported to Engineering and Operations, where regional personnel assess if the site can be remediated by standard methods or requires further investigation.

If more rigorous solutions are required, regional staff contact head office where a mutual agreement is made after further site inspection. A document entitled "Materials Engineering Best Practice for Minor Slides on Highway Embankments" is available internally in the event that slides are manageable by standard reconstruction means. A bank of funds is available where the cost of rehabilitation falls between $10,000 and $20,000. Typical methods for rehabilitation of minor slides are restoration of embankment failure with existing or native materials, slope re-grading, and toe berm or granular fill placement.

A detailed site investigation is necessary providing any of these methods are deemed insufficient. A repository of funds is available for in-house investigations conducted by both regional and provincial staff. If external, a request for proposals is distributed by MIT signing authorities. In either case, a report is delivered containing results and recommendations for rehabilitative measures; in some cases these include continued motoring programs.

If measures get to this stage, solutions can become bureaucratically dominated. MIT publish three or five year programs describing future projects and their budgets. As yet these programs only include regular highway construction, maintenance, or rehabilitation and omit slope instabilities. In order to receive funding for detailed design and implementation of remedial measures, these projects must first enter the term program or await the end of August, where remaining funds from under budget projects can provide necessary funds. It is not uncommon for this procedure to take anywhere between five and fifteen years.

This particular process could be streamlined by implementing a system of risk management for landslide hazards. If sites could be ranked according to importance, on a level understood by signing authorities, resources can be assigned much quicker, or at minimum much more systematically. It would become simpler for slope instabilities to enter the term program and funding could become consistently available.

## 2.2 Review of Relevant Literature

### 2.2.1 Application of Risk Management in Geotechnical Engineering

This work is building on a model established by SDHT where a risk management system was applied in 2003 to its highway network (Kelly *et al.* 2004) using the Alberta Transportation Landslide Management System as a template. Manual inspections of various highways in proximity to water bodies were investigated and assessed using specified probability and consequence factors, resulting in assigned risk for sites examined. Risk factors were divided into four groups: urgent, priority, routine and inactive (Table 3.3). Besides implementation of a modern system of inspecting and classifying sites in order of importance, a method of allocating resources for response and mitigation was provided, resulting in better decision making. In the event of a newly developed slope concern, a committee of individuals equipped and educated in the system could assess probability and consequence factors to establish relative risk to existing rated sites. Resources are then allocated if necessary to remediate the site. The unstructured system, before risk management, had no method of distributing resources and caused conflicts with regional staff and construction timing. SDHT is one of many agencies using risk management to improve quality and management of their infrastructure.

Recently, British Columbia has begun adopting risk management programs for assessing rock fall hazard along highway networks in mountainous terrain. Wylie (2005) described rock fall hazards along major and residential routes as highly manageable using a risk based approach, where probability and consequence factors took form using rock fall characteristics. Failure probability is developed using physically observable characteristics such as roadway width, slope height, and rock fall history, and consequence being the combination of mitigation costs, fall type, delays, and economical impact. Wylie (2005) also suggested a more probabilistic approach using Bayes' Rule to quantify numerical probability of an individual event occurring.

Several other methods of evaluation also exist. Lacasse (2005) suggested consequence be divided into multiplying 'vulnerability' and 'elements at risk'. Lacasse (2005) describes elements at risk as the physical objects in harms way in the event of a landslide (*i.e.* life, infrastructure, property, activities, natural and urban environment and history). Vulnerability is described as the degree of loss of an element at risk and takes on bounds of 0 to 1. These values are statistically correlated between a particular element at risk (E) and the magnitude (M) and scale (S) of individual slides. The most notable benefit of such an approach is that all possible events are considered rather than a single extreme. A strong disadvantage of this approach is forming initial probabilistic assumptions of M and S.

Risk management approaches are not always statistically based, that is, the probability of failure is not always represented numerically as a value between 0 and 1. In some instances, such as that described by Lin (2004), massive amounts of data can be collected that lead to a mathematical expression of failure probability. The Chi-Chi earthquake in Taiwan triggered several landslides and yielded vast amounts of data pertaining to landslide triggers and as such, allowed Lin (2004) to develop a landslide failure algorithm. Coupled with GIS software, Lin (2004) was able to develop a contour map of the probability of failure across central Taiwan with great success. The same has been developed for slopes in western Puerto Rico (Divakarla 1998). By inputting several known triggers within GIS software, Divakarla (1998) was able to output a thematic map visibly displaying risk along sections of roadway.

Further variables such as failure mode can be introduced by creating a probability matrix comprised of failure mode linked to their likelihood of occurrence in a region. Sadek *et al.* (2005) implemented this along a roadway network in Beirut and was able to generate a map of failure probability for several failure modes.

Worldwide importance of risk management in engineering is growing with significant effort placed on geotechnical phenomena due to its complex nature. Understanding the essential concepts of risk and regional specific environmental, climatic and geological circumstances, can make hazard management readily applicable wherever desired.

### 2.2.2 Application of Geographic Information Systems as Tools in Geotechnical Engineering

GIS has raised expectations as a potential tool for managing geotechnical phenomena. SDHT have developed a risk management system for use in assessment programs. Including GIS can allow for manipulation and/or isolation of spatial regions and assign an unlimited number of attributes. Any information pertaining to a physical point, line, or area can be summarized in a geospatial layer when GIS is combined with GPS. Not only can surficial geology be described thematically by varying display parameters, but endless amounts of information can be linked to geospatial objects for further segregation and identification. Aerial images can be linked to coincide with physical features and by use of DEMs, three-dimensional images to any exaggeration can be created. These capabilities have led to the integration of geotechnical engineering knowledge and GIS to improve management of physical infrastructure.

Carrara *et al.* (1999) described the use of GIS in predicting and managing landslide hazards. GIS is described as an environment in which users manipulate databases to output single answers to single questions. As most engineers are taught, computer software cannot be trusted unless users understand inputs as well as results. Carrara *et al.* (1999) further discussed the importance of hand calculations and verification of results to provide adequate certainty that computations are satisfactory for their intended purpose. Besides concentrating on user subjectivity, Carrara *et al.* (1999) also showed that through optimal understanding and verification, GIS can be a highly useful tool for mapping and managing landslides.

The Chi-Chi earthquake in Taiwan triggered several landslides over a broad area where a large amount of data was obtained by field reconnaissance. Aside from aiding in developing a risk management system, GIS was also used as a platform for isolating hazardous areas based on a mathematical algorithm. Lin (2004) spent significant time building a failure model and further verified its predictions using independent field investigations. Divakarla (1998) also incorporated GIS into risk management of slopes in western Puerto Rico where real-time user defined parameters aided in creating thematic terrain maps of hazardous areas.

The greatest contribution of GIS in engineering is within the transportation sector. Network analysis capabilities have opened opportunities to construct transportation models using intelligent transportation systems (ITS) to monitor real-time traffic data and routing analysis. Furthermore, these characteristics can be imported to geotechnical risk management systems when landslide-prone areas are in proximity to roadway infrastructure. Player *et al.* (2004) discussed geotechnical use of GIS in three transportation based projects where potentially damaging combinations of attributes were observed by overlapping geospatial layers, such as topography, geography, and highway geometry. These attributes include: traffic counts, detours, subsurface conditions, utilities, and construction phasing.

Real-time monitoring of roadways can also be used as a framework for road repair and maintenance. Sadek *et al.* (2005) used real-time inputs coupled with geospatial layers to create thematic maps of hazardous areas by type of landslide failure. By knowing what reactionary method is best suited for specific failure types Sadek *et al.* (2005) was able to influence decisions required to mobilize resources for varying sections of roadway as shown in Figures 2.10 and 2.11.

GIS has also been used to assess impact of highway construction on soil erosion. Agrawal *et al.* (2003) developed several geospatial layers across India: land use/land cover, rainfall, soil erodibility, slope-length, cropping management (vegetative cover dependent), and conservation practice. Total soil erodibility was estimated through several methods of interpretation. Overlapping this layer with proposed highway geometries before, during and after construction aided engineers in selecting alternative design construction methods, as shown in Figures 2.12 and 2.13.

Saha *et al.* (2005) also coupled GIS with geotechnical knowledge to aid in planning roadways through landslide prone-areas. By understanding the geotechnical triggers required to induce failure, raster images were produced where each pixel contained an associated cost. The cost is a numerical value representing construction and maintenance costs, and landslide potential as shown in Figure 2.14. Figure 2.15 shows a raster image of automating GIS software to determine paths by minimizing distance, cost, and relief and helped estimate the cost of design decisions with and without risk management.

### 2.2.3 Probabilistic Quantification of Slope Failure

Developing a probabilistic model to describe slope failure is a difficult and rigorous task. Several approaches exist with each one requiring assumptions regarding the high variability of landslides.

The simplest method for developing probability of failure models is analysis of a single cross-section and varying soil parameters statistically to yield a distribution function of the factor of safety. This type of analysis, known as Monte Carlo Simulation (MCS), is widely accepted and yields a normal curve able to describe the likelihood a factor of safety falls beneath a desired value. This simulation is generally used for single cross-sections and is not widely applied across large regions with varying ground conditions.

Factors of safety and reliability in engineering have been extensively researched using several investigation methods. Yong *et al.* (1977) conducted several analyses on reliability of safety factors using statistically distributed inputs. Yong *et al.* (1977) experimented by varying cohesion and friction angles statistically on two orders. First, parameter variations based on testing depth and second, variations based on the in-situ testing method employed. Rigorous analysis of covariances between soil characteristics and methods where obtained and resulted in a real measure of safety factor reliability.

Significant efforts are placed on describing probability of failure as a value between 0 and 1. Whether meaningful or not for its imposed purposes, it's numerically reasonable and generally formulated by conceptualizing all possible failure modes at a site and manually assigning probabilities that when summed equal 1. Using Bayes' Rule of subjective probability, a single value describing global probability of failure can be calculated. This particular method is used in detail by Roberds (1991) for optimizing rock slope preventative maintenance programs. Preventative maintenance activities and costs associated with failure consequences can be minimized by designating a numerical value between 0 and 1 to failure modes. An example matrix is shown in Figure 2.16. Ferris (2003) describes a similar methodology using more quantitative methods of estimating probability of site specific occurrences. Various components within a system are assessed and ranked using failure modes and effects analysis. The resulting quantitative risk assessment (QRA) process is a powerful screening tool that highlights areas of concern at any given location and allows site specific comparisons.

Lacasse (2006) suggests several potential methods for determining probability of failure, these include: frequency, heuristics, and statistical or physically-based methods. Lacasse (2006) described the analysis as being a combination of deterministic (*i.e.* numerical methods) and probabilistic (*i.e.* Monte Carlo Simulation) techniques.

Cheung and Tang (2005) found reliability of slopes to be normally distributed for a 50-year lifespan, where the average of the failure density function fell below unity (null), approximately -0.5, and that of non-failed slopes fell much higher above unity, approximately 2, as shown in Figure 2.17. This indicated to Cheung and Tang (2005) that reliability of slopes can be approximately normally distributed.

Gao (1991) found that chi-square tests of terrain-related variables revealed that landslide distribution is statistically dependent on slope configuration, elevation, and slope gradient at the crest. He also found that mathematical equations regressed from the probability of landslide distribution against elevation and slope gradient when used as weighted functions in the failure model. That is, upon applying weights to elevation and slope gradient in the probabilistic model, accuracy of probability assessment worsened, implying that all dependencies are equally influential on failure.

One could reasonably justify that probability of failure along a single slope or region follows a normal distribution with several factors taken into consideration. In GIS-based models this possibility is limited in that the only numerical input is elevation and subsequently, grade. So in order to assume that grade can be a significant factor in determining probability of failure, values would have to be segregated over spatially relevant areas and manual manipulations applied afterwards to include other triggers.

### 2.2.4 Integration of Slope Failure Models and Geographic Information Systems

Several GIS software packages are available with differing capabilities. Generally these packages exhibit one of two major distinctions: user interaction or automation. Automation allows mathematical algorithms to be manually inserted that yield desired results and require a user defined combination of steps to be analyzed. Saha *et al.* (2005) created three distinct movement patterns within a computerized terrain model: the Rook, Bishop, and Knight movements from Chess to aid in route planning. By restricting movements to random continuous selections of these patterns the GIS model output a series of routes through landslide-prone areas in the Himalayas.

Lan (2005) conducted a similar analysis in Hong Kong, linking dynamic characteristic analysis of shallow landslides to rainfall events. Geospatial layers included rainfall, unsaturated seepage modeling, slope hydraulic response, and coupled stability modeling; the result was a slope's global response to rainfall. Additionally, varying rainfall intensity, plan area, and length of event, yielded raster images that exhibit areas of varying stability over time, as shown in Figure 2.18. From this, a curve is developed to represent the approximate factor of safety and pore pressure changes at varying depths over time as shown in Figure 2.19. Lan (2005) concluded that water pressure distribution and slope stability at any depth can be assessed using dynamic GIS modeling, providing an efficient means of evaluating a slope's response to hydraulic and mechanical changes during any predetermined rainfall event.

More often, GIS is used in a more user intimate setting where active researchers are an integral part of the experimentation and verification process. Through overlapping geospatial layers and manually interpreting data, users can employ judgment to develop realistic results. Algorithms yield single ranges of solutions for a strictly set criterion, and take significant resources to develop. Though good for a single project of larger magnitude, expansion to adjacent regions is difficult and requires a full understanding of how the algorithm was developed initially. In more user friendly interfaces, query reconstruction is the only action necessary to expand over environmentally and geologically different regions.

Player (2004) showed the ease of user defined GIS failure model development to help interpret hazardous areas for three distinct transportation based projects within a small timeframe. Altering conditions such as average daily traffic, detours, and construction phasing and planning, yielded significant changes in initial and boundary conditions when interpreting problematic traffic related areas. By understanding the underlying principles used in GIS and forming the right queries, Player (2004) was able to geospatially interpret project surroundings and design sensible solutions.

Divakarla (1998) and Lin (2004) conducted similar GIS analyses of landslides in their respective regions. Geospatial layers were either manually altered or entirely replaced. Under automated or dynamic conditions, this would produce computing errors and could require almost complete model reconstruction. Divakarla (1998) and Lin (2004) found it was simply a matter of interpreting and manipulating layers to output desired results. Landslides in Taiwan and slope instabilities in Puerto Rico were then further segregated based on these results, yielding accurate reproduction and development of failure probability modeling using GIS.

Sadek *et al.* (2005) and Agrawal *et al.* (2003) also conducted priority searches by overlapping user defined and geological based layers. By understanding what induces failure, representing them as geospatial layers, and varying combinations of each, substantial improvements to the GIS framework were made. Construction, repair and maintenance improved drastically based on knowledge provided by geospatially interpreting failure.

Between an automated or user defined GIS failure model, selection should be based on project magnitude, time constraints, future requirements, and most importantly on the limitations and current understanding of the chosen software. Both methods cater thoroughly to decision makers, yet success of either is highly dependent on weighing the capabilities of the system compared against project needs.

### 2.2.5 Geographic Information Systems as Proactive Risk Management Tools

The past sections have shown individually how GIS and risk management have been used in geotechnical engineering. They have each also shown GIS used as risk management tools. Actively, these sections show the capability GIS presents to manage infrastructure and influences on economical decisions.

Webster's Dictionary defines risk as "the possibility of loss or injury" and management as "the act or art of managing;" a fairly broad set of definitions but understandable. Success of risk management is tough to define since unlimited socio-economical elements could be used as a basis for optimization. Success could be defined as dollars saved, deaths prevented, service life of infrastructure, decreased rehabilitation and maintenance times, or something as simple as resource availability. In most cases, success of a risk management system is examined by asking a single question, has the process by which decisions are made improved?

As concluded by Divakarla (1998) and Lin (2004), both solutions modeled risk fairly accurately and aided government agencies to form structured decisions towards how to approach reconstructing or maintaining hazardous areas to optimize cost and safety in Puerto Rice and Taiwan.

Sadek *et al.* (2005) and Agrawal *et al.* (2003) created roadway maintenance and construction management systems that helped governments and construction agencies mobilize the proper equipment, resources and knowledge to proceed in lieu of the once unknown in Beirut and India.

Automated or dynamic GIS models were able to isolate at-risk areas due to rainfall in Hong Kong with astonishing accuracy, Lan *et al.* (2005), and aid in designing a suitable highway through the Himalayas so to avoid landslide-prone areas, Saha *et al.* (2005). In both instances, governments used the results to monitor and construct roadways with the added security of knowing an optimum design was selected.

Predictive analysis of traffic conditions and transportation construction projects improved because of real-time GIS geospatial updates to accurately model surrounding conditions, as conducted by Player (2004), for high priority projects in and around Ottumwa, Iowa.

A system of preventative maintenance was also created for a 116km stretch of highway through high landslide risk areas in Malaysia. Lloyd *et al.* (2001) showed that by conducting a risk/hazard analysis using real-time monitoring data that high risk areas could be identified geospatially resulting in preventative maintenance procedures as shown in Figure 2.20.

Significant banks of information are not required to show that risk management systems accomplish what they are designed to do. Once implemented, success can be defined in more ways than one and provide benefits to every user of the system, from decision making bodies to everyday users.

## 2.3 Justification of the Development of a GIS based Risk Management System for Manitoba's Highway Network

The majority of western Manitoba's highway network is situated on soft clays underlain by soft cretaceous clay shales. When superimposed with dendritic drainage patterns and large amounts of precipitation, roadways in proximity to bodies of water and large relief are at risk of slope instabilities. As discussed, MIT does not currently employ a system of collectively allocating resources to maintaining these locations of concern. Mitigation is reactionary and costly due to short time frames when mobilizing monitoring and rehabilitative measures.

Saskatchewan faced similar concerns which led to development of a risk management system. Several sites are investigated and prioritized according to risk on a periodic basis. Since its inception, the risk management system has created a method of ranking problematic areas based on their probability and consequence of failure. This system is proven to complete its desired task with great success, yet has room for improvement.

Improvement comes in the form of predictive analysis using GIS. GIS has been shown to be the preferred tool of geospatial terrain analysis and has become a tool for proactive risk management of geotechnical hazards. By overlapping several layers of data and understanding how these combinations lead to failure, GIS can highlight areas of concern. Ranking high risk sites then allows for prioritized site inspection and manual risk assessment.

MIT, instead of adopting the SDHTRMS directly, has decided to provide an additional step to proactively rank hazardous sites, potentially omitting several years of reactive maintenance costs by recognizing potential hazards before they arise. By adopting this, MIT will not only become a leader in roadway management across Canada but will also manage their sparse resources in a more economical fashion.

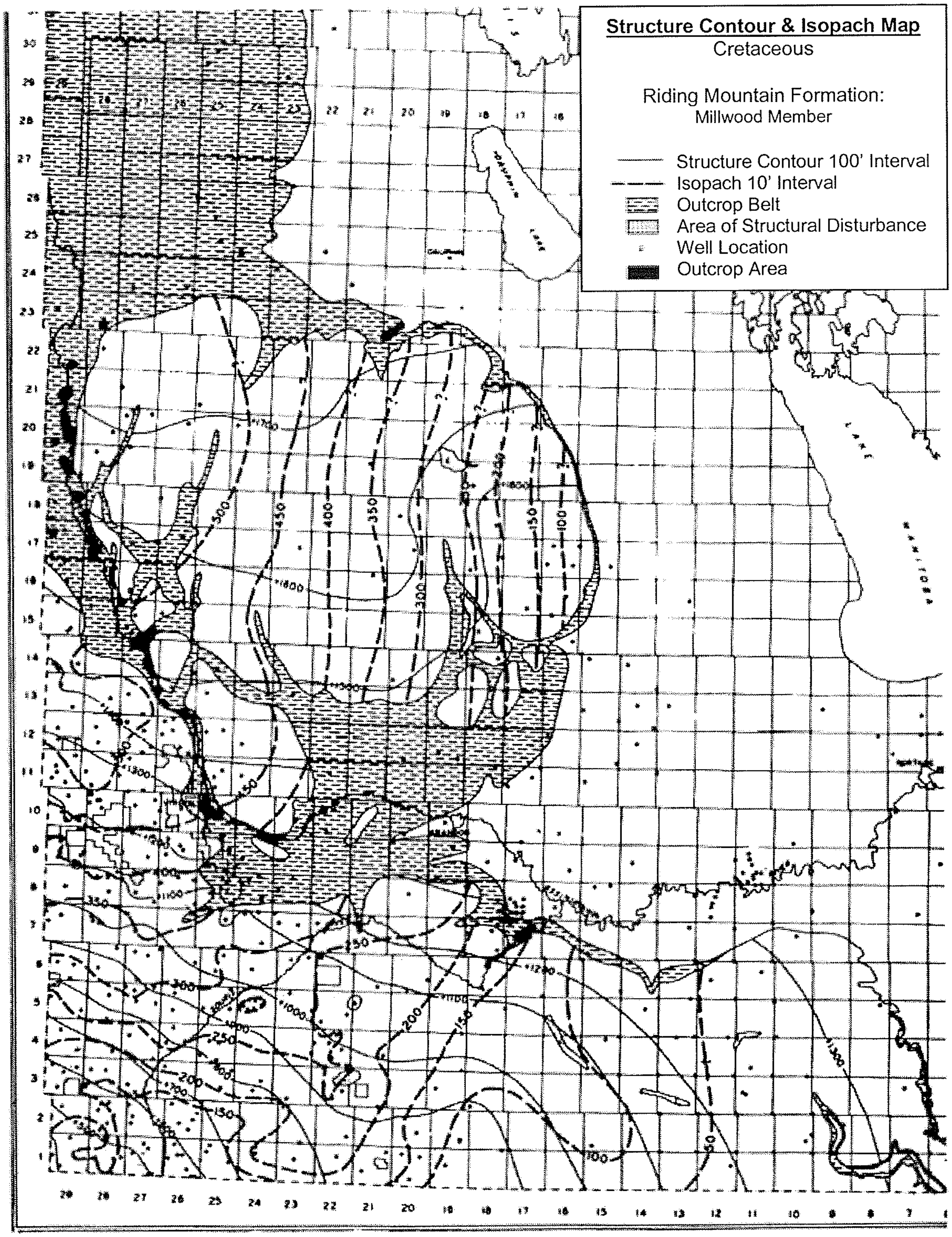

Figure 2.1 – Millwood Member outcrop in western Manitoba (after Bannatyne 1970)
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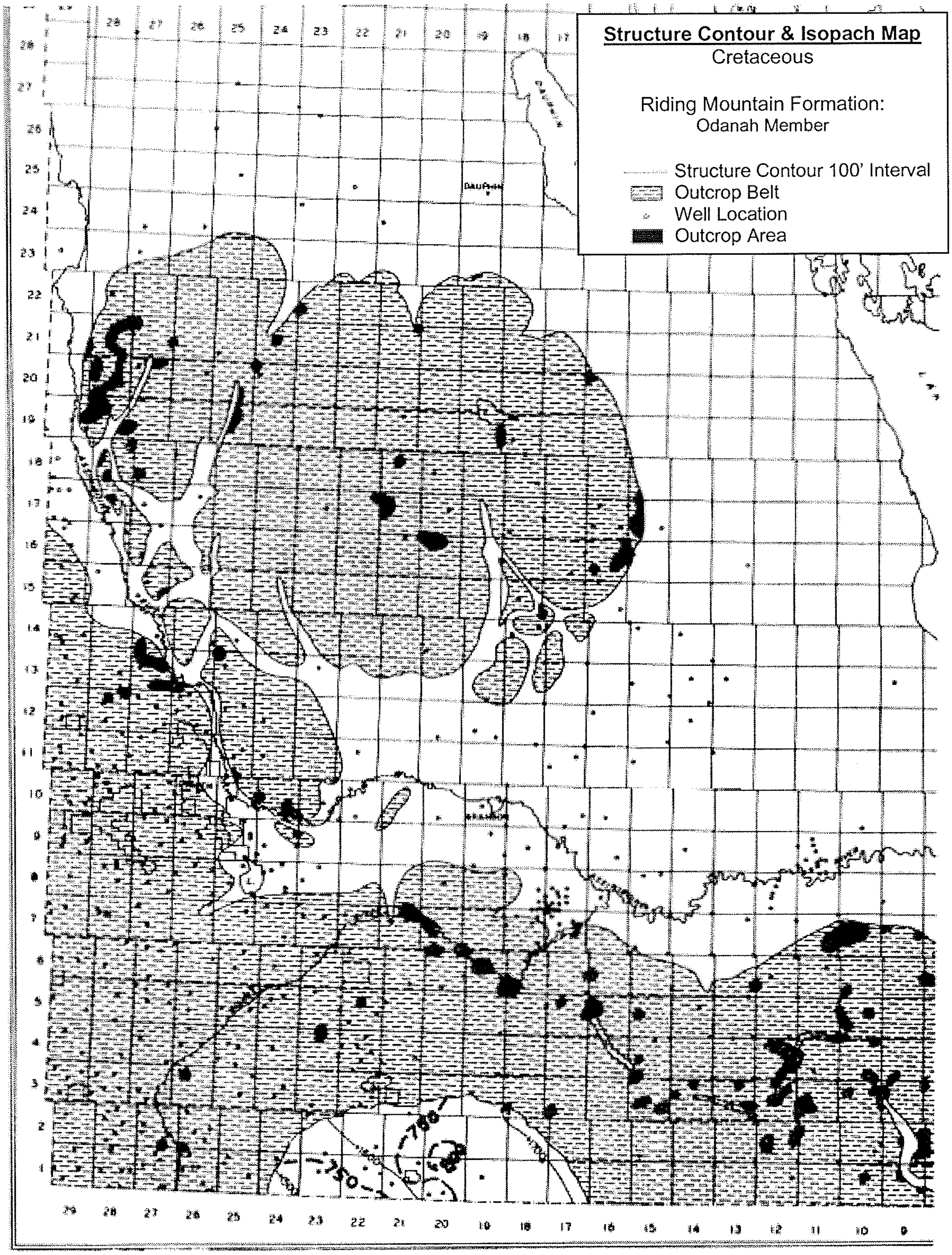

Figure 2.2 – Odanah Member outcrop in western Manitoba (after Bannatyne 1970)
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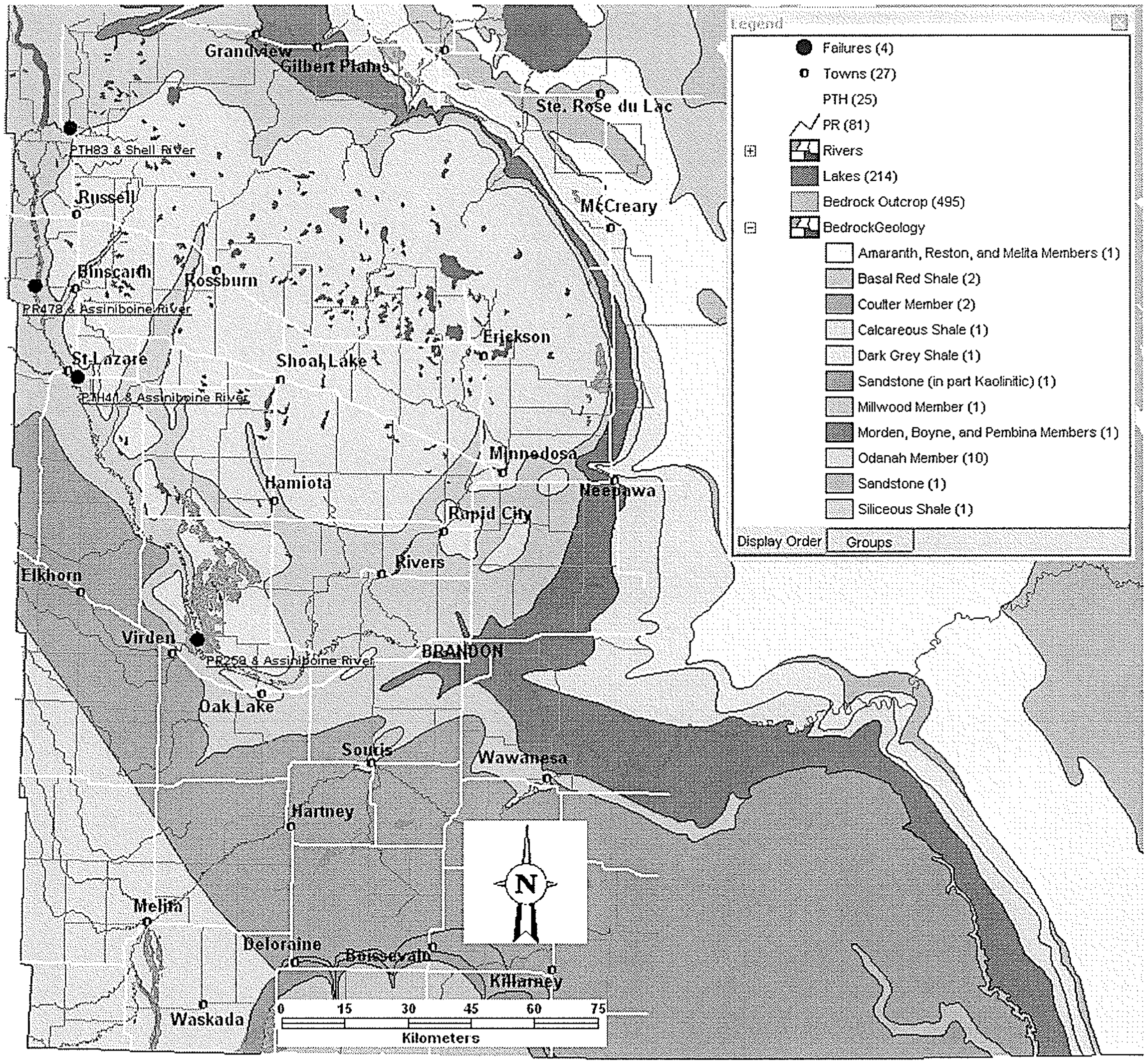

Figure 2.3 – Bedrock geology map of western Manitoba

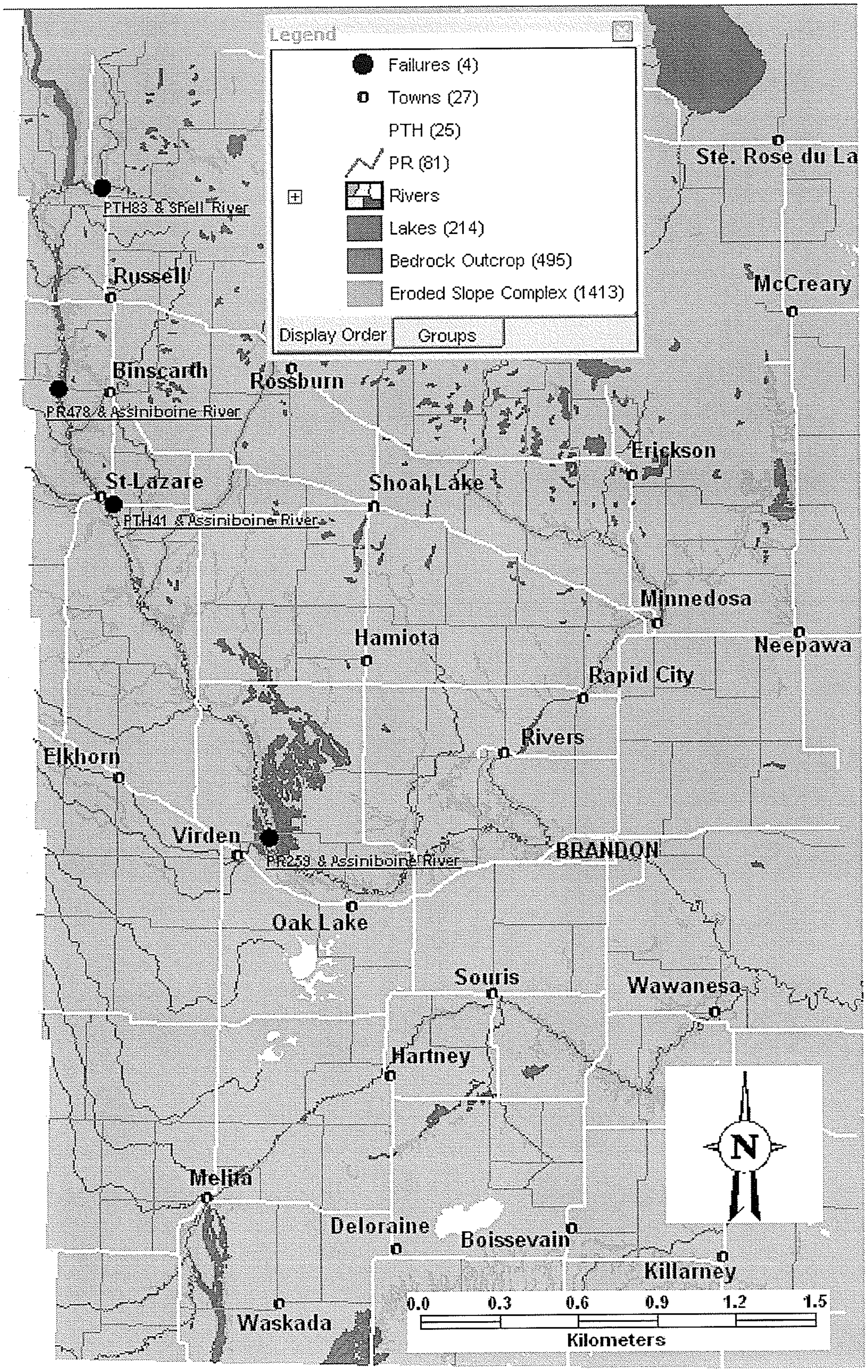

Figure 2.4 – Bedrock outcrop and eroded slope complex map of western Manitoba

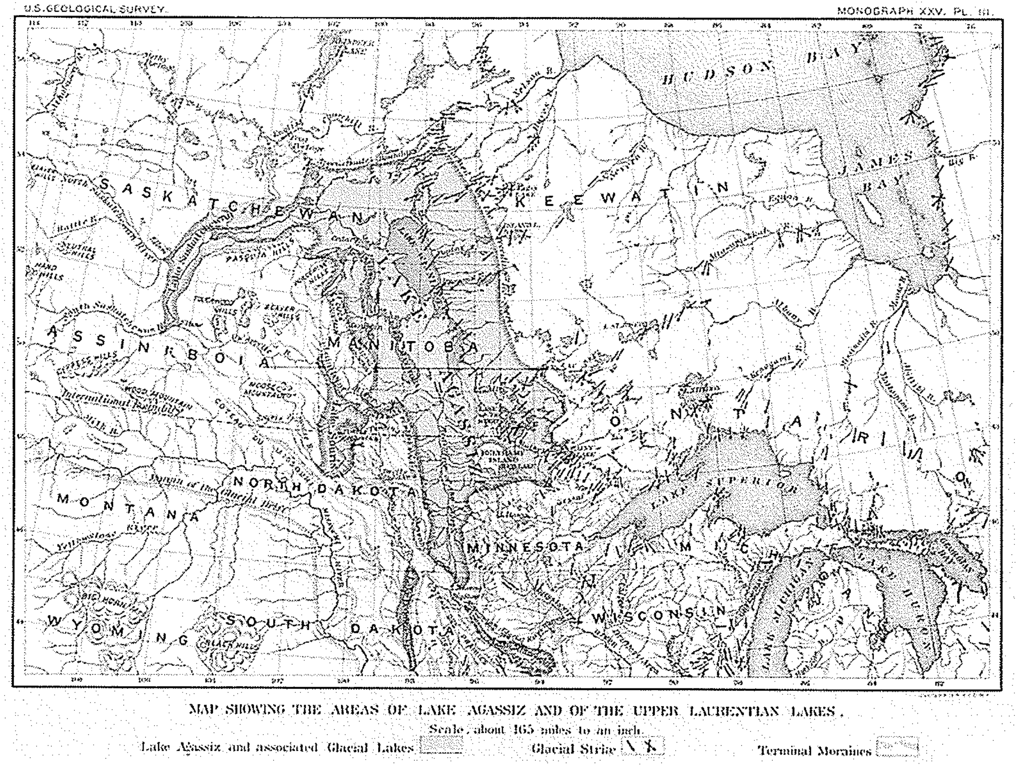

Figure 2.5 – Lake Agassiz geological extents from the United States Geological Survey: Volume XXV, Plate III

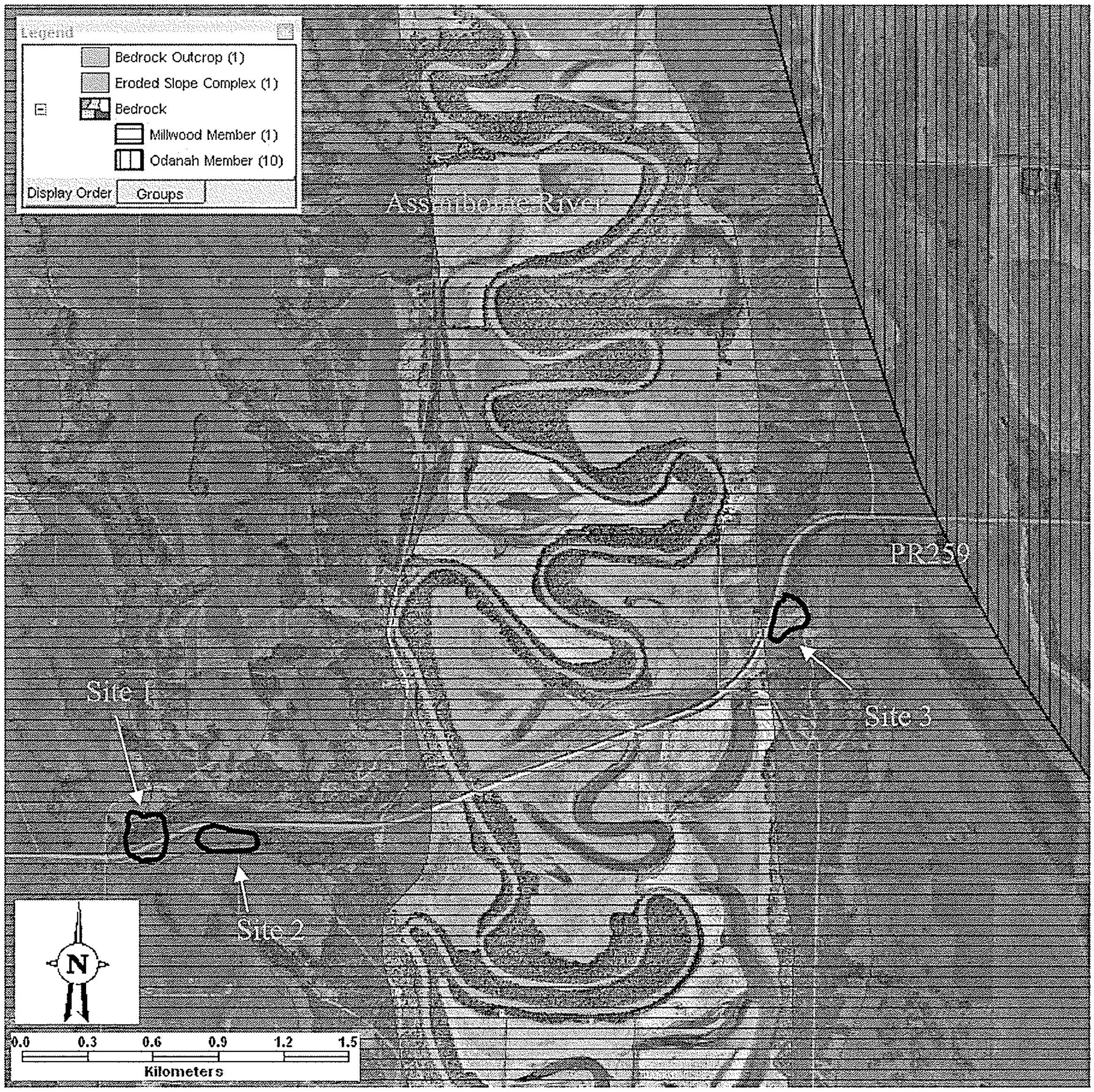

Figure 2.6 – Superimposed view of PR259 and the Assiniboine River with outcropping bedrock and eroded slope complex

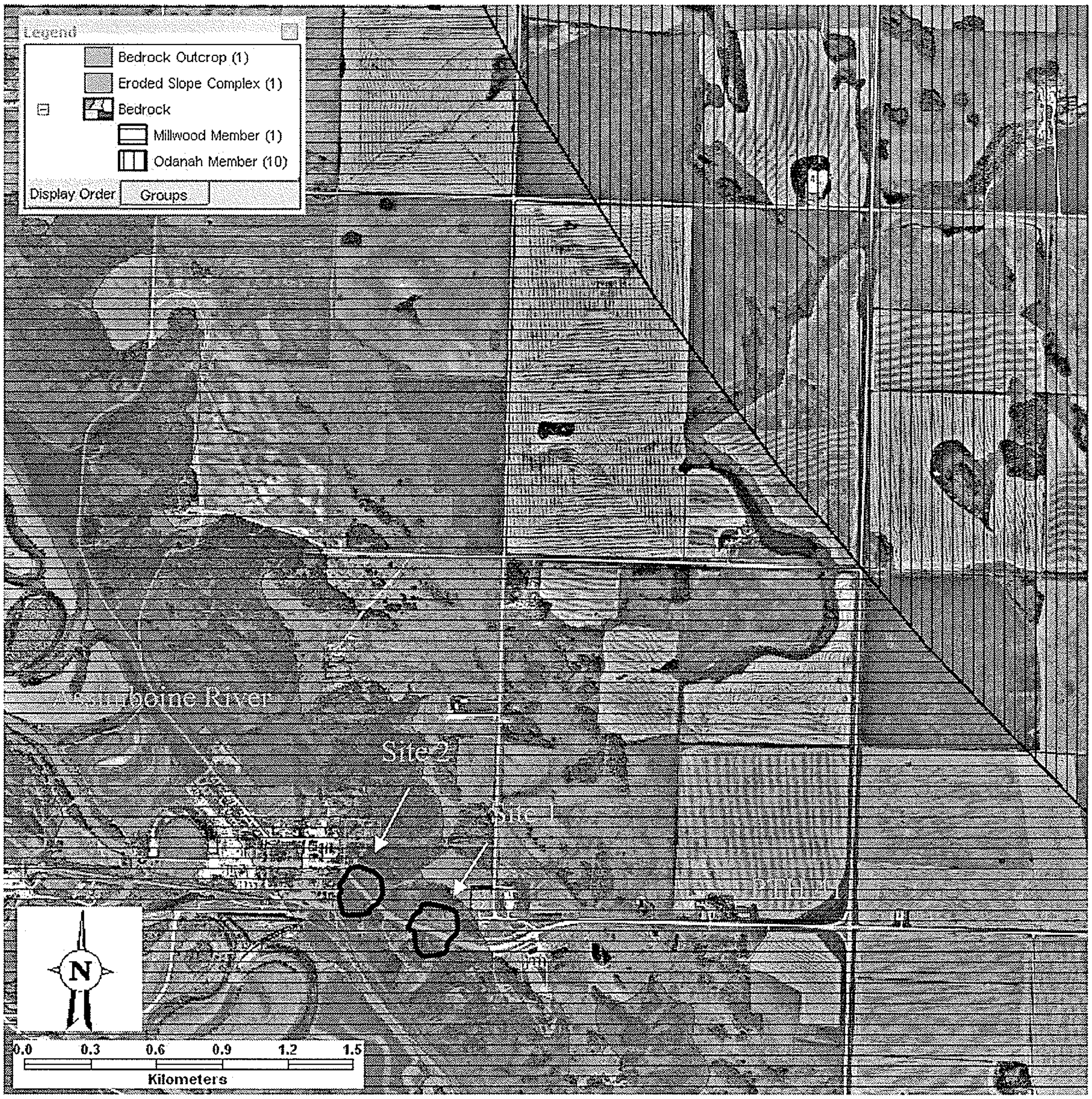

Figure 2.7 – Superimposed view of PTH41 and the Assiniboine River with outcropping bedrock and eroded slope complex

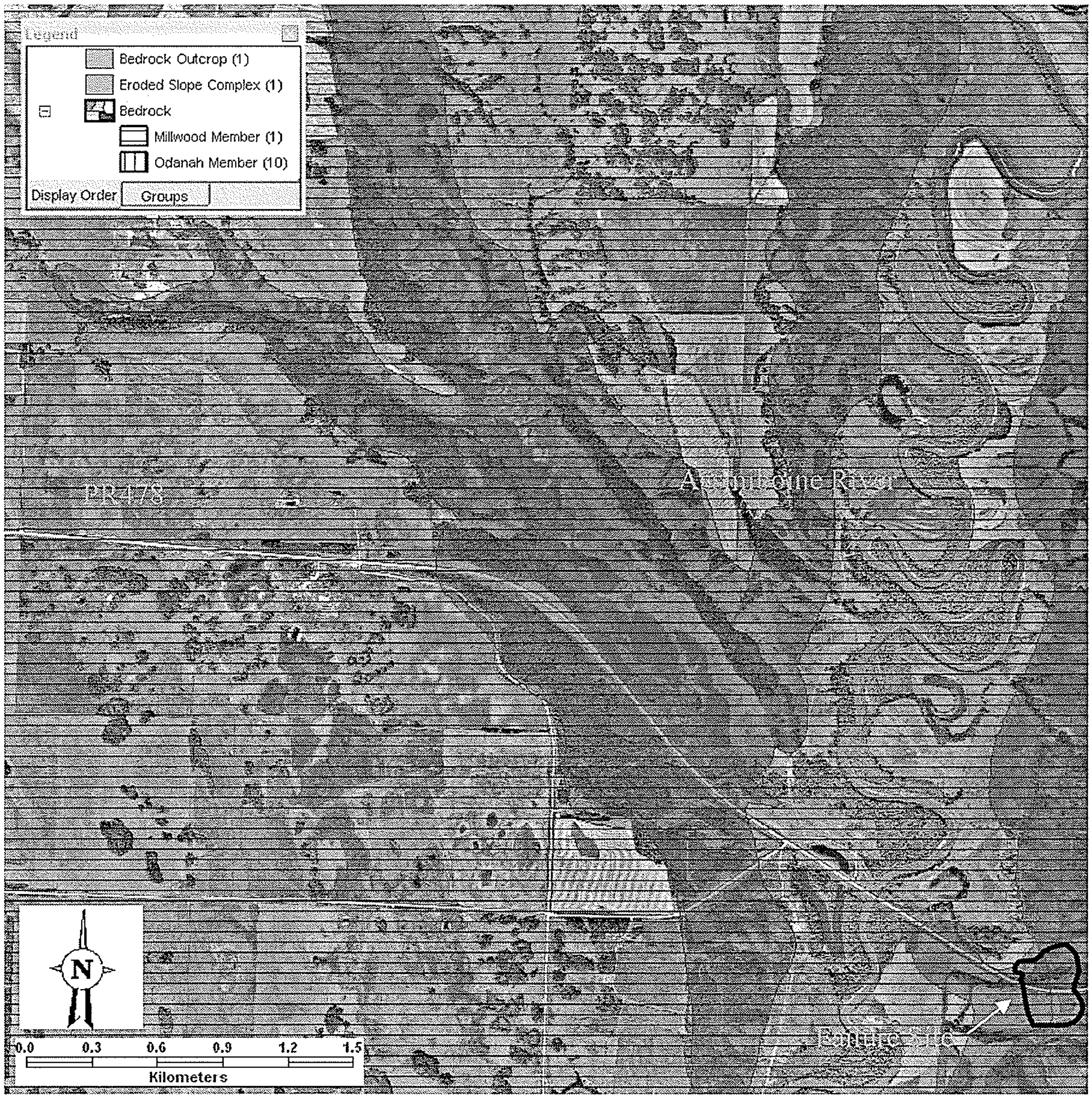

Figure 2.8 – Superimposed view of PR478 and the Assiniboine River with outcropping bedrock and eroded slope complex

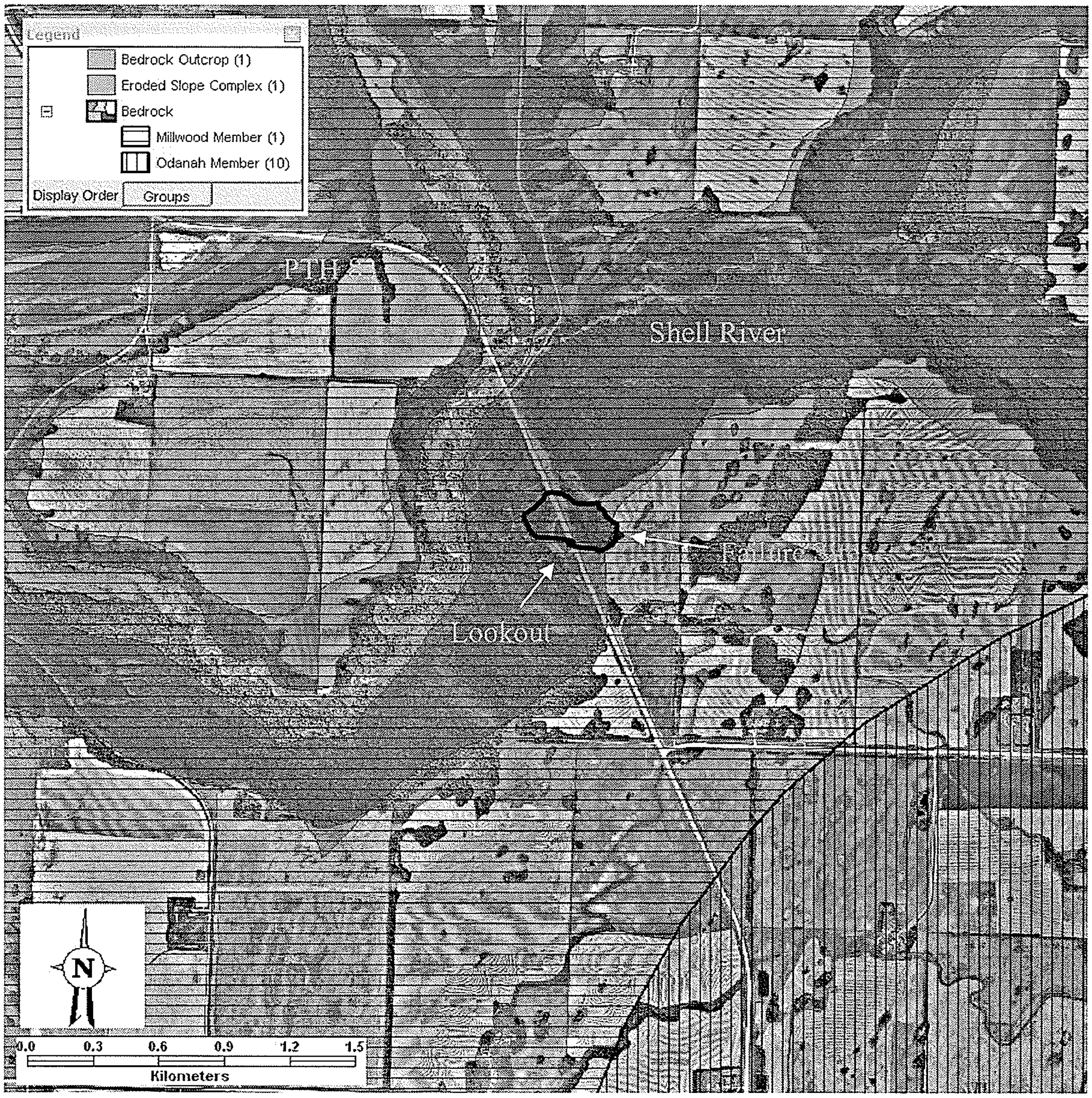

Figure 2.9 – Superimposed view of PTH83 and the Shell River with outcropping bedrock and eroded slope complex

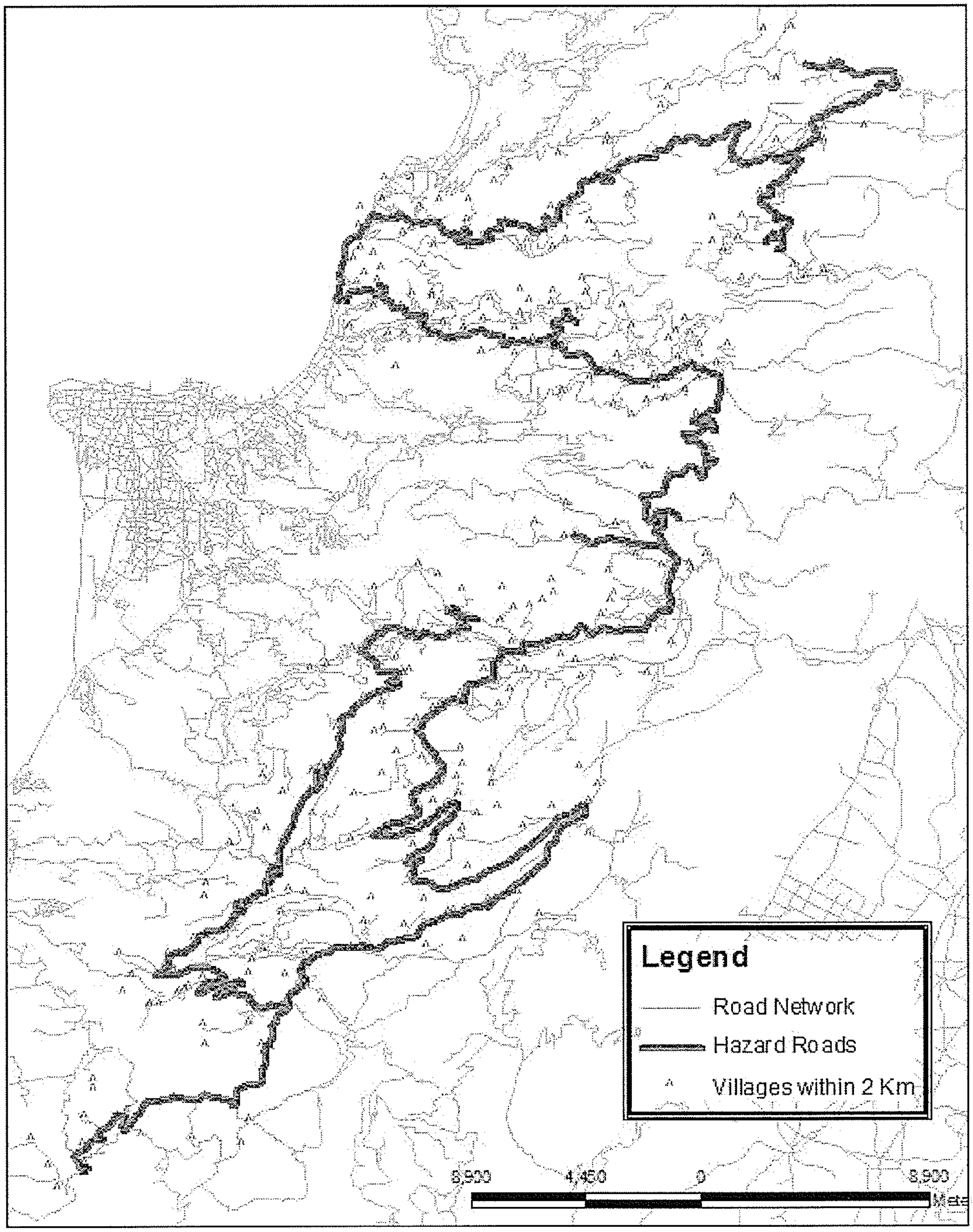

Figure 2.10 – Hazard map showing high risk roads in Beirut (after Sadek *et al.* 2005)
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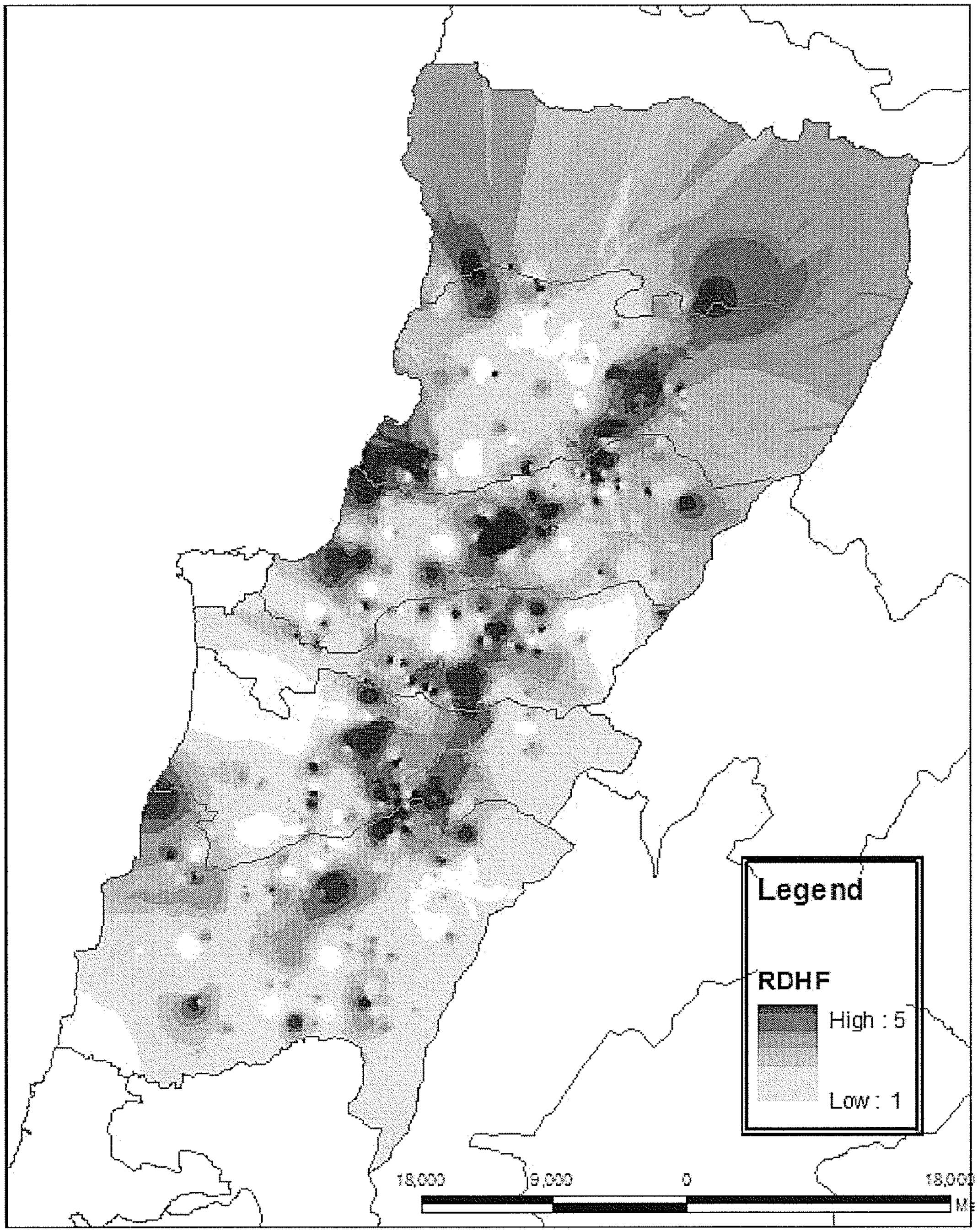

Figure 2.11 – Hazard map highlighting high risk zones in Beirut (after Sadek *et al.* 2005)
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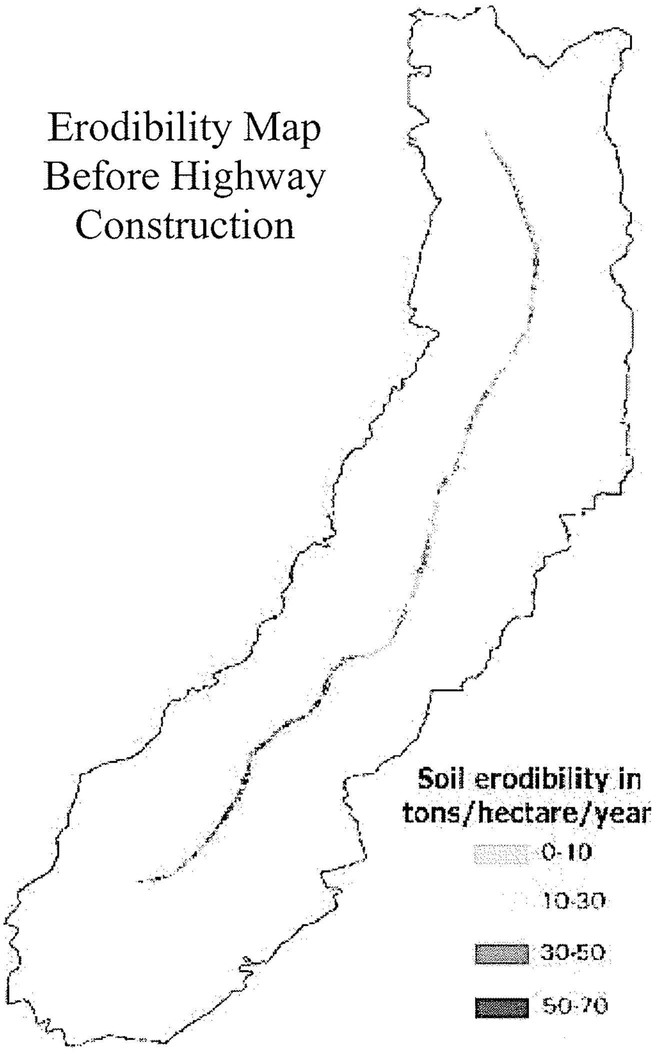

Figure 2.12 – Soil erodibility map along a highway before construction in India (after Agrawal *et al.* 2003)
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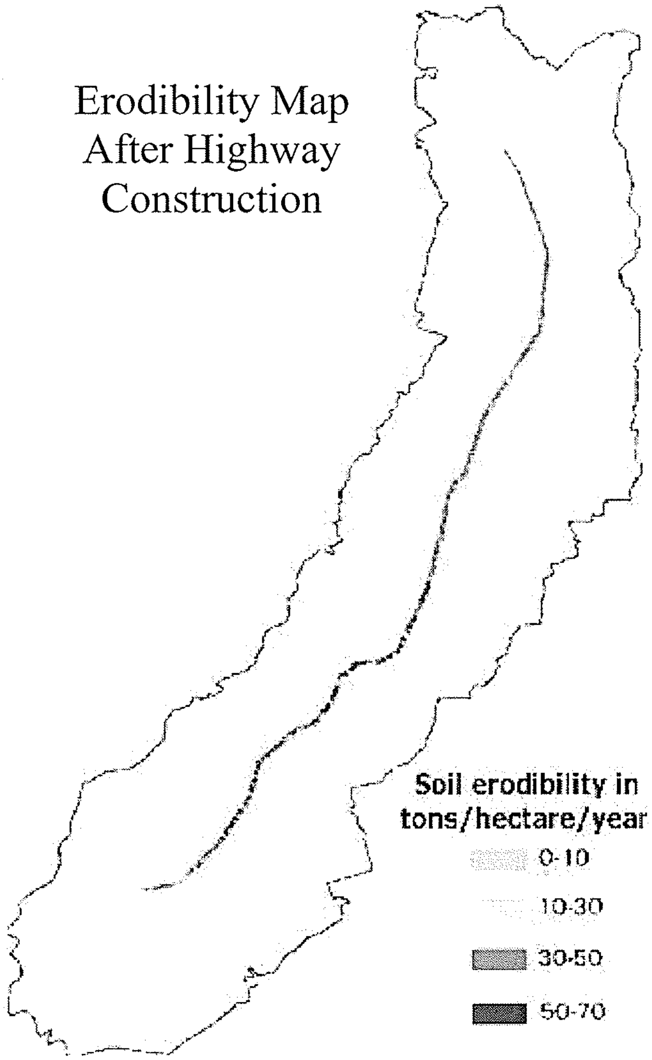

Figure 2.13 – Soil erodibility map along a highway after construction in India (after Agrawal *et al.* 2003)
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Figure 2.14 – Thematic cost map (after Saha *et al.* 2005)
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Figure 2.15 – Alternate Himalayan route results (after Saha *et al.* 2005)
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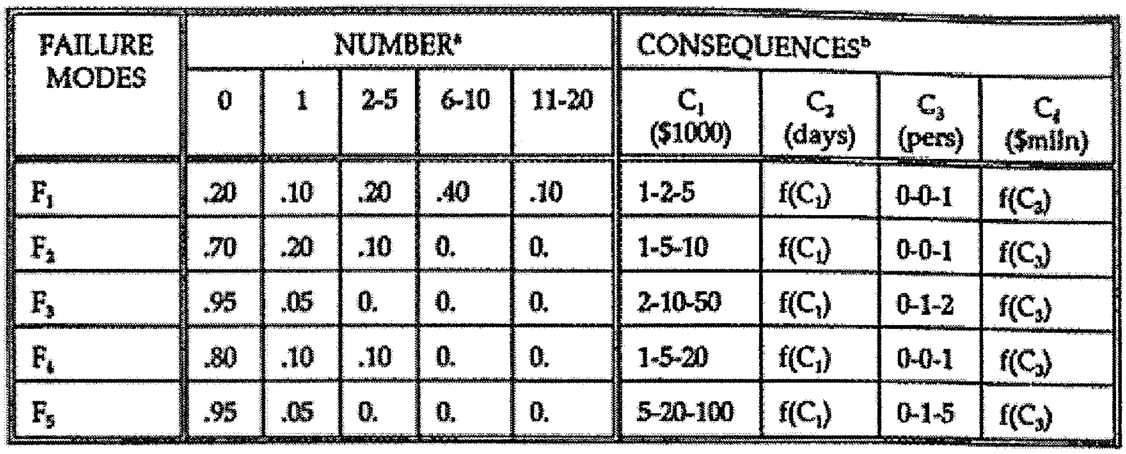

| FAILURE MODES | NUMBER[a] | | | | | CONSEQUENCES[b] | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2-5 | 6-10 | 11-20 | $C_1$ (\$1000) | $C_2$ (days) | $C_3$ (pers) | $C_4$ (\$mlln) |
| $F_1$ | .20 | .10 | .20 | .40 | .10 | 1-2-5 | $f(C_1)$ | 0-0-1 | $f(C_3)$ |
| $F_2$ | .70 | .20 | .10 | 0. | 0. | 1-5-10 | $f(C_1)$ | 0-0-1 | $f(C_3)$ |
| $F_3$ | .95 | .05 | 0. | 0. | 0. | 2-10-50 | $f(C_1)$ | 0-1-2 | $f(C_3)$ |
| $F_4$ | .80 | .10 | .10 | 0. | 0. | 1-5-20 | $f(C_1)$ | 0-0-1 | $f(C_3)$ |
| $F_5$ | .95 | .05 | 0. | 0. | 0. | 5-20-100 | $f(C_1)$ | 0-1-5 | $f(C_3)$ |

Figure 2.16 – Assessment of effectiveness of alternative preventative maintenance activities (after Roberds 1991)
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Figure 2.17 – Distribution of reliability index for failed and non-failed slopes (after Cheung and Tang 2005)
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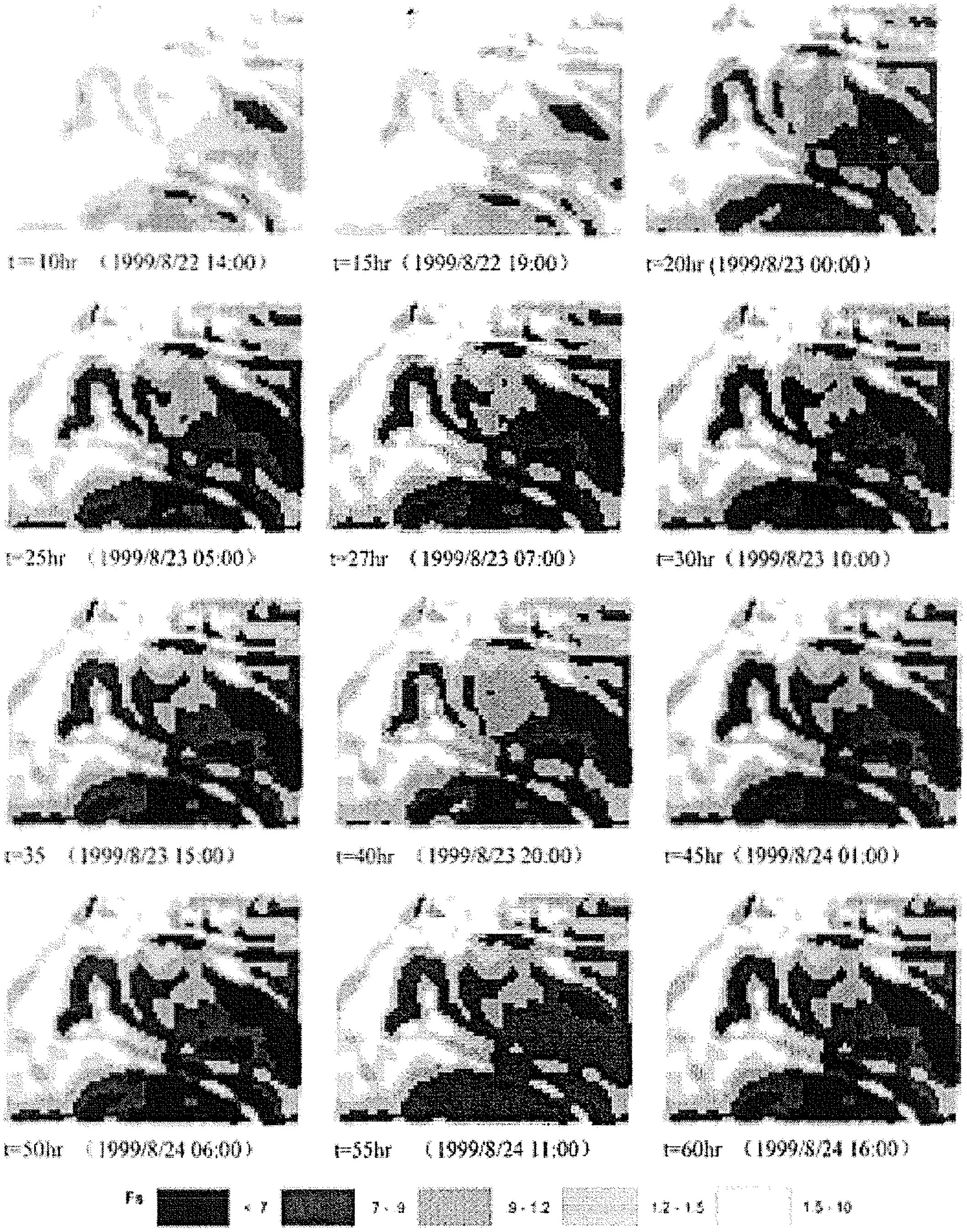

t = 10hr (1999/8/22 14:00) t=15hr (1999/8/22 19:00) t=20hr (1999/8/23 00:00)

t=25hr (1999/8/23 05:00) t=27hr (1999/8/23 07:00) t=30hr (1999/8/23 10:00)

t=35 (1999/8/23 15:00) t=40hr (1999/8/23 20:00) t=45hr (1999/8/24 01:00)

t=50hr (1999/8/24 06:00) t=55hr (1999/8/24 11:00) t=60hr (1999/8/24 16:00)

Figure 2.18 – Spatial distribution of landslide hazard in response to rainfall in Taiwan (after Lan *et al.* 2005)
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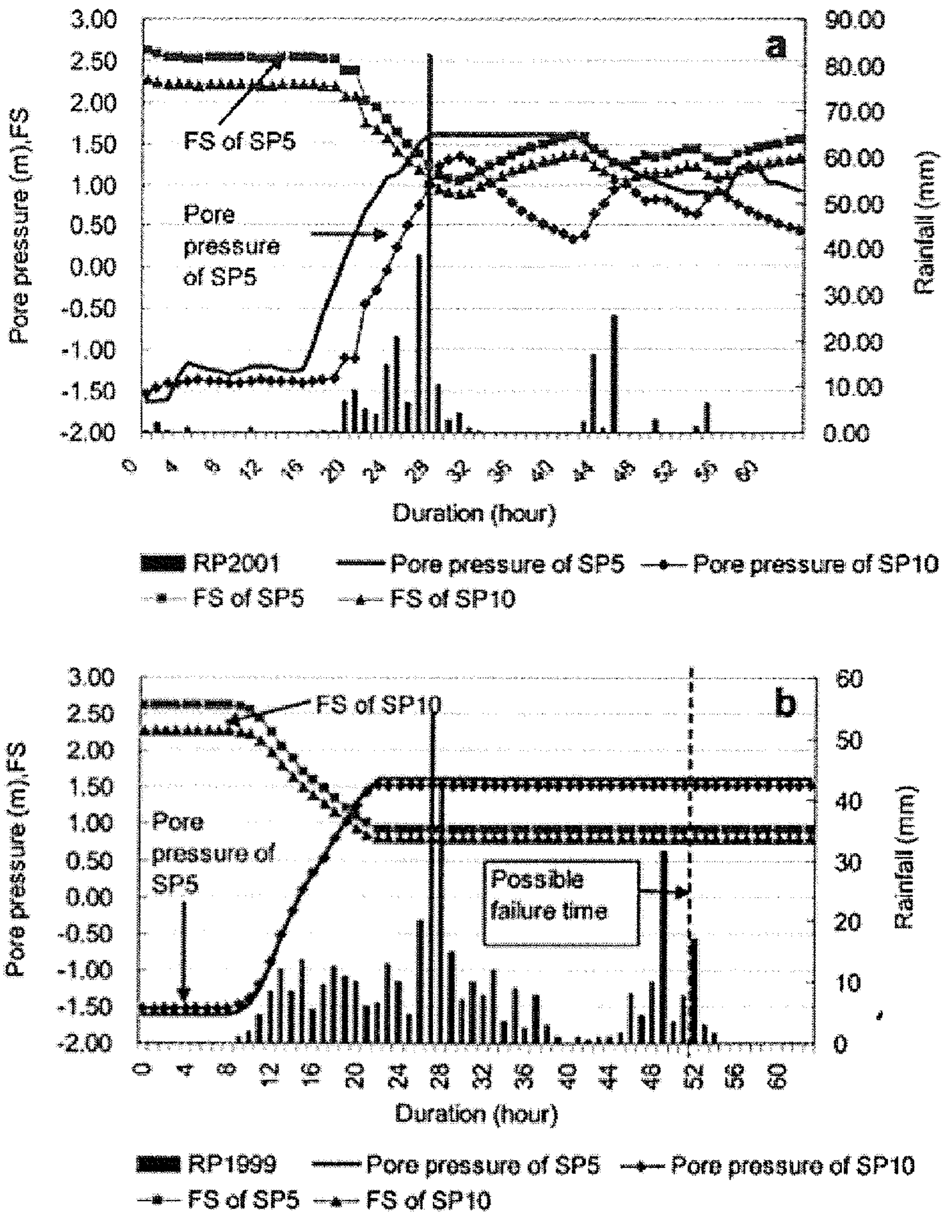

Figure 2.19 – Pore pressure and safety factor fluctuation over time during two rainfall events in Taiwan (after Lan *et al.* 2005)
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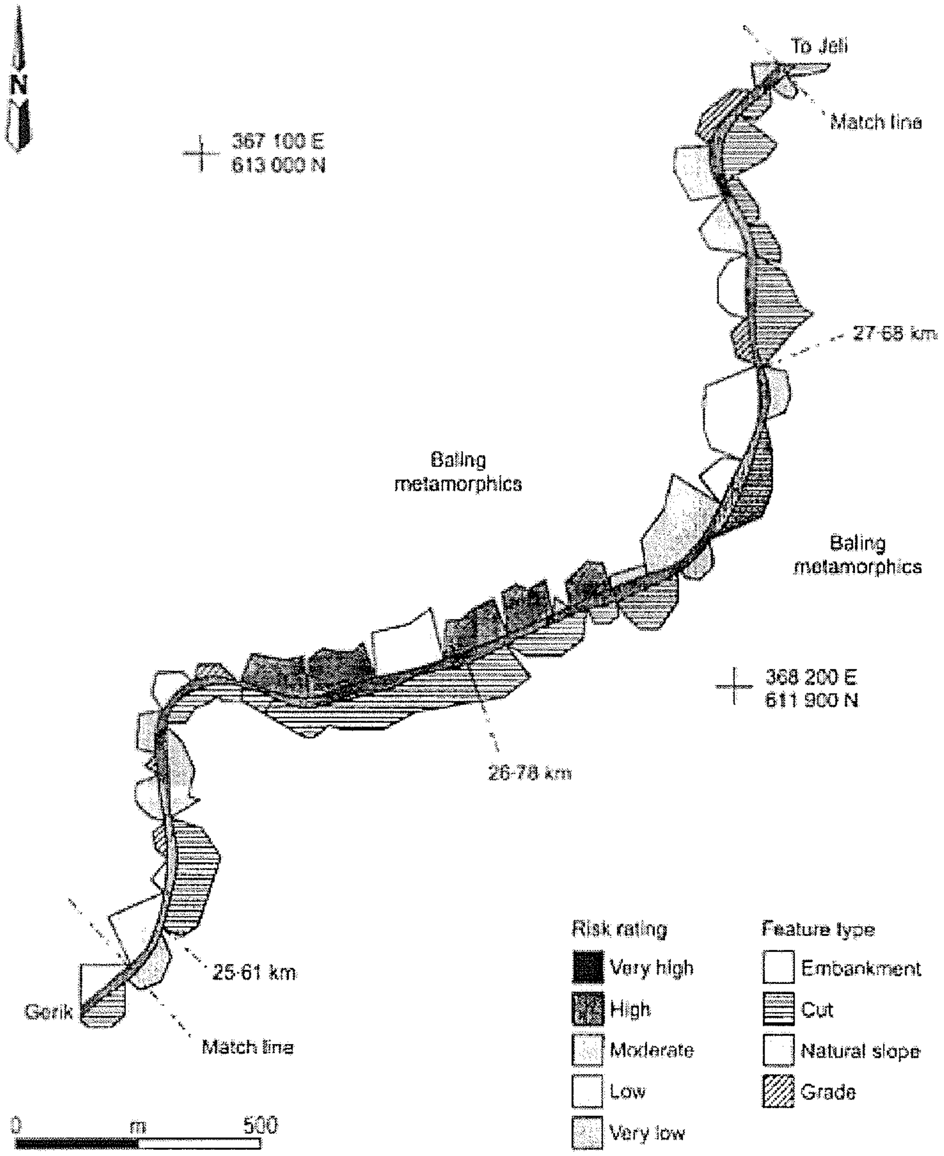

Figure 2.20 – Risk map along the East-West Highway in Malaysia (after Lloyd *et al.* 2001)
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# 3 Review of the SDHT Landslide Management System

## 3.1 Introduction

SDHT created a system of managing slopes and embankments near roadways in response to an increasing demand for limited resources. Since beginning landslide investigations in the early 1960's, the number of unstable sites has progressively increased on a yearly basis. Response measures, remedial works, and ongoing instrumentation have increased in application. Remediation technologies and monitoring methods have also advanced substantially over this period where Kelly *et al.* (2004) combined knowledge to create a systematic method of assessing landslide risk along Saskatchewan's highway network. Together a system of managing landslide hazards is able to:

1) Assess the degree of hazard that may be associated with unstable sites;
2) Evaluate the need for ongoing monitoring and inspection;
3) Provide for early warning or emergency response where public safety concerns warrant; and,
4) Establish priorities for investment of resources.

## 3.2 Review

### 3.2.1 Description

SDHT used the Alberta Transportation Landslide Management System as a template due to its relative success in application in Alberta. It also seemed fitting that two neighboring Canadian provinces use the same landslide management method. The basis of evaluating risk by Alberta and subsequently Saskatchewan is defined by the multiplication of a probability and consequence factor, PF and CF respectively.

PF reflects the likelihood of landslide occurrence as assessed by a qualified geotechnical engineer and is selected using a twenty point scale for both natural and engineered slopes as shown in Table 3.1. A separate set of criteria for each type is necessary since features and characteristics differ appreciably. CF represents the effect failure would have on surrounding safety and infrastructure should failure occur. A ten point scale is used as the basis for the CF selection as shown in Table 3.2.

Multiplying PF and CF yields risk level, a qualitative value representing landslide hazard at a site. By multiplying PF and CF, each places a limited amount of emphasis on their product. The twenty point scale of probability influences risk at twice the weight than that of the ten point consequence scale. In the event that each term is assessed as one of both extremes (*i.e.* low probability and high consequence), a different result is expected if the roles were reversed. Resulting risk is divided into four categories, each with differing response levels and management approaches as shown in Table 3.3.

Table 3.1 – SDHT probability factors (Kelly *et al.* 2004)

| PF | Natural Slope | Engineering Slope |
|---|---|---|
| 1 | Geologically Stable. **Very low probability** of landslide occurrence. | FS > 1.5 on basis of effective stress analysis with calibrated data and model*. Historically stable. **Very low probability** of landslide. |
| 3 | Inactive, apparently stable slope, **Low probability** of landslide occurrence or remobilization. | 1.5 > FS > 1.3 on basis of effective stress analysis with calibrated data and model. Historically stable. **Low probability** of landslide. |
| 5 | Inactive landslide with **moderate probability** of remobilization. Moderate uncertainty level; or, active slope with very slow constant rate of movement; or, indeterminate movement patters. | 1.3 > FS > 1.2 on basis of effective stress analysis with calibrated data and model. Minor signs of visible movement. **Moderate probability** of landslide |
| 7 | Inactive landslide with **high probability** of remobilization, or additional hazards present. Uncertainty level high. Perceptible movement rate with defined zones of movement. | 1.2 > FS > 1.1 on basis of effective stress analysis with calibrated data and model. Perceptible signs of movement or additional hazards present. **High probability** of landslide. |
| 9 | Active landslide with **moderate, steady or decreasing rate of movement** in defined shear zone. | FS < 1.1 on basis of effective stress analysis with calibrated data and model. **Obvious signs of ongoing slow to moderate movement**. |
| 11 | Active landslide with **moderate, increasing rate of movement**. | Active landslide with **moderate, increasing rate of movement**. |
| 13 | Active landslide with **high rate of movement at steady or increasing rate**. | Active landslide with **high rate of movement at steady or increasing rate**. |
| 15 | Active landslide with **high rate of movement with additional hazards****. | Active landslide with **high rate of movement with additional hazards**. |
| 20 | **Catastrophic landslide** is occurring. | **Catastrophic landslide** is occurring. |

Notes:

* If the described conditions for slope analysis are unknown or not met, increase the PF by one category, e.g. if quality of data used in analysis is not know, increase PF from 1 to 3. FS = Factor of Safety.

** Additional hazards are factors which can greatly increase the rate of movement, e.g. eroding toe, groundwater, etc.

Table 3.2 – SDHT consequence factors (Kelly *et al.* 2004)

| CF | Typical Consequences |
|---|---|
| 1 | Shallow cut slopes where slide may spill into ditches or fills where slide does not impact pavement to driver safety, maintenance issues. |
| 2 | Moderate fills and cuts, not including bridge approach fill or headslopes, loss of portion of the roadway or slide onto road possible, small volume. Shallow fills where private land, water bodies or structures may be impacted. Slides affecting use of roadways and safety of motorists, but not required closure of the roadway. Potential rock fall hazard sites. |
| 4 | Fills and cuts associated with bridges, intersectional treatments, culverts and other structures, high fills, deep cuts, historic rack fall hazards areas. Sites where partial closure of the road or significant detours would be a direct and avoidable result of a slide occurrence. |
| 6 | Sites where closure of the road would be a direct and unavoidable result of a slide occurrence. |
| 10 | Sites where the safety of public and significant loss of infrastructure facilities (such as a bridge abutment) or privately owned structures will occur if a slide occurs. Sites where rapid mobilization of a large-scale slide is possible. |

Table 3.3 – SDHT risk factor, response level and resulting management approach (Kelly *et al.* 2004)

| Risk Factor | Response Level | Management Approach |
|---|---|---|
| > 125 | Urgent | Inspect at least once per year. Monitor instrumentation at least twice per year in the spring and fall. Investigate and evaluate mitigation measures. |
| 75 to 125 | Priority | Inspect once per year. Monitor instrumentation at least once per year. |
| 27.5 to 75 | Routine | Inspect every 3 years. Monitor instrumentation at least every 3 years with an increased frequency for selected sites as required. |
| < 27.5 | Inactive | No set instrumentation monitoring or inspection schedule. Monitored and inspected as required in response to maintenance requests. |

### 3.2.2 Application

Upon initial application of SDHTRMS, 46 sites were assessed by an expert panel. Individuals assigned PF and CF to each site independently and risk level became the mean value of all assessments. The resulting ranked sites yielded 11 inactive, 21 routine, 10 priority, and 4 urgent response levels. Several sites became test subjects in that further investigations were conducted to validate assigned PF and CF. The landslides in the Frenchman River valley, near Shaunavon, and Prince Albert are presented.

The Frenchman River valley near Highway 37, Kelly *et al.* (2005), was the location of a remobilized landslide during roadway realignment. The landslide management system yielded a PF of 15 because of rapid movements and potential hazards caused by creek erosion, and a CF of 10 because there were public safety issues. Resulting risk level was 150 and fell in the urgent response level category. Immediate action was taken to remove commuting public from potential hazard and site investigations were initiated. Slope inclinometers showed two layers of movement on the order of 3 and 9 mm/day and stability modeling showed factors of safety near unity. Remedial measures included realignment of the roadway and removal of crest load.

Two landslides near Prince Albert along Highway 302, Kelly *et al.* (2005), were an example of two sites in close proximity with two very different risk levels. Both sites, 3.5 and 4.5 km west of the Saskatchewan Penitentiary, yielded PFs of 15 because they were both active and had high rates of movement with additional hazards, such as toe erosion and groundwater discharge on the river bank. A CF of 5 was assigned to the first site because partial road closure could result while a CF of 10 was assigned to the second due to risk of road closure and public safety issues should large sudden movements occur. Two sites near the Saskatchewan River and the same highway yielded differing risk levels because of hazard proximity to infrastructure, an expected result and reproduced using the available risk management system.

Since its inception in highway management, the system has become a pivotal resource in itself to prioritize sites and allocate resources accordingly. SDHT is no longer required to react urgently to every mobilized slide mass and also began to include real-time instrument monitoring at urgent risk level sites to offset and manage risk. This allows for instantaneous observation of ground movements by slope inclinometer and water levels by piezometers. Without ranking landslide-prone sites along the Saskatchewan highway network there would not be structure when selecting desirable sites for electronic monitoring. From any point of view, it is more economical to select sites where measurements are required on a regular basis.

### 3.2.3 Results

Several results are a direct function of the implementation of SDHT's risk management program, improved decision structure being the most significant. By classifying sites with respect to probability, consequence and resulting risk level, a systematic procedure is available to guide decision makers from initial observations to instrumentation and remediation methods. Suggested management approaches let SDHT assign resources and justify executive decisions based on quantifiable data. Other results include reducing time and money spent reacting to newly developed landslides, safer roads and surrounding infrastructure, and improved transportation corridors.

## 3.3 Suggested Improvements

This particular system contains several areas for improvement; it can be reactionary and does not permit for proactive analysis. Highways in proximity to water bodies are numerous in Saskatchewan and deciding which new sites to investigate is largely arbitrary. Several sites are known for instability, yet hundreds or perhaps even thousands of others may exist without direct knowledge. It would be unrealistic to expect a group of individuals to visit every site periodically unless it was their sole purpose. In this light, this system falls short of managing potentially hazardous landslide areas effectively.

Several additional factors should also be included when assessing probability and consequence of sites. When considering failure in a specific region, certain spatial attributes could become indicative of potential for failure; anything from vegetative cover to bedrock type. Consequence should include exposure in the form of public dependency on the roadway (exposure), such as AADT and minimum detour lengths. Furthermore, it should also include roadway classification, and specific nearby land use beyond that of government infrastructure (elements at risk).

Prediction of what sites should be visited before stepping foot outside the office would be ideal in that time and resources could be optimized. Assessing highest risk sites and implementing instrumentation and remediation works before working towards routine sites could eliminate guesswork and increase productivity within decision makers. GIS could aid in this process by manipulating and summarizing geospatial data to any user desired discretion.

Failure probability can be described by overlapping geospatial layers and by interpreting regional relief and subsequent grade. Creating spatial averages of what is required to trigger failure allows other sites to be compared and rated accordingly. This method is completely user governed in that experience and judgment dominates geotechnical engineering and user interpretation allows for manual alternations of a site's PF.

Consequence factor is treated differently in that there is no set criterion, simply evaluation of surrounding conditions. Network analysis can determine shortest detours should sections of roadway be severed, and roadway attributes such as AADT and functional classification can be weighted based on several factors.

Furthermore, assignment of PF and CF should be done in two phases: before and after site inspection (BSI and ASI). BSI is the process of assigning PF and CF to sites within a predetermined area so to allocate them in an unbiased fashion. ASI follows where focus is placed on sites with high BSI risk levels and sites with PF above a certain value regardless of initial CF. This is done to observe potential failure mode and their subsequent effect on safety which could in turn change a site's rating. Consequence is treated similarly though certain features remaining constant between initial and final observations: AADT, detour length, and roadway classification.

All things considered, one valuable addition to the SDHT risk management model is predictive risk analysis using GIS. This allows appropriate governing bodies to take economic stability of risk management to another level in that resources can be dispatched to priority sites before those of lesser potential hazard levels.

# 4 Slope Hazards Tour Summary

## 4.1 Introduction

On Monday, October 23rd and Tuesday, October 24th, 2006, a team of 11 individuals representing the University of Manitoba, MIT, SDHT and two external agencies conducted a landslide hazard assessment tour at four landslide sites in Western Manitoba.

The primary objective of the fall landslide hazard assessment tour was to obtain field data to use in the MIT risk management system. A binder for each site visited was prepared, containing all relevant information for each site. Following the visit, all four binders were completed and provided as a template for future site documentation. A second objective was to gather field observations and data from each site to use in the geospatial failure model. GPS data was collected to outline the failure extents and create failure cross-section profiles.

A site assessment package was created for each member and was divided into four sections; one for each site visited. An executive summary of each site was provided and contained all pertinent information and preliminary estimates of PF and CF. A series of site maps were also provided, showing geological location, topography, various physical attributes, and location of instrumentation (to be observed and monitored if possible). Instrumentation plots were included to give each member of the team an idea of past site activity and site inspection forms were available for everyone to complete. PF and CF were determined for each site by individual members using provided information and engineering judgment.

## 4.2 Site Discussion

A large component of the assessment was a follow up discussion. Members spoke freely about personal observations and views of what each site's PF and CF should be. A concentrated review of the SDHT risk management system yielded consensus when forming final PF and CF assessments for each site. Discussions with respect to failure mechanisms, triggers, geology, terrain, and others gave the assessment team confidence that selected factors were representative of current conditions. A summary of all discussions and subsequent site ratings follow.

### 4.2.1 PR259 and the Assiniboine River

#### 4.2.1.1 Site 1

Located approximately 700m from Assiniboine River on the west valley wall, as shown in Figure 4.1, several immediate observations were made. Retrogressive in nature, the first block slipped in a north-easterly direction. A second block followed with a larger drop towards a more northerly direction then the first, leaving a scarp of approximately 1 to 1.5m as seen in Figures 4.2 and 4.3. A third block likely slipped as a result of the large vertical scarp face left by the second block. Water flow in a small ravine located near the toe is blocked by a beaver dam, which raises concern that perhaps failure has been triggered by hydraulic related activities (*i.e.* rapid drawdown). Deep rooted vegetative cover surrounds the site with the exception of the actual failure surface itself. Small tension cracks can be seen in the pavement, on the order of 2 to 3mm. Instrumentation on site is no longer functioning due to excessive displacements.

If current conditions continue, failure at this site could result in potential lane closures which would require a lengthy construction period to repair the highway. PF was determined to be 11 based on increasing movements and a CF of 6 has been chosen because scarp would cut into the roadway.

#### 4.2.1.2 Site 2

Located approximately 300m east of site 2, as shown in Figure 4.1, it has been location of extensive studies by the University of Manitoba. Several shallow failures are scattered along the upper slope, as shown in Figure 4.4, and have been determined to be triggered primarily by excessive precipitation.

Failure at this site could result in blockage of the drainage ditch or potentially a lane of traffic. This would be easily mitigated by removal of the failed mass. Vegetative cover is dominantly field grass except for trees located along the sides of the upper slope. PF and CF were chosen as 9 and 4, respectively, because continued movement is evident and partial closure of the roadway would result.

#### 4.2.1.3 Site 3

Located approximately 1km from the Assiniboine River on the east valley wall this particular site is large and clay shale dominated, as shown in Figures 4.1 and 4.5. Outcropping of the Millwood clay shale bedrock along the valley face is a key contributor to this failure. Large amounts of precipitation likely activated a shear plane and superimposed with the soft nature of this particular material resulted in a large scale translational failure, exposing more underlying clay shale as seen in Figures 4.6 and 4.7. Although the site appears dormant in terms in movement, geometry of the existing embankment is similar along the entire length of highway cut into the valley face.

Vegetative cover is dominantly field grasses, except in areas of exposed clay shale where there is none.

A PF of 7 was assigned due to limited on site monitoring data to show the current rate of movement, if any. A CF of 6 was chosen to reflect a required lane closure, potentially both, if failure were to occur.

## 4.2.2 PTH41 and the Assiniboine River

### 4.2.2.1 Site 1

Located approximately 500m upslope from St. Lazare, as shown in Figure 4.8, the failure is currently affecting the road embankment with scarp initiating above the roadway and cutting down through the paved surface. Movements are visible above and below the road surface in the cut valley wall. Due to continued movements, nearly all instrumentation has been sheared off. Retrogressive in nature, several slide masses can be identified as shown in Figure 4.9. Private property is a concern at this site if movements continue. Several tension cracks very close to the highway on the lower side are observed and are on the order of 6 to 7mm as shown in Figure 4.10. Vegetative cover is dominantly field grasses except for a few trees located along the top of the upper slope.

A PF of 13 was chosen because movements are steady or increasing, evident by active scarps. A CF of 10, the highest possible, was chosen because of potential impacts on utility and private property and the proximity of scarps to the roadway.

#### 4.2.2.2 Site 2

Located approximately 100m upslope from St. Lazare, as shown in Figure 4.8, failure encompasses the entire roadway. Several scarps are visible above the roadway, generally 5 to 10cm in height, and extend for moderate lengths, approximately 20 to 30m as shown in Figure 4.11. Past movement at the toe of the slope forced MIT to purchase and relocate a private residence. Instrumentation is still functioning though not monitored on a regular basis. Vegetative cover is dominantly field grasses except for trees located along the top of the upper slope.

A PF of 11 was chosen due to moderate or increasing rates of movement and a CF of 10 because of proximity to private residences and utilities, as seen in Figure 4.12.

### 4.2.3 PR478 and the Assiniboine River

This site is located along a ravine on the east wall of the Assiniboine Valley, as shown in Figure 4.13. The Valley is relatively wide and contains several retrogressive failures. The largest scarp sits at the top of the upper face, approximately 1.5 to 2m in height, and extends for approximately 75 to 100m as shown in Figures 4.14 and 4.15. Several smaller failure surfaces are held within the larger mass, with evident scarp and toe locations. Previous works include construction of a toe berm on the down-slope side of the highway, sand drains, and drainage works as shown in Figure 4.16. Several slope indicators and piezometers are located within the site.

A PF of 9 was chosen because available data suggests moderate, steady, or decreasing movement. A CF of 6 was selected based on the likelihood of road closure should a failure take place.

### 4.2.4 PTH83 and the Shell River

Located on the southern wall of the Shell River Valley, as shown in Figure 4.17 and 4.18, with 100m of relief between prairie level and the valley floor, this failure is the largest of all those visited. Failure encompasses the entire roadway and is monitored on a regular basis; installation of several piezometers was taking place during the assessment. A small retrogressive failure on the upper slope contains a scarp of approximately 1 to 1.5m located just ahead of a larger scarp, approximately 3m high, which likely belongs to that of the larger failure as shown in Figures 4.18 and 4.19. Both are aligned in a similar direction with the smaller centered along the larger mass. Deep rooted vegetative cover is dominant with exception of the lookout area, as shown in Figure 4.20.

A PF of 13 was selected due to ongoing movements and the potential for future large mass movements. A CF of 10 was chosen because of unavoidable roadway closure should failure take place.

## 4.3 Risk Summary

Relative risk factor and ranking for all sites examined are summarized in Table 4.1. The two top ranked landslides both have a high risk levels that relate to loss of the roadway. Based on the risk level values, management approaches can be determined using the SDHT model. Table 4.2 summarizes and categorizes each site's risk level with respect to their appropriate response level and management approach.

Table 4.1 – Relative risk factor and ranking for all visited sites

| Highway | Site | Probability Factor | Consequence Factor | Risk Level | Rank |
|---|---|---|---|---|---|
| PTH 83 | 1 | 13 | 10 | 130 | 1 |
| PTH 41 | 1 | 13 | 10 | 130 | 1 |
| PTH 41 | 2 | 11 | 10 | 110 | 3 |
| PR 259 | 1 | 11 | 6 | 66 | 4 |
| PR 478 | 1 | 9 | 6 | 54 | 5 |
| PR 259 | 3 | 7 | 6 | 42 | 6 |
| PR 259 | 2 | 9 | 4 | 36 | 7 |

Table 4.2 – Tour response level summary

| Risk Level | Response Level | Management Approach | Inspected Sites |
|---|---|---|---|
| >125 | Urgent | Inspect at least once per year. Monitor instrumentation at least twice per year in the spring and fall. Investigate and evaluate mitigation measures | PTH 41: Site 1<br>PTH 83 |
| 75 to 125 | Priority | Inspect once per year. Monitor instrumentation at least once per year. | PTH 41: Site 2 |
| 27.5 to 75 | Routine | Inspect every 3 years. Monitor instrumentation at least every 3 years with an increased frequency for selected sites as required | PR 259: Site 1<br>PR 259: Site 2<br>PR 259: Site 3<br>PR 478 |
| <27.5 | Inactive | No set instrumentation monitoring or inspection schedule. Monitored and inspected as required in response to maintenance requests. | |

Relative ranking incorporates input from the entire team of individuals involved with the landslide hazard assessment tour. Summary tables demonstrate which sites are priorities after visiting and assessing each using the SDHT landslide management system. Magnitude of risk levels does not in itself represent any meaningful design parameter; it is only used to establish the relative level of mitigation works required as indicated in the management approach. The system is conclusive in that it is highly applicable in western Manitoba and information gathered allow for preliminary GIS development.

## 4.4 Conclusion

The first landslides hazards tour was a considerable success in terms of establishing a baseline application of the SDHT landslide management system. Six sites were visited and characterized by 11 individuals using this system. Assessment results have been summarized and details of GIS development are ready to be introduced.

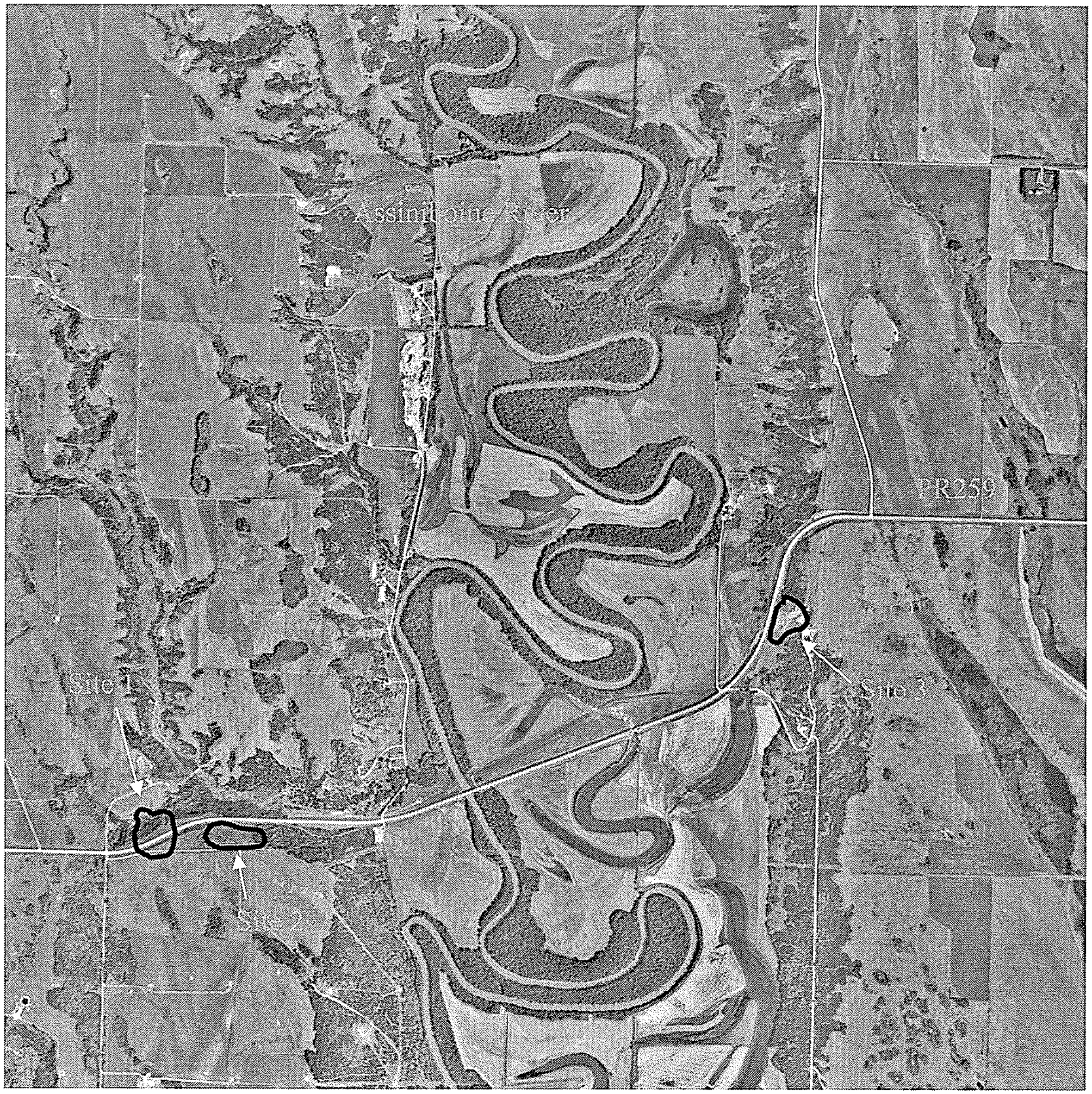


Figure 4.1 – Aerial view of PR259 and Assiniboine River

Figure 4.2 – Site 1 of PR259 and Assiniboine River, block 2 scarp east view

Figure 4.3 – Site 1 of PR259 and Assiniboine River, block 2 scarp west view

Figure 4.4 – Site 2 of PR259 and Assiniboine River, scattered retrogressive shallow shear failures

Figure 4.5 – Site 3 of PR259 and Assiniboine River, large scale failure

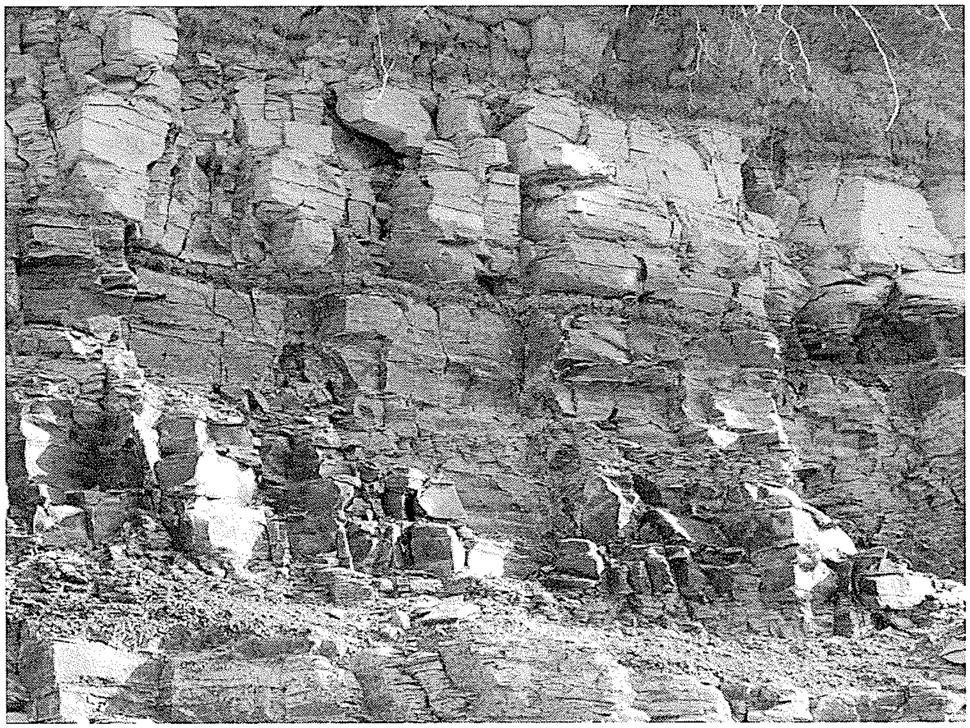


Figure 4.6 – Site 3 of PR259 and Assiniboine River, scarp

Figure 4.7 – Site 3 or PR259 and Assiniboine River, close up of the platy Millwood clay shale structure

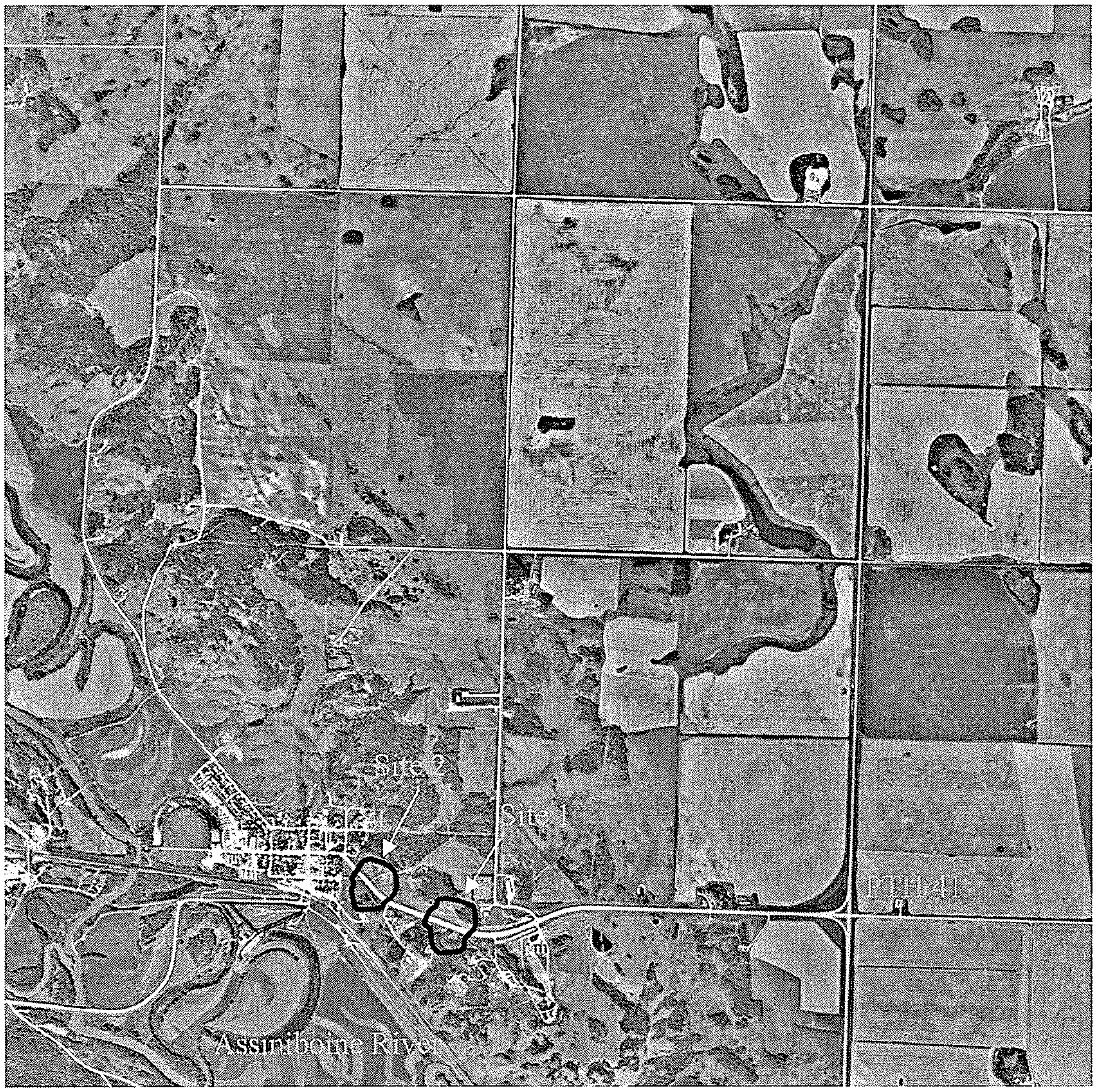


Figure 4.8 – Aerial view of PTH41 and Assiniboine River

Figure 4.9 – Site 1 of PTH41 and Assiniboine River, retrogressive failure located on upper embankment

Figure 4.10 – Site 1 of PTH41 and Assiniboine River, large tension crack near roadway

Figure 4.11 – Site 2 of PTH41 and Assiniboine River, scarps located on upper embankment

Figure 4.12 – Site 2 of PTH41 and Assiniboine River, proximity to private residences

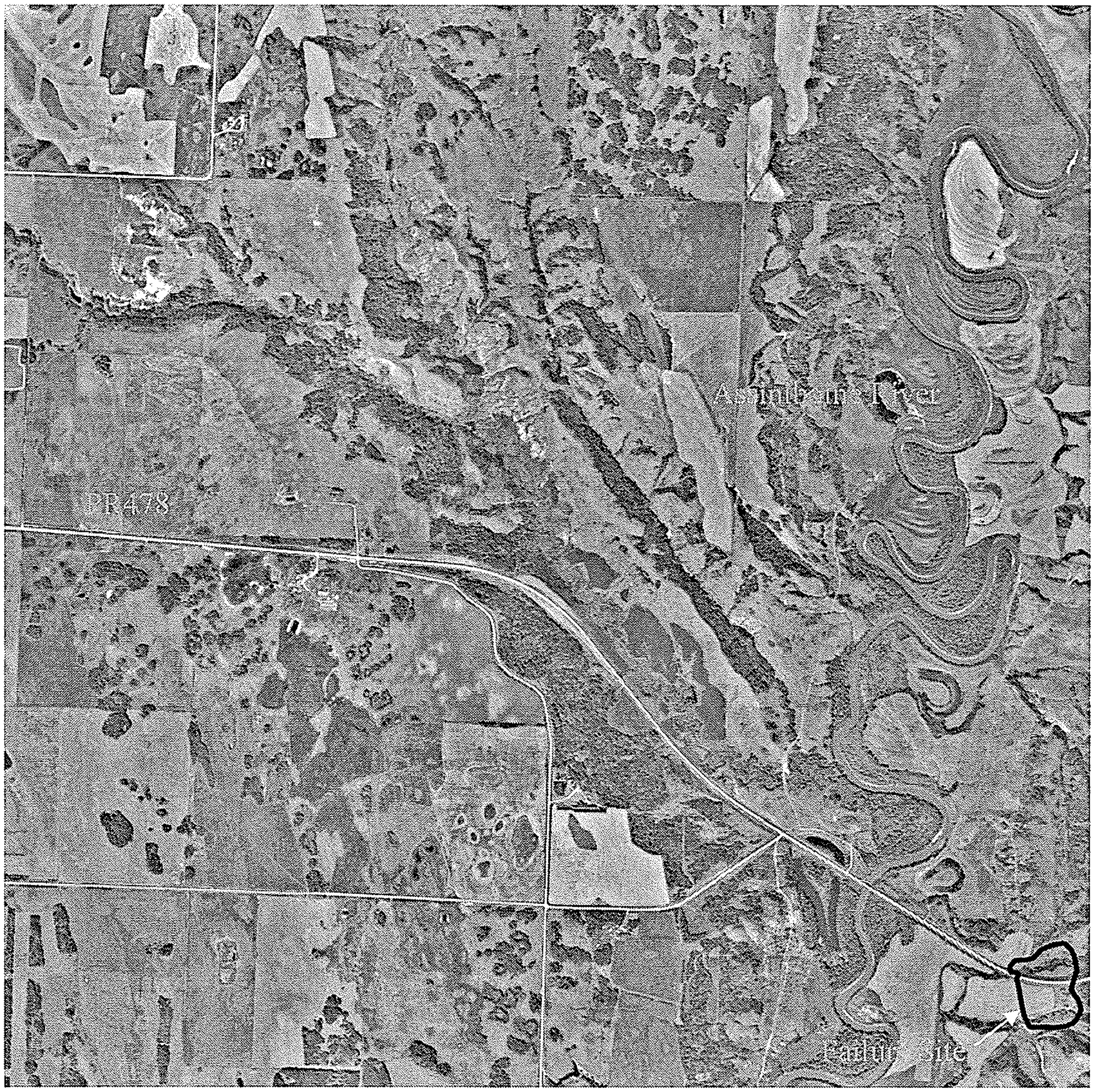


Figure 4.13 – Aerial view of PR478 and Assiniboine River

Figure 4.14 – PR478 and Assiniboine River, head scarp at top of upper slope

Figure 4.15 – PR478 and Assiniboine River, head and toe scarp

Figure 4.16 – PR478 and Assiniboine River, drainage mitigation

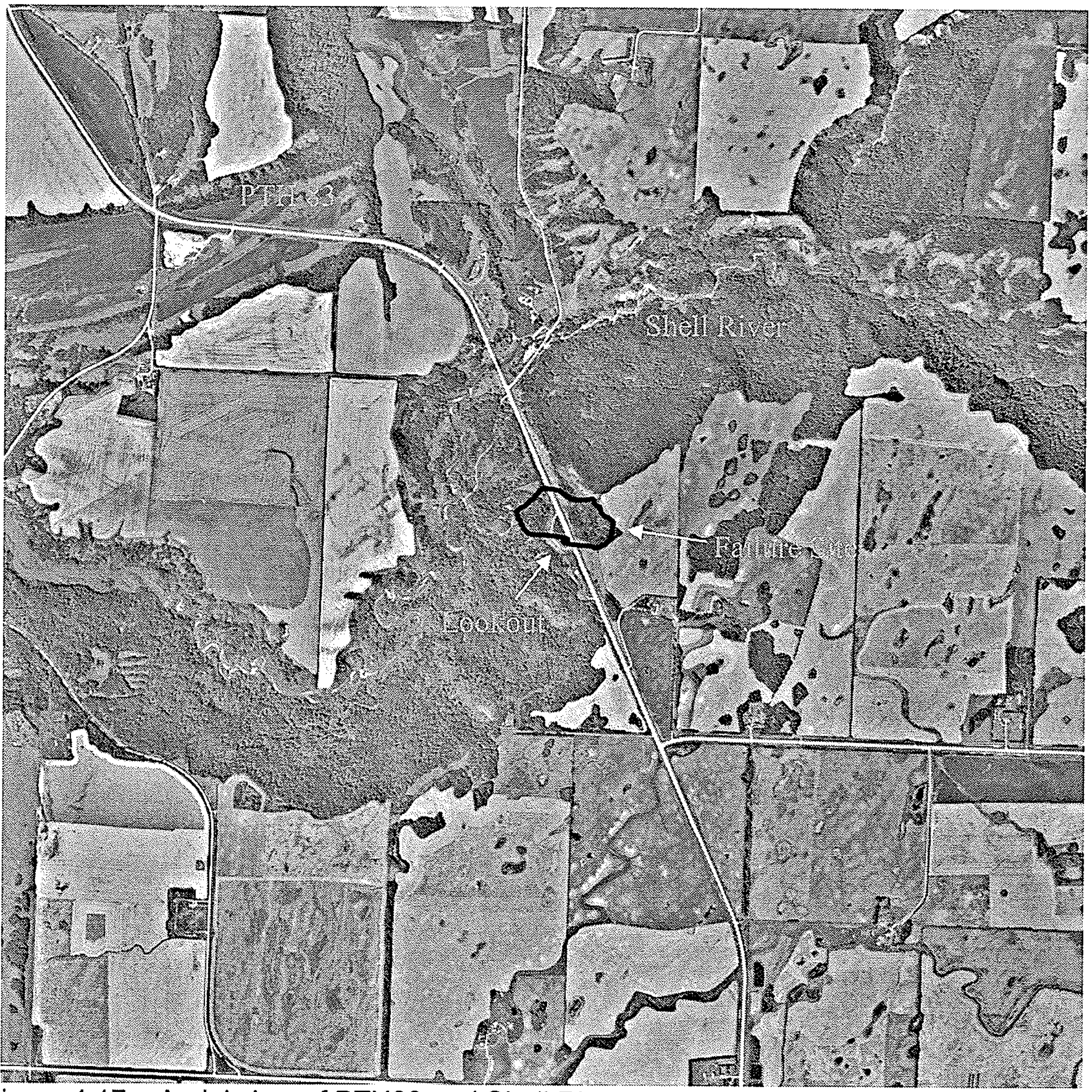


Figure 4.17 – Aerial view of PTH83 and Shell River

Figure 4.18 – PTH83 and Shell River, toe view of upper scarp

Figure 4.19 – PTH83 and Shell River, upper scarp of the larger mass movement

Figure 4.20 – PTH83 and Shell River, vegetative cover

# 5 GIS Development and Theory

## 5.1 Introduction

Vast amounts of information can be stored, manipulated and summarized in GIS software packages. Any point, line, or area established in a geospatial database can be attributed to unlimited amounts of data and vice versa. This can make segregating meaningful data difficult. GIS packages use differing methods of data documentation and file associations. GeoMedia Professional is one of the only GIS based software packages that can connect to varying file types from an array of other packages, known as warehouses, and has been selected to carry out the GIS portion of this research. Two extensions have also been incorporated: GeoMedia Grid and GeoMedia Transportation Manager.

Software has become a significant addition to engineering practice and design; decreasing analysis and design times with increasing calculation and analysis capabilities. It is important to always use engineering judgment when using software to model reality and all outputs should be scrutinized to the utmost degree. As such, when developing evaluation methods of probability and consequence at landslide hazard sites, results must always be checked against input validity.

PF and CF development begins at a commonality, a geospatial template that contains several layers identified as indicative of failure: roadway proximity to fluvial waterways, surficial soil, bedrock type, and grade. Probability and consequence development then diverges with separate analysis types that result in a numerical quantity representative of risk. This chapter presents the Manitoba Infrastructure and Transportation Risk

Management System (MITRMS) development and theory, and discusses manual adjustments necessary to include engineering judgment and obviate software deficiencies.

## 5.2 Geospatial Template

Several overlapping layers of information comprise the template for the GIS portion of this research. Information gathered from each failure site during the tour, further compiled into project binders, have led to features that are indicative, in some shape or form, of potential instabilities. These are proximity to highways and fluvial bodies, moderate to high relief and grade along valley walls, clay shale and/or outcropping bedrock, surficial soil type, piezometric surface, artesian pressures, precipitation, infiltration, runoff, aspect, and local vegetation.

Geospatial layers are complex to build. Comprised of points, lines, and areas; they can be tagged with unlimited amounts of information, known as attributes. In general, these geometries remain constant and only attributed information can be easily manipulated. This creates difficulty when developing layers meant to fluctuate over time or with respect to other layers, such as infiltration and runoff as a result of precipitation, soil type and vegetative cover. Inclusion of these in developing PF and CF within GIS is impractical and is recommended to be considered in manual application of the risk management system.

Geospatial layers used to create the GIS template are obtained through the Manitoba Land Initiative (MLI), Manitoba Mines and Linnet Geomatics, each of which contributed pivotal information. A 500,000 scale basemap, obtained through MLI, includes roadway, water bodies, township/range, land use, and bedrock geometries. Surficial geology was obtained through Manitoba Mines and 2m resolution aerial images and DEMs are available though a CD resource library from Linnet Geomatics.

Two GIS software packages are utilized to develop the master template, ArcView 3.3 and GeoMedia Professional. Significant efforts were placed on assuring layer coincidence once summarized in GeoMedia, where several layer geometries were corrected to portray realistic conditions accurately. Several additional amounts of information are necessary for PF and CF considerations. These include AADT, roadway functional classification, weight classification, and speed as set by MIT. These were input manually from maps and data gathered through MIT. Additional functional attributes include roadway length and travel time for network analysis and detour calculations.

Within the GIS workspace, roadway, water body, bedrock, and surficial soil geometries are overlapped to create a geospatial template where all further spatial manipulations are to be based on, as shown in Figure 5.1.

## 5.3 Failure Model

When developing a method of calibrating failure probability within a geospatial system, confidence is required for selecting features and triggers indicative of failure. A true/false criterion is impractical and so a buffer zone is necessary for considering varying conditions of failure criteria inputs.

Well documented failures have taken place at five sites: two sites at PR259 and Assiniboine River, PTH41 and Assiniboine River, PR478 and Assiniboine River, and PTH83 and Shell River. As such, it's sensible to use known and determinate information from these as the criteria for failure model development. GIS based information is used to create the model with results from the spring hazards tour used as guidance.

### 5.3.1 Geospatial Layers

The geospatial template, as discussed prior, is a starting point for failure model development. On top of roadway, water body, bedrock, and surficial geology geometries, additional layers are required; most importantly, DEMs.

DEMs are generally provided as point data, that is, several points over an area have three coordinates: latitude, longitude and altitude (x, y, z). Each point, in two-dimensional plan view space are seen as a series of points in a plane. The true addition DEMs bring to GIS is in three-dimensional space, where any geospatial layer can be draped in order to create a three-dimensional image.

GeoMedia Grid is an extension to GeoMedia Professional that gives users the ability to create raster images of DEMs. By creating a grid across regions comprised of pixels, specified attributes can be assigned to each to create an image of the attribute in question. Points in the given DEMs are spaced at approximately 120m, as shown in Figure 5.2, and so all subsequent images and calculations are subject to this resolution. For desk study purposes, this resolution is acceptable since significant differences in elevation and grade are readily visible. Raster images of elevation and grade as created by GeoMedia Grid are provided in Figures 5.3 and 5.4. These are plan view images of the Assiniboine River at its mouth in Lake of the Prairies. Complete aerial views of elevation and grade for this research's extents are shown in Figures 5.5 and 5.6, respectively.

Raster images can take any form given suitable input data, that is, each pixel can be assigned any geospatial type data value, *i.e.* grade, aspect, and isoline (topographical applications). Grade can be one of two values, maximum or average. Each is computed by selecting a single point and calculating the slope with respect to the eight surrounding it. Average slope is the average of these and maximum slope is the relative maximum. The action of assigning each pixel a value based on overlapping attributes can also be reversed. Raster images created by GeoMedia made up of a finite number of pixels can be vectorized into point geometries. Points are defaulted coordinates of the center of each pixel it represents, and are written with attributes identical to that of each. For this research purpose, maximum slope is calculated using the DEMs and subsequently vectorized back into point data form. This allows for ease of manipulation for later queries and is heir in known as the 'grade point' geospatial layer.

Other layers used for assessing PF are truncated versions of bedrock and surficial geology. It is well known that clay shale bedrock can be indicative of slope instability. Single units of bedrock generally cover large areas, and in areas of deep soil, bedrock has less of an impact on surficial instability. Therefore, areas where clay shale bedrock is exposed at the surface are isolated and become another GIS based trigger, as shown in Figure 2.4. Manitoba Mines describes areas of fluvial erosion/deposition, both past and present, as Eroded Slope Complex (ESC) and is also isolated to become another area indicative of potential instabilities, also shown in Figure 2.4.

In the event the above mentioned geospatial layers are overlapped; focus is narrowed to specific regions along fluvial waterways near day lighting bedrock. This in itself has refined the search for hazardous sites where all are considered equal in terms of hazard, so focus needs to be further specified.

In addition to the above, supplementary geospatial layers can be added in order to further refine the search for hazardous sites. These include, but are not limited to: watershed, floodplain, and bridge geometries. It would be highly beneficial for both PF and CF analysis and development to include these layers, for they could place more emphasis on sites near vital infrastructure. These geospatial layers were not made to be available for this research.

### 5.3.2 Spatial Query Conceptualization

To further refine searches for potentially hazardous sites, focus must be narrowed to areas of quantifiable significance. Unstable areas along a river bank are typical; instabilities are a function of natural erosional processes governed by several environmental factors. In areas of little use or public inhabitance, slope movements are of little concern, where in developed areas containing public and government infrastructure, consequence of damages are much higher. MIT is concerned about instabilities in proximity to their PRs and PTHs near fluvial water bodies, private and Crown property, right-of-way, and utilities. To accomplish this, a buffer distance is required around roadways and fluvial water bodies, where the overlap is the objective.

Final output of the overlapping geospatial layers needs to be considered prior to assigning buffer distances. Overlapping the ESC, river buffer and roadway buffer

Where $\mu$ and $\sigma^2$ are the dataset mean and variance, respectively. A random variable, X, is described as being distributed normally when:

$$X \sim Normal(\mu, \sigma^2) \qquad [5.2]$$

Gamma distributions are also two-parameter continuous probability distributions that represent the sum of $k$ exponentially distributed random variables, each of which with a mean of $\theta$. Mathematically, its *pdf* is expressed in terms of the gamma function and defined as:

$$f(x;k,\theta) = x^{k-1}\frac{e^{-x/\theta}}{\theta^k\Gamma(k)} \text{ for } x > 0 \qquad [5.3]$$

Where $\theta$ and $k$ are the scale and shape parameters, respectively, and are both positive. These are both approximated by:

$$\theta = \frac{1}{kN}\sum_{i=1}^{N} x_i \qquad [5.4]$$

And

$$k \approx \frac{3 - s + \sqrt{(s-3)^2 + 24s}}{12s} \qquad [5.5]$$

Where

$$s = \ln(\frac{1}{N}\sum_{i=1}^{N} x_i) - \frac{1}{N}\sum_{i-1}^{N} \ln(x_i) \qquad [5.6]$$

The gamma function is defined as:

$$\Gamma(k) = (k-1)! \text{ for } k > 0 \qquad [5.7]$$

A random variable, X, is said to be distributed using gamma when:

$$X \sim Gamma(\theta, k) \qquad [5.8]$$

Consolidating grade points within the overlapped geospatial layers at five known failure sites yields one of each distribution type for each roadway buffer distance tested. With increments of 100m, evolution of the failure model with varying roadway buffers for both distribution types are provided in Figure 5.7 and 5.8.

All left equal, it can be seen that variability across roadway buffer distance is much higher using a gamma distribution over that of the normal distribution. Significant differences yield large changes in the function's shape and curvature. Large jumps in magnitude, in either direction, occur irrespective of varying buffer distance, indicating no justifiable logic for using the gamma distribution to describe grade point occurrence. The sole consistent change during increasing roadway buffer distance is the slow shift of peak magnitude toward the center of the curve. At no point does the skewed gamma curve resemble that of a bell, though the slow migration of its peak could suggest that over long enough test periods, it could.

Normal curve distribution however, changes very little from roadway buffer lengths of 100m to 1,000m. Variance is slight, with the mean, $\mu$, remaining fairly constant, between 8 and 10 degrees. In fact, evolution begins to truncate noticeably following the 500m buffer distance event. This indicates that buffer distances larger than 500m have little or no significant influence on the two parameters determining normal *pdf* curvature.

These two distribution types are most suitable since they have both been used to model natural worldly events more often than any other distribution type. Other distributions, such as Beta and Chi, were investigated with conclusive evidence that these types would not be suitable or representative for these purposes. The Beta distribution is used to model proportions, that is, values between 0 and 1, and as such is bounded on both sides of the function. This is impractical since grade of an embankment can vary over a much larger range. The Chi distribution, though usable, for these purposes is impractical. The risk management system is being built such that a user friendly interface increases its attraction; including rigorous statistical analysis, even before any final results are evident, would do the opposite.

Sites are assessed by proximity to failure using a simple statistical process of normalizing and evaluating the probability that a value should fall anywhere below an upper maximum. Figure 5.9 a) is a normalized bell curve with mean and variance of 0 and 1, respectively, and should be reviewed coincidentally with the following.

A *pdf* can not be evaluated at a single point. This is described conceptually as the area under a line, which does not exist. Probability is described as a density, bound by limits selected by the user. Queries must be posed in the form of regions, *i.e.* the probability of randomly selecting a value above the mean. In Figure 5.9 a) this results in evaluating area under the curve to the right of 0, a 50 percent probability of selecting a value in this region. Several approaches can be taken in order to evaluate the random selection of a bound value. Desired results are a numerically understandable term that describes failure, or resemblance to the failure model. A viable method for evaluating the probability of selecting values that fall between a sample data set's mean plus and minus standard deviation, described mathematically as:

$$P(\mu - \sigma < X < \mu + \sigma) \sim Normal(0,1) \qquad [5.9]$$

If a data set, irrespective of that which created the curve, has a mean and standard deviation of 1.5 and 0.5, respectively, the probability of selecting this value would be approximately 13.6 percent, as shown in Figure 5.9 b). A significant, yet difficult error to detect has occurred in doing this. If a data set was to have a mean and standard deviation of -1.5 and 0.5, respectively; it would result in the same probability, also shown in Figure 5.9 b). For these purposes, each data set is a hazardous site as interpreted by the GIS. If two data sets were compared, with the aforementioned parameters, it should be implicit that failure probability would be higher in that of the higher mean. This is not the case when utilizing this approach and is not representative of real conditions.

A similar, more convergent approach is leaving the lower bound limitless, that is, testing the probability that a randomly selected value lies below the dataset mean plus standard deviation, descried mathematically as:

$$P(X < \mu + \sigma) \sim Normal(0,1) \qquad [5.10]$$

Using the example above would force the data sets to differ by approximately 64.1 percent, as shown in Figure 5.9 c), a much more realistic distinction between two slopes of highly differing grades.

Using *pdf*s to evaluate spatially varying grades requires relating dataset parameters to those of the standard normal case by utilizing:

$$Z = \frac{X - \mu}{\sigma} \qquad [5.11]$$

This takes any known data set, when randomly normally distributed and shapes it to resemble that of the standard normal. This then allows data sets of any parameter values to be evaluated as described.

Using a failure model of varying roadway buffer distances, any site can be evaluated if their mean and variance are known. Through systematically selecting sites, using this model, and outputting a probability that a randomly selected value falls beneath it's mean plus standard deviation can create a list of sites with associated failure probability. These values are bound between 0 and 1, numerically meaningful when addressing probability, and numerically representative of how grade is statistically distributed throughout an area.

### 5.3.4 Spatial Query Selection

Varying distance buffer about roadways and fluvial waterways allows suitable statistical distributions to be selected in order to describe grade occurrence across a sloped area as segregated by overlapping geospatial layers. It also aids in developing ways of assessing stability at a site using statistical distributions. In order to further refine and select an appropriate buffer distance, comparisons against the failure model using results from the spring slope hazards tour is required.

At its widest, the Assiniboine River valley is approximately two to three kilometers from crest to crest. Choosing a waterway buffer suitable to encompass both valley walls is necessary, even in the case that meandering has forced the water body to approach an extreme side. Slope stability is known to be affected by long ranges of piezometric surfaces; to address this, a buffer of 1500 meters to either extreme of a fluvial body has been chosen. Figure 5.10 displays the buffer applied along the Assiniboine River near Miniota, where the full width is required to encompass eroded slope along the west valley wall.

The slope hazards tour resulted in manual assessment of PFs at five sites. These results are based on physical observations, which among others include slope of embankment. Selection of an appropriate roadway buffer distance begins similarly to statistical distribution selection. For varying roadway buffer distances, a failure model is created and used for comparison against the same five failure sites found within the GIS.

A mean and standard deviation from each site allows statistical analysis to be conducted using the approach described previously. A graph depicting failure probability at five sites is shown in Figure 5.11 plotted against increasing buffer distance. Ranks change consistently with few exceptions for buffer distances less than 500m. Only at 600m and thereafter do ranks satisfactorily truncate, with the exception of PTH41 and Assiniboine River where it consistently increases.

Table 5.1 summarizes rank for the 600m buffer distance case. An exact match is evasive, though patterns are evident. PTH83 and Assiniboine River remains ranked the highest, and PR259W and Assiniboine River is higher than that of its eastern counterpart. Further similarities would increase confidence though it should be made clear that results of the analysis are based on slope data only, whereas that of the tour encompassed a full spectrum of engineering knowledge and experience. Fundamentally though, a systematic method of ranking hazardous sites with respect to failure probability based solely on probable grade at a site has been accomplished. This is an important first step.

Table 5.1 – Summary of probability ranking between results of the slope hazards tour and 600m roadway buffer distance

| Rank | Slope Hazards Tour Ranking | GIS Based Ranking |
|---|---|---|
| 1 | PTH83 and Shell River | PTH83 and Shell River |
| 2 | PTH41 and Assiniboine River | PR478 and Assiniboine River |
| 3 | PR259W and Assiniboine River | PR259W and Assiniboine River |
| 4 | PR478 and Assiniboine River | PR259E and Assiniboine River |
| 5 | PR259E and Assiniboine River | PTH41 and Assiniboine River |

Choosing larger buffer distances creates two problems; increased complexity within the software to process larger amounts of point data and increased likelihood of importing non-representative environmental conditions. Ranking remains constant between buffer distances of 600m and 800m. The former has been selected to conclude the analytical GIS portion of PF determination. Figure 5.12 depicts the 600m roadway buffer applied along PR467 near Miniota overlapped with the waterway buffer. The translucent black area is the spatial overlap of discussed failure trigger layers and defines the extents of potentially hazardous areas. Point geometries contained within this area are grade points, the data used for statistical analysis at a site. The study region contains a number of these areas in need of statistical review in order to find the higher failure probability sites. Figure 5.13 shows the normally distributed GIS based failure model that results from statistical grade point analysis of overlapping 1500m waterway buffer, 600m roadway buffer, and ESC geometries. Figure 5.14 is the failure model as a cumulative distribution function (*cdf*) which can be described mathematically as the integration of the *pdf*. Conceptually this implies that values along the y-axis correspond to the probability of selecting a random value below its corresponding value along the x-axis.

GPS profiles of each site were created during the hazards tour in order to create an updated model for failure probability assessment. Data from GIS are only reflective of past conditions and are not representative of real-time changes. The process at which the GPS failure model is created is similar to that of the GIS model. Grade is calculated between each GPS data point for each site and summarized. The data is distributed normally, as shown in Figure 5.15, and creates the basis for all post assessment quantification of failure probability. The *cdf* is shown in Figure 5.16.

## 5.4 Probability Factor

### 5.4.1 Initial Considerations

Creating a method of classifying failure probability at hazardous sites, without setting foot outside the office, requires several pivotal considerations in order to develop an accurate and logical prioritization list. Critically thinking about what surrounding physical factors can and should be included in the study is a must, with significant efforts placed on what is, has, or can be known about specific sites within a short amount of time. Two approaches are necessary to complete a full analysis of a site; a desk study to initially prioritize site visits and a follow-up manual assessment to assign final risk. Due to constraints in GIS software and an overwhelming requirement for human intervention, the desk study portion is further divided into two sections. They are separated by strict, well distinguishable analysis types; those from GIS and those not from GIS. Manual assessment is similar to that of the fall slope hazards tour where the MITRMS site inspection form (Appendix A) is used.

Desk studies begin with statistical analysis of a site's failure probability as taken from the failure model discussed previously. This comprises the primary PF selection, which categorizes sites on a twenty point scale. Secondary analysis is a process of category shifting based on known or unknown site specific conditions. This is necessary because the failure probability as taken from the failure model is only indicative of a site's spatially varying slope as dated in 1999 (the date at which Linnet created the DEMs in use). These are not real-time data files and as such are only reflective of conditions from that time. Manual interpretations of environmental surroundings are important to address a site's true susceptibility to failure. During the desk study portion, these manual adjustments are governed by questions to be answered using a predetermined scale and description, to be discussed later.

By using the primary and secondary PF assessments, users are involved with the entire risk management process. This enforces critical thinking about what is truly taking place at a site and requires a user to become well informed of a site's history and current state.

Manual assessment is the ultimate goal of the desk study. It yields a prioritized list of sites to be inspected, therefore forcing proper decisions to be made on which locations, on a preliminary basis, require attention. An addition to this process includes developing a cross-section profile of sites, for an updated statistical calibration of failure probability based on the GPS failure model.

### 5.4.2 Selection Table

SHTS's methodology of selecting PF is shown to be successful. The SDHTRMS is used as a baseline for this research, so it's appropriate that only small alterations are included to address current developments.

The sole significant addition is the method at which PF is initially selected through preliminary stages of assessment. Failure probability should be treated closer to an exponential variable than linear. The SDHT model incorporates an approximate linear type relationship, as shown in Figure 5.17. It links consistent changes in factor of safety to consistent changes in PF. This is not representative of our natural association of risk and failure. Consequence increases at an exponential rate of change as a system approaches failure, thus PF should be treated similarly. It should be noted that factor of safety and PF for the SDHT approach was never intended to be strictly related in the form shown in Figure 5.17.

In order to calibrate numerical adjustments, values between 0 and 1 are taken from the failure model characteristics and categorized. This is done by creating ten groups and forcing the first to encompass null to 25 percent failure probability. Ten groups are chosen to reflect broad areas of probability, while segregating those that are of less significance from those that are of higher significance. Forcing the initial group to encompass less than 25 percent chance of failure is set qualitatively, yet it reflects creation of a suitable exponential basis of selecting PF. Figure 5.18 shows the exponential relationship between category selection and failure probability as calibrated using the GIS failure model. Table 5.2 below contains the updated MITRMS PF selection table. This selection table is more significantly directed towards site investigations, where personnel must be on hand to calibrate the noted descriptions against physical observations. Inclusion of failure probability is for visualization purposes only.

### 5.4.3 Before Site Investigation

#### 5.4.3.1 GIS Interpretations

GIS interpretations are limited to the primary PF selection, that is, mathematical interpretation of failure based on spatially varying grade of an area. A GIS created failure model is used for calibration of any site within the confines at which it is applicable.

Table 5.3 shows the current distribution of known failure sites using the GIS failure model; note the failure model itself is category 11. This is appropriate since the failure model is a boundary at which failure is likely to occur, to any extent. It is also appropriate since it was developed using known failure sites, which range from category 5 to 17. Now it can be understood that any site resembling the failure model does not indicate eminent failure and a high PF rating. A known property of normal curves is that probability of randomly selecting a value between its average plus and minus its standard deviation is approximately 68.26 percent. Using the approach adopted for assessing a site's failure probability results in a percent of approximately 84.13, category 11. Other GIS interpretations also include query based adjustments based on the presence of outcropping clay shale bedrock.

Table 5.2 – MITRMS probability factor selection table

| PF | $P(Z < \mu_i + \sigma_i) \sim N(\mu_f, \sigma_f)$ | Natural Slope | Engineered Slope |
|---|---|---|---|
| 1 | 0 – 0.2499 | Geologically Stable. **Very low probability** of landslide occurrence. | FS > 1.5 on basis of effective stress analysis with calibrated data and model*. Historically stable. **Very low probability** of landslide. |
| 3 | 0.2500 – 0.4399 | Inactive, apparently stable slope, **Low probability** of landslide occurrence or remobilization. | 1.5 > FS > 1.3 on basis of effective stress analysis with calibrated data and model. Historically stable. **Low probability** of landslide. |
| 5 | 0.4400 – 0.5899 | Inactive landslide with **moderate probability** of remobilization. Moderate uncertainty level; or, active slope with very slow constant rate of movement; or, indeterminate movement patters. | 1.3 > FS > 1.2 on basis of effective stress analysis with calibrated data and model. Minor signs of visible movement. **Moderate probability** of landslide |
| 7 | 0.5900 – 0.6999 | Inactive landslide with **high probability** of remobilization, or additional hazards present. Uncertainty level high. Perceptible movement rate with defined zones of movement. | 1.2 > FS > 1.1 on basis of effective stress analysis with calibrated data and model. Perceptible signs of movement or additional hazards present. **High probability** of landslide. |
| 9 | 0.7000 – 0.7899 | Active landslide with **moderate, steady or decreasing rate of movement** in defined shear zone | FS < 1.1 on basis of effective stress analysis with calibrated data and model. **Obvious signs of ongoing slow to moderate movement** |
| 11 | 0.7900 – 0.8599 | Active landslide with **moderate, increasing rate of movement** | Active landslide with **moderate, increasing rate of movement** |
| 13 | 0.8600 – 0.9099 | Active landslide with **high rate of movement** | Active landslide with **high rate of movement** |
| 15 | 0.9100 – 0.9499 | Active landslide with **high rate of movement at steady or increasing rate** | Active landslide with **high rate of movement at steady or increasing rate** |
| 17 | 0.9500 – 0.9799 | Active landslide with **high rate of rate of movement with additional hazards**** | Active landslide with **high rate of movement with additional hazards** |
| 19 | 0.9800 – 1.000 | **Catastrophic landslide** is occurring | **Catastrophic landslide** is occurring. |

Table 5.3 – Known failure site calibration list using the MITRMS GIS failure model

| Category | $P( Z < \mu_i + \sigma_i ) \sim N(\mu_f, \sigma_f)$ | Sites |
|---|---|---|
| 1 | 0 – 0.2499 | |
| 3 | 0.2500 – 0.4399 | |
| 5 | 0.4400 – 0.5899 | PTH41 and Assiniboine River |
| 7 | 0.5900 – 0.6999 | PR259W and Assiniboine River |
| 9 | 0.7000 – 0.7899 | PR259E and Assiniboine River |
| 11 | 0.7900 – 0.8599 | Failure Model |
| 13 | 0.8600 – 0.9099 | PR478 and Assiniboine River |
| 15 | 0.9100 – 0.9499 | |
| 17 | 0.9500 – 0.9799 | PTH83 and Assiniboine River |
| 19 | 0.9800 – 1.000 | |

### 5.4.3.2 GIS Limitations

As stated previously, development of the failure model used to calibrate primary PF at sites is subject to the origin of DEMs. In 1999, Linnet conducted a land navigation survey that yielded several 2m resolution aerial photographs and accompanying point data containing projected coordinates in all three directions. Grade was calculated as a function of these points and as such is taken to be accurate for the time at which the survey was conducted.

GeoMedia is limited in its ability to be completely automated, though not necessarily a limitation, it still falls short of optimum for handling tedious and repetitive analysis. Isolating sites is a function of overlapping geospatial layers, where any further work is done manually. Grade points at a site are manually selected and mathematically interpreted outside the confines of GIS, an unavoidable, rigorous, time consuming process.

A very important limitation of GIS is lessening the uncertainty of failure mode and physical extents of potential failure. As such, above and beyond that of manually assessing sites with high risk, any site where failure model calibration yields a PF category of fifteen or higher should be manually inspected. Failure type/mode is significantly influential on failure likelihood and PF should be adjusted accordingly through investigation.

### 5.4.3.3 Manual Adjustments

Manually adjusting primary PF is the method at which categories are shifted up and down the PF selection table. This creates an introduction of site knowledge and engineering judgment. It can not be expected that the GIS system would result in exact or even relatively accurate results indicative of failure probability. Including a site's history or up-to-date conditions brings the system to a level that provides necessary insight to how and what can be done to improve understanding.

Three questions, with several potential answers and multiple combinations are available in order to paint an accurate picture. These questions pertain to environmental and physical conditions that are known or can be established by site visits.

#### 5.4.3.3.1 Outcropping Clay Shale Bedrock?

The first query is true or false, is there outcropping clay shale bedrock? Answers to this can be found using the Geospatial template, as shown in Figure 5.1. Since it has been shown that the presence of outcropping clay shale is a trigger for instability, it is appropriate to include this in secondary PF assessment. False is associated with no proximate day-lighting clay shale. If clay shale does exist nearby, then a category jump is necessary to reflect further potential for instability. Table 5.4 summarizes query responses.

Table 5.4 – Response list for outcropping bedrock

| Response | Description | Category Shift |
|---|---|---|
| Yes | Outcropping clay shale bedrock is proximate | 1 |
| No | Outcropping clay shale bedrock is not proximate or present | 0 |

#### 5.4.3.3.2 Slope Movements?

The second question requires slightly more knowledge of a site; is it currently moving? If instrumentation is available then assessing movements should be simple. If instrumentation is not available, several alternative methods are available such as past experience or periodic photographs. Unless data is readily available, this query should receive an unknown response, where it receives a category shift due to lack of knowledge for desk study purposes. This shift is less than it would be if movements are known. Four potential responses are available to address this query, as shown in Table 5.5.

Table 5.5 – Response list for slope movement query

| Response | Description | Category Shift |
|---|---|---|
| Unknown | Unknown | 1 |
| Insignificant | None, decreasing or slow rates of movement over longer periods of time | 0 |
| Moderate | Steady or slowly increasing rates of movement over longer periods of time | 2 |
| Considerable | Steady or increasing rates of movement over shorter periods of time | 4 |

#### 5.4.3.3.3 Past Mitigation?

Lastly, have mitigative measures been implemented in the past? This is the only positive feedback query available for secondary PF assessment. If several sites are under consideration within a region, where one particular site has been the source of instability and has seen observable improvements following remediation, then its PF and resulting hazard should be decreased accordingly. This query should only be answered if information is readily available for desk study purposes. Otherwise, unknown should be selected where PF should not be adjusted due to of lack of knowledge. Four potential responses are available to address this query, as shown in Table 5.6.

Table 5.6 – Response list for past mitigation query

| **Response** | **Description** | **Category Shift** |
|---|---|---|
| Unknown | Unknown | -1 |
| Insignificant | None, periodic maintenance personnel interjections, or no observable improvements post remediation | 0 |
| Moderate | Moderate observable improvements following remediation of any type | -2 |
| Considerable | Considerable observable improvements following remediation of any type | -4 |

On average, over an entire area, most of the latter two queries will result in an unknown response during desk studies. This classifies the sites in question without bias, making all things equal, and highlighting those of higher priority. This should instinctively force the user to have unknowns answered by dispatching personnel for assessment. A considerable improvement in the ranking may be gained by simply reducing uncertainty (*i.e.* ‘unknown’) through observation.

Desk studies precede site investigations but do not directly initiate them. It should be noted that PF is only one of two necessary inputs for assessing risk; consequence being the other. Both factors should be investigated before mobilizing site assessment personnel. Before CF development is addressed, PF development after site investigation is discussed below.

## 5.4.4 After Site Investigation

### 5.4.4.1 GPS Interpretation

As noted earlier, a failure model for post site inspection from a profile's cross-section at a site using GPS is necessary. This was done to make up for the low density of GIS based DEM data points and creates an updated representation of a slope's grade distribution. A cross-section for each case is shown in Figure 5.19 for the PR259E and Assiniboine River site.

During visual inspection, GPS points are collected over a site's approximate failure profile. Three meter spacing is recommended along portions of constant grade, one meter along portions of slightly varying grade, and a single point at any change in geometry (*i.e.* crest, toe, scarp, and tension cracks).

Failure probability is calibrated using the GPS failure model; this portion of the analysis resembles that of the desk study. Summarizing data sets comprised of grades at a point for mean and variance yield interpretive failure probabilities. PFs of investigated sites can then be refined to express updated failure probability and secondary PF adjustments. Table 5.7 lists results of the five known failure sites as calibrated using post-inspection techniques.

Table 5.7 – Known failure site calibration list using the MITRMS GPS failure model

| **Category** | **$P( Z < \mu_i + \sigma_i ) \sim N(\mu_f, \sigma_f)$** | **Site** |
|---|---|---|
| 1 | 0 – 0.2499 | |
| 3 | 0.2500 – 0.4399 | |
| 5 | 0.4400 – 0.5899 | PTH41 and Assiniboine River |
| 7 | 0.5900 – 0.6999 | |
| 9 | 0.7000 – 0.7899 | PR478 and Assiniboine River |
| 11 | 0.7900 – 0.8599 | Failure Model<br>PR259E and Assiniboine River |
| 13 | 0.8600 – 0.9099 | PR259W and Assiniboine River |
| 15 | 0.9100 – 0.9499 | PTH83 and Assiniboine River |
| 17 | 0.9500 – 0.9799 | |
| 19 | 0.9800 – 1.000 | |

### 5.4.4.2 Manual Assessment

The main role of manual assessment is to get a perspective of what is truly occurring at a site. The GIS failure model provides sufficient guidance, but can only go so far. Physical observations are required to properly assess a site for best results. Inspection of high priority sites allows the risk management system to truly show its benefits. Once the GIS system has ranked the sites, this forms a basis for selecting top sites to be visited based on potential risk

Besides redefining a site's failure probability using the GPS failure model, it also puts precedence on clearly answering two manual adjustment queries. Once on site, slope movements can be visible through a variety of methods and past mitigative measures, if any, can be assessed with respect to their success. Site inspection personnel should employ the SDHT PF selection table, Table 5.2, as a redundancy check of the GIS aided PF assessment.

### 5.4.5 Final Considerations

Without imposing bounds, manual adjustment of primary PF can force a final PF above twenty. This is not meaningful when a finite range of resultant risk is required. In the event this occurs, regardless of final risk response, resources should be mobilized to inspect these sites so to increase confidence level of manual adjustment responses and reduce obvious uncertainties regarding data for the site. These include any case where primary site PF falls on or above category fifteen. Appendix A contains the recommended site inspection form.

Numerical representations selected within this section are reflective of qualitative analysis. This risk management system is built as a user interactive application, where probabilities and subsequent category shifts must be altered to reflect that of any user's opinion based on their own system applications.

## 5.5 Consequence Factor

### 5.5.1 Initial Considerations

Quantifying PF is rigorous and time consuming. Setting failure probability in terms of percentage makes sense and when created using sound principles, is difficult to dispute. Determinate factors are used to decide whether failure is probable based on statistics and observable characteristics of a site. Consequence, unfortunately, does not share the same characteristics. Consequences generally take the form of meaningful societal based variables, where bounds are placed based on current trends and public behavior. Putting dollar values on the cost of a single life is controversial and a highly disputed concept yet is required to some degree in risk management applications.

In terms of transportation infrastructure and potential for road closure due to slope instabilities, several extremes must be considered. Roadways are connectors, without them a critical means of communication is lost. Cities, towns, or rural communities may not receive manufactured or processed goods. Travel time is increased as a result of detours on both in public and commercial domains. Further, these two are affected proportionally to a roadway's AADT. Functional and weight classifications are also significant factors to be considered when developing CFs.

These factors are quantifiable numerically, that is, based on GIS capabilities and information available through MIT, they can be assigned numerical values. Upper limits can be set for detour length and AADT where if breached, can make constructing temporary detours more practical.

Functional classification can only be one of seven possibilities: Expressway (4-lane) Expressway (2-lane), Primary Arterial, Secondary Arterial, and type 'A, B or C' Collectors. These have been set by MIT and are mainly a function of a roadway's importance in terms of use and necessity. Weight classification can only be one of five possibilities: RTAC, Class A1, Class A1 (Seasonal), Class B1, and Class B1 (Seasonal). These are a function of a roadway's importance to commercial transportation and structural ability to withstand varying axle weights. When functional and weight class options are given associated scaled values, they can influence CF in a numerically understandable fashion. As with PF development, features summarized through GIS is termed primary CF.

Due to GIS software limitations, not all relevant information at a site can be observed by site reconnaissance and investigation. These include proximate land use; a site surrounded by private infrastructure could be considered more negatively influential than Crown or right-of-way infrastructure. Surrounding utilities are also of concern. These concepts formulate the secondary CF, where through a method of adjusting primary CF based on known or unknown site specific conditions could alter the overall CF of a site. However, if a bridge infrastructure geospatial layer becomes available, this could become a primary CF trigger as opposed to a secondary CF adjustment. A method of addressing this could be updating Table 5.9 to including proximate bridge infrastructure by assigning a weight, where its influence on primary CF could be an interpolation of the bridge's capital cost or exposure.

Manual assessment is the ultimate goal of desk studies. Regardless of ultimate risk, if surrounding infrastructure near a site is unknown, risk is increased since there is inherent uncertainty regarding neighboring infrastructure. Manual assessment of a site that would normally have differing consequence due to unknowns should be assessed in order to represent actual circumstances.

### 5.5.2 Selection Table

Consequence factor selection, as outlined by SDHT, is shown to be successful at manual assessment levels. However, its description and typical triggers are unable to be interpreted using GIS. For the most part, physical observations are the dominant traits which lead to CF selection, with little significance placed on stimulus outside immediate view. Fundamentally, the SDHT selection table lacks the ability to direct users to interpret importance of functional and weight classification, detour susceptibility, and public/commercial dependence.

The primary CF selection table is a function of the four discussed characteristics of a site, each weighted based on its global importance on systems in question. More similar to a flow chart, primary CF determination is calculated based on numerically observable quantities at a site. Table 5.8 is a generic summary of the inputs and is shown in order to supply a representation of how individual factors influence primary CF calculation.

Table 5.8 is for conceptualization purposes only. The four primary determinate CF contributors are discussed further in following sections. The SDHT CF selection table is recommended for continued use during manual assessments when coupled with the above criterion. This can be an exceptional tool for cross-referencing CF before and after site investigations.

Table 5.8 – Generic MITRMS consequence factor summary

| Primary CF | Generic Summary |
|---|---|
| 1 | Little to no detour length<br>Little to no AADT<br>Collector "B or C"<br>Class B1 (Seasonal) or Class A1 (Seasonal) |
| 2 | Moderate to no detour length<br>Moderate to little AADT<br>Collector "A, B or C" or Secondary Arterial<br>Class B1 (Seasonal), Class A1 (Seasonal) or Class B1 |
| 4 | Moderate to small detour length<br>Moderate AADT<br>Collector "A", or Secondary or Primary Arterial<br>Class A1 (Seasonal), Class B1, or Class A1 |
| 6 | Moderate to long detour length, temporary construction in extreme case<br>High to moderate AADT<br>Secondary or Primary Arterial, or Expressway (2-lane)<br>Class B1, Class A1, or RTAC |
| 10 | Temporary construction or significantly long detour length<br>High AADT<br>Expressway (2-lane) or (4-lane)<br>RTAC |

### 5.5.3 GIS Interpretation

This section discusses four numerically determinate influences on primary CF calculation: detour, AADT, and functional and weight classification. Before detailed discussion begins, appropriate proportions must be assumed in order to properly determine a factor's influence on primary CF. Similar to the SDHT model, a scale of ten is used and as such, even in the most extreme case the upper value should not be exceeded. Table 5.9 summarizes assumed proportions.

Table 5.9 – Summary of assumed influence of primary CF input

| Input | Percent of Total (%) | Maximum Value |
|---|---|---|
| Detour | 20 | 2 |
| AADT | 20 | 2 |
| Functional Classification | 30 | 3 |
| Weight Classification | 30 | 3 |
| Total | 100 | 10 |

#### 5.5.3.1 Detour Analysis

A GIS extension program, GeoMedia Transportation Manager, is required for network analysis. Analysis types include best path for minimized distance or travel time, best stops for multiple paths, and network coverage. Generating detour influence on consequence strictly requires best path analysis.

Transportation networks are created through a variety of layers and queries. Traversable edges must be established with coincident geometries to ensure turning abilities. Nodes must be established to represent terminates and beginnings of an edge segment. Costs must be attributed to travel time by creating a functional attribute corresponding to segment length divided by segment speed. Restrictor attributes are required to establish loss of roadways within a network. And lastly, stop points are required in order to set the bounds of best path analysis. Only once all of these have been established can network analysis begin. Western Manitoba's roadway network and nodes are shown in Figure 5.20.

Detour length is limitless; to be precise, detour lengths can range from a few kilometers to several hundred if local alternate paths are not available. Detour influence on primary CF calculation must be truncated to its maximum value, as shown in Table 5.9, by selecting an upper limit. Conceptually, an acceptable detour travel time could be approximately thirty minutes and can be considered standard in rural areas. This travel time likely wouldn't impose any distress on its users. Thus it seems reasonable to assume that a sixty minute detour travel time could be a realistic upper limit. This corresponds to a distance of 100 kilometers assuming 100 km/hr as an average speed in rural areas. Calculating detour influence on primary CF is a matter of linear interpolation assuming that 100 kilometers corresponds to a maximum consequence of two.

Two best path analysis types are available, minimized distance or travel time. It is very probable that resulting travel length from both analysis types could differ widely. This is tested by plotting minimized travel time versus minimized travel distance as interpreted by network analysis at five known failure sites, shown in Figure 5.21. A line of best fit is evidently linear which indicates redundancy between analysis types, thus restricting best path analysis to minimizing travel distance is suitable. In any instance where minimizing travel time yields significant decreases in travel time versus that of minimizing distance, detour construction would be more suitable since detour lengths would extend past the upper limit of 100 kilometers. This is not surprising considering that rural traffic conditions would dictate limited start and stop impacts. The results would be expected to be quite different inside a city.

Figure 5.22 is a snapshot of detour analysis at PR259 and Assiniboine River. Restricting travel along highway segments between stops forces the software to interpolate a best alternate path, as shown.

### 5.5.3.2 AADT

Methods of collecting traffic data are few; roadways are set up with traffic counters that reset every twenty-four hours. Over the period of time these devices are in service, daily traffic counts are plotted with respect to time of day, days of week, weeks, months, and seasons. AADT is daily traffic averaged over the data collection time frame. This figure is only representative of number of vehicles and does not segregate vehicle types and/or use. Traffic counters that distinguish vehicle types are in use in Manitoba but only in limited amounts and thus can not be applied over the entire study region due to lack of data. When this data becomes available for every roadway segment within the study extents, each vehicle type could be assigned a subsequent weight to that shown in Table 5.9.

Similar to detour analysis, AADT is limitless. An unlimited number of vehicles can travel a segment of highway and thus, an upper limit must also be selected to truncate maximum influence to a value of two, as noted in Table 5.9.

Figure 5.23 is a roadway map where line thickness is proportional to AADT. Thematics are skewed as a result of daily traffic counts in the 10,000 range in the city of Brandon. It can be seen however, that traffic counts along the Trans Canada Highway are in the range of 3,000 vehicles per day. 4-lane expressways, such as the Trans Canada and Yellowhead Highways, are cases where daily traffic data is much higher than average. Across the region, average AADT is approximately 750 vehicles per day. Using similar logic used to define an upper limit of detour length, an upper limit of 1500 vehicles per day is a realistic value to define. Including AADT in primary CF calculation is a matter of using linear interpolation, knowing that 1500 vehicles per day corresponds to a maximum consequence of two.

### 5.5.3.3 Functional Classification

As stated earlier, functional classification is determined based on roadway importance and connective abilities. MIT ultimately decides, based on roadway and user characteristics, appropriate classification of each segment of highway. Figure 5.24 is a map of western Manitoba's roadways themed as functional classification.

Developing a numerical scale at which importance is assigned to each classification type is simply a method of weighing a segment's importance to the global system. If 4-lane expressways are known to be twice as important as secondary arterials then it should be reflected when assigning numerical proportions. Developing a fitting scale to express distribution of functional classification importance is a qualitative task where each type receives a numerical value based on a user determined scale. Specifically, if the most essential classification receives a rating of ten, then all other types receive a proportional rating based on their respective value. Table 5.10 is a generalized expression of how this functions. Using functional classification influence on primacy CF calculations, as shown in Table 5.9, can be mathematically manipulated to set a maximum influence of three.

Table 5.10 – Summary of functional classification's influence on primary CF

| Functional Classification | Numerical Value | Primary CF Influence |
|---|---|---|
| Expressway (4-lane) | $FC_1 = 7$ | $FC_1/FC_{MAX} = 1.00$ |
| Expressway (2-lane) | $FC_2 = 6$ | $FC_2/FC_{MAX} = 0.86$ |
| Primary Arterial | $FC_3 = 5$ | $FC_3/FC_{MAX} = 0.71$ |
| Secondary Arterial | $FC_4 = 4$ | $FC_4/FC_{MAX} = 0.57$ |
| Collector "A" | $FC_5 = 3$ | $FC_5/FC_{MAX} = 0.42$ |
| Collector "B" | $FC_6 = 2$ | $FC_6/FC_{MAX} = 0.29$ |
| Collector "C" | $FC_7 = 1$ | $FC_7/FC_{MAX} = 0.14$ |
| $FC_{MAX}$ = Relative maximum of functional classification numerical values | | |

### 5.5.3.4 Weight Classification

Weight classification is set by MIT as a result of rural trucking routes and roadway segment weight bearing abilities. Specific routes are pivotal for trucking operations based in rural areas and if roadway segments are severed, detours are further constrained by surrounding roadway restrictions. Detour analysis results may not be traversable by certain truck types and are forced to take far more lengthy detours. Detour analysis for these purposes is complex since several truck orientations yield several alternate axle weight distributions. Roadways are set to allow assortments of truck geometries and weight distributions and as such, would result in several detour paths. Figure 5.25 is a themed map displaying roadway weight classification in western Manitoba.

Determining numerical representation is similar to that of functional classification. Upon determining each classification type's proportion to that of the highest influence primacy CF can be established. Table 5.11 depicts a generalized mathematical approach to developing weight classification influence on primary CF. With this established, mathematical manipulations can enforce a maximum primary CF influence of three, in accordance with Table 5.9.

Table 5.11– Summary of weight classification's influence on primary CF

| Weight Classification | Numerical Value | Primary CF Influence |
|---|---|---|
| RTAC | $WC_1 = 10$ | $WC_1/WC_{MAX} = 1.00$ |
| Class A1 | $WC_2 = 8$ | $WC_2/WC_{MAX} = 0.80$ |
| Class A1 (Seasonal) | $WC_3 = 3$ | $WC_3/WC_{MAX} = 0.30$ |
| Class B1 | $WC_4 = 6$ | $WC_4/WC_{MAX} = 0.60$ |
| Class B1 (Seasonal) | $WC_5 = 1$ | $WC_5/WC_{MAX} = 0.10$ |
| $WC_{MAX}$ = Relative maximum of weight classification numerical values | | |

## 5.5.4 GIS Limitations

GIS contribution to primacy CF is restricted to network analysis; all other inputs are qualities or quantities as collected or established by MIT. Limitations are few since interpretation of best alternate path can be visibly confirmed and corrected if necessary. In terms of developing best alternate routes for tucks, limitations remain in the complexity of deciding which truck types utilize which routes most frequently and constructing GIS feature classes that exhibit associated restricted routes. This can be added in the future if deemed necessary based on importance.

## 5.5.5 Manual Adjustments

Similar to PF development, adjustments must be made based on site specific conditions in order to orient final CF as a more accurate portrayal of actual conditions. Manual adjustments are based on surrounding infrastructure and their respective consequences should damage occur resulting from slope movements.

### 5.5.5.1 Proximity to Utilities

The first of three manual adjustments is based on proximity to utilities. If a potential slide could impact nearby utilities then consequences should be adjusted accordingly. There are three available primary responses: unknown, yes and no. Further to true or false statements stating if a site is proximate to utility infrastructure is asserting what value or importance it has on its surroundings. If there are utilities present, four further options are available to express value: none, low, medium, and high. Table 5.12 is a summary of the aforementioned responses and their description.

Table 5.12 – Proximity to utilities response and description summary

| Proximity Response | Maximum Category Shift | |
|---|---|---|
| Unknown | 1 | |
| Yes | 2 | |
| No | 0 | |
| **If Yes: Value Response** | **Percent of Maximum Category Shift (%)** | **Description** |
| None | 0 | Proximate with no significant value |
| Low | 0 | Proximate with low value and no significant negative affects if lost |
| Medium | 50 | Proximate with moderate value and long term affects if lost |
| High | 100 | Proximate with high value and severe consequences if lost |

A response of unknown should be defaulted if no immediate information is available for desk study purposes. A category shift is necessary since there is a potential probability that utilities are present. In the case that proximity is none or unknown, value responses make no contribution to maximum category shifts.

### 5.5.5.2 Private Land Proximity

Private land proximity is an important consideration when determining a hazardous site's consequence. Loss of private land or infrastructure, such as a private dwelling or community centre, involves potential injury and litigations, and cost of life. Placing a dollar value on loss of life or well-being is subject to years of collected data. It is desirable to avoid any ramifications as a result of disruption to public property and placing large influences on consequence is a rational mechanism to suitably weigh the consequences for those cases. Methods at which private land proximity are treated is identical to that of utilities with appropriate alterations applied to weight and category shifts. Table 5.13 is a summary of responses for private land secondary CF considerations.

Table 5.13 – Proximity to private property response and description summary

| **Proximity Response** | **Maximum Category Shift** | |
|---|---|---|
| Unknown | 1 | |
| Yes | 4 | |
| No | 0 | |
| **If Yes: Value Response** | **Percent of Maximum Category Shift (%)** | **Description** |
| None | 0 | Proximate with no significant value |
| Low | 25 | Proximate with low importance and costs (i.e. farm field) |
| Medium | 75 | Proximate with moderate consequences if affected (i.e. private yard, public park) |
| High | 100 | Proximate with large consequences if affected (i.e. house, school, recreational facility) |

During a desk study, a response of unknown should be defaulted if no immediate information is available. Category shifts are necessary since there is inherent probability that privately owned land could be present. In the case that proximity is none or unknown, value responses make no contribution to maximum category shifts.

### 5.5.5.3 Crown Land and Right-of-Way Proximity

The final secondary CF inclusion is Crown land and right-of-way infrastructure considerations. If utilities and/or privately owned land do not surround the site under scrutiny, it likely belongs to the Crown. Typical examples of Crown land and right-of-way infrastructure include drainage ditches, access roads, and bridges. These are treated similarly to the first two secondary CF influences, where if present, rely on associated values to shift categories. Table 5.14 is a summary of responses.

Table 5.14 – Proximity to Crown land and right-of-way response and description summary

| **Proximity Response** | **Maximum Category Shift** | |
|---|---|---|
| Unknown | 1 | |
| Yes | 3 | |
| No | 0 | |
| **If Yes: Value Response** | **Percent of Maximum Category Shift (%)** | **Description** |
| None | 0 | Proximate with no significant value |
| Low | 33 | Proximate with little to no consequences if affected (i.e. forested land) or no immediate concerns |
| Medium | 66 | Proximate with moderate consequences if affected |
| High | 100 | Proximate with large consequences if affected (i.e. bridges, roadway, pumping station) |

During a desk study, a response of unknown should be defaulted to unknown if no immediate information is available. Category shifts are necessary since there is inherent probability that Crown or right-of-way infrastructure could be present. In the case that proximity is none or unknown, value responses make no contribution to maximum category shifts.

### 5.5.6 Manual Assessment

The main role of manual assessment is to get a perspective of what is truly occurring at a site. Primary CF is the result of known site conditions as interpreted using GIS and available information from MIT. These should remain consistent within CF development, unless updated information becomes available periodically, *i.e.*, AADT. Influential inputs are manual adjustments imposed by the secondary CF. During desk studies, solutions to these questions may be unknown and as such should be clarified via physical inspection. Refining consequence using site inspections increases system confidence, providing for more precise prioritized site lists. Site inspections should also include use of the SDHT CF selection table, Table 5.3, as a redundancy check, similar to that suggested during manual PF assessment.

### 5.5.7 Final Considerations

Since primary CF can be any of the full ten categories, manual adjustments could force category jumps to induce a final CF above the maximum limit of ten. This is not meaningful when a finite range of resultant risk is required. In the event this occurs, regardless of final risk response, resources should be mobilized to inspect these sites so to increase confidence level and reduce uncertainty of manual adjustment responses. Appendix A contains the recommended site inspection form.

Numerical representations selected within this section are concluded qualitatively. This risk management system is built as a user interactive application, where weights and subsequent numerically represented consequences must be altered to reflect that of any user's opinion based on their own system applications.

## 5.6 Risk Factor

### 5.6.1 Considerations

Probability and CF scales are chosen to resemble that of the SDHTRMS for several reasons; most predominately for direct comparison. If two adjacent provinces use a similar method and scale for classifying hazardous landslide sites then communication of results is simplified. Adaptation of supplementary methodologies from each other can be effortless also. Potential considerations for risk factors are specific to ranges of risk and response procedures due to slight changes in the methodology of PF and CF selection and resources available to MIT.

A final risk classification table, a function of all methodologies and developments discussed, is provided in Table 5.15. The table is similar to that of SDHT's with slight additions to response level management approaches. Additions have been included that pertain to inspection schedule and prospective mitigative responses. These are suggestions for developing management approaches for individual sites only.

Table 5.15 – MITRMS risk factor classification table

| Risk Level | Response Level | Suggested Management Approach |
|---|---|---|
| >125 | Urgent | Inspect at least twice per year. Monitor instrumentation at least twice per year in the spring and fall. Site investigation and evaluation of mitigation measures are recommended. |
| 75 to 125 | Priority | Inspect once per year. Monitor instrumentation at least once per year. Investigate and evaluate MIT "best practice" mitigation measures. |
| 27.5 to 75 | Routine | Inspect every two to three years. Monitor instrumentation at least every three years with an increased frequency for selected sites as required. |
| <27.5 | Inactive | No set instrumentation monitoring or inspection schedule. Monitored and inspected as required in response to maintenance requests. |

## 5.7 Conclusion

The development of the GIS based risk management system has been provided in detail. Five known failure sites, assessed through manual inspection and GIS, have provided guidance for developing and evaluating potential means to systematically assign failure probability, consequence and therefore risk to hazardous sites. PF and CF are both divided into primary and secondary contributions. Primary factors are results of GIS based or quantifiable knowledge and secondary factors are the result of category shifting after applying site specific knowledge. Manual inspection is shown to be pivotal for updating the MITRMS where sites to be visited are a direct result of desk studies.

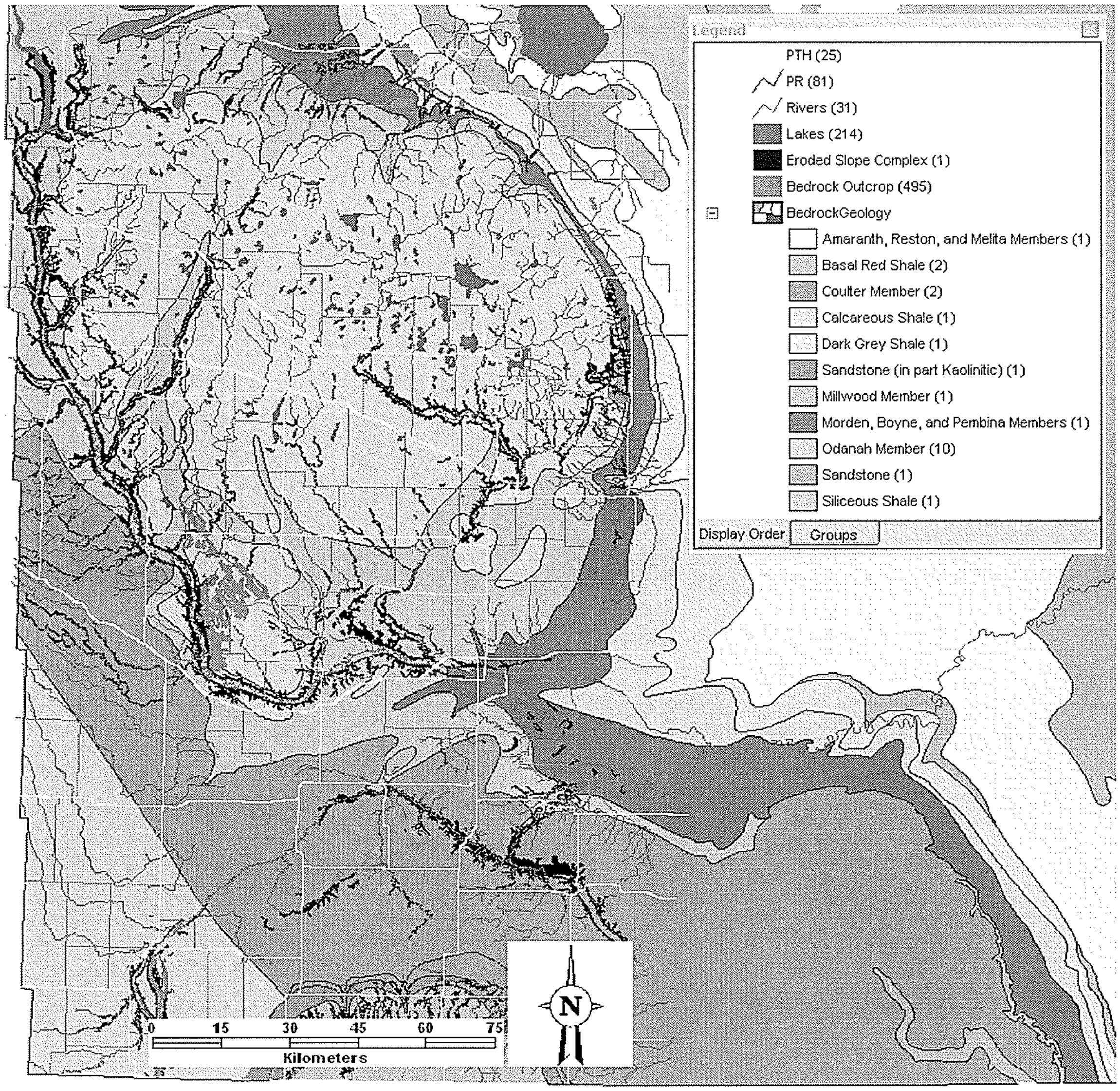


Figure 5.1 – Geospatial template

Figure 5.2 – Plan view of DEM over a small region of western Manitoba

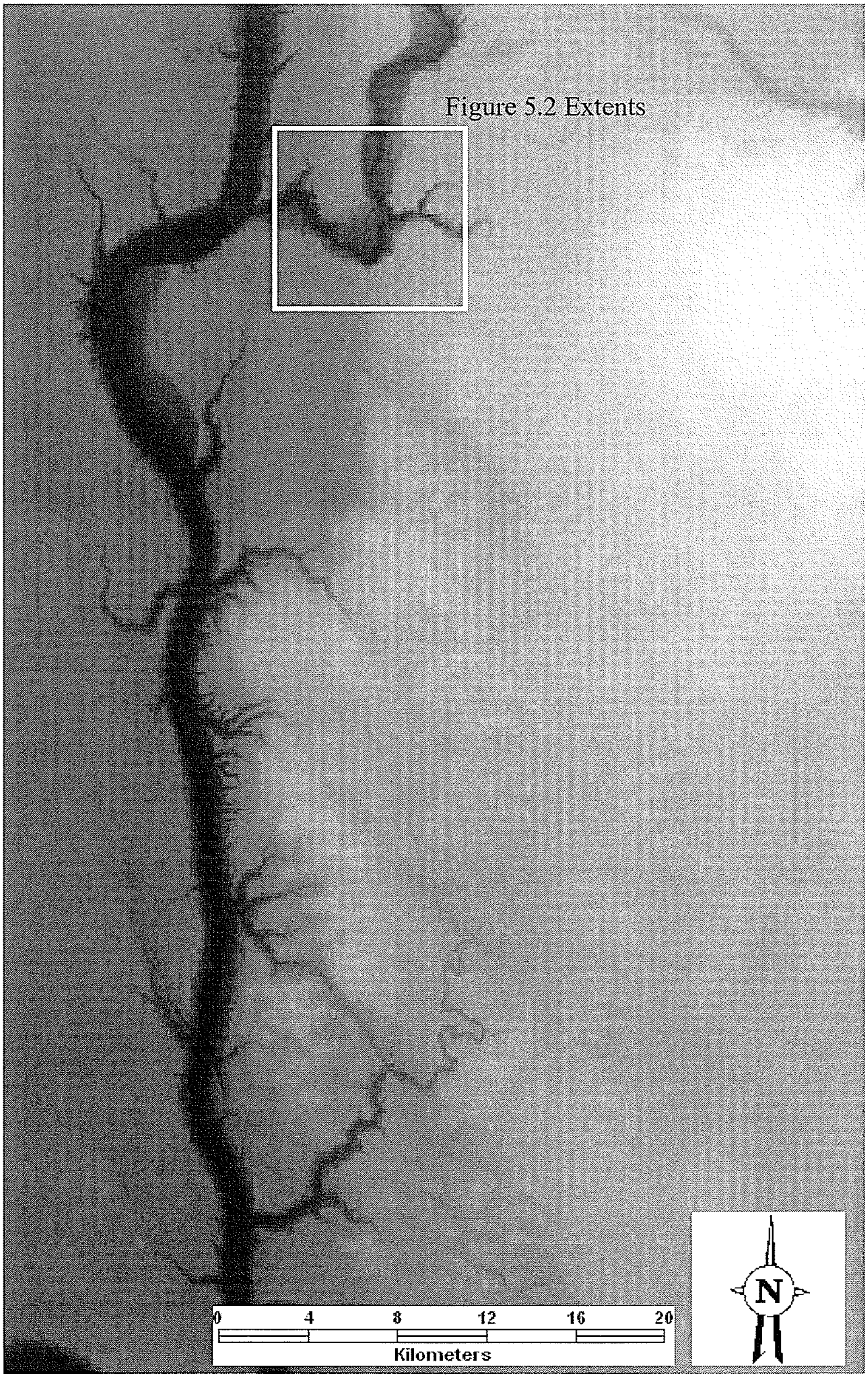


Figure 5.3 – Expanded plan view elevation raster of Figure 5.2

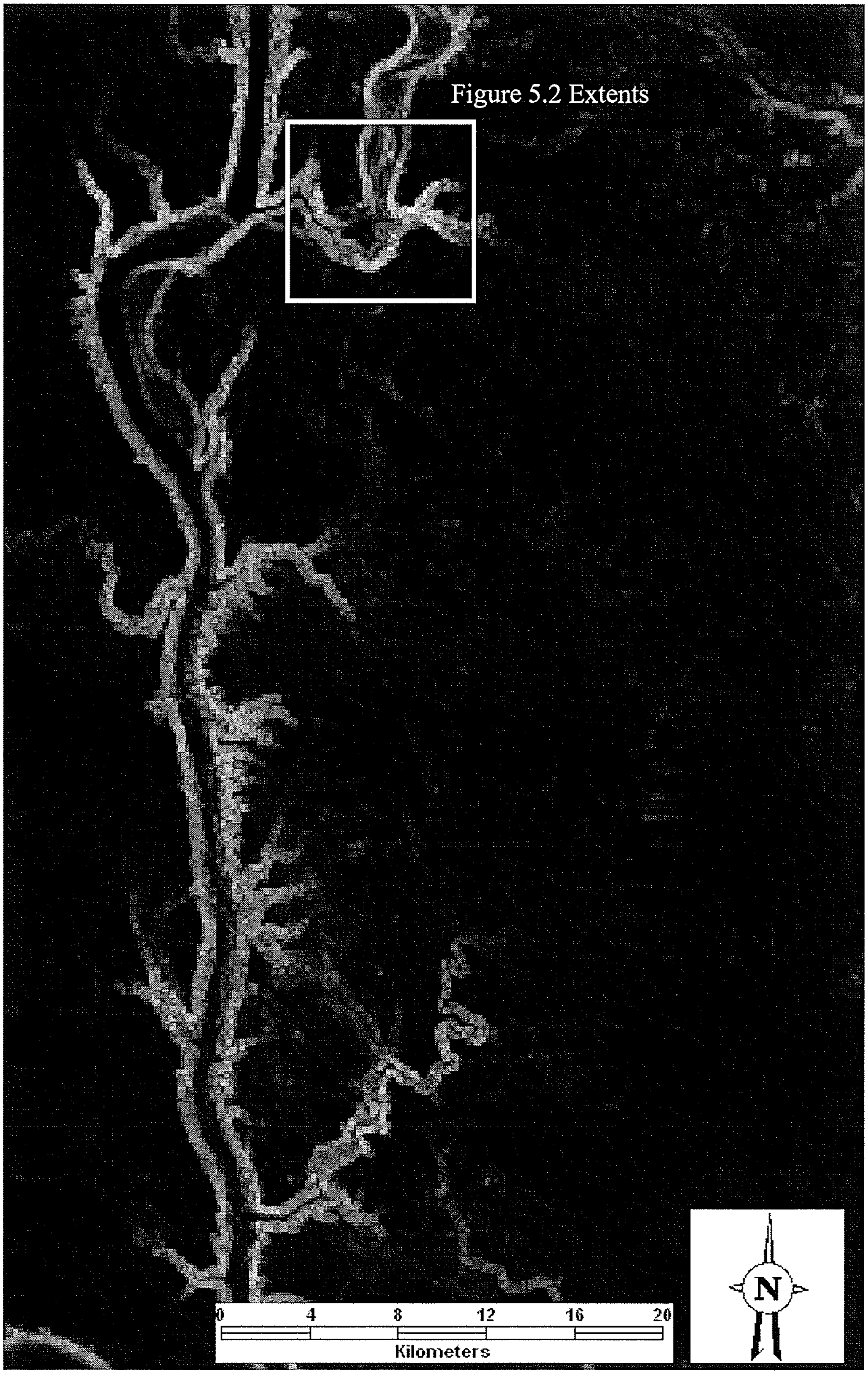


Figure 5.4 – Expanded plan view grade raster of Figure 5.2

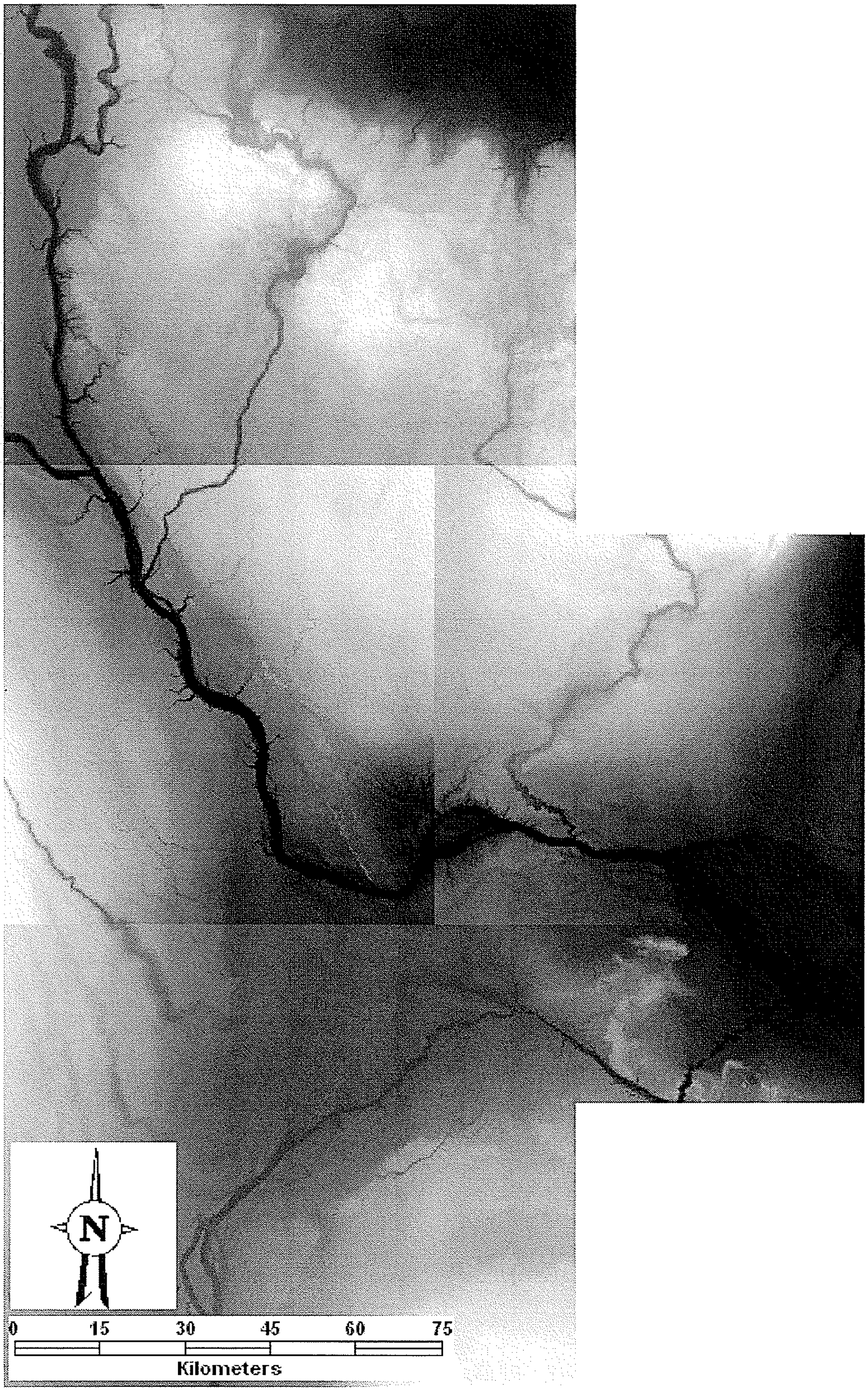


Figure 5.5 – Plan view elevation raster of research extents

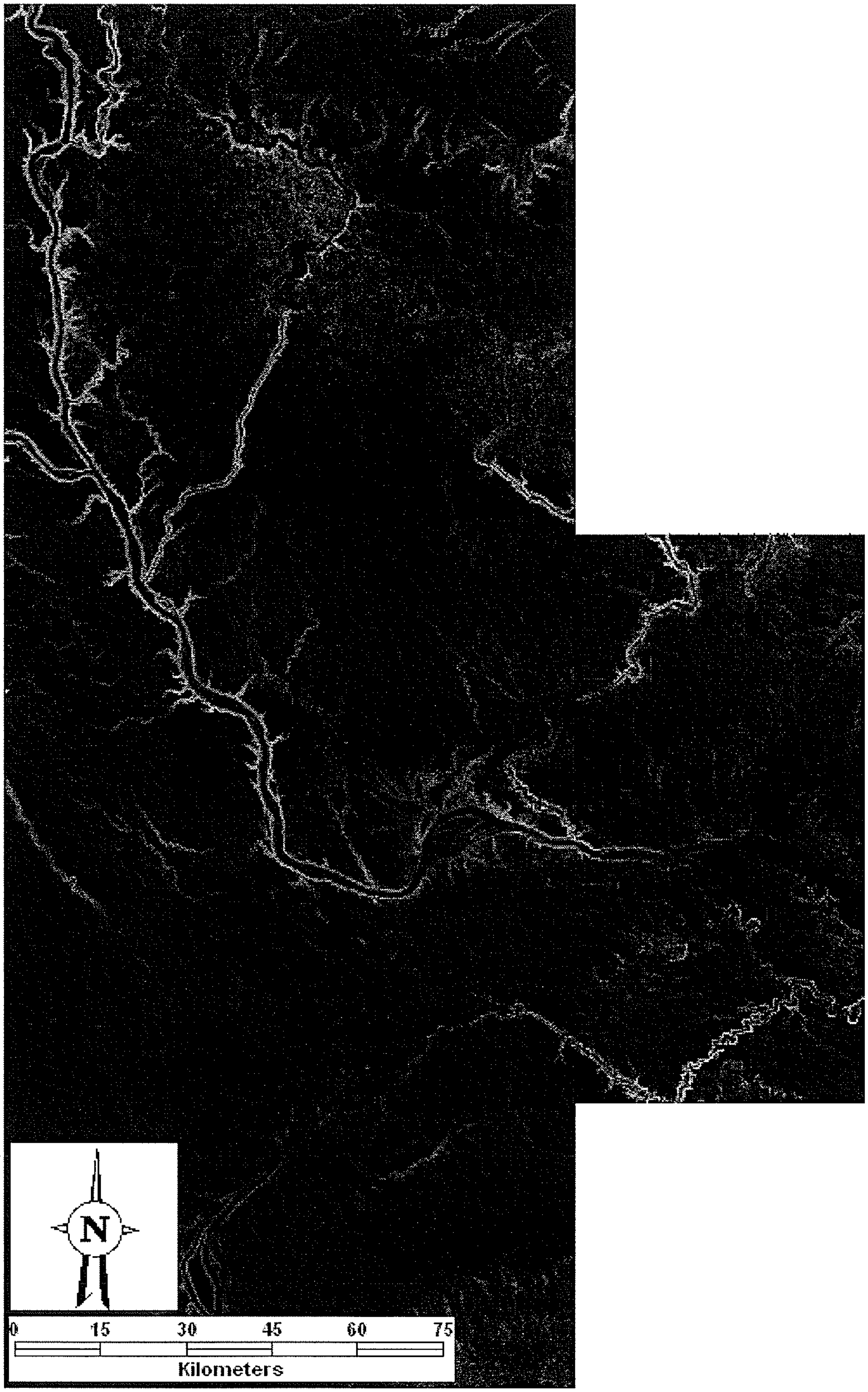


Figure 5.6 – Plan view grade raster of research extents

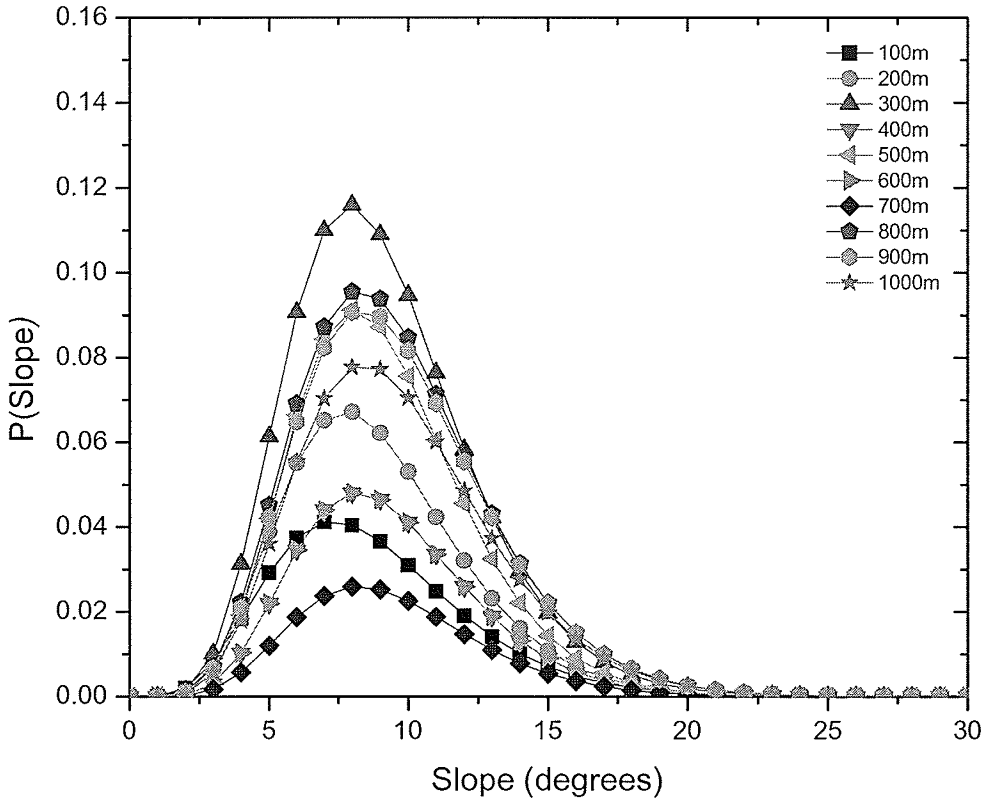


Figure 5.7 – Evolution of the gamma failure distribution *pdf* with increasing roadway buffer distance

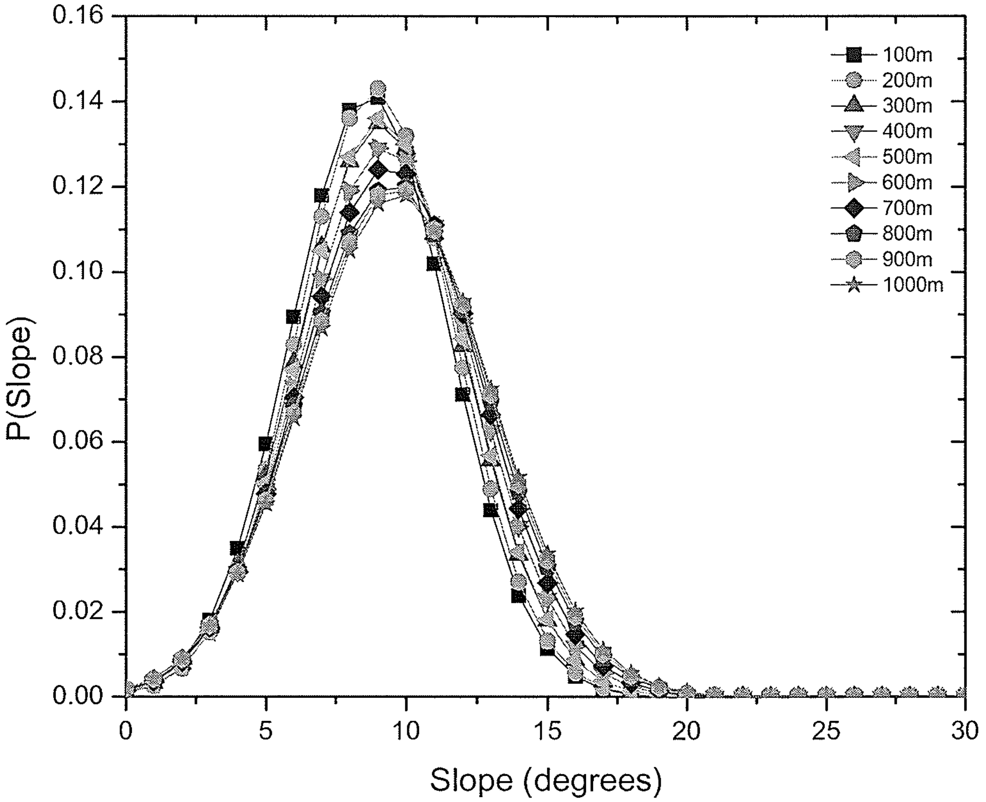
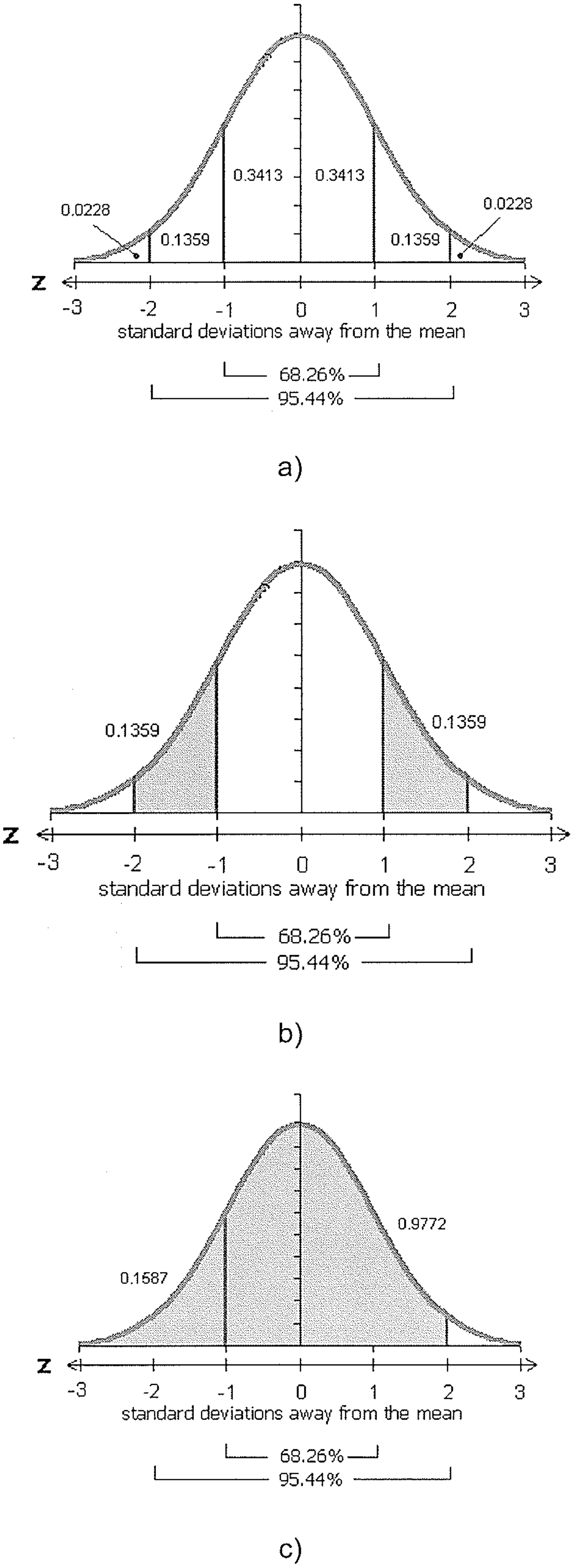


Figure 5.8 – Evolution of the normal failure distribution *pdf* with increasing roadway buffer distance



a)

b)

c)

Figure 5.9 – Schematic representation of the standard normal *pdf*

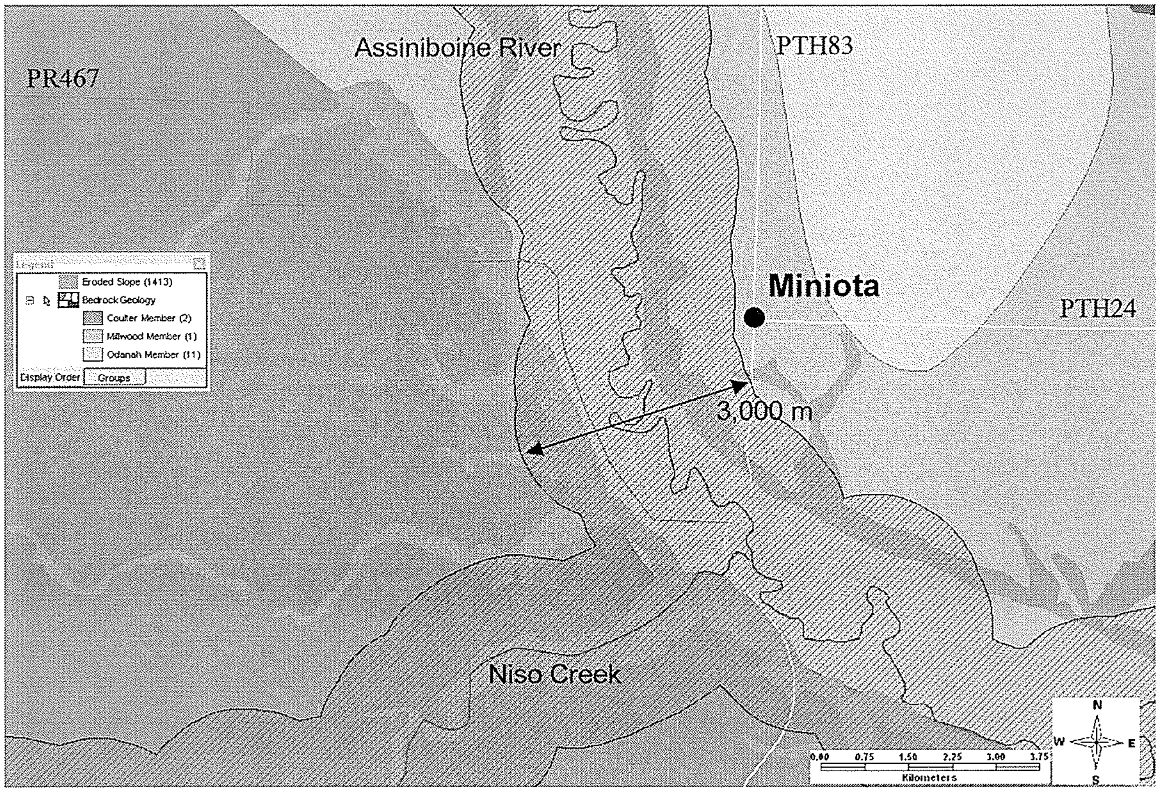


Figure 5.10 – Plan view of the 1,500m waterway buffer zone

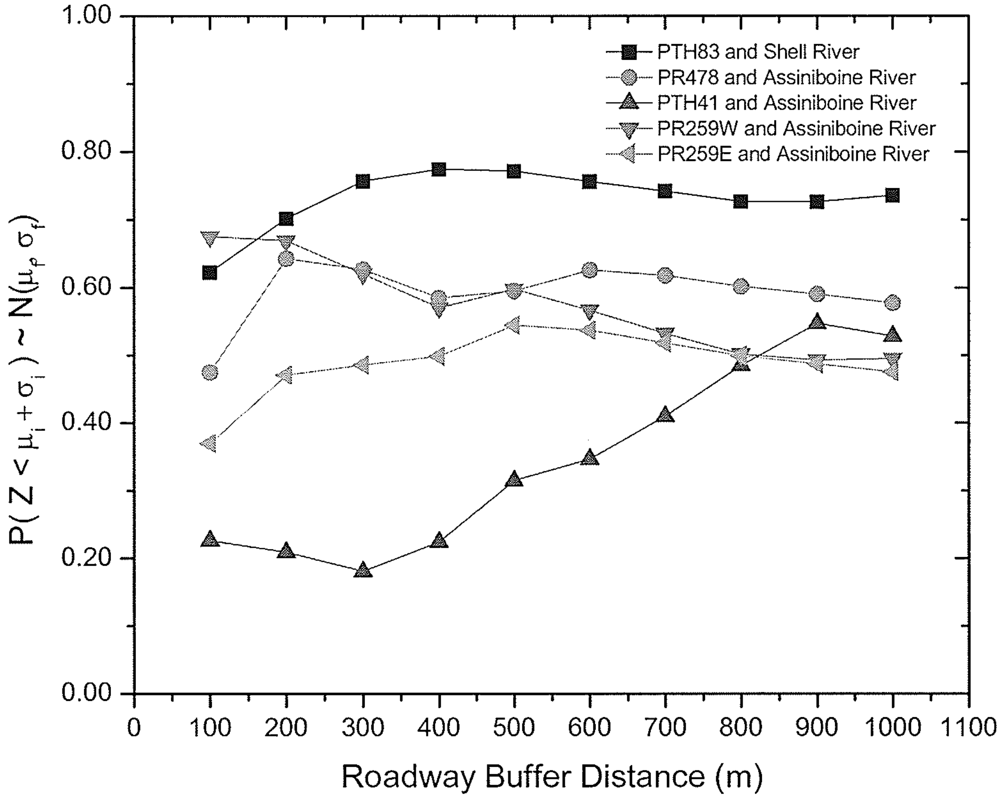


Figure 5.11 – Known failure site rank plotted versus roadway buffer distance

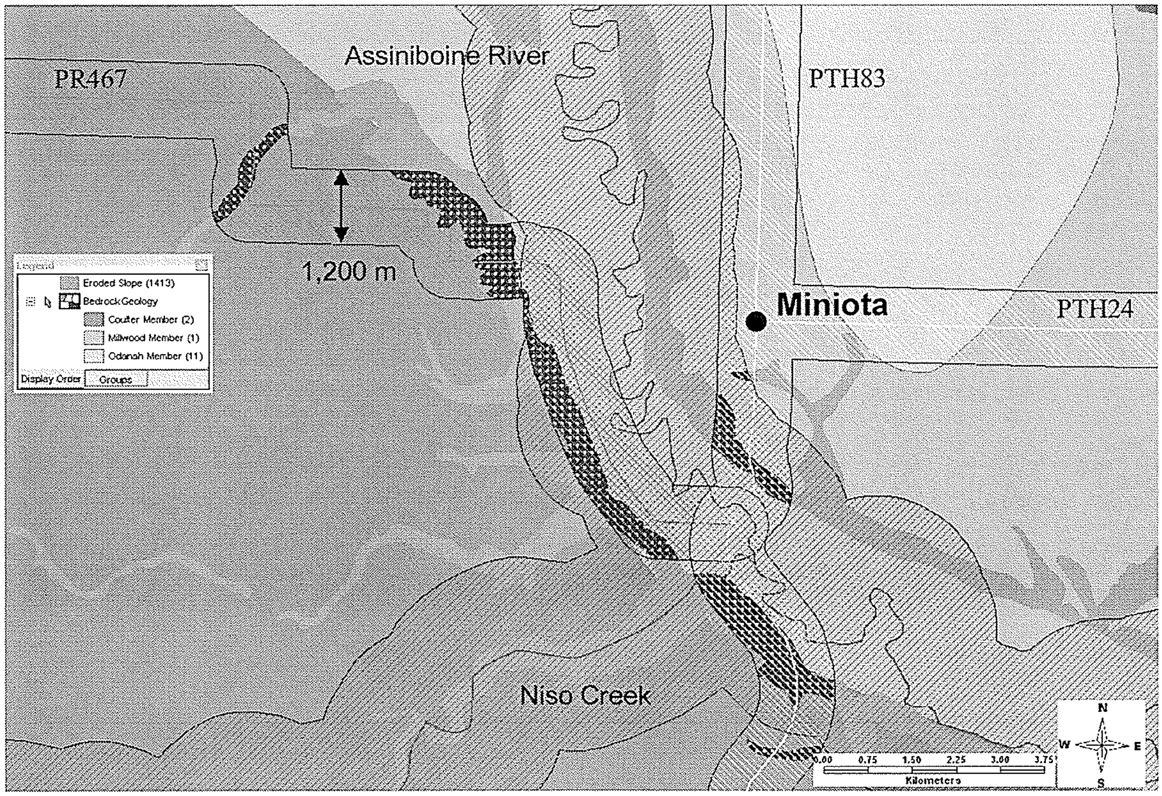


Figure 5.12 – Plan view of the 600m roadway buffer overlapped with the 1,500m waterway buffer

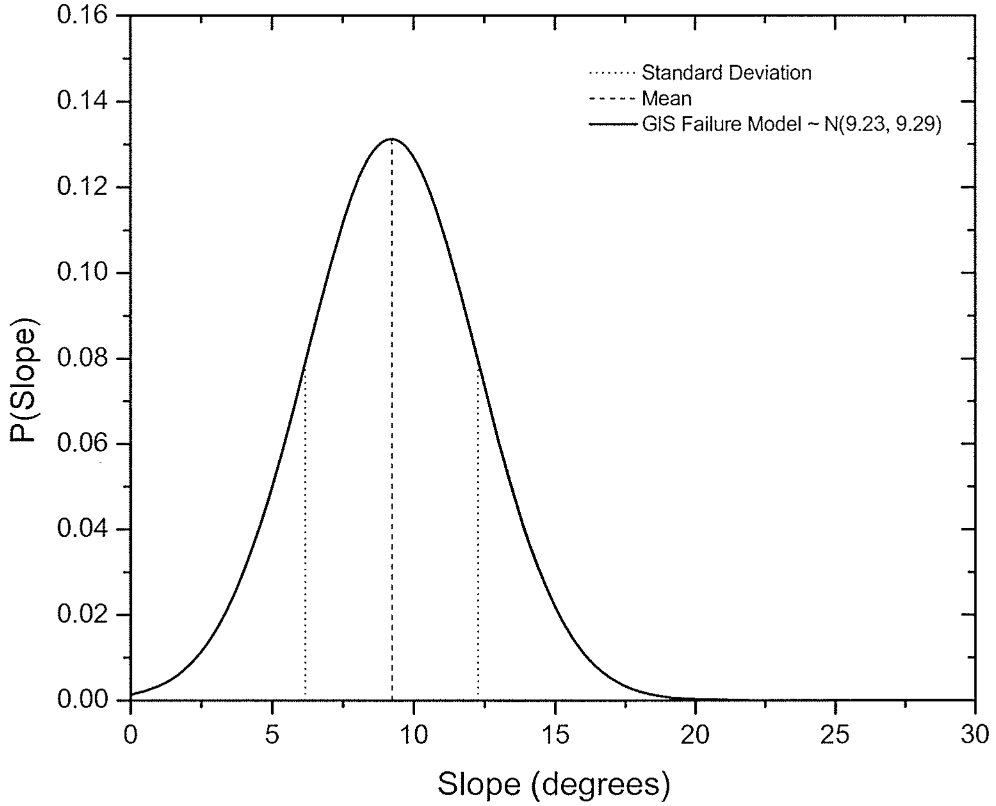


Figure 5.13 – GIS *pdf* failure model

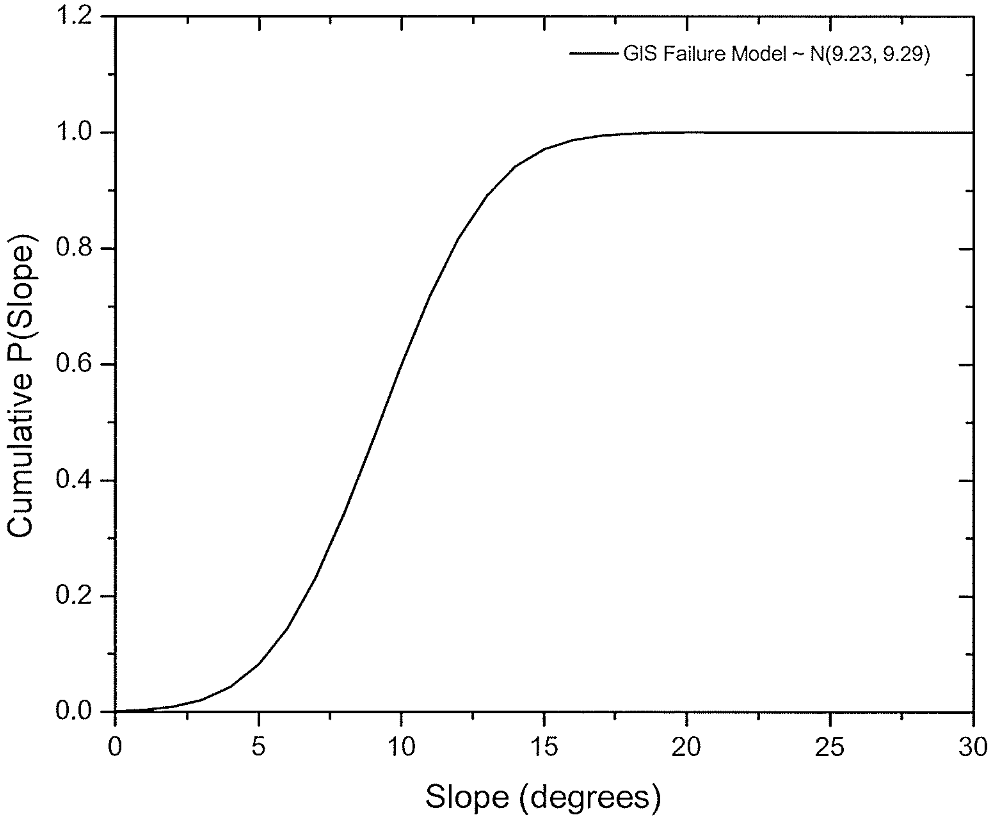


Figure 5.14 – GIS *cdf* failure model

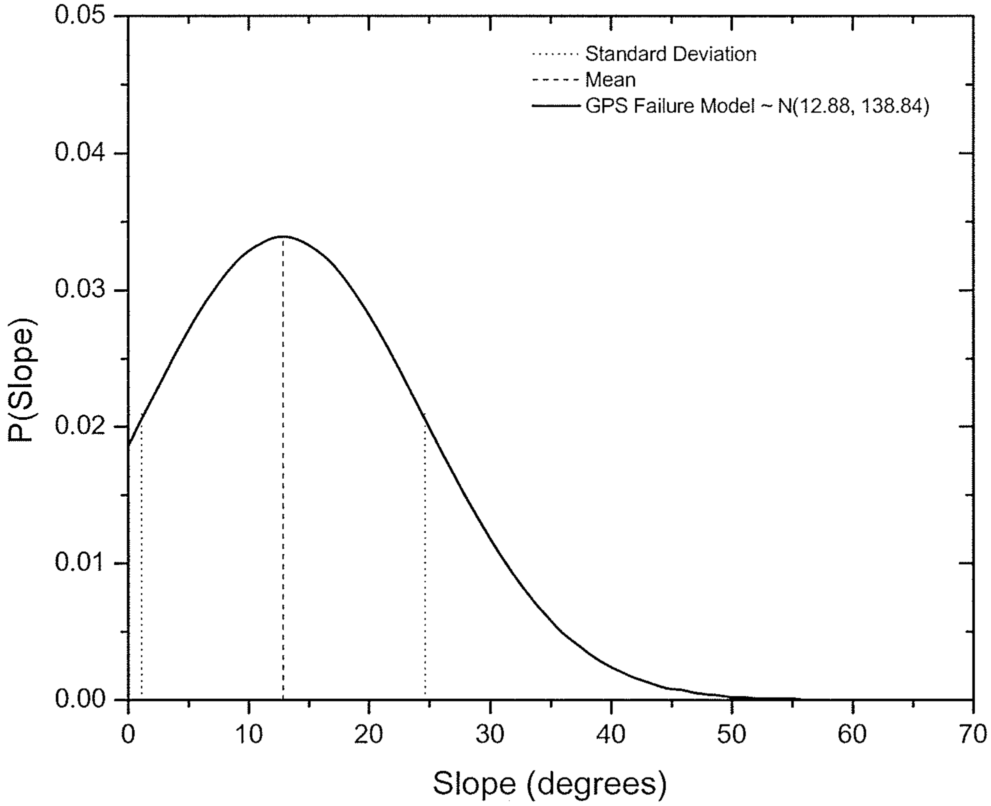


Figure 5.15 – GPS *pdf* failure model

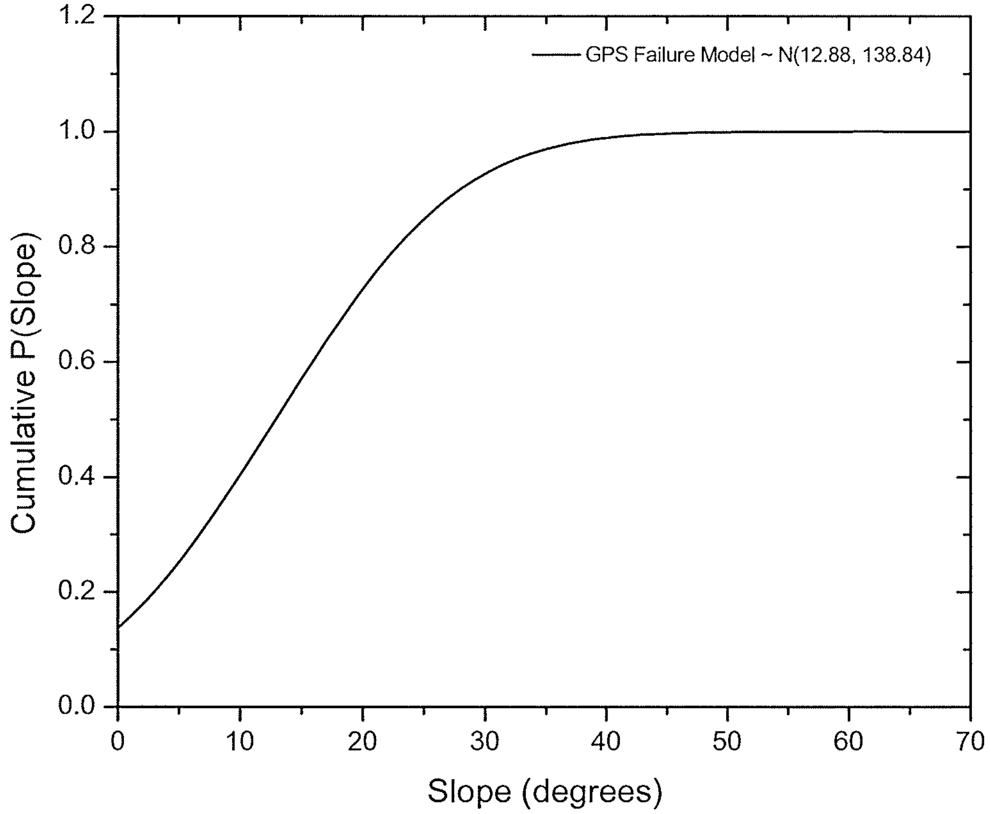


Figure 5.16 – GPS *cdf* failure model

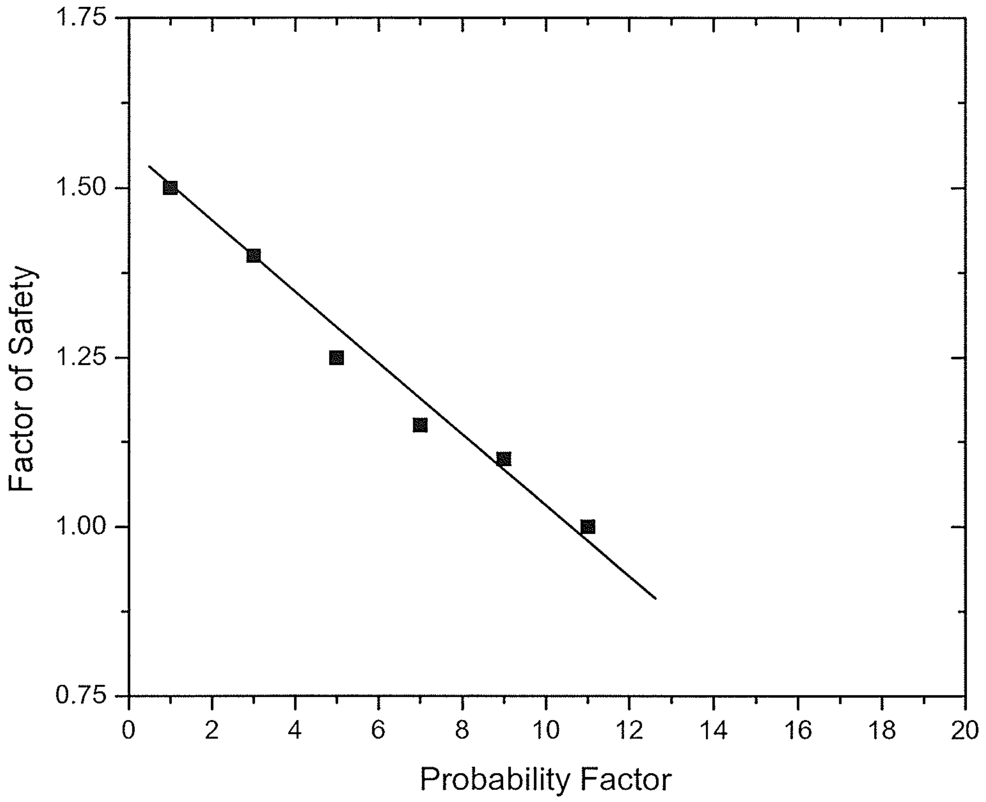


Figure 5.17 – Factor of safety versus probability factor from the Saskatchewan Highways and Transportation risk management system

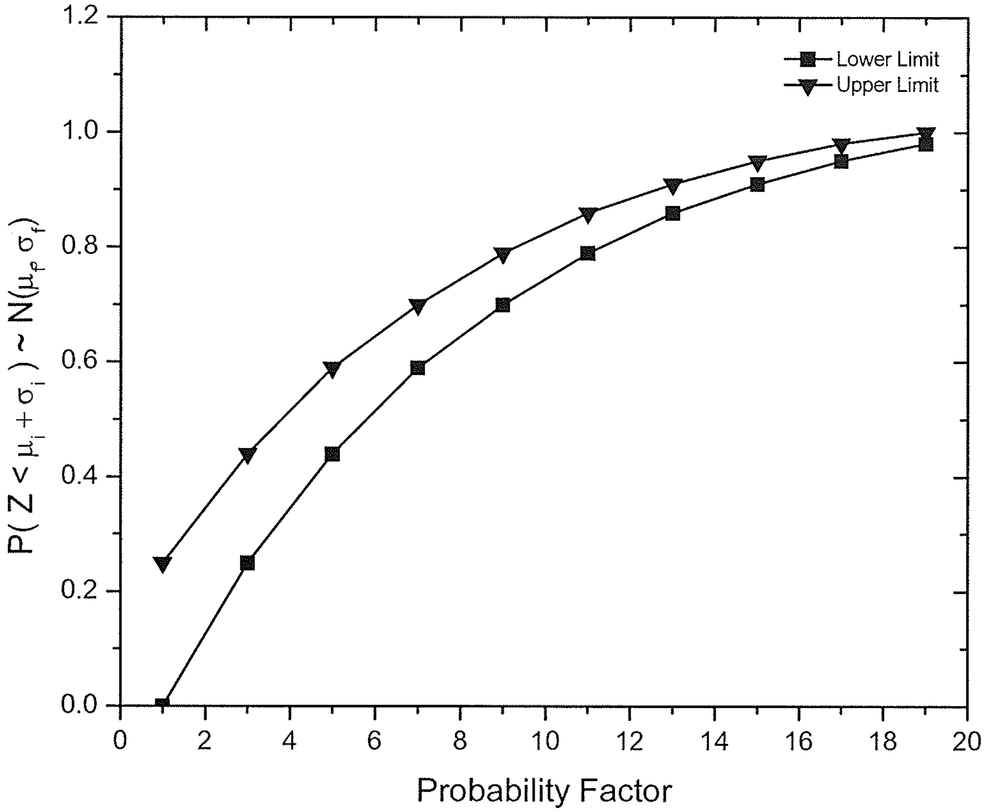


Figure 5.18 – Recommended probabilistic selection criteria versus probability factor

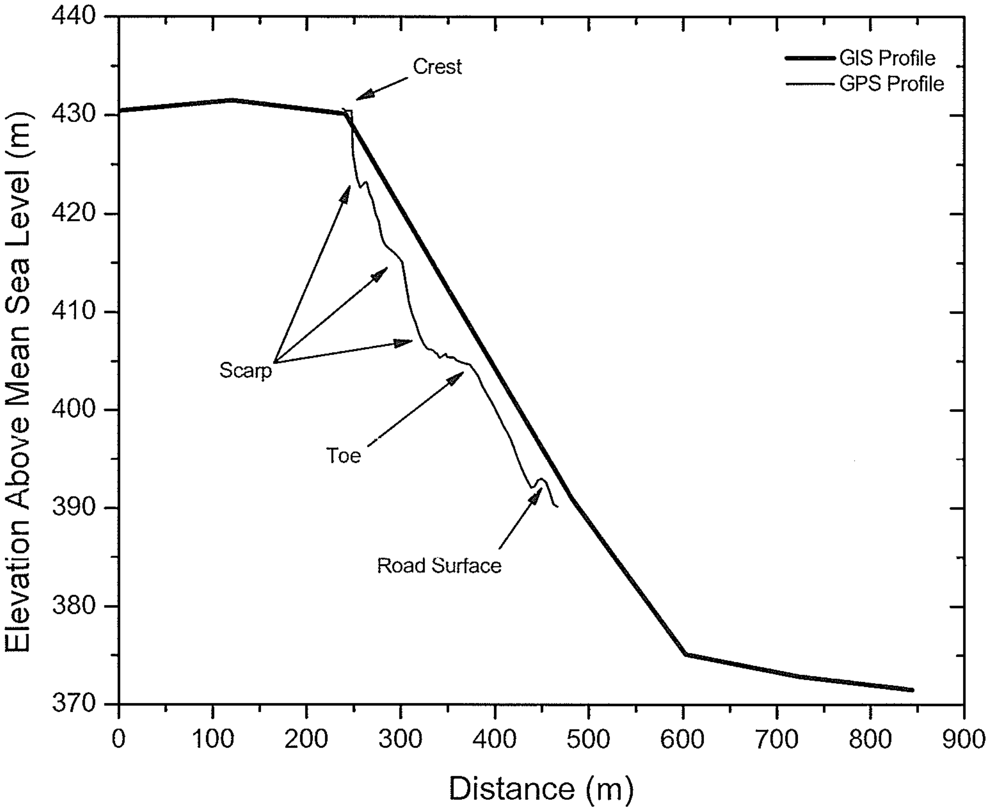


Figure 5.19 – GIS and GPS cross-sections of PR259E and Assiniboine River

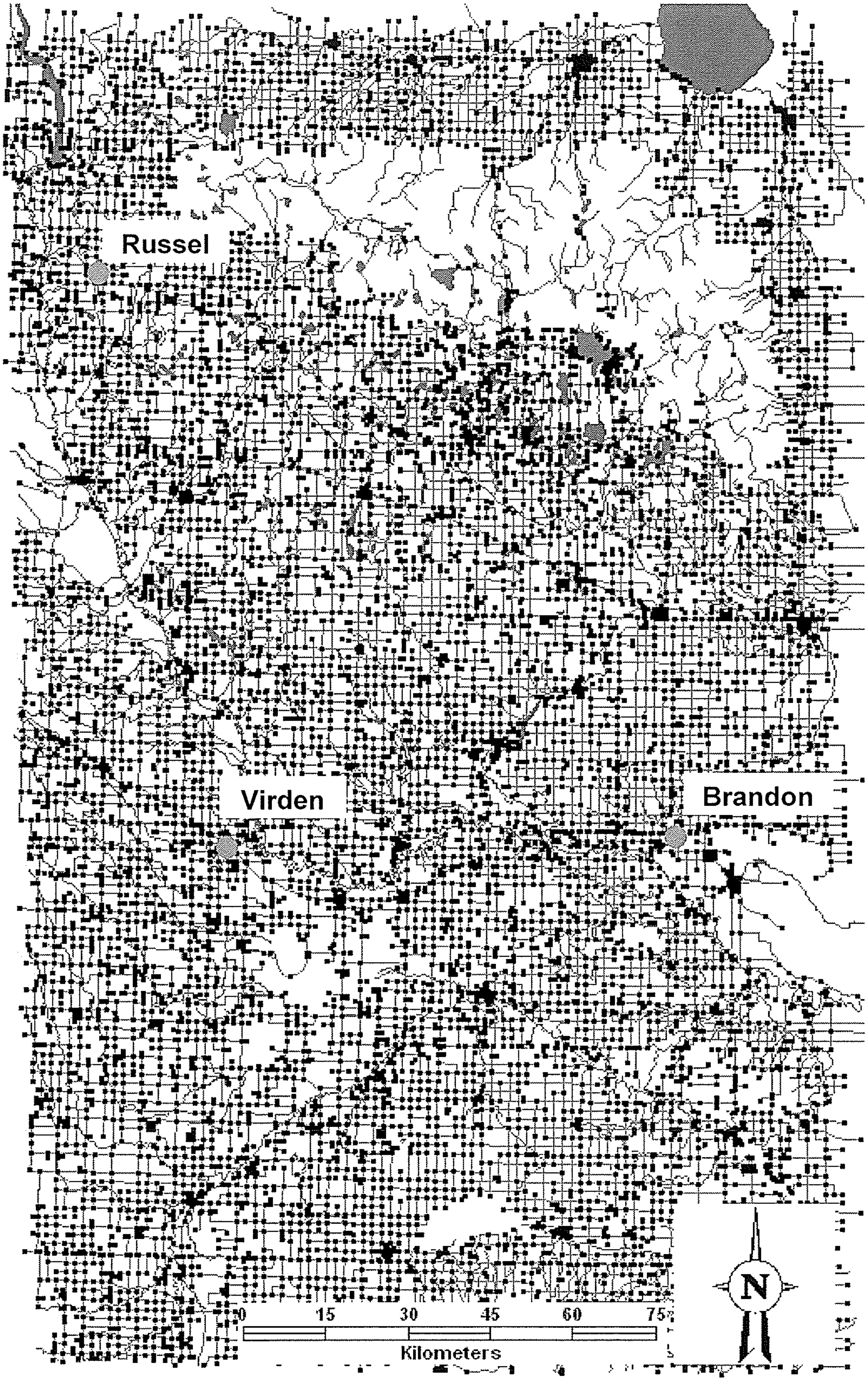


Figure 5.20 – Plan view of roadway network and nodes in western Manitoba

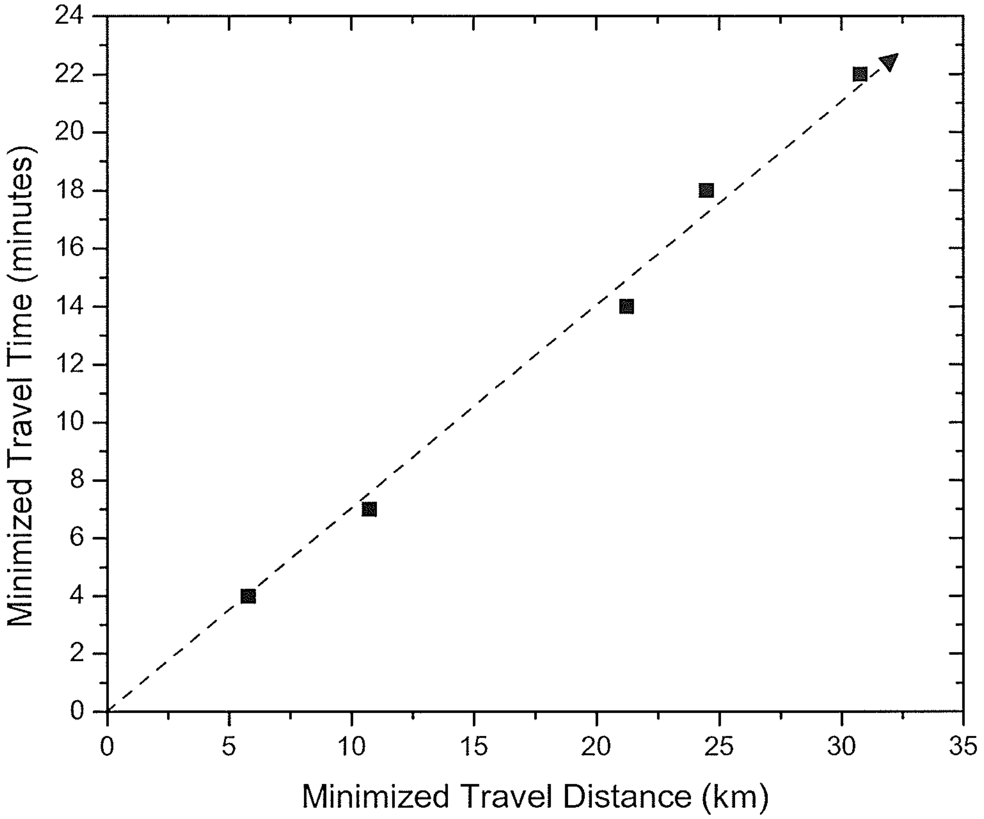


Figure 5.21 – Network analysis minimized travel time versus minimized travel time

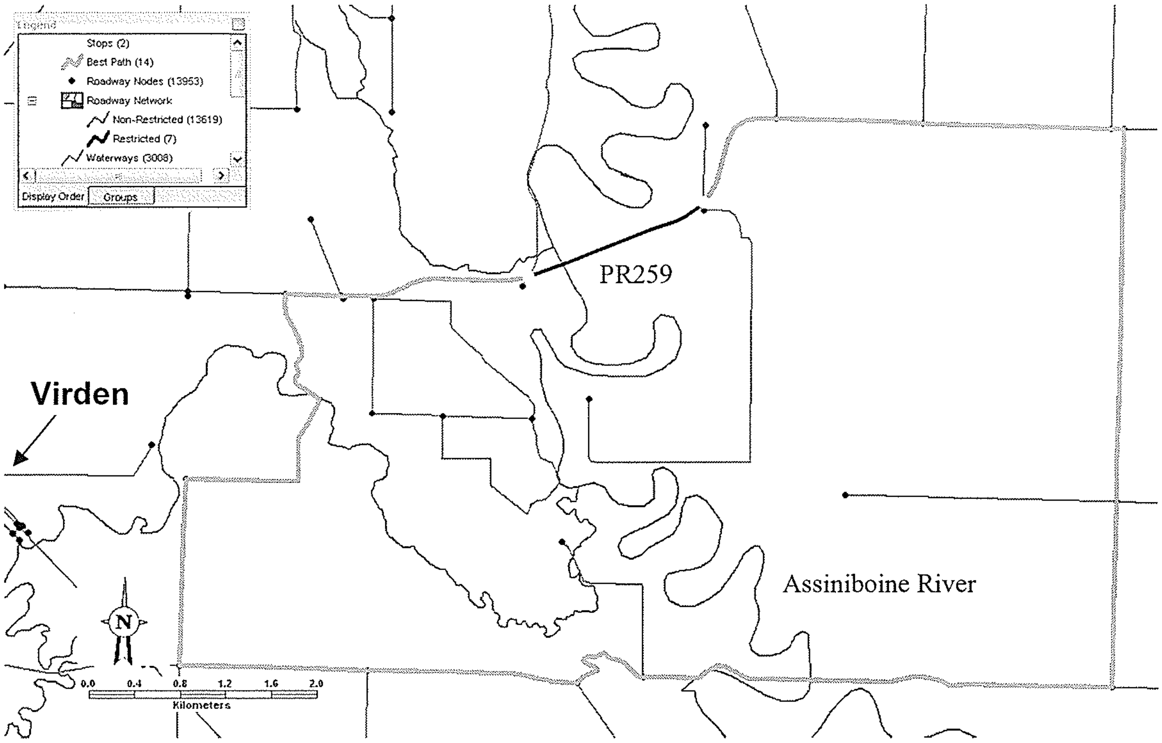


Figure 5.22 – Best path analysis at the intersection of PR259 and Assiniboine River

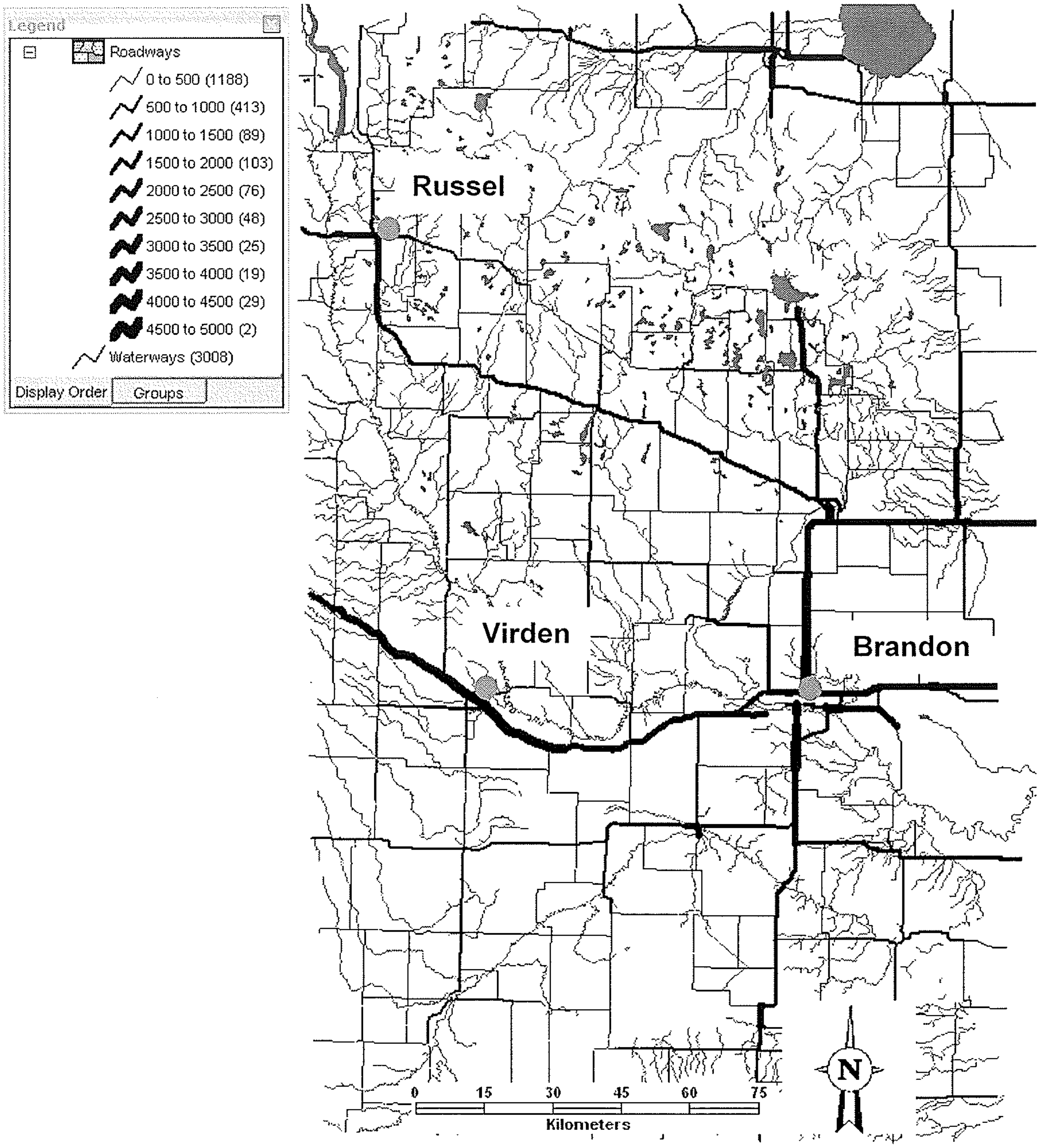


Figure 5.23 – Map of AADT in western Manitoba

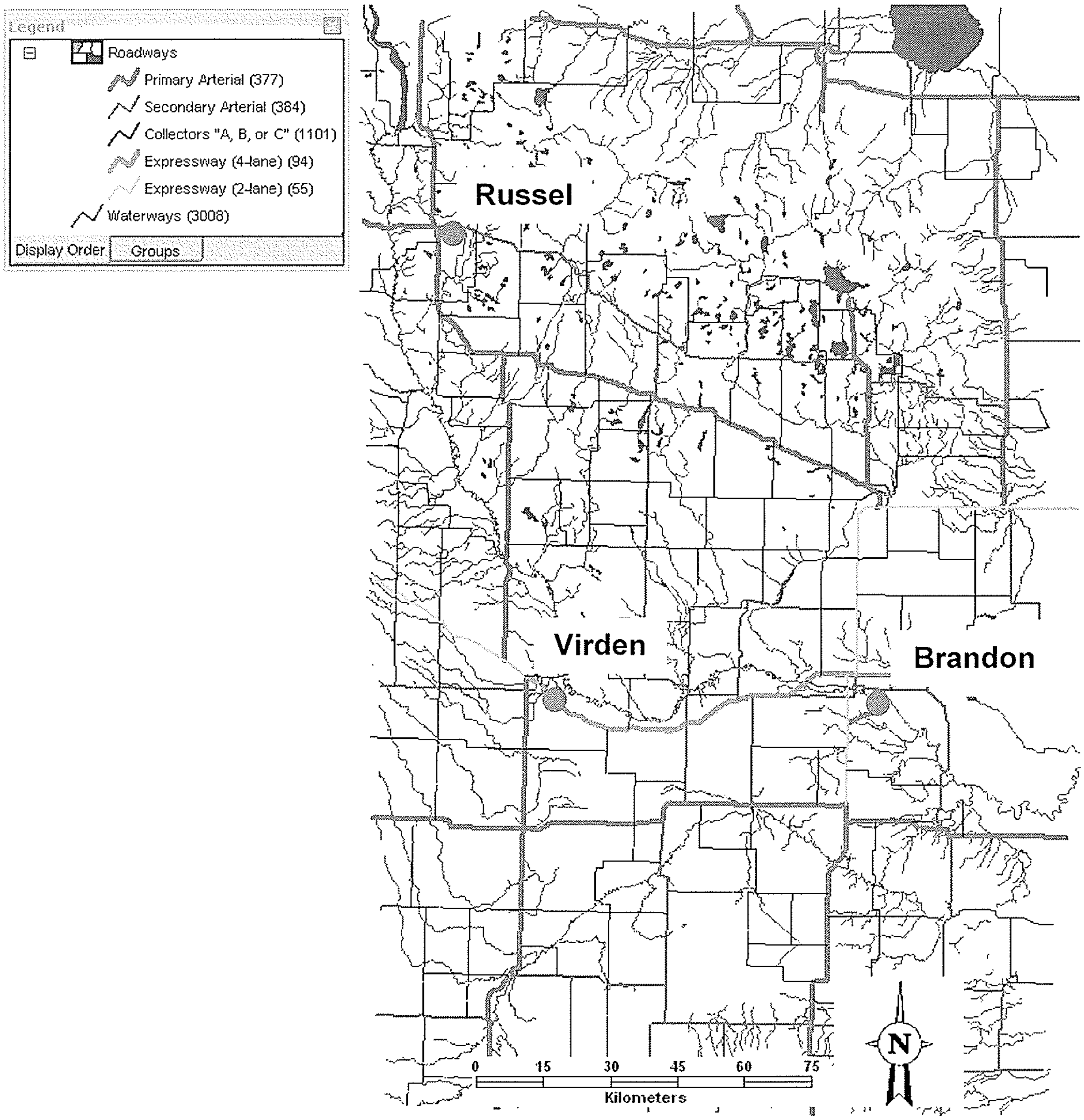


Figure 5.24 – Map of functional classification in western Manitoba

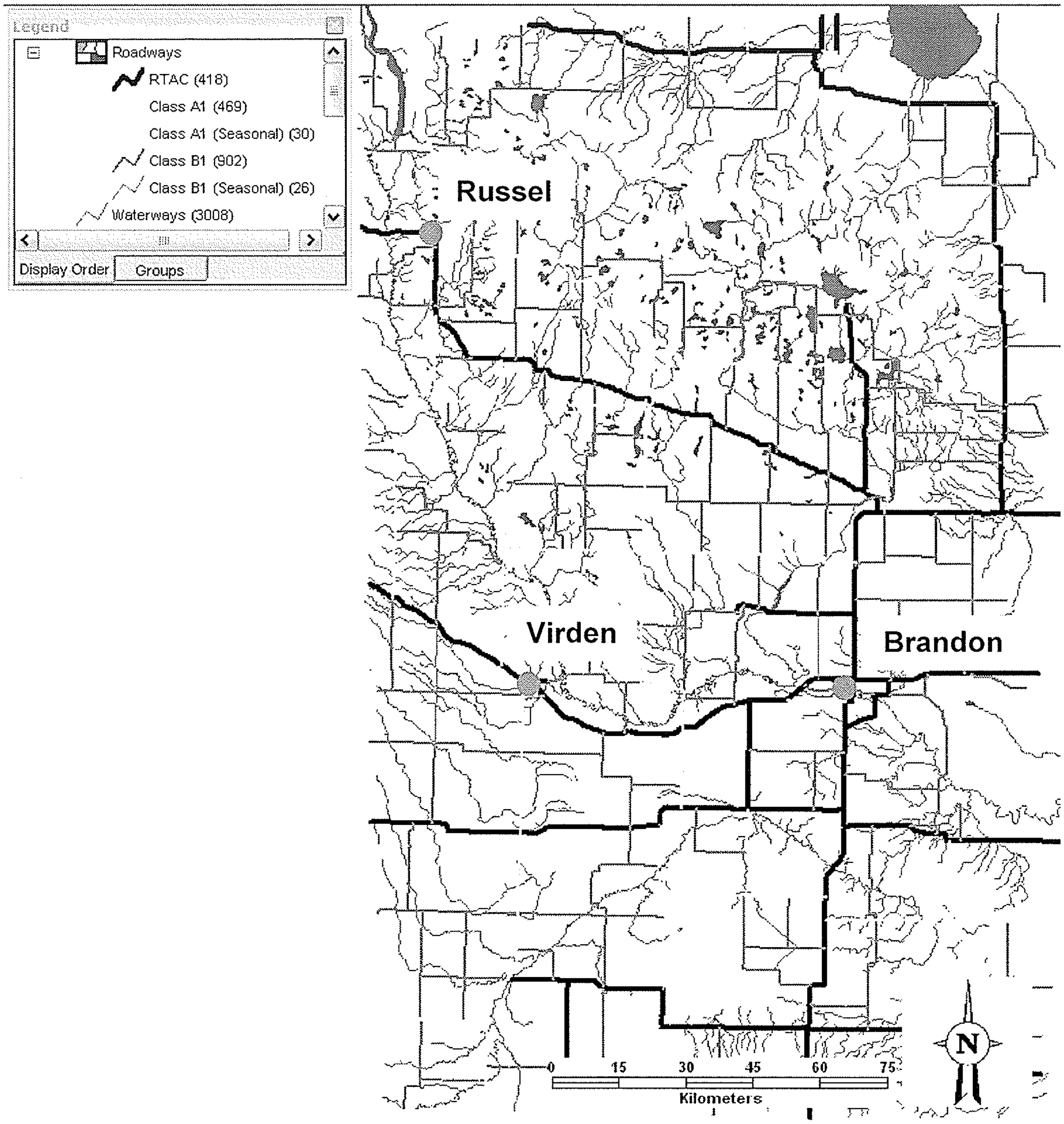


Figure 5.25 – Map of weight classification of western Manitoba

# 6 GIS Application

## 6.1 Introduction

Five sites have been used as the source for development of the MITRMS. Significant amounts of information available through a variety of sources have been used to create a failure model and system of use as presented in Chapter 5. This chapter discusses the application of MITRMS throughout the study extents, presenting methods of use and interpretation. Sections are brief, with significant effort placed on explaining the use and interpretations of the results.

Focus is placed on areas of PTH and PR proximity to rivers and creeks of western Manitoba; ravines and other small fluvial water bodies are excluded. PF and CF assessment is discussed in general terms using the intersection of PR478 and Assiniboine River as an example. Methods of applying preliminary factors and adjusting secondary factors are presented; screenshot examples of the software are provided for visualization. Two spreadsheets have been created to accelerate computations and decrease analysis time. One for preliminary PF influence calculations of failure probability and another designed to contain PF and CF summaries, effectively referred to as the MITRMS summary sheet. This sheet houses PF and CF assessments, as previously discussed, where embedded calculations yield highlighted final results that can be sorted and suitably summarized. At the end of this chapter, a comprehensive prioritized list of sites with respect to risk is provided.

## 6.2 Before Site Investigation

### 6.2.1 Preliminary PF

Preliminary PF investigation is a combination of several tasks. Overlapped geospatial layers have already identified several sites to be investigated and analyzed. Data points are taken from each site, labeled, and plotted against the GIS failure model. A site's mean and variance, $\mu_i$ and $\sigma_i^2$, become the criteria for statistical comparison versus the failure model. Assuming a data set has mean and variance of 9.23 and 3.05, respectively, calculation of failure probability takes the following form:

$$P(X < 12.28 + 3.05) \sim Normal(9.23, 9.29) \qquad [6.1]$$

Completing the above analysis yields a probability of approximately 0.9772, as shown in Figure 6.1 and 6.2, which corresponds to a preliminary PF of 17. Spreadsheets offer a quick method of conducting this analysis, a sample of which is provided in Figure 6.3. Built into the spreadsheet is the GIS based failure model and all calculations necessary to approximate failure probability upon insertion of data set values. The red outlined area highlights where data is inputted and blue outlined area highlights its respective failure probability. Sample use is provided in Figure 6.4 using grade point data taken from the PR478 and Assiniboine River failure site. Failure probability is found to be approximately 0.87. Inputting this into the MITRMS summary sheet yields a primary PF of 13, as shown in Figure 6.5.

Applying this to every site of concern yields a comprehensive prioritized list according to preliminary PF which is now prepared for secondary PF adjustments.

### 6.2.2 Secondary PF

Upon completion of primary PF assessment based solely on site grade, secondary PF factors are required to adjust for site specific conditions. Outcropping bedrock is a function of geospatial template interpretation and seeking exposed clay shale geometries in proximity to a site. The remaining two queries are included for manual assessment purposes. Unless information pertaining to a site is readily available, unknown should be assigned to each site under scrutiny; this inherently increases secondary PF to all sites at which it is applied. This is meant to encourage prompt assessment team mobilization to seek out proper query responses. Thus a direct benefit to obtaining this information is shown by the system.

The intersection of PR478 and Assiniboine River is found to have proximate outcropping Millwood member clay shale nearby, and past mitigation and slope movements are set as unknown. This results in a secondary PF of 2, as shown in Figure 6.6. Adding preliminary and secondary PF together yields a final PF of 15 on a scale of 20.

### 6.2.3 Preliminary CF

Assessing preliminary CF begins with roadway network and nodes, as shown in Figure 5.20, which creates a basis for best path analysis. The roadway network is comprised of several segments, where each node is a segment beginning and end point. This creates a traversable digital path used by network processing software to calculate minimized alternate routes. Also necessary for conceptualizing detour analysis is total travel time, created by dividing segment length by posted segment speed. Within the GIS, segment length and travel time are functional attributes; these continuously update as a function of input speed and geometric length, if altered. Properties of a roadway segment are shown in Figure 6.7 as observed in GeoMedia. Functional attributes are represented as shaded cells, not changeable by users. An attribute titled 'Restricted' is used to inform the computing software if a segment is blocked. Any value between 0 and 3, inclusive, can be chosen, where 3 indicates fully blocked, 1 and 2 indicate blocked in a single direction, and 0 indicates no blockage. This allows multiple alternate routes to be tested. Finally, route beginning and end points need to be established, known as stops, in order to complete the analysis. Selection of these points is simple in that the two closest nodes to a site and attached to an adjoining roadway segment satisfy the criteria. Figure 5.22 displays a typical shortest path result near PR259 and Assiniboine River.

Roadway network and nodes are established, available as part of the MITRMS package while determining roadway blockage and stops are subject to varying user interpretation. Attributing blockage is accomplished by selecting a roadway segment of concern and assigning a value of 3 to the 'Restricted' attribute cell. Creating stops begin by opening the 'Stop Manager' and selecting the 'Stops' feature class to be applied along the roadway network, as shown in Figure 6.8. To create a new stop set, stops are manually selected by choosing the 'Create stops from map' option, highlighted in red in Figure 6.9. Upon selecting desired stops, selecting 'Apply' engages those created and applies them to the network. Following these steps readies the roadway network for best path analysis.

Detour analysis begins by selecting 'Best Path Analysis,' this opens a dialogue where users input desired path criteria. On the edges tab of network properties, the roadway network should be chosen, followed by selecting 'Restricted' in the blockage field. Length should be set to the attribute titled 'FunctionalLength' with units of kilometers, as shown in Figure 6.10. Under the costs tab, check 'use edge costs' and select the attribute titled 'FunctionalTravelTime' in the edge cost field with units set to minutes, as shown in Figure 6.11. With network properties set, a stops feature class and subsequent stop set must be chosen. Before running the analysis, 'use blockages' should be selected so that the best path analysis includes roadway segment restrictions; the best path dialogue should resemble Figure 6.12. Analysis at PR478 and Assiniboine River results are shown in Figure 6.13.

The best path query data window summarizes roadway segments in use, along with cumulative travel time are distance with every subsequent row. Final detour distance and travel time and copied into the MITRMS summary sheet as part one of four preliminary CF determinates.

The final three manual adjustments are a function of AADT, functional classification and weight classification. These are summarized for each roadway segment in GeoMedia as shown in Figure 6.7. These are inputted into the MITRMS summary sheet where embedded equations calculate primary CF. Table 6.1 contains a summary of primary CF inputs for PR478 and Assiniboine River. Figure 6.14 is a snapshot of the MITRMS summary sheet upon attribute insertion, where preliminary CF is assessed to be 4.2.

Table 6.1 – Summary or primary CF influences at PR478 and Assiniboine River

| **Primary CF Influences** | **Value** |
|---|---|
| Detour Length | 30.77 km |
| Travel Time | 22 minutes |
| AADT | 380 vehicles / day |
| Functional Classification | Collector 'A' |
| Weight Classification | Class B1 |

### 6.2.4 Secondary CF

Secondary CF is a function of a site's physical surroundings; these can be one of three possibilities: utilities, private or Crown/right-of-way. During desk studies, proximity response should be set as unknown unless site specific information is available. This inhibits bias and user subjectivity, it also encourages swift manual inspection of sites to remove uncertainty that penalizes the site based on lack of information.

Several response scenarios are available to adjust for varying surrounding infrastructure. As such, the more knowledge pertaining to a site, the more accurate secondary CF becomes. The MITRMS summary sheet contains flags in the event secondary CF pushes final CF above 10. A maximum consequence of 10 is defaulted in this event, though knowledge of this event should also encourage more accurate information to be gathered so to positively affect secondary CF.

All three queries are set as unknown for PR478 and Assiniboine River, which results in a secondary CF of 3, as shown in Figure 6.15. Final CF is subsequently found to be 7.2 on a 10 point scale.

### 6.2.5 Risk Factor

Risk factor alone does not represent much during desk studies if several unknowns are included due to lack of information, unless several sites with lacking data are compared analogous to each other. When several sites are compared side by side, they can be prioritized in terms of which sites likely require a visit more so than others. This system allows resources to be effectively allocated so to decrease uncertainty and increase confidence of the MITRMS.

Primary and secondary PF and CF assessment of PR478 and Assiniboine River, based on available information, has yielded a risk factor of 108 out of a maximum of 200, which corresponds to a priority response level. Because several unknowns have been included in the analysis, it would be suggested that personnel be dispatched in order to refine PF and CF assessments.

Table 6.2 contains a risk summary of five known failure sites as taken from a simulated MITRMS desk study and compared to results from the fall slope hazards tour. The order at which these sites rank with respect to each other is fairly similar. Response level results vary between sites with PTH41 and Assiniboine River being affected the most. A significant drop in risk can be a function of misrepresentation during the slope hazards tour or unrepresentative inputs in MITRMS. All these factors show a need for increasing site specific knowledge.

Table 6.2 – Known failure site slope hazards tour and desk study results summary

| **Risk Range** | **Response Level** | **Slope Hazards Tour Results** | | **MITRMS Desk Study Results** | |
|---|---|---|---|---|---|
| | | **Site** | **RF** | **Site** | **RF** |
| > 125 | Urgent | PTH83 & Shell River | 130 | PTH83 & Shell River | 138 |
| 75 to 125 | Priority | PTH41 & Assiniboine River | 120 | PR478 & Assiniboine River | 108 |
| | | | | PR259E & Assiniboine River | 82 |
| 27.5 to 75 | Routine | PR478 & Assiniboine River | 54 | PR259W & Assiniboine River | 67 |
| | | PR259E & Assiniboine River | 51 | PTH41 & Assiniboine River | 49 |
| | | PR259W & Assiniboine River | 42 | | |
| < 27.5 | Inactive | | | | |

## 6.3 After Site Investigation

### 6.3.1 Preliminary PF

Preliminary PF assessment after site investigation is similar to its desk study counterpart where differences lie in method of grade point calculation. A GPS profile of the site in question is taken, where grade between each point is calculated and statistically compared to the GPS failure model described previously. Assuming a sample profile's grade points have mean and standard deviation of 24.66 and 11.78, respectively, failure probability is expressed as the following:

$$P(X < 24.66 + 11.78) \sim Normal(12.88, 138.84) \qquad [6.2]$$

Completing analysis yields a probability of approximately 0.9772, as shown in Figure 6.16 and 6.17, which corresponds to a preliminary PF of 17. In both preliminary PF examples, the mean and standard deviation are set to the failure model's mean plus standard deviation and standard deviation, respectively. Though these values significantly change between both cases, they are arbitrarily set in a similar fashion, thus preliminary PF is identical. The MITRMS summary sheet is also used to contain all updates and modifications made to a site. This way, upon completion of manual adjustments, both models can be observed together. Comparison between pre- and post-inspection can also aid in understanding the enhancement manual observation provides.

The failure probability at PR478 and Assiniboine River is found to be 0.77, category 9, a moderate decrease from 13 during the desk study, as shown in Figure 6.18.

### 6.3.2 Secondary PF

Secondary PF is evaluated one of two ways, documentation of previous site investigations or physical observation. Slope movements are measured through migration of slope inclinometers or observed as tension cracks and scarps develop. In either case, engineering experience and judgment are a dominant factor when choosing appropriate query responses for secondary PF assessment. General definitions have been discussed where utmost caution should be used when assigning these values.

After inputting insignificant slope movements and moderate past works along PR478 and Assiniboine River, secondary PF becomes -1. This creates a final PF of 8, as shown in Figure 6.19, a large reduction from desk study assessments of 15. This is a prime example of the result of increasing site specific knowledge adjusting final PF.

### 6.3.3 Preliminary CF

These values should not change in any event unless updated values and classifications are made available through MIT. Primary CF for PR478 and Assiniboine River remains at 4.2.

### 6.3.4 Secondary CF

Magnitude of the secondary CF influence on final assessment is entirely dependent on surrounding infrastructure and the magnitude each are affected should failure occur. The MITRMS is designed such that proximity to utilities, private property, and Crown land or right-of-way can be extremely influential should high consequences result from slope movements. During manual inspection, appropriate proximate selections are made where each present and potentially impacted local land use type receives an associated value. There are four options in each case: none, low, medium, and high. Each is subject to logic and rationale review when making decisions on infrastructure value.

Utilities are not present near the PR478 and Assiniboine River failure site. Farm land is owned privately near the slope's crest, were low consequences are a result should damage occur. Remaining land is Crown and is mainly composed of small drainage ditches and roadway infrastructure. Head and toe scarps are far enough away from the road surface that it likely would not be immediately impacted. As of current, there are low consequences should failure obstruct crown property. Secondary CF is assessed as 2, as shown as Figure 6.20, resulting in a final CF of 6.2. This again is a prime example of increasing certainty of site specific knowledge resulting in adjusted consequence.

### 6.3.5 Risk Factor

Desk study portions of the MITRMS support selection and prioritization of which sites to manually inspect. Uncertainties as a result of unavailable information negatively affect sites that would otherwise receive low risk factors. More concerning is the event should deserving sites of high risk factor not receive one during dusk studies; this is justification for catch-all triggers. Desk study sites that receive a primary PF of 15 or higher and a final CF that must be truncated to 10 should also be inspected coincidentally with those of high risk. A summary of adjustments at five known failure sites before and after site investigation using MITRMS is provided in Table 6.3.

Table 6.3 – Known failure site desk study and post-inspection results summary

| Risk Range | Response Level | MITRMS Desk Study Results | | MITRMS Post-Inspection Results | |
|---|---|---|---|---|---|
| | | Site | RF | Site | RF |
| > 125 | Urgent | PTH83 & Shell River | 138 | PTH83 & Shell River | 147 |
| 75 to 125 | Priority | PR478 & Assiniboine River | 108 | PR259W & Assiniboine River | 87 |
| | | PR259E & Assiniboine River | 82 | PTH41 & Assiniboine River | 80 |
| 27.5 to 75 | Routine | PR259W & Assiniboine River | 67 | PR259E & Assiniboine River | 65 |
| | | PTH41 & Assiniboine River | 49 | PR478 & Assiniboine River | 50 |
| < 27.5 | Inactive | | | | |

Risk at PR478 and Assiniboine River decreased to 50 from 108, indicating over estimation during the initial desk study. Unknowns during initial analysis forced larger secondary PF and CF thus inherently attributing higher risk than required. This site was selected as a representative example of manual inspection resulting in significant risk adjustments, and in this case, risk reduction.

Table 6.4 is a summary comparing results before and after site investigation for the five known failure sites. The only change where a site moved up was the intersection of PR259W and Assiniboine River where the slope hazards tour suggested a routine response level whereas MITRMS post-inspection results suggest a priority response. This can be a function of site misinterpretation during the tour or placing excessive trigger weights during MITRMS assessments. In any event, alterations can be made to site inspection focus or category shifts. As discussed previously, the MITRMS system is created such that users can select trigger weights and category shifts according to personal judgment where all PF, CF and resulting risk adjust instantaneously. The process and approach are the key developments of this work.

Table 6.4 – Known failure site hazards tour and post-inspection results summary

| Risk Range | Response Level | Slope Hazards Tour Results | | MITRMS Post-Inspection Results | |
|---|---|---|---|---|---|
| | | Site | RF | Site | RF |
| > 125 | Urgent | PTH83 & Shell River | 130 | PTH83 & Shell River | 147 |
| 75 to 125 | Priority | PTH 41 & Assiniboine River | 120 | PR259W & Assiniboine River | 87 |
| | | | | PTH41 & Assiniboine River | 80 |
| 27.5 to 75 | Routine | PR478 & Assiniboine River | 54 | PR259E & Assiniboine River | 65 |
| | | PR259E & Assiniboine River | 51 | PR478 & Assiniboine River | 50 |
| | | PR259W & Assiniboine River | 42 | | |
| < 27.5 | Inactive | | | | |

## 6.4 Results

Desk study application of the MITRMS over research extents has yielded 116 sites, each of which assessed and categorized with respect to resulting risk factor and response level during a simulated desk study. Due to large quantities of information, the list is provided in Appendix B. A histogram featuring frequency versus response level is provided in Figure 6.21. Site statistics suggest a suitable distribution of site frequency within each response level category, with a much smaller urgent portion than inactive. Figure 6.22 contains a response level thematic map, spatially presenting where each of the desk study assessed sites lie within western Manitoba. This list and map are provided as a part of this research's deliverables, where every site identified has been evaluated using previously discussed procedures. This should form the direction needed to plan landslide assessment focus for the next two years.

The MITRMS summary sheet is simplified, where query selection and responses are limited to those discussed in Chapter 5. Trigger weights, maximum limits, and magnitude of category shifts can be altered according to user judgment and experience. MITRMS results, when compared to those of the fall slope hazards tour, are overwhelmingly similar and thus, changes to these values are not recommended. Sites with primary PF equal to or above 15, truncated final CF, and urgent response levels, as per the desk study, should be manually assessed promptly.

## 6.5 Conclusion

MITRMS application is a systematic process of primary assessment based on GIS components and ending with secondary assessments based on site specific conditions. Desk studies aid in prioritizing and mobilizing resources for manual inspection, which in turn allow for swift monitoring or mitigative procedures to be undertaken. A comprehensive list of 116 sites with research extents is provided, summarizing risk and response level.

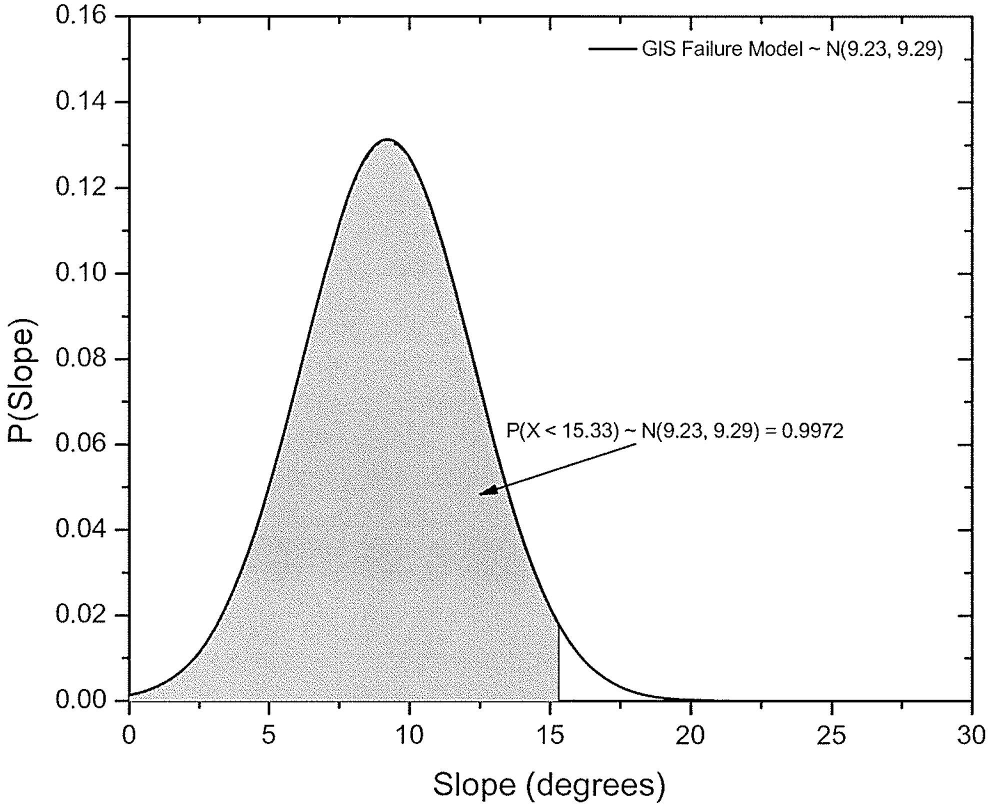


Figure 6.1 – Sample use of GIS *pdf* failure model

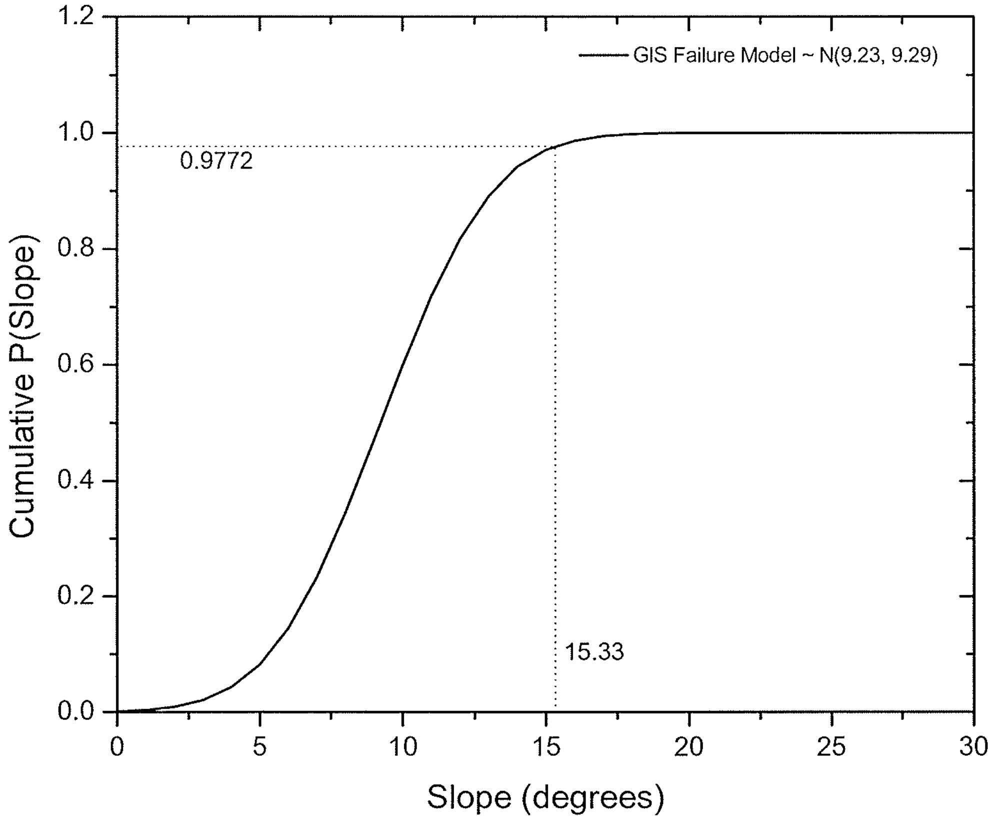
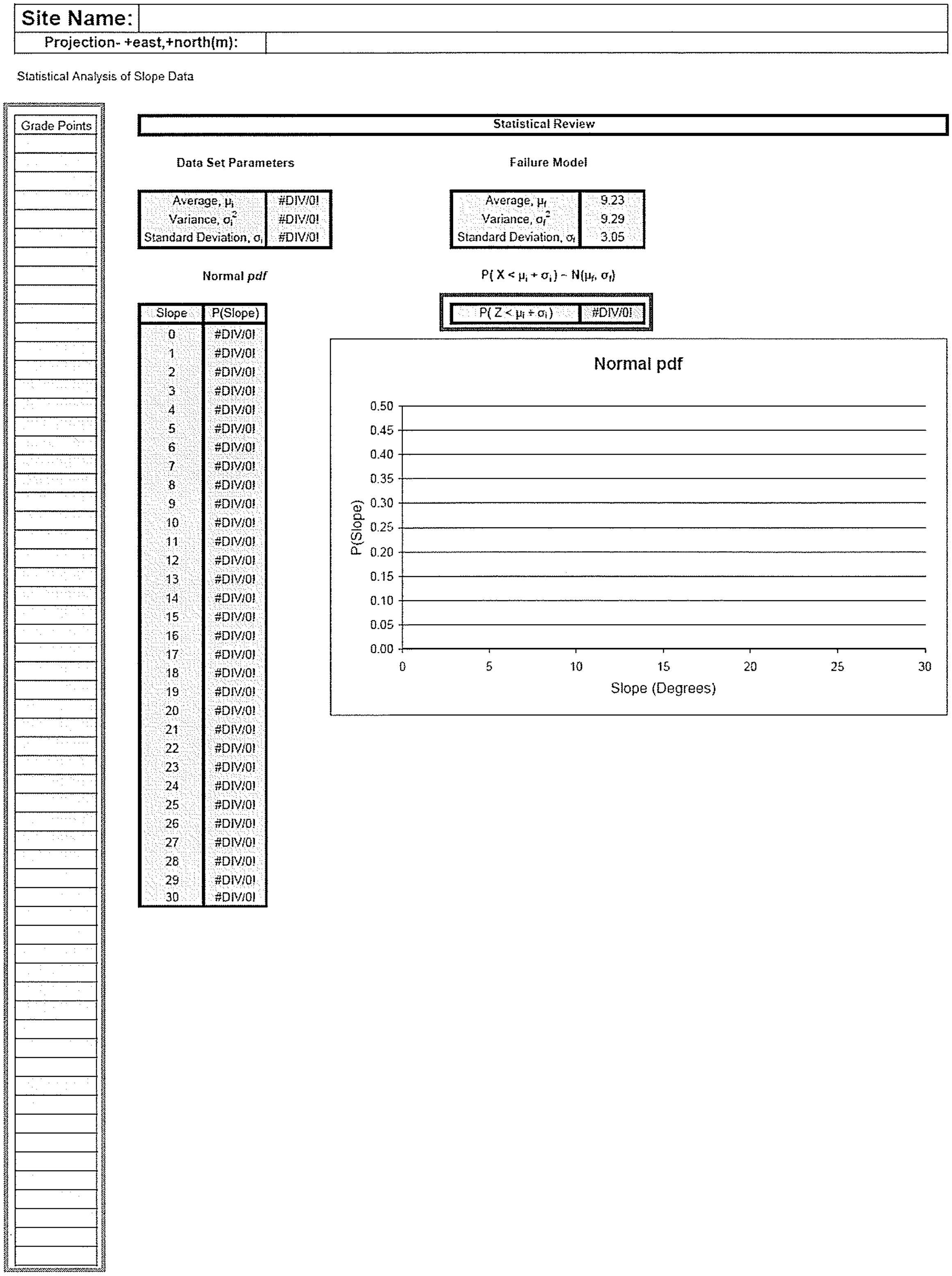


Figure 6.2 – Sample use of GIS *cdf* failure model



| | |
|---|---|
| **Site Name:** | |
| **Projection- +east,+north(m):** | |

Statistical Analysis of Slope Data

| Grade Points |
|---|

**Statistical Review**

**Data Set Parameters**

| | |
|---|---|
| Average, $\mu_i$ | #DIV/0! |
| Variance, $\sigma_i^2$ | #DIV/0! |
| Standard Deviation, $\sigma_i$ | #DIV/0! |

**Failure Model**

| | |
|---|---|
| Average, $\mu_f$ | 9.23 |
| Variance, $\sigma_f^2$ | 9.29 |
| Standard Deviation, $\sigma_f$ | 3.05 |

**Normal *pdf***

| Slope | P(Slope) |
|---|---|
| 0 | #DIV/0! |
| 1 | #DIV/0! |
| 2 | #DIV/0! |
| 3 | #DIV/0! |
| 4 | #DIV/0! |
| 5 | #DIV/0! |
| 6 | #DIV/0! |
| 7 | #DIV/0! |
| 8 | #DIV/0! |
| 9 | #DIV/0! |
| 10 | #DIV/0! |
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| 27 | #DIV/0! |
| 28 | #DIV/0! |
| 29 | #DIV/0! |
| 30 | #DIV/0! |

**$P(X < \mu_i + \sigma_i) \sim N(\mu_f, \sigma_f)$**

| | |
|---|---|
| $P(Z < \mu_i + \sigma_i)$ | #DIV/0! |

Figure 6.3 – GIS failure probability spreadsheet template

| **Site Name:** | **PR478 and Assiniboine River** |
|---|---|
| **Projection- +east,+north(m):** | 330177.80, 5610496.19 |

Statistical Analysis of Slope Data

| Grade Points |
|---|
| 9.65 |
| 12.95 |
| 16.17 |
| 16.17 |
| 14.04 |
| 10.20 |
| 10.20 |
| 10.20 |
| 10.20 |
| 9.09 |
| 9.09 |
| 9.09 |
| 5.71 |
| 9.09 |
| 11.86 |
| 11.31 |
| 11.31 |
| 12.95 |
| 11.31 |
| 11.31 |
| 14.57 |
| 10.76 |
| 10.20 |
| 14.57 |
| 10.20 |
| 10.20 |
| 9.65 |
| 9.65 |
| 7.97 |
| 6.28 |
| 10.20 |
| 10.76 |
| 7.41 |
| 8.53 |
| 10.20 |
| 8.53 |
| 10.20 |
| 10.20 |
| 10.20 |
| 7.41 |
| 10.20 |
| 10.20 |
| 15.11 |
| 13.50 |
| 15.11 |
| 13.50 |
| 9.09 |
| 7.97 |
| 9.09 |
| 12.41 |
| 9.09 |
| 11.86 |
| 9.09 |
| 11.86 |
| 4.00 |
| 2.29 |
| 7.41 |
| 7.97 |
| 9.65 |
| 9.09 |
| 7.97 |

**Statistical Review**

Data Set Parameters

| | |
|---|---|
| Average, $\mu_i$ | 9.90 |
| Variance, $\sigma_i^2$ | 7.81 |
| Standard Deviation, $\sigma_i$ | 2.79 |

Failure Model

| | |
|---|---|
| Average, $\mu_f$ | 9.23 |
| Variance, $\sigma_f^2$ | 9.29 |
| Standard Deviation, $\sigma_f$ | 3.05 |

Normal *pdf*

| Slope | P(Slope) |
|---|---|
| 0 | 2.68E-04 |
| 1 | 8.94E-04 |
| 2 | 2.62E-03 |
| 3 | 6.76E-03 |
| 4 | 1.53E-02 |
| 5 | 3.06E-02 |
| 6 | 5.39E-02 |
| 7 | 8.32E-02 |
| 8 | 1.13E-01 |
| 9 | 1.35E-01 |
| 10 | 1.43E-01 |
| 11 | 1.32E-01 |
| 12 | 1.08E-01 |
| 13 | 7.72E-02 |
| 14 | 4.87E-02 |
| 15 | 2.70E-02 |
| 16 | 1.32E-02 |
| 17 | 5.68E-03 |
| 18 | 2.15E-03 |
| 19 | 7.14E-04 |
| 20 | 2.09E-04 |
| 21 | 5.38E-05 |
| 22 | 1.22E-05 |
| 23 | 2.43E-06 |
| 24 | 4.26E-07 |
| 25 | 6.57E-08 |
| 26 | 8.93E-09 |
| 27 | 1.07E-09 |
| 28 | 1.12E-10 |
| 29 | 1.04E-11 |
| 30 | 8.43E-13 |

$P( X < \mu_i + \sigma_i ) \sim N(\mu_f, \sigma_f)$

| | |
|---|---|
| $P( Z < \mu_i + \sigma_i )$ | 0.8723 |

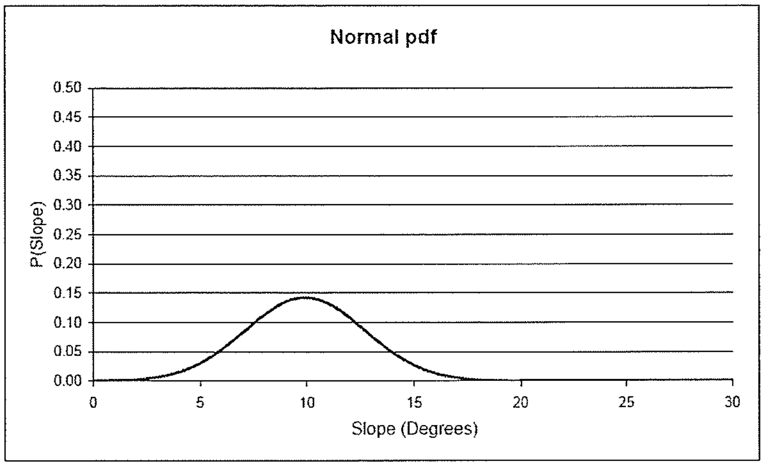
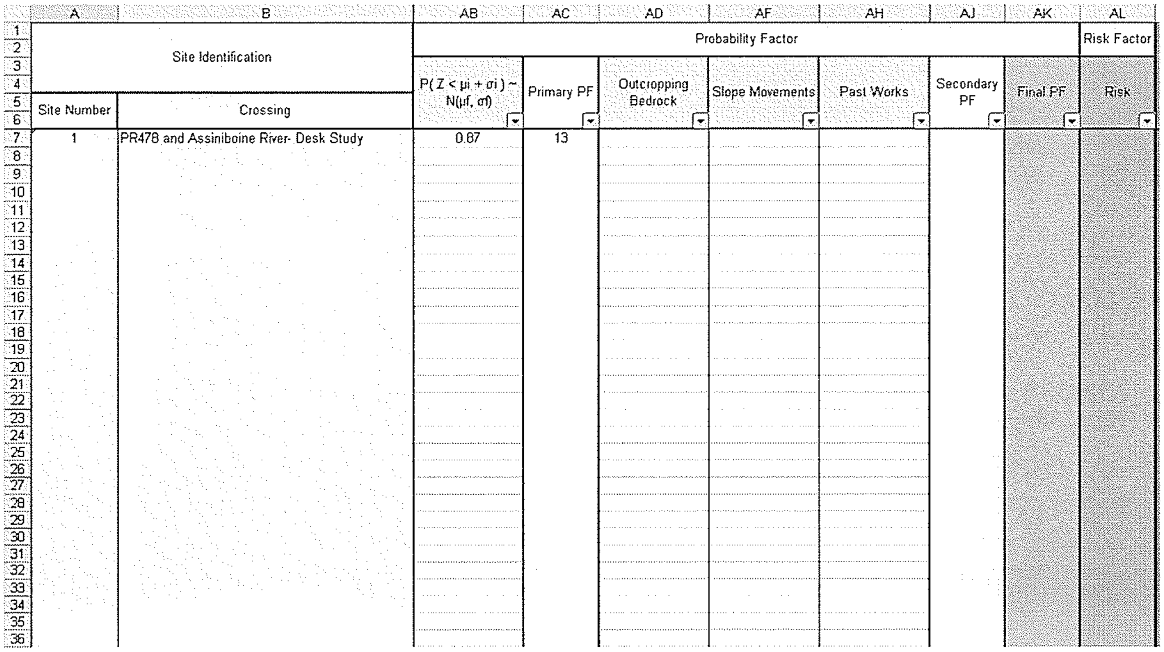
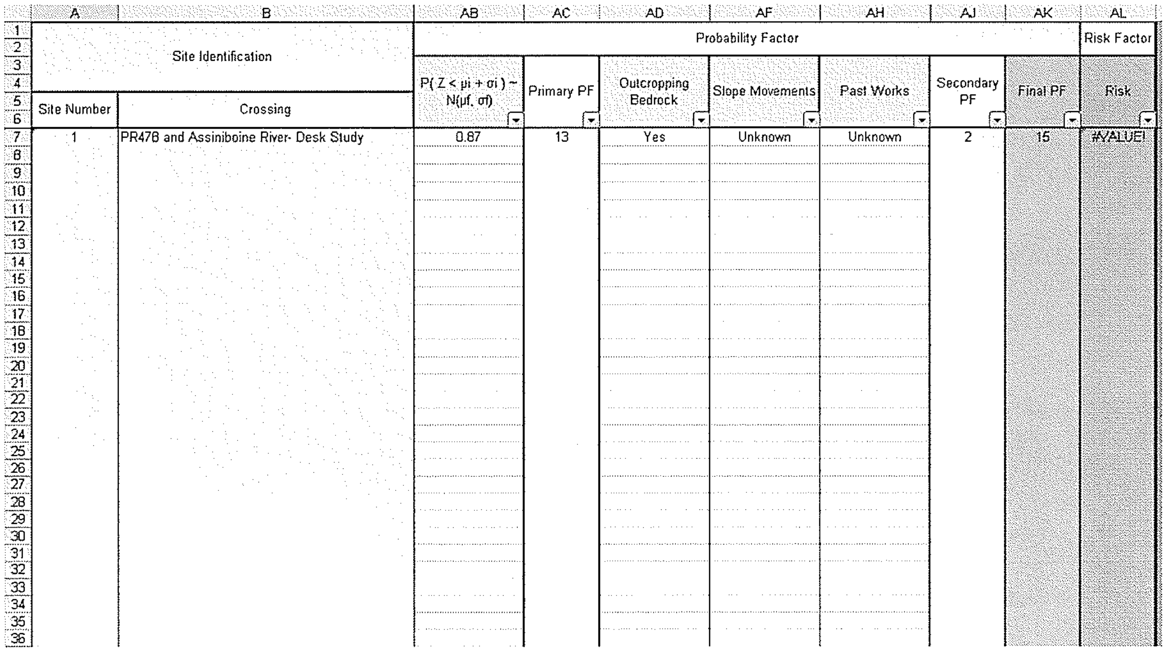


Figure 6.4 – Sample use of failure probability spreadsheet utilizing PR478 and Assiniboine River grade point data



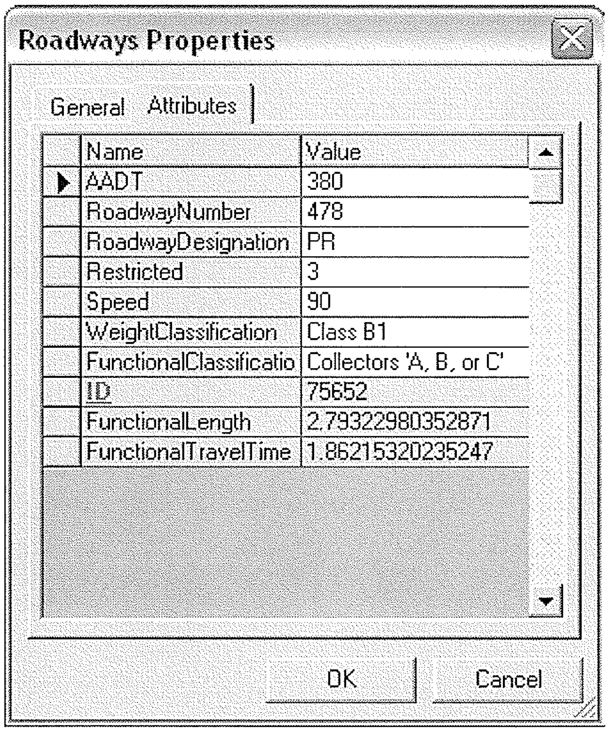
| | A | B | AB | AC | AD | AF | AH | AJ | AK | AL |
|---|---|---|---|---|---|---|---|---|---|---|
| 1–3 | Site Identification | | Probability Factor | | | | | | | Risk Factor |
| 4–6 | Site Number | Crossing | P( Z < μi + σi ) ~ N(μf, σf) | Primary PF | Outcropping Bedrock | Slope Movements | Past Works | Secondary PF | Final PF | Risk |
| 7 | 1 | PR478 and Assiniboine River- Desk Study | 0.87 | 13 | | | | | | |

Figure 6.5 – Desk study primary PF of PR478 and Assiniboine River using the MITRMS summary sheet



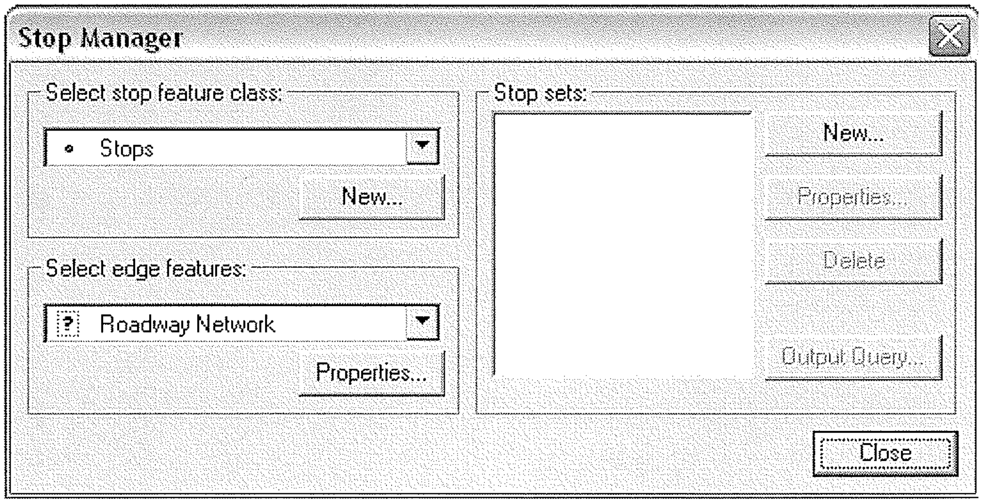
| | A | B | AB | AC | AD | AF | AH | AJ | AK | AL |
|---|---|---|---|---|---|---|---|---|---|---|
| 1–3 | Site Identification | | Probability Factor | | | | | | | Risk Factor |
| 4–6 | Site Number | Crossing | P( Z < μi + σi ) ~ N(μf, σf) | Primary PF | Outcropping Bedrock | Slope Movements | Past Works | Secondary PF | Final PF | Risk |
| 7 | 1 | PR478 and Assiniboine River- Desk Study | 0.87 | 13 | Yes | Unknown | Unknown | 2 | 15 | #VALUE! |

Figure 6.6 – Desk study secondary PF of PR478 and Assiniboine River using the MITRMS summary sheet



| Name | Value |
|---|---|
| AADT | 380 |
| RoadwayNumber | 478 |
| RoadwayDesignation | PR |
| Restricted | 3 |
| Speed | 90 |
| WeightClassification | Class B1 |
| FunctionalClassificatio | Collectors 'A, B, or C' |
| ID | 75652 |
| FunctionalLength | 2.79322980352871 |
| FunctionalTravelTime | 1.86215320235247 |

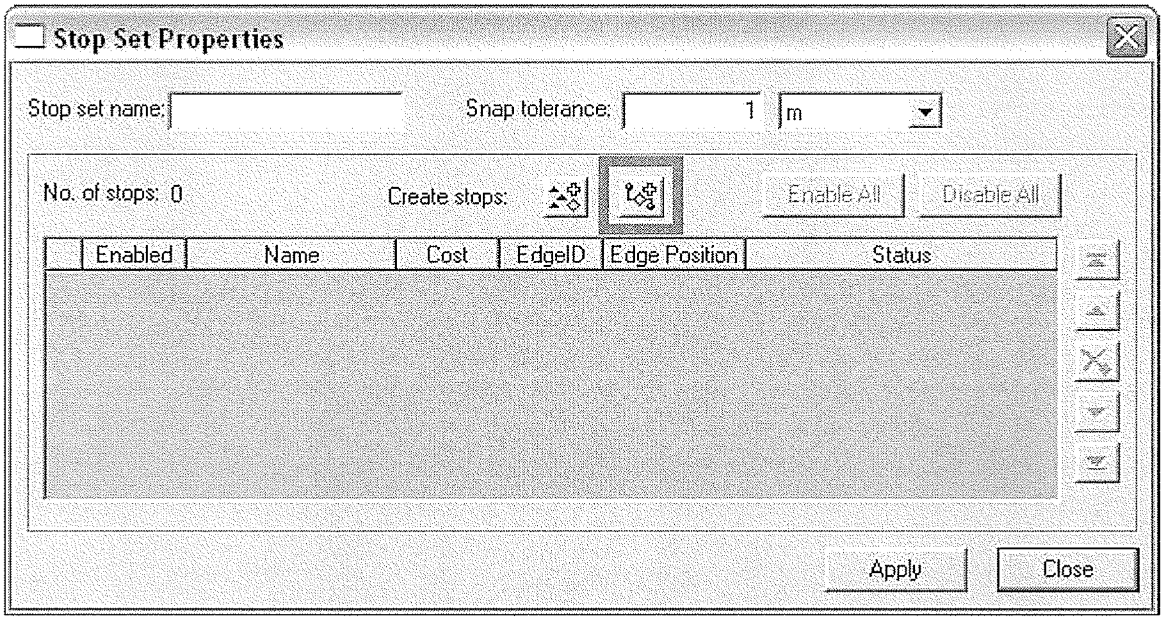
Figure 6.7 – Sample attribute summary as observed in GeoMedia



Select stop feature class: Stops

Select edge features: Roadway Network

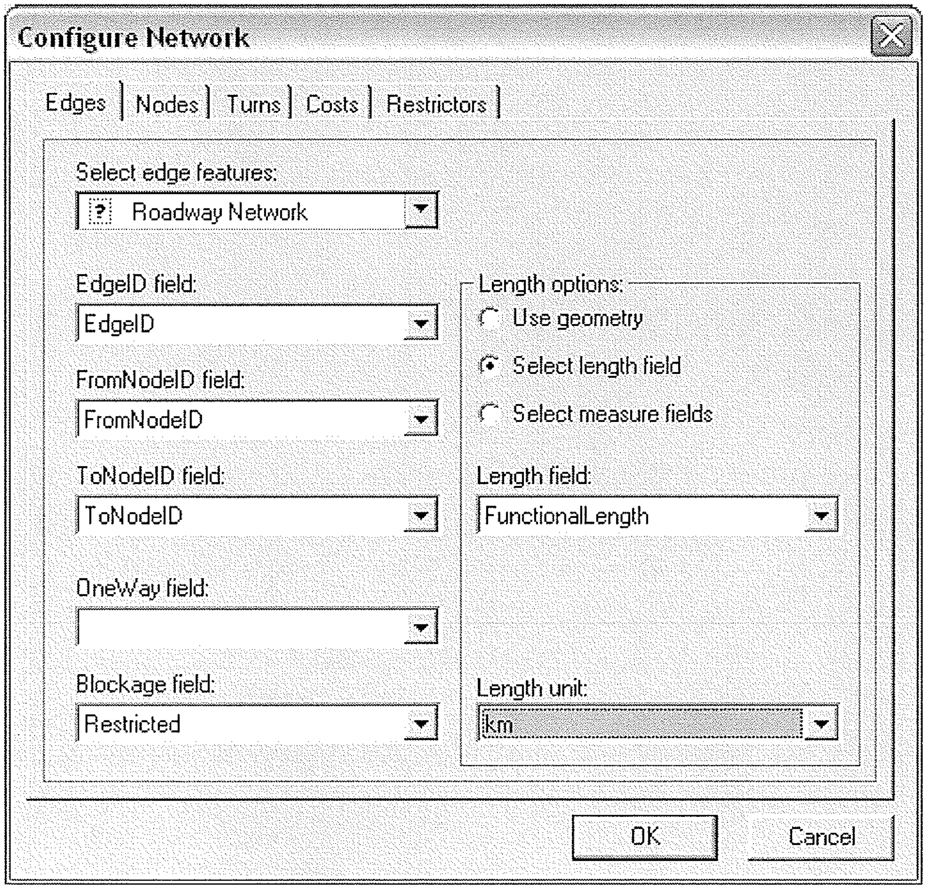
Figure 6.8 – Stop manager dialogue



Stop set name:

Snap tolerance: 1 m

Figure 6.9 – Stop set properties dialogue



Select edge features: Roadway Network

EdgeID field: EdgeID

FromNodeID field: FromNodeID

ToNodeID field: ToNodeID

OneWay field:

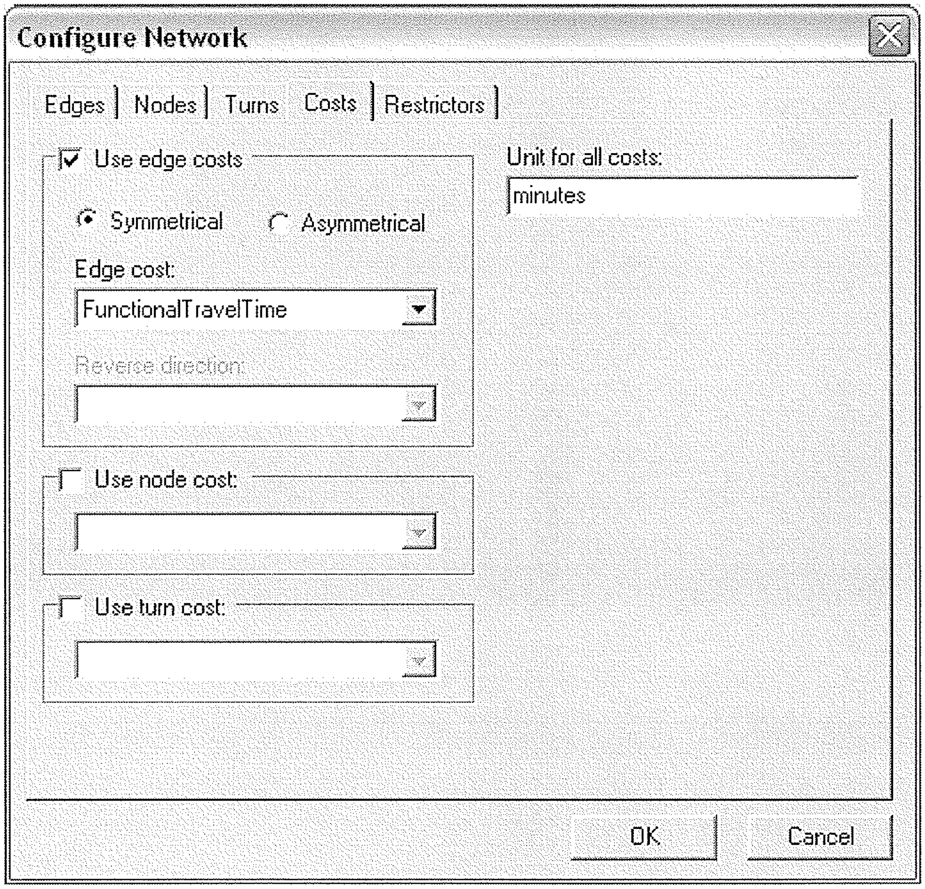
Blockage field: Restricted

● Select length field

Length field: FunctionalLength

Length unit: km

Figure 6.10 – Configure network dialogue: edges



☑ Use edge costs

● Symmetrical ○ Asymmetrical

Edge cost: FunctionalTravelTime

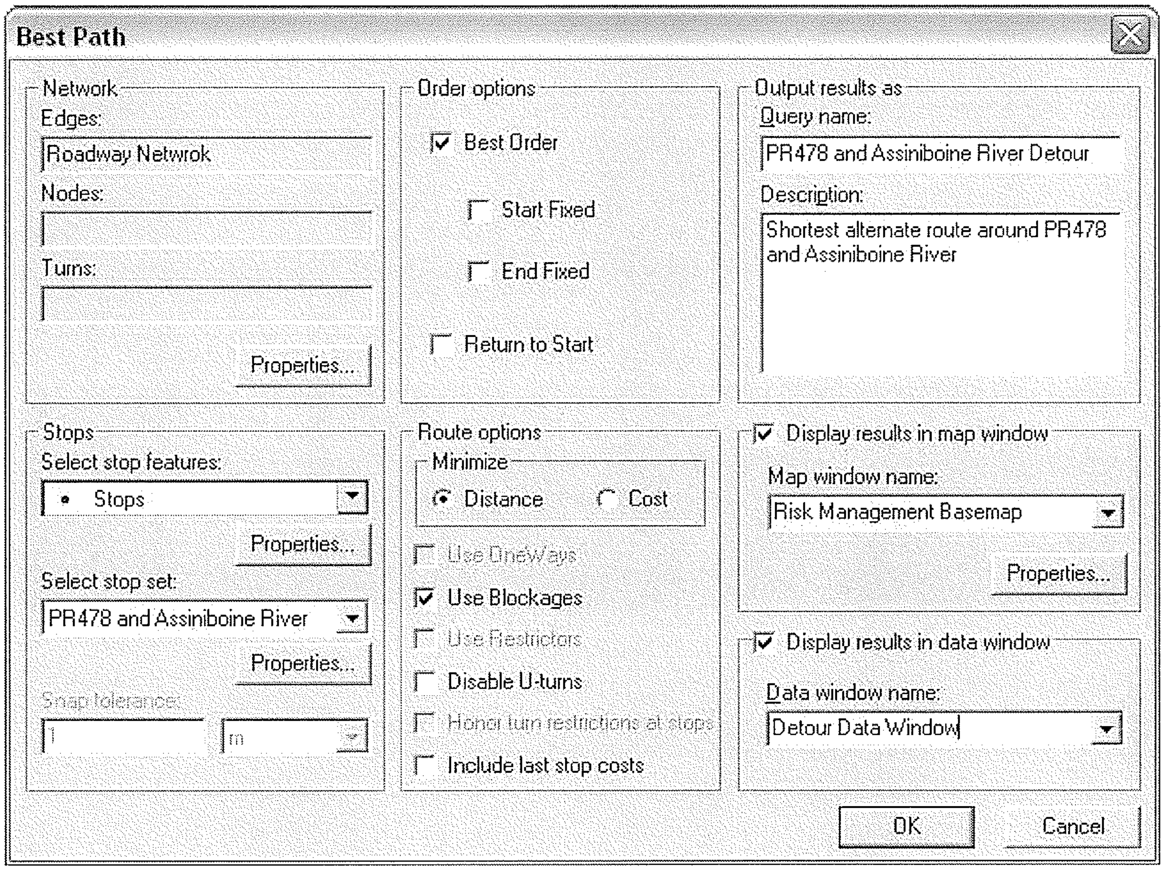
Reverse direction:

☐ Use node cost:

☐ Use turn cost:

Unit for all costs: minutes

Figure 6.11 – Configure network dialogue: costs



Network
Edges: Roadway Netwrok
Nodes:
Turns:

Order options
☑ Best Order
☐ Start Fixed
☐ End Fixed
☐ Return to Start

Output results as
Query name: PR478 and Assiniboine River Detour
Description: Shortest alternate route around PR478 and Assiniboine River

Stops
Select stop features: Stops
Select stop set: PR478 and Assiniboine River
Snap tolerance: 1 m

Route options
Minimize
● Distance ○ Cost
☐ Use OneWays
☑ Use Blockages
☐ Use Restrictors
☐ Disable U-turns
☐ Honor turn restrictions at stops
☐ Include last stop costs

☑ Display results in map window
Map window name: Risk Management Basemap

☑ Display results in data window
Data window name: Detour Data Window

Figure 6.12 – Best path dialogue

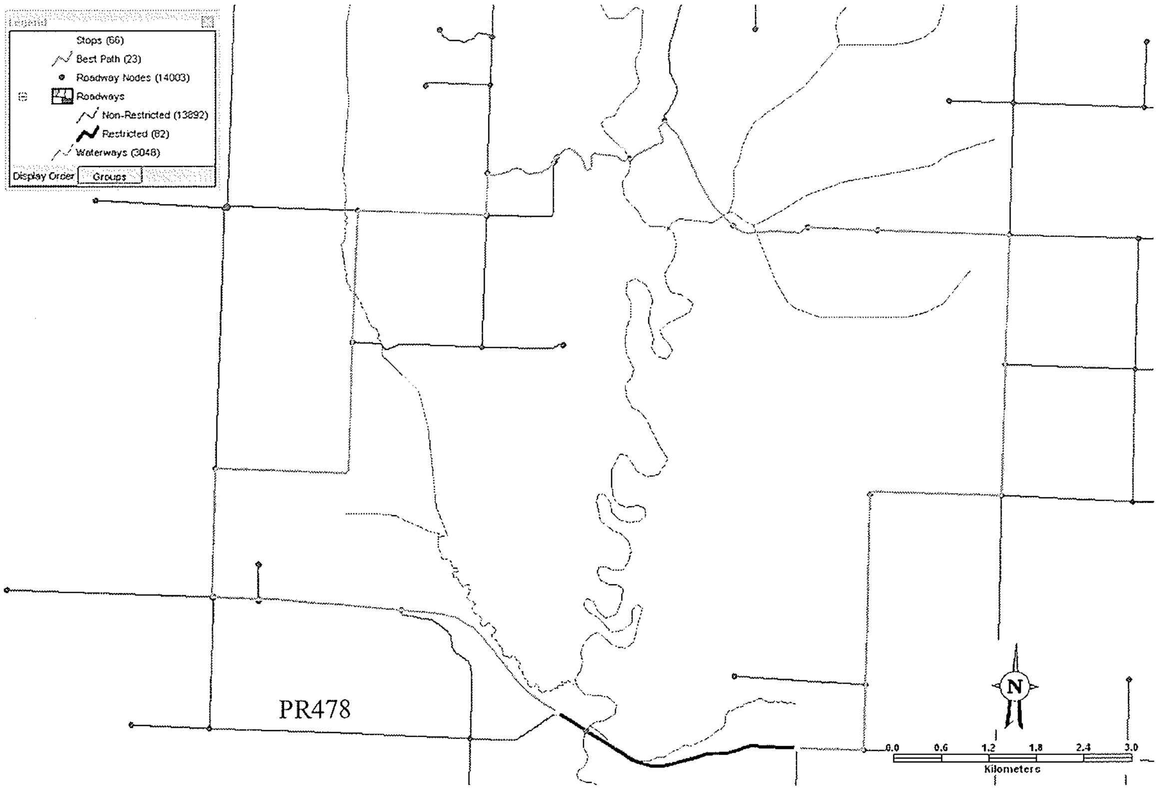
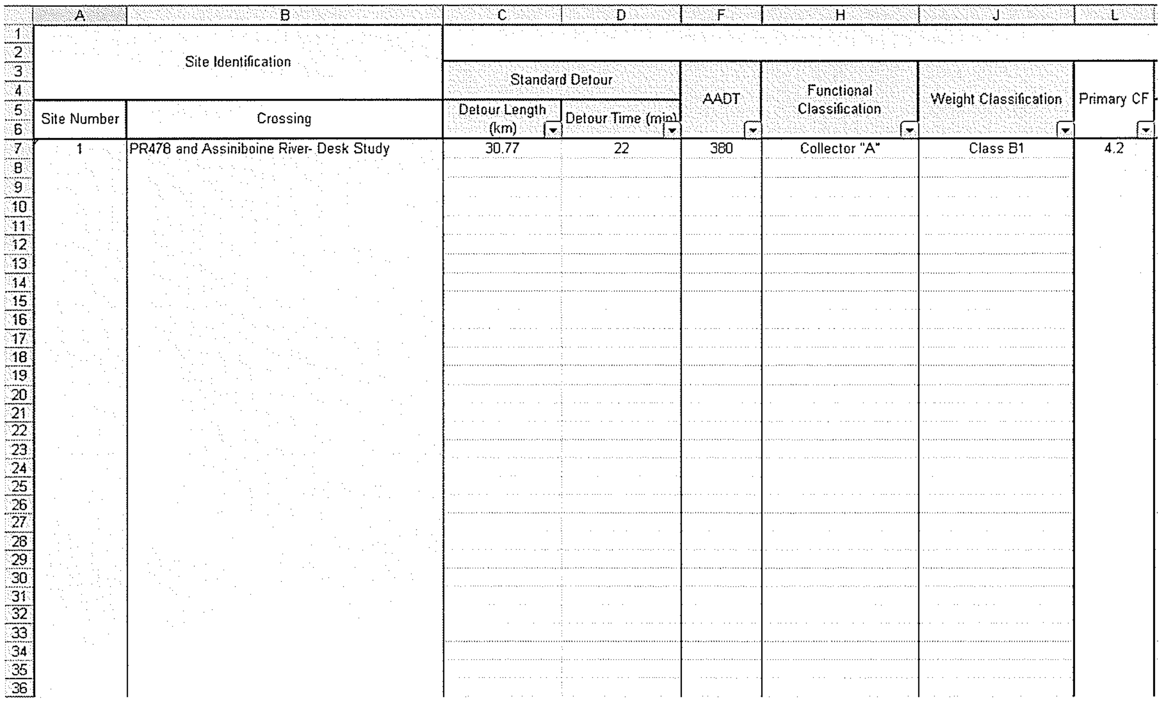


Figure 6.13 – Sample detour analysis about PR478 and Assiniboine River



| | A | B | C | D | F | H | J | L |
|---|---|---|---|---|---|---|---|---|
| 1 | Site Identification | | | | | | | |
| 2 | | | | | | | | |
| 3 | | | Standard Detour | | AADT | Functional Classification | Weight Classification | Primary CF |
| 4 | | | | | | | | |
| 5 | Site Number | Crossing | Detour Length (km) | Detour Time (min) | | | | |
| 6 | | | | | | | | |
| 7 | 1 | PR478 and Assiniboine River- Desk Study | 30.77 | 22 | 380 | Collector "A" | Class B1 | 4.2 |
| 8 | | | | | | | | |
| 9 | | | | | | | | |
| 10 | | | | | | | | |
| 11 | | | | | | | | |
| 12 | | | | | | | | |
| 13 | | | | | | | | |
| 14 | | | | | | | | |
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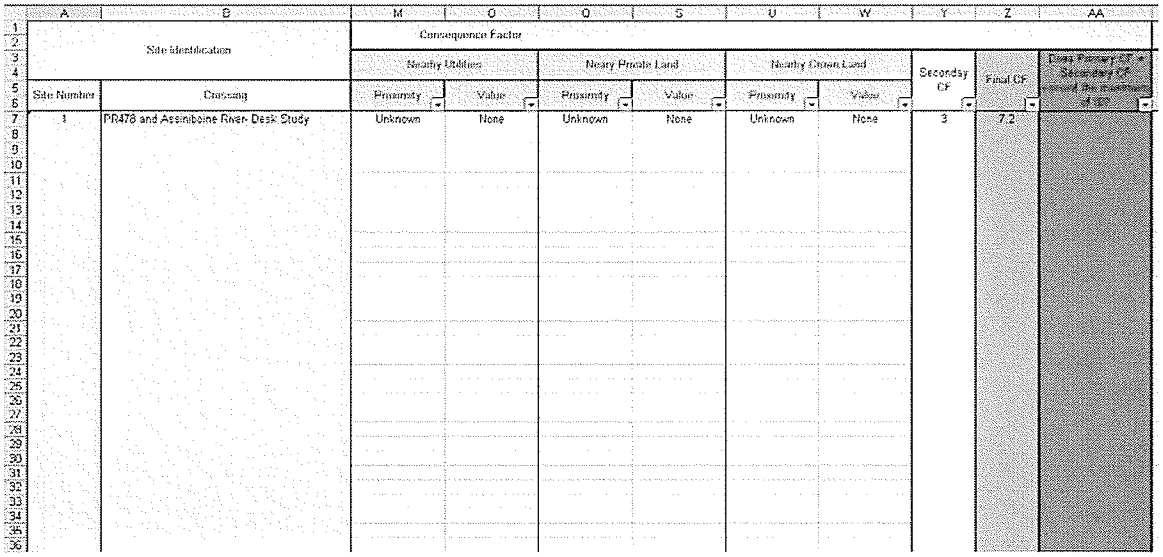
| 30 | | | | | | | | |
| 31 | | | | | | | | |
| 32 | | | | | | | | |
| 33 | | | | | | | | |
| 34 | | | | | | | | |
| 35 | | | | | | | | |
| 36 | | | | | | | | |

Figure 6.14 – Desk study primary CF of PR478 and Assiniboine River using the MITRMS summary sheet



| Site Identification | | Consequence Factor | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Nearby Utilities | | Neary Private Land | | Nearby Crown Land | | Seconday CF | Final CF | Does Primary CF + Secondary CF exceed the maximum of 10? |
| Site Number | Crossing | Proximity | Value | Proximity | Value | Proximity | Value | | | |
| 1 | PR478 and Assiniboine River- Desk Study | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | |

Figure 6.15 – Desk study secondary PF of PR478 and Assiniboine river using the MITRMS summary sheet

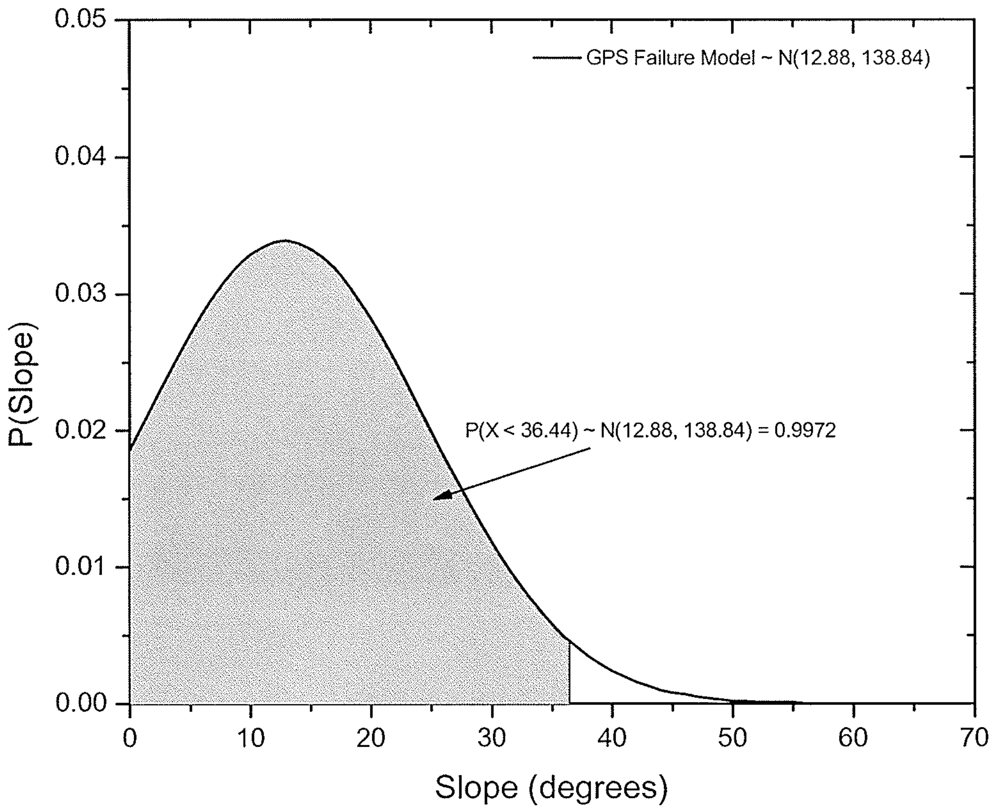


Figure 6.16 – Sample use of GPS *pdf* failure model

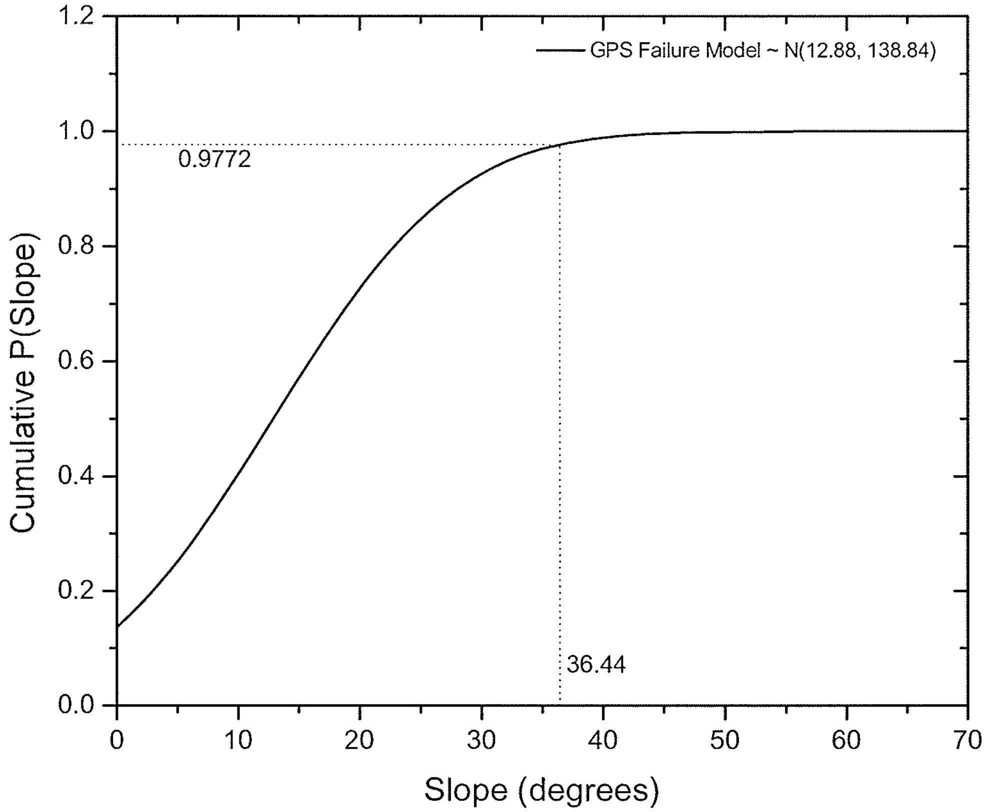
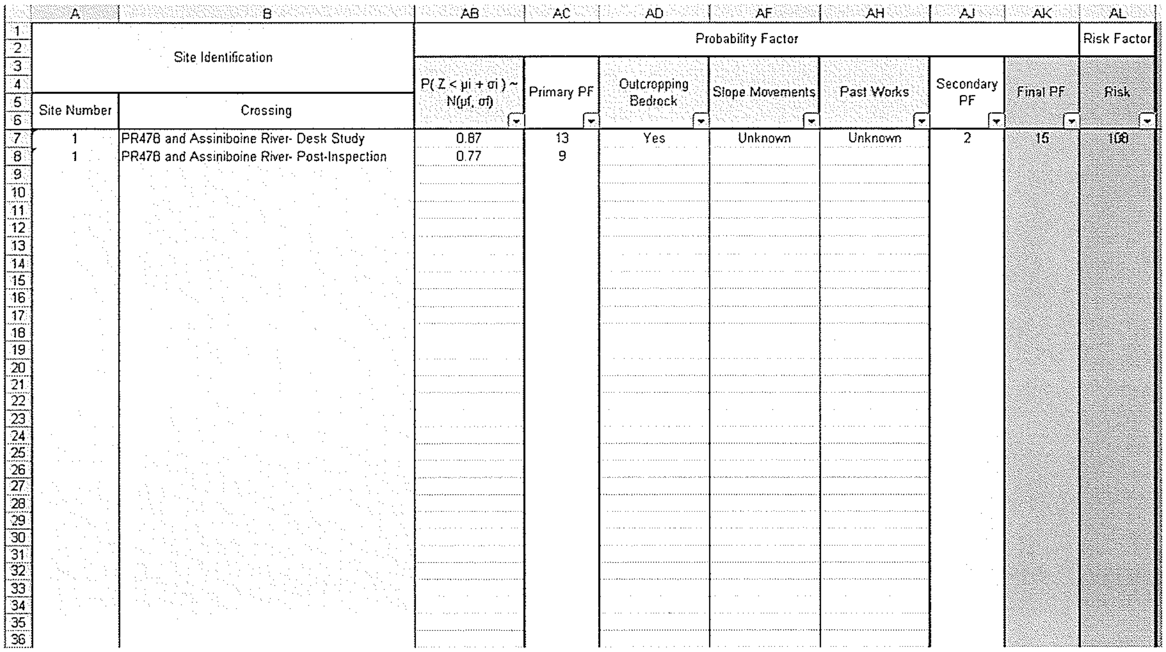
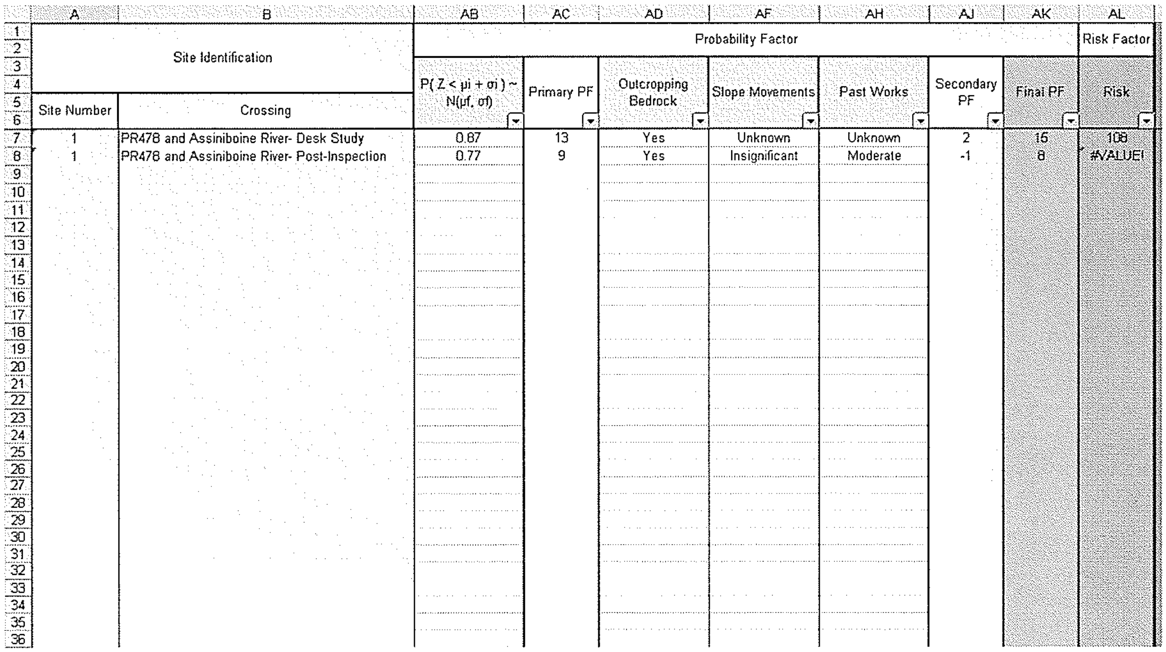


Figure 6.17 – Sample use of GPS *cdf* failure model



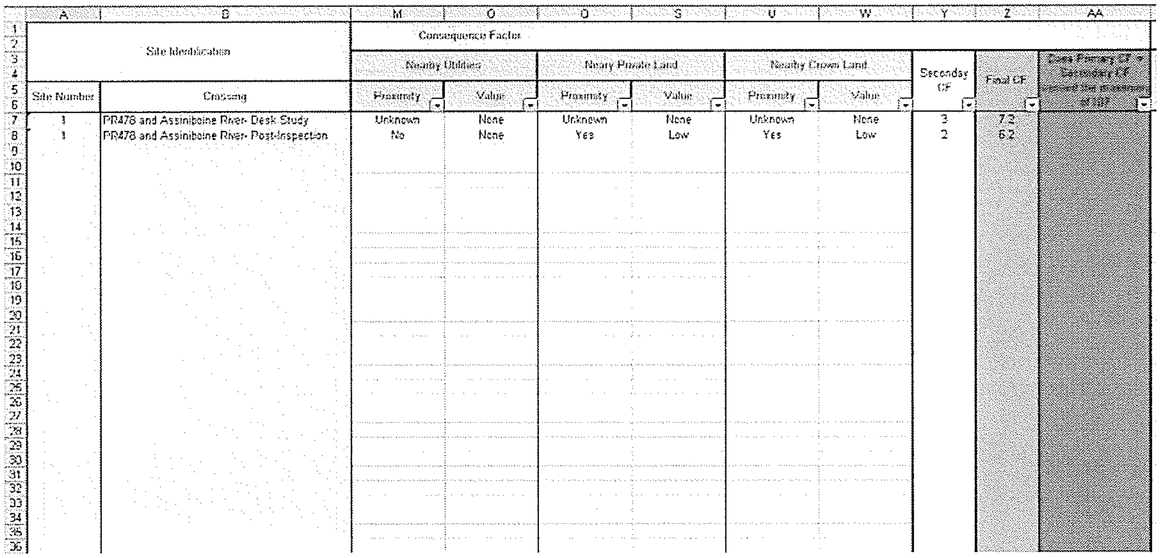
| | A | B | AB | AC | AD | AF | AH | AJ | AK | AL |
|---|---|---|---|---|---|---|---|---|---|---|
| | Site Identification | | Probability Factor | | | | | | | Risk Factor |
| | Site Number | Crossing | P( Z < μi + σi ) ~ N(μf, σf) | Primary PF | Outcropping Bedrock | Slope Movements | Past Works | Secondary PF | Final PF | Risk |
| 7 | 1 | PR478 and Assiniboine River- Desk Study | 0.87 | 13 | Yes | Unknown | Unknown | 2 | 15 | 108 |
| 8 | 1 | PR478 and Assiniboine River- Post-Inspection | 0.77 | 9 | | | | | | |

Figure 6.18 – Post-investigation primary PF of PR478 and Assiniboine River using the MITRMS summary sheet



| | A | B | AB | AC | AD | AF | AH | AJ | AK | AL |
|---|---|---|---|---|---|---|---|---|---|---|
| | Site Identification | | Probability Factor | | | | | | | Risk Factor |
| | Site Number | Crossing | P( Z < μi + σi ) ~ N(μf, σf) | Primary PF | Outcropping Bedrock | Slope Movements | Past Works | Secondary PF | Final PF | Risk |
| 7 | 1 | PR478 and Assiniboine River- Desk Study | 0.87 | 13 | Yes | Unknown | Unknown | 2 | 15 | 108 |
| 8 | 1 | PR478 and Assiniboine River- Post-Inspection | 0.77 | 9 | Yes | Insignificant | Moderate | -1 | 8 | #VALUE! |

Figure 6.19 – Post-investigation secondary PF of PR478 and Assiniboine River using the MITRMS summary sheet



| Site Identification | | Consequence Factor | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Nearby Utilities | | Neary Private Land | | Nearby Crown Land | | Seconday CF | Final CF | Does Primary CF + Secondary CF exceed the maximum of 10? |
| Site Number | Crossing | Proximity | Value | Proximity | Value | Proximity | Value | | | |
| 1 | PR478 and Assiniboine River- Desk Study | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | |
| 1 | PR478 and Assiniboine River- Post-Inspection | No | None | Yes | Low | Yes | Low | 2 | 6.2 | |

Figure 6.20 – Post-investigation secondary CF of PR478 and Assiniboine River using the MITRMS summary sheet

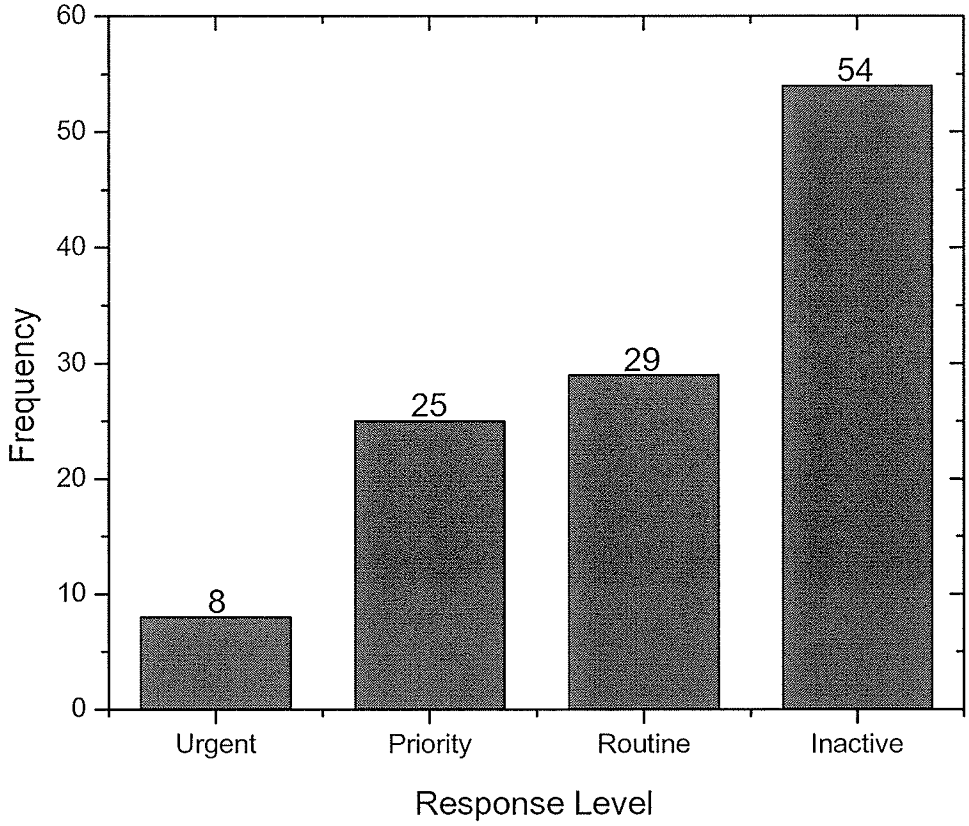


Figure 6.21 – Research extents response level histogram

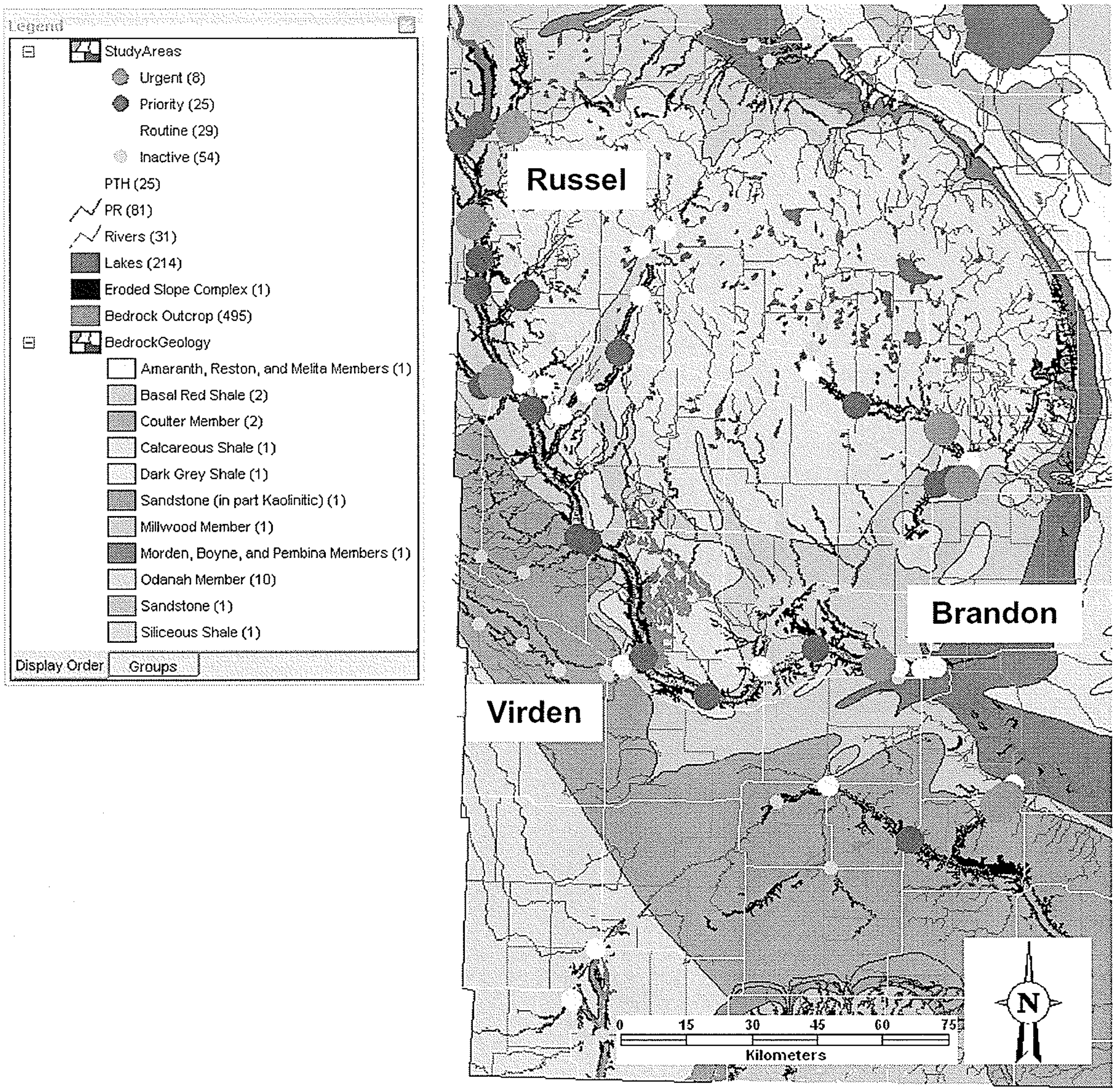


Figure 6.22 – Research extents response level theme map

# 7 Verification

## 7.1 Introduction

Three sites are the focus of the MITRMS verification study: PR250 and Assiniboine River, PTH16A and Little Saskatchewan River, and PR254 and Assiniboine River. The latter site chosen by MIT personnel based on reoccurring slope instability and the two former sites selected based on desk study results. Assessments were conducted, as discussed in Chapter 5, with focus placed on manual secondary adjustments to PF and CF and using GPS to create a profile and grade point distribution to be compared with the GPS failure model.

The three sites were selected based on proximity to one another where desk assessments resulted in priority, urgent, and routine response levels. PTH16A and Little Saskatchewan River was selected due to its urgent response level and proximity to Minnedosa with little or no history of instability. The PR250 and Assiniboine River site was selected due to a high risk level while being relatively inactive with no history of notable instabilities. PR254 and Assiniboine River was selected due to frequent movements and rehabilitation while being ranked the lowest of the three. Table 7.1 briefly summarizes desk study results.

All three sites, when initially considered, do not necessarily fall within the response levels initially assumed. Verification of MITRMS is conducted to show that through manual inspection, sites can be evaluated equally against each other to accomplish two things. First, sites considered before MITRMS implementation can be shown to be of varying significance. Secondly, increasing the number of sites manually assessed allows MITRMS to become increasingly reliable.

Table 7.1 – Desk study summary of sites for verification

| Site | Risk Factor | Response Level |
|---|---|---|
| PTH16A and Little Saskatchewan River | 154 | Urgent |
| PR250 and Assiniboine River | 107 | Priority |
| PR254 and Assiniboine River | 65 | Routine |

## 7.2 Site Discussion

### 7.2.1 PR250 and Assiniboine River

Desk study results suggest the northern section of this site requires a priority response level while MIT regional staff feels there is no need for action. This site, as shown in Figure 7.1, is chosen for verification in order to test if MITRMS would result in a similar conclusion following manual inspection. Updated grade point data resulted in preliminary PF assessment of 15. Slope movements have taken place, as shown in Figure 7.2, and are found to be decreasing or slow rates of movement over longer periods. This results in an insignificant query response. There has been no past remediation. A Manitoba Hydro and Manitoba Telecom Services pole is located approximately one meter from the crest, as shown in Figure 7.3. If this were to be immediately impacted, local residents would lose hydro and communication capabilities for no more than a day thus a medium value is chosen. Local farmland is proximate, resulting in a low value for proximate private land. At most a drainage ditch would be negatively affected, resulting in a low

Crown or right-of-way value. Manual assessment of this site increases RF to a value of 114.

### 7.2.2 PR254 and Assiniboine River

Located along the southern Assiniboine River valley wall, as shown in Figure 7.4, this section of PR250 is relatively new, constructed in the mid 1980's. Desk study results suggest a routine response level. Recent instabilities are attributed to high nearby groundwater discharge where periodic maintenance work has yielded little or no resolution to recurring problems. Slope movements are found to be considerable, as shown in Figures 7.5 and 7.6, resulting in pinched drainage along the roadway. A buried fiber optic line is located along the opposing side of the roadway, yielding an insignificant value to proximate infrastructure since it will not be impacted. Local farmland is located near the crest, resulting in an insignificant private property value. Drainage is likely the only significant item affected should movements continue and so insignificant has also been assessed for the Crown or right-of-way query response. Including a primary PF change to 17, a significant jump from 9, assessment of this site increases RF to 111.

### 7.2.3 PTH16A and Little Saskatchewan River

This site is located along the northern Little Saskatchewan River valley wall, as shown in Figure 7.7, just north of the town of Minnedosa. No significant signs of instability were observed nor is there a history of remediation. A GPS profile was taken to update preliminary PF to 19. No utilities were found to be proximate and low value private property is nearby. Crown or right-of-way infrastructure includes roadway and drainage ditches, where each would be affected insignificantly if failure should occur. Manual assessment of this site increase RF to a value of 164.

## 7.3 Risk Summary

Risk factor and response for verification sites before and after site investigation are shown in Table 7.2.

Table 7.2 – Risk factor and response summary for verification sites

| **Crossing** | **MITRMS Desk Study** | | **MITRMS Manual Assessment** | |
|---|---|---|---|---|
| | **Risk Factor** | **Response Level** | **Risk Factor** | **Response Level** |
| PTH16A and Little Saskatchewan River | 154 | Urgent | 114 | Urgent |
| PR250 and Assiniboine River | 107 | Priority | 111 | Priority |
| PR254 and Assiniboine River | 64 | Routine | 164 | Priority |

Two sites, PR250 and PTH16A, were predicted to become at the most a routine response level after manual inspection. Both sites came out of post-inspection with ratings larger then that going in; this concept may cause confusion. MITRMS is designed such that sites are ranked with respect to each other based on site specific conditions. It is not meant to indicate that failure has or will take place but to allow MIT to begin assigning proper resources to sites of potential hazard. That is, these two sites should be treated as their respective management approach suggests in order to make certain that if instabilities occur, timely decisions can be made. The sites identified at PR250 and PTH16A have reached their response levels due to actual site knowledge and should be managed appropriately. Manual inspection of PR254 yielded expected results, an increase in response level from routine to priority.

Appendix C summarizes post-inspection results for all sites assessed during this research. Figure 7.8 is a histogram displaying response level frequency with respect to inspected sites. Out of eight sites total, 2 are urgent and routine and 4 are priority response levels. It is recommended that each site's management approach be implemented promptly. Figure 7.9 contains a response level thematic map, spatially presenting where each of the post inspection sites for the verification study lie within western Manitoba.

## 7.4 Conclusion

Verification using three supplementary sites has shown again that MITRMS is a powerful tool for quantifying risk of landslides along western Manitoba's highway network. The sites selected were done so to demonstrate how varying initial risk estimates can change drastically following manual assessment. Desk study results are not completely accurate with initial assumptions yet it provides a significant means of mobilizing resources for improving site specific knowledge. In total, eight sites have been assessed using MITRMS, all exhibiting excellent results and applicability.

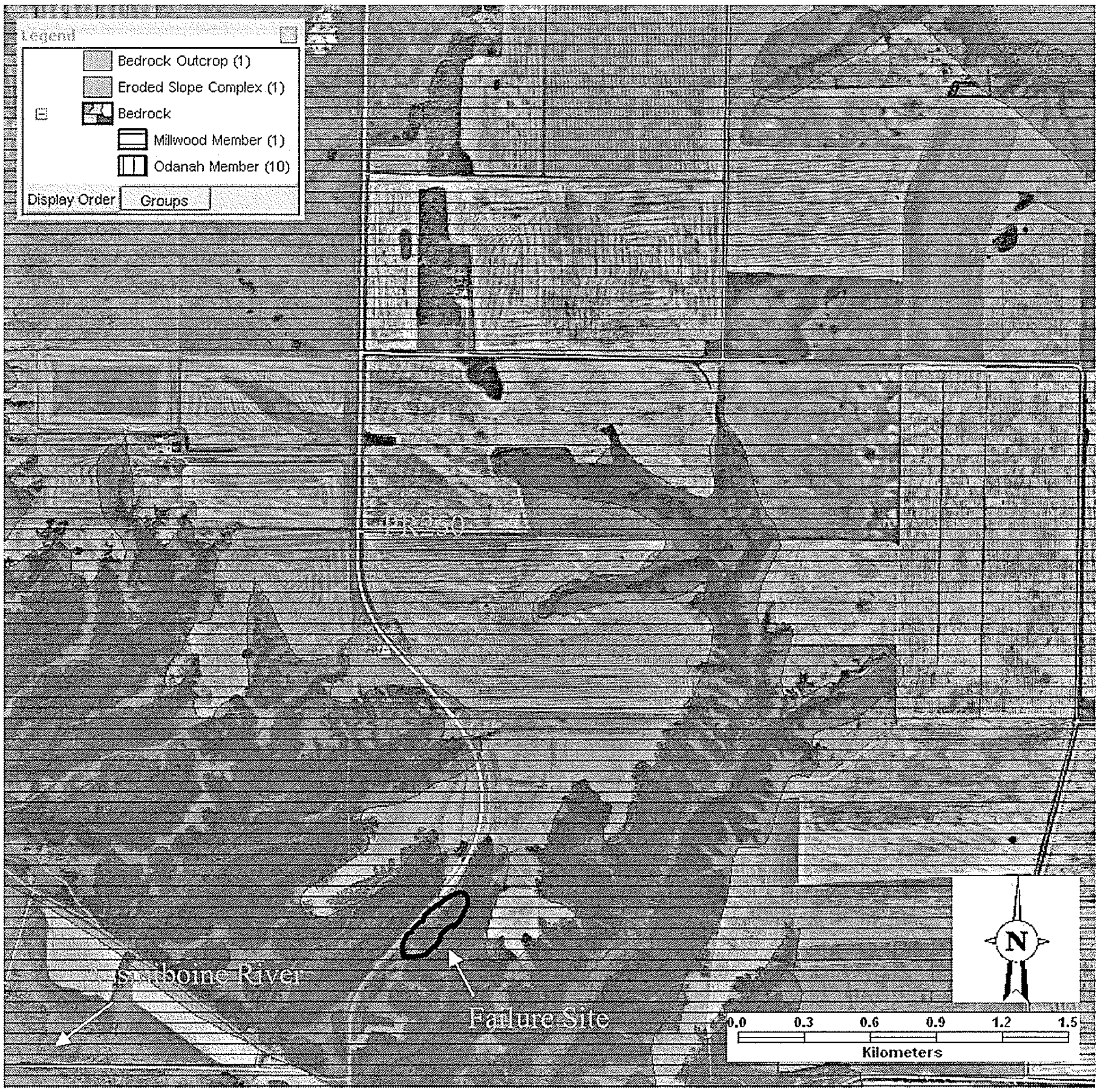


Figure 7.1 – Aerial view of PR250 and Assiniboine River

Figure 7.2 – PR250 and Assiniboine River, top scarp south view

Figure 7.3 – PR250 and Assiniboine River, utility proximity

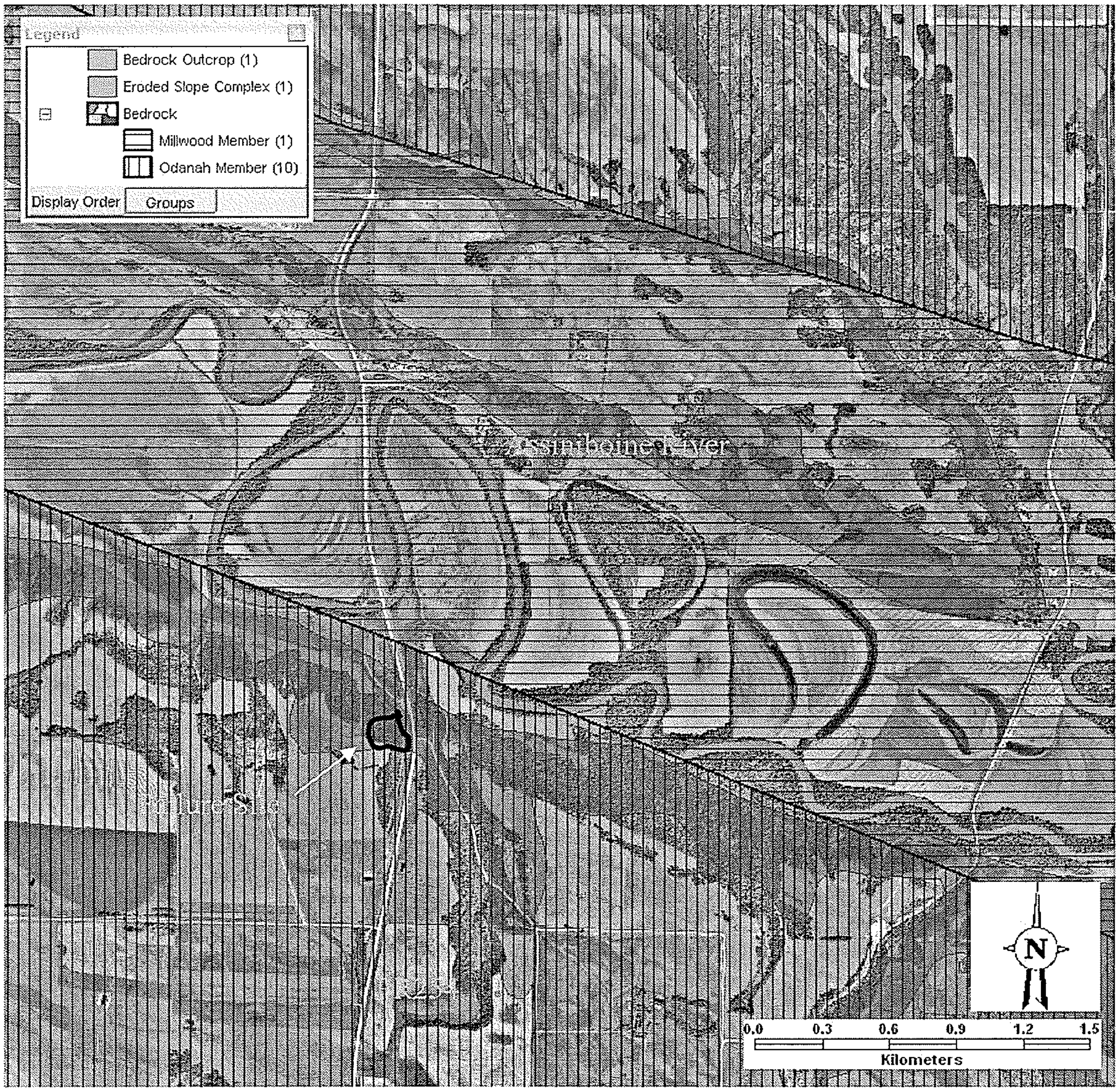


Figure 7.4 – Aerial view of PR254 and Assiniboine River

Figure 7.5 – PR254 and Assiniboine River, slide mass

Figure 7.6 – PR254 and Assiniboine River, top scarp east view

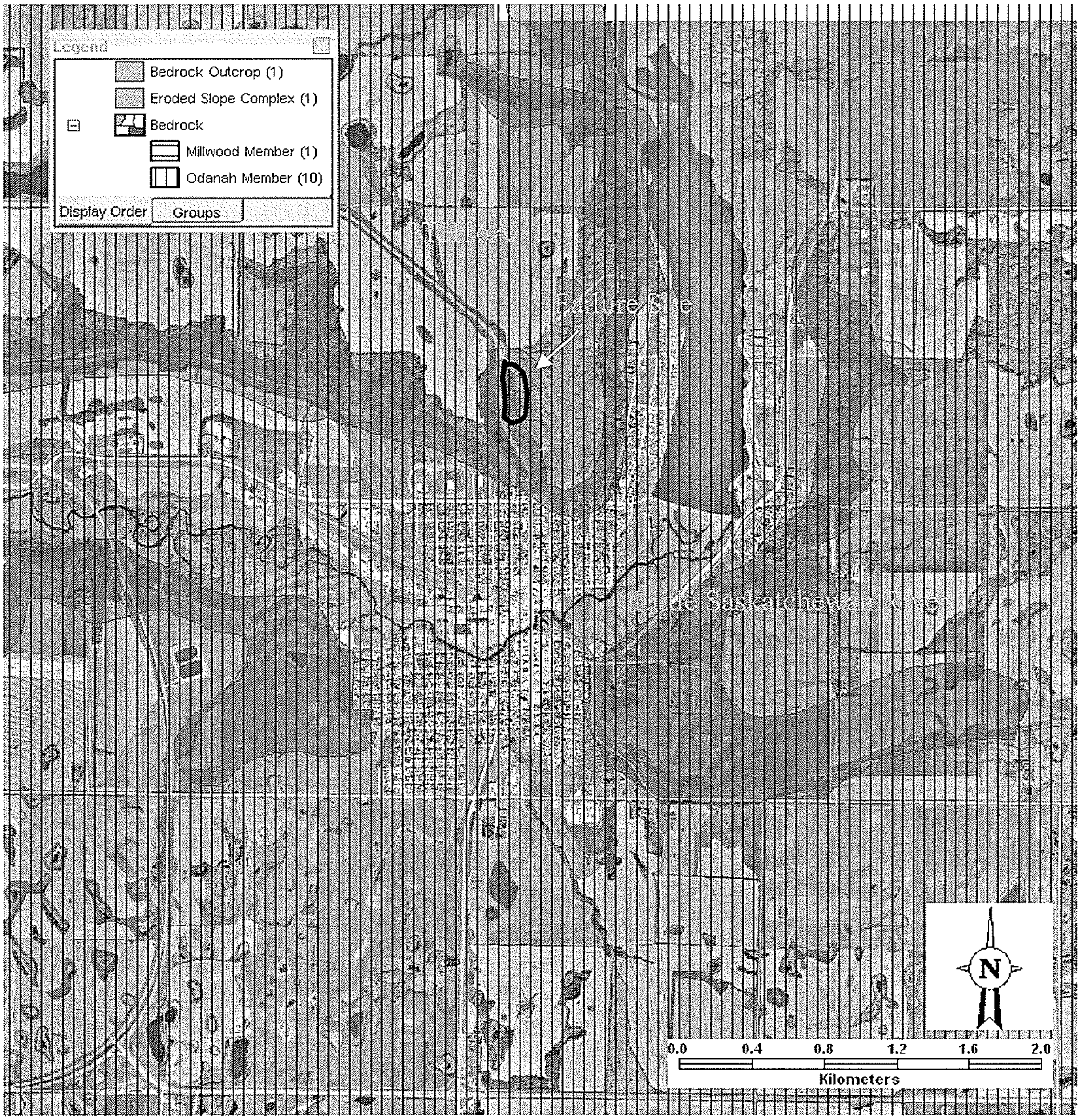


Figure 7.7 – Aerial view of PTH16A and Little Saskatchewan River

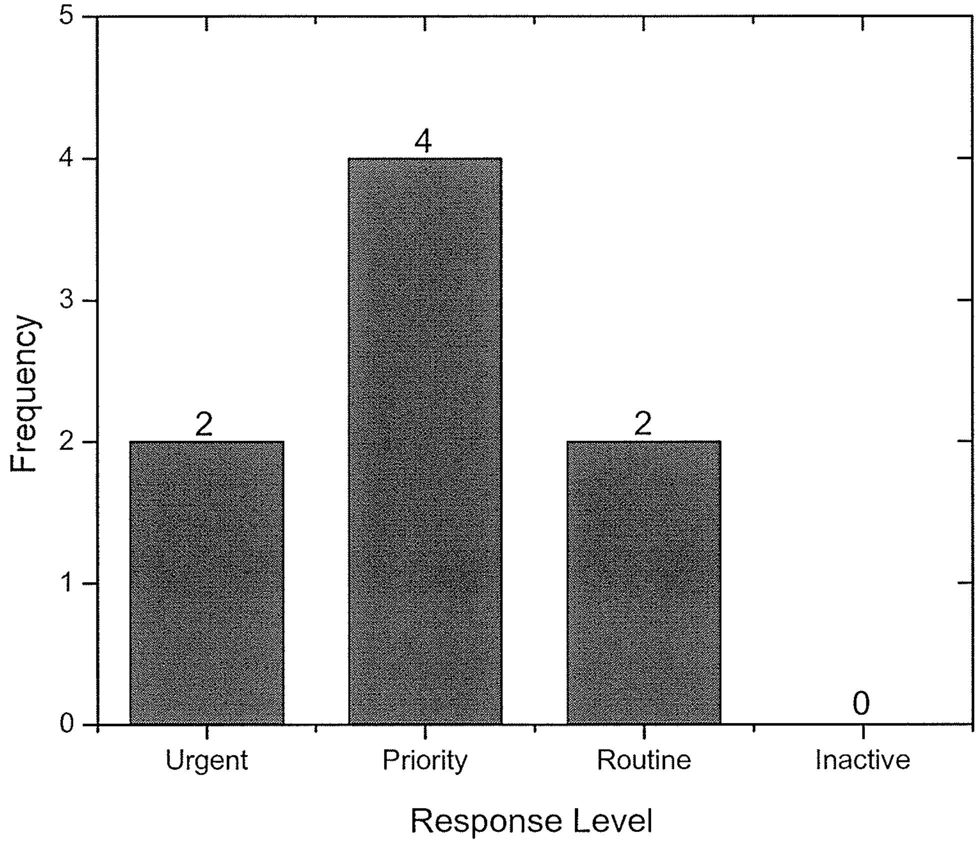


Figure 7.8 – After site inspection response level histogram

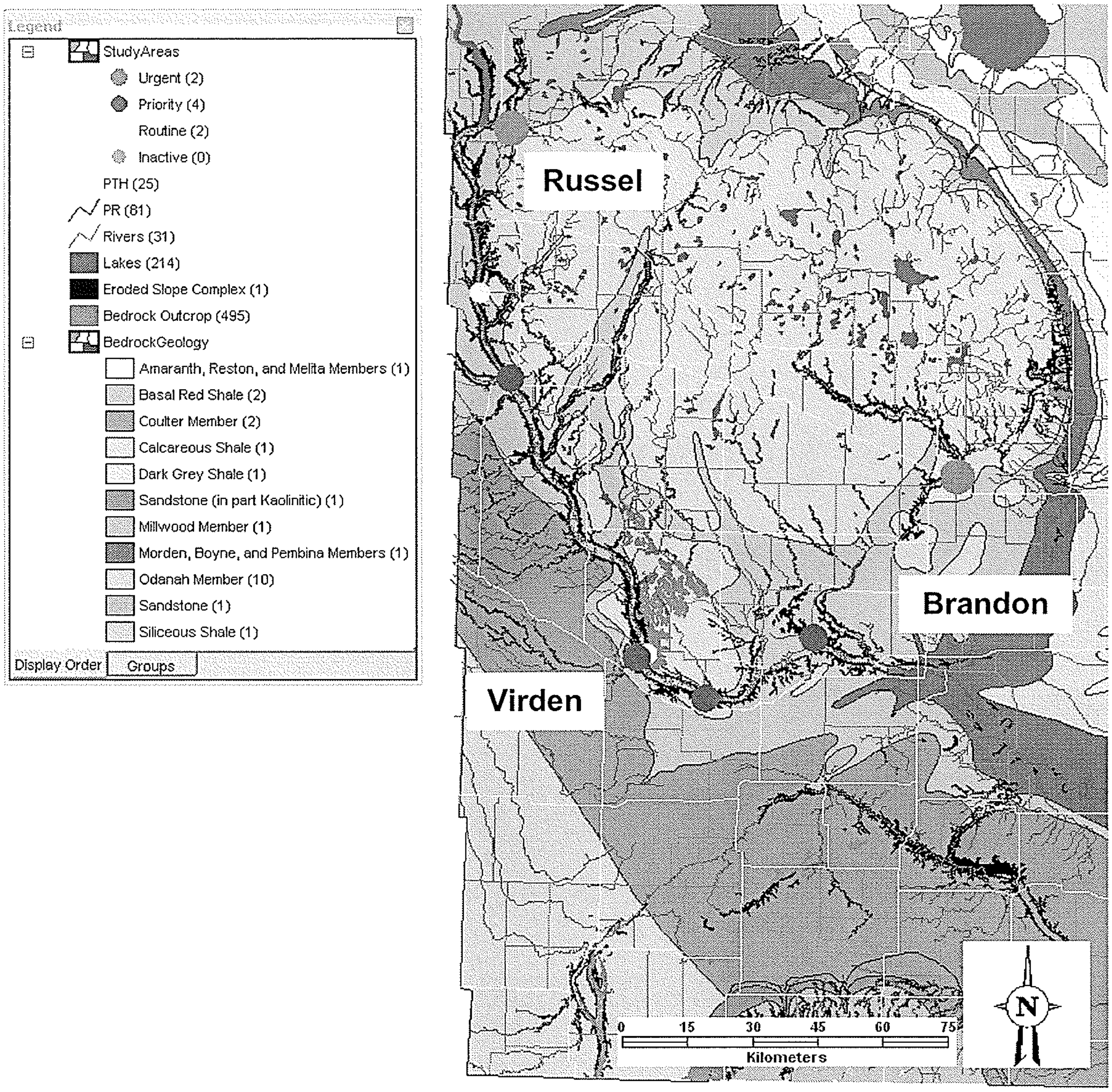


Figure 7.9 – After site investigation response level theme map

# 8 Conclusions and Recommendations

## 8.1 Conclusions

### 8.1.1 Applicability

This research has shown that quantifying slope instability triggers using geospatial information leads to a tool for predicting landslide risk in western Manitoba. Superimposed geospatial layers isolate potential areas of concern and create a basis for interpreting and assessing hazards along highways in proximity to fluvial water bodies. Statistical analysis of grade at known failure sites creates a foundation for failure model development, where contrasts in slope yield a numerically understandable value of failure probability at alternate sites. Public dependence and roadway classifications yield a basis for quantifying consequence should a roadway segment become restricted. These values, when assessed according to point scales result in a risk value; a single numerical value that represents hazard that can ultimately be used to rank and prioritize site specific response at potential landslide locations along the highway network in western Manitoba.

Accuracy of computational results should continuously be questioned. Digital elevation model density and unknown site specific land use, surrounding infrastructure, and history, create inherent uncertainty. As a result, manual inspection of high risk and urgent response level sites is recommended to improve confidence. In addition, sites which show increased probability or consequence uncertainty should be assessed to ensure risk is appropriately allocated. Increasing the number of sites manually inspected improves this system through unbiased comparison techniques.

### 8.1.2 GIS as a Proactive Risk Management Tool

Several selected sites were used to calibrate and verify the MITRMS. In one case, the SHT risk management system was employed to assess risk at six sites, five of which where used for calibration purposes. These sites were readily identified using GIS and reviewed using desk study procedures. Results were approximate when compared to those of the spring hazards tour until manual inspection provided secondary adjustments to be included. In general, risk and response level were comparable and very consistent in some cases.

Three sites were used for verification, where two were selected based on MITRMS desk study results and the other based on current MIT concerns. Two sites, though not known to have a significant history of instabilities, resulted in higher risk factor levels because of nearby utilities and high probability factors. The high consequence situations warrant closer attention than failure concerns would warrant. The third site, one of ongoing instabilities and periodic small scale rehabilitations, yielded a final risk factor confirming initial MIT predictions.

Each of the sites used to calibrate and verify MITRMS have shown differing assessment scenarios. Initial assumptions in some cases were either affirmed or negated following manual assessment. In the event a site does not fall within a response level category initially predicted this does not indicate failure of the system, rather potentially erroneous initial assumptions. Consequences are affected by several factors: proximity to infrastructure, detour distance, and public and commercial dependence. These figures may be evasive during initial assumptions where quantification becomes possible upon

GIS implementation. MITRMS takes several hazard triggers and makes them more evident in terms of surrounding influence.

Management approaches are suggestive in that they lead MITRMS users towards logical treatment methodologies. Upon investigating supplementary sites, true long term benefits of MITRMS implementation become increasingly apparent. Currently, the eight sites investigated provide MIT with a bias in terms of those eight sites specifically. Adding more sites to the post-investigation MITRMS summary sheet will allow MIT to truly understand its benefits and apply it appropriately.

Influence factors for this research can be altered to fit that of MIT more suitably. That is, the weight at which primary and secondary PF and CF influences risk level outcome are only suggestive and should be altered or at least reviewed and approved by MIT staff. The MITRMS summary sheet contains a section where influences and inputs can be altered where site ratings are updated instantaneously. It is recommended that MIT review the default weights and make any changes if deemed necessary.

It is recommended that MITRMS be implemented shortly. This includes investigating remediation techniques for the sites already assessed and further site investigations based on initial desk study results. Based on the results presented, there are enough sites of concern to warrant planning for landslide assessment studies for the next two years.

As more sites develop instabilities they can be included in the failure model to allow for dynamic integration. Varying conditions lead to failure and by including up-to-date failures within its development can further increase failure probability accuracy. This is done by including the grade point data set of new failures within that of the failure model. Updated data set mean and variance shifts the normal *pdf* indicative of failure, where all other sites can be subsequently revised.

### 8.1.3 Hypothesis

Hypothesis:

"Geographic Information Systems can be used as a predictive tool for assessing, ranking and prioritizing landslide risk along highway embankments in western Manitoba using available geospatial data"

Previous discussions have shown that available geospatial data can be used as a predictive tool for assessing, ranking and prioritizing landslide risk along highway embankments in western Manitoba. In no way was this research an addition to transportation engineering or GIS-based research and development. These were simply used as tools and/or identifiers for risk management based purposes.

## 8.2 Recommendations for Further Research

Recommendations for further research include: geospatial data improvements, full automation, commercial truck detours, supplementary geospatial layers, and expansion to other regions.

### 8.2.1 Geospatial Data Improvements

Current DEM point density is sufficient for initial approximations of failure probability but can be improved. In most cases, the magnitude of failure probability measurements between proximate sites is reasonable. Trends diverge when distance between sites increase, and makes comparing sites at extreme extents less accurate. Higher density DEMs would improve grade point results and would therefore improve the GIS failure model and subsequent site failure probability.

### 8.2.2 Full Automation

GeoMedia currently does not support full automation, that is, users do not have the ability to develop a macro that would isolate sites, quantify probability based on failure model comparisons, conduct detour analysis, and output resulting risk. It is not suggested that this approach be taken, but perhaps further computational capability could be incorporated into the GIS portion in order to increase user productivity. These could be defined as attributes that are a function of several others, internal failure probability calculations, and dynamic site identification, as examples.

### 8.2.3 Commercial Truck Detours

Highway weight classes have set standards with respect to axle weight according to truck orientation type. Assessing consequence could be improved if detour analysis was conducted taking site specific predominant truck types into consideration. Detour distances could vary significantly under these circumstances and may take precedent if a truck/roadway segment proves pivotal to surrounding economy.

### 8.2.4 Supplementary Geospatial Layers

Further amounts of geospatial information can be created based on supplementary instability triggers. These include groundwater surface, rainfall, infiltration, runoff, and vegetative cover. These are dynamic, in that they change with time. A site can be calibrated with respect to how these globally affect stability through numerical modeling and engineering judgment. Regional values can be created in that instabilities are affected during rainfall events or vegetative cover types. This would be a rigorous process and could require extensive research. As an example, peak rainfall events could be determined by the system such that if an extreme event occurred, sections at high risk could be shut down to protect safety.

### 8.2.5 Expansion to Include Geohazards

Geohazards includes riverbank erosion and soil erodibility. Surficial geology can be overlapped with floodplain, watershed, and piezometric water surface geometries too potentially to identify areas of erosion susceptibility. Doing so could allow all forms of geotechnical phenomena to be monitored by way of risk management methods, thus strengthening even further MIT's inception into asset management.

### 8.2.6 Expansion to Other Regions

The MITRMS has been designed so that triggers and factors determining failure probability, PF, and CF magnitudes can be altered. As such, MITRMS can be applied to other regions of varying geology, instabilities triggers and types, consequences, and hazards. Similar procedures when developing a failure model should be undertaken, placing utmost scrutiny on input parameters and computational results. Undertaking this could improve the fashion at which landslides hazards are managed across Manitoba. The system developed here has been applied to one specific geological region and should not be applied elsewhere without appropriate modifications.

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# Appendix A:

# MITRMS Site Inspection Form

# Manitoba Infrastructure and Transportation
# Risk Managem System (MITRMS)

## Site Inspection Form

| | |
|---|---|
| LOCATION | PREVIOUS INSPECTION<br>DATE: |

### SECONDARY PROBABILITY FACTOR ADJUSTMENTS

**Slope Movements**

| | | |
|---|---|---|
| If Yes | Insignificant | *None, decreasing or slow rates of movement over longer periods of time* |
| | Moderate | *Steady or slowly increasing rates of movement over longer periods of time* |
| | Considerable | *Steady or increasing rates of movement over shorter periods of time* |

Additional Comments:

**Past Remediation**

| | | |
|---|---|---|
| If Yes | Insignificant | *None, periodic maintenance personnel interjections, or no observable improvements post remediation* |
| | Moderate | *Moderate observable improvements following remediation of any type* |
| | Considerable | *Considerable observable improvements following remediation of any type* |

Additional Comments:

### SECONDARY CONSEQUENCE FACTOR ADJUSTMENTS

**Utility Proximity** YES NO

| | | |
|---|---|---|
| Value | None | *Proximate with no significant value* |
| | Low | *Proximate with low value and no significant negative affects if lost* |
| | Medium | *Proximate with moderate value and long term affects if lost* |
| | High | *Proximate with high value and severe consequences if lost* |

Additional Comments:

**Private Property** YES NO

| | | |
|---|---|---|
| Value | None | *Proximate with no significant value* |
| | Low | *Proximate with low importance and costs (i.e. farm field)* |
| | Medium | *Proximate with moderate consequences if affected (i.e. private yard, public park)* |
| | High | *Proximate with large consequences if affected (i.e. house, school, recreational facility)* |

Additional Comments:

**Crown Property and Right-of-Way** YES NO

| | | |
|---|---|---|
| Value | None | *Proximate with no significant value* |
| | Low | *Proximate with little to no consequences if affected (i.e. forested land) or no immediate concerns* |
| | Medium | *Proximate with moderate consequences if affected* |
| | High | *Proximate with large consequences if affected (i.e. bridges, roadway, pumping station)* |

Additional Comments:

### ADDITIONAL RECOMMENDATIONS

### AUTHENTIFICATION

Date: ______________________________

Name (print): ________________________ Signature: ______________________________

# Appendix B:

# MITRMS Desk Study Results

| Site Identification | | Consequence Factor | | | | | | | | | | | | | | | Probability Factor | | | | | | | | Risk Factor | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Standard Detour | | AADT | Functional Classification | Weight Classification | Primary CF | Nearby Utilities | | Neary Private Land | | Nearby Crown Land | | Seconday CF | Final CF | Does Primary CF + Secondary CF exceed the maximum of 10? | $P( Z < \mu i + \sigma i ) \sim N(\mu f, \sigma f)$ | Primary PF | Does Primary PF equal or exceed category 15? | Outcropping Bedrock | Slope Movements | Past Works | Secondary PF | Final PF | Risk | Response Level |
| Site Number | Crossing | Detour Length (km) | Detour Time (min) | | | | | Proximity | Value | Proximity | Value | Proximity | Value | | | | | | | | | | | | | |
| 001 | PTH10 & Little Saskatchewan River- N1, X | 5.48 | 4 | 1730 | Expressway (4 Lane) | RTAC | 8.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 1.00 | 19 | Yes | No | Unknown | Unknown | 1 | 20 | 200 | Urgent |
| 006 | PTH16 & Assiniboine River- E, X | 15.10 | 11 | 1600 | Primary Arterial | RTAC | 7.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.95 | 17 | Yes | Yes | Unknown | Unknown | 2 | 19 | 190 | Urgent |
| 011 | PTH16A & Little Saskatchewan River- N, X | 3.39 | 2 | 1590 | Primary Arterial | Class A1 | 6.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.6 | | 0.91 | 15 | Yes | No | Unknown | Unknown | 1 | 16 | 154 | Urgent |
| 002 | PR344 & Souris River, X | 6.18 | 4 | 450 | Collector "A" | Class A1 | 4.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.4 | | 0.98 | 19 | Yes | No | Unknown | Unknown | 1 | 20 | 148 | Urgent |
| 010 | PTH41 & Qu'Appelle River, L | 115.93 | 73 | 180 | Collector "A" | Class A1 | 5.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.9 | | 0.92 | 15 | Yes | No | Unknown | Unknown | 1 | 16 | 143 | Urgent |
| 014 | PTH1 & Assiniboine River- N, X | 25.12 | 16 | 1860 | Expressway (4 Lane) | RTAC | 8.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.90 | 13 | | No | Unknown | Unknown | 1 | 14 | 140 | Urgent |
| 017 | PTH2 & Souris River- E, X | 7.62 | 5 | 1580 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.89 | 13 | | No | Unknown | Unknown | 1 | 14 | 140 | Urgent |
| 008 | PTH83 & Shell River- S, X | 10.75 | 7 | 670 | Primary Arterial | Class A1 | 5.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.7 | | 0.93 | 15 | Yes | No | Unknown | Unknown | 1 | 16 | 138 | Urgent |
| 004 | PR482 & Assiniboine River- E, X | 16.64 | 12 | 290 | Collector "A" | Class B1 | 3.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.8 | | 0.97 | 17 | Yes | No | Unknown | Unknown | 1 | 18 | 122 | Priority |
| 003 | PR545 & Qu'Appelle River, L | 50.00 | 10 | 80 | Collector "B" | Class B1 | 3.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.8 | | 0.97 | 17 | Yes | No | Unknown | Unknown | 1 | 18 | 122 | Priority |
| 020 | PTH16 & Birdtail Creek- E, X | 9.15 | 7 | 1360 | Primary Arterial | RTAC | 7.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.85 | 11 | | No | Unknown | Unknown | 1 | 12 | 120 | Priority |
| 025 | PTH16 & Birdtail Creek- W, X | 9.15 | 7 | 1360 | Primary Arterial | RTAC | 7.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.80 | 11 | | No | Unknown | Unknown | 1 | 12 | 120 | Priority |
| 009 | PR340 & Souris River- S, X | 7.59 | 5 | 370 | Secondary Arterial | Class B1 | 4.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | | 0.92 | 15 | Yes | No | Unknown | Unknown | 1 | 16 | 115 | Priority |
| 033 | PTH16 & Assiniboine River- W, X | 15.10 | 11 | 1600 | Primary Arterial | RTAC | 7.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.72 | 9 | | Yes | Unknown | Unknown | 2 | 11 | 110 | Priority |
| 018 | PR478 & Assiniboine River- E, X | 30.75 | 22 | 380 | Collector "A" | Class B1 | 4.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | | 0.87 | 13 | | Yes | Unknown | Unknown | 2 | 15 | 108 | Priority |
| 023 | PTH83 & Assiniboine River- S, X | 23.10 | 16 | 750 | Primary Arterial | Class A1 | 6.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.0 | | 0.80 | 11 | | No | Unknown | Unknown | 1 | 12 | 108 | Priority |
| 012 | PR250 & Assiniboine River- N, X | 35.10 | 24 | 310 | Secondary Arterial | Class B1 | 4.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.6 | | 0.91 | 13 | | No | Unknown | Unknown | 1 | 14 | 107 | Priority |
| 007 | PR549 & Assiniboine River- W, X | 16.98 | 12 | 130 | Collector "A" | Class B1 | 3.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.6 | | 0.93 | 15 | Yes | No | Unknown | Unknown | 1 | 16 | 106 | Priority |
| 005 | PR568 & Snake Creek, X | 21.23 | 15 | 70 | Collector "C" | Class B1 | 2.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 5.7 | | 0.96 | 17 | Yes | No | Unknown | Unknown | 1 | 18 | 103 | Priority |
| 016 | PR579 & Assiniboine River- E, X | 31.83 | 23 | 50 | Collector "A" | Class B1 | 3.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.8 | | 0.89 | 13 | | Yes | Unknown | Unknown | 2 | 15 | 102 | Priority |
| 029 | PTH10 & Little Saskatchewan River- N, X | 8.10 | 6 | 3900 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.78 | 9 | | No | Unknown | Unknown | 1 | 10 | 100 | Priority |
| 034 | PTH10 & Souris River, X | 2.43 | 2 | 1560 | Primary Arterial | RTAC | 7.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.72 | 9 | | No | Unknown | Unknown | 1 | 10 | 100 | Priority |
| 015 | PR250 & Little Saskatchewan River- S, X | 8.38 | 6 | 300 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.90 | 13 | | No | Unknown | Unknown | 1 | 14 | 93 | Priority |
| 013 | PR355 & Little Saskatchewan River, L | 12.34 | 8 | 130 | Collector "A" | Class B1 | 3.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.5 | | 0.90 | 13 | | No | Unknown | Unknown | 1 | 14 | 91 | Priority |
| 019 | PR467 & Assiniboine River, L | 17.43 | 13 | 60 | Collector "B" | Class B1 | 3.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.1 | | 0.87 | 13 | | No | Unknown | Unknown | 1 | 14 | 85 | Priority |
| 035 | PR259 & Assiniboine River- E, X | 24.49 | 18 | 650 | Collector "A" | Class B1 | 4.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.4 | | 0.71 | 9 | | Yes | Unknown | Unknown | 2 | 11 | 82 | Priority |
| 043 | PTH16 & Silver Creek, X | 1.44 | 1 | 2100 | Primary Arterial | RTAC | 7.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.64 | 7 | | No | Unknown | Unknown | 1 | 8 | 80 | Priority |
| 044 | PTH10 & Little Saskatchewan River- S, X | 8.10 | 6 | 3900 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.61 | 7 | | No | Unknown | Unknown | 1 | 8 | 80 | Priority |
| 026 | PR250 & Little Saskatchewan River- North, X | 8.38 | 6 | 300 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.80 | 11 | | No | Unknown | Unknown | 1 | 12 | 80 | Priority |
| 030 | PR478 & Assiniboine River- W, X | 30.75 | 22 | 380 | Collector "A" | Class B1 | 4.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | | 0.78 | 9 | | Yes | Unknown | Unknown | 2 | 11 | 79 | Priority |
| 021 | PR254 & Assiniboine River- N, X | 15.91 | 11 | 100 | Collector "A" | Class B1 | 3.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.5 | | 0.85 | 11 | | No | Unknown | Unknown | 1 | 12 | 78 | Priority |
| 027 | PR579 & Assiniboine River- W, X | 31.83 | 23 | 50 | Collector "C" | Class B1 | 2.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 5.9 | | 0.79 | 11 | | Yes | Unknown | Unknown | 2 | 13 | 77 | Priority |
| 022 | PR478 & Silver Creek- E, X | 6.34 | 4 | 130 | Collector "A" | Class B1 | 3.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.4 | | 0.81 | 11 | | No | Unknown | Unknown | 1 | 12 | 77 | Priority |
| 024 | PR568 & Birdtail Creek, X | 21.81 | 16 | 100 | Collector "C" | Class B1 | 2.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 5.8 | | 0.80 | 11 | | No | Unknown | Unknown | 1 | 12 | 70 | Routine |
| 045 | PTH83 & Shell River- N, X | 10.75 | 7 | 670 | Primary Arterial | Class A1 | 5.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.7 | | 0.61 | 7 | | No | Unknown | Unknown | 1 | 8 | 69 | Routine |
| 028 | PR482 & Assiniboine River- W, X | 16.64 | 12 | 290 | Collector "A" | Class B1 | 3.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.8 | | 0.79 | 9 | | No | Unknown | Unknown | 1 | 10 | 68 | Routine |
| 042 | PTH45 & Birdtail Creek- W, X | 12.87 | 9 | 810 | Secondary Arterial | Class A1 | 5.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.5 | | 0.64 | 7 | | No | Unknown | Unknown | 1 | 8 | 68 | Routine |
| 041 | PR259 & Assiniboine River- W, X | 24.49 | 18 | 650 | Collector "A" | Class B1 | 4.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.4 | | 0.67 | 7 | | Yes | Unknown | Unknown | 2 | 9 | 67 | Routine |
| 046 | PR259 & Bosshill Creek, L | 4.07 | 3 | 650 | Collector "A" | RTAC | 5.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.2 | | 0.60 | 7 | | No | Unknown | Unknown | 1 | 8 | 66 | Routine |
| 031 | PR254 & Assiniboine River- S, X | 15.91 | 11 | 100 | Collector "A" | Class B1 | 3.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.5 | | 0.77 | 9 | | No | Unknown | Unknown | 1 | 10 | 65 | Routine |
| 036 | PTH42 & Snake Creek, X | 24.25 | 17 | 340 | Collector "A" | Class A1 | 4.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.6 | | 0.69 | 7 | | No | Unknown | Unknown | 1 | 8 | 61 | Routine |
| 032 | PR264 & Birdtail Creek, L | 8.17 | 6 | 180 | Collector "B" | Class B1 | 3.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.1 | | 0.76 | 9 | | No | Unknown | Unknown | 1 | 10 | 61 | Routine |
| 051 | PTH1 & Assiniboine River- S, X | 25.12 | 16 | 1860 | Expressway (4 Lane) | RTAC | 8.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.55 | 5 | | No | Unknown | Unknown | 1 | 6 | 60 | Routine |
| 040 | PR459 & Assiniboine River, L | 7.02 | 5 | 270 | Collector "A" | Class B1 | 3.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.6 | | 0.68 | 7 | | No | Unknown | Unknown | 1 | 8 | 53 | Routine |
| 053 | PR457 & Assiniboine River, L | 9.24 | 6 | 1940 | Secondary Arterial | Class B1 | 5.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.7 | | 0.51 | 5 | | No | Unknown | Unknown | 1 | 6 | 52 | Routine |
| 037 | PR262 & Little Saskatchewan River- N, L | 12.95 | 9 | 440 | Collector "B" | Class B1 | 3.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.5 | | 0.69 | 7 | | No | Unknown | Unknown | 1 | 8 | 52 | Routine |
| 038 | PR354 & Little Saskatchewan River- S, X | 19.28 | 13 | 90 | Collector "B" | Class B1 | 3.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.2 | | 0.68 | 7 | | No | Unknown | Unknown | 1 | 8 | 49 | Routine |
| 050 | PTH41 & Assiniboine River, L | 5.77 | 4 | 180 | Collector "A" | Class A1 | 4.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.0 | | 0.56 | 5 | | Yes | Unknown | Unknown | 2 | 7 | 49 | Routine |
| 039 | PR359 & Birdtail Creek- E, X | 17.83 | 13 | 30 | Collector "B" | Class B1 | 3.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.1 | | 0.68 | 7 | | No | Unknown | Unknown | 1 | 8 | 48 | Routine |
| 052 | PTH42 & Birdtail Creek- W, X | 2.09 | 2 | 670 | Collector "A" | Class A1 | 4.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.6 | | 0.52 | 5 | | No | Unknown | Unknown | 1 | 6 | 46 | Routine |
| 047 | PTH42 & Assiniboine River, L | 3.29 | 2 | 340 | Collector "A" | Class A1 | 4.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | | 0.59 | 5 | | No | Unknown | Unknown | 1 | 6 | 43 | Routine |
| 048 | PR478 & Silver Creek- W, L | 12.24 | 9 | 410 | Collector "A" | Class B1 | 3.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.9 | | 0.57 | 5 | | No | Unknown | Unknown | 1 | 6 | 41 | Routine |
| 049 | PR262 & Little Saskatchewan River- S, L | 2.62 | 2 | 820 | Collector "B" | Class B1 | 3.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.8 | | 0.56 | 5 | | No | Unknown | Unknown | 1 | 6 | 41 | Routine |
| 063 | PTH10 & Assiniboine River- N, X | 8.10 | 5 | 4290 | Expressway (2 Lane) | Class A1 | 7.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.26 | 3 | | No | Unknown | Unknown | 1 | 4 | 40 | Routine |
| 058 | PTH16A & Little Saskatchewan River- S, X | 3.39 | 2 | 1590 | Primary Arterial | Class A1 | 6.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.6 | | 0.38 | 3 | | No | Unknown | Unknown | 1 | 4 | 38 | Routine |
| 062 | PTH22 & Souris River, X | 33.38 | 22 | 2930 | Collector "A" | Class A1 | 6.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.4 | | 0.29 | 3 | | No | Unknown | Unknown | 1 | 4 | 37 | Routine |
| 059 | PTH83 & Assiniboine River- N, X | 23.10 | 16 | 750 | Primary Arterial | Class A1 | 6.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.0 | | 0.32 | 3 | | No | Unknown | Unknown | 1 | 4 | 36 | Routine |
| 057 | PTH21 & Oak River- W, X | 22.41 | 15 | 750 | Secondary Arterial | Class A1 | 5.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.6 | | 0.39 | 3 | | No | Unknown | Unknown | 1 | 4 | 34 | Routine |
| 061 | PTH83 & Gainsborogh Creek, X | 23.52 | 17 | 300 | Primary Arterial | Class A1 | 5.4 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.4 | | 0.29 | 3 | | No | Unknown | Unknown | 1 | 4 | 34 | Routine |
| 054 | PTH42 & Birdtail Creek- E, X | 2.09 | 2 | 670 | Collector "A" | Class A1 | 4.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.6 | | 0.42 | 3 | | No | Unknown | Unknown | 1 | 4 | 30 | Routine |
| 055 | PR340 & Souris River- N, L | 7.59 | 5 | 370 | Secondary Arterial | Class B1 | 4.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | | 0.41 | 3 | | No | Unknown | Unknown | 1 | 4 | 29 | Routine |
| 089 | PTH3 & Souris River, X | 31.59 | 21 | 740 | Secondary Arterial | RTAC | 6.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.3 | | 0.06 | 1 | | Yes | Unknown | Unknown | 2 | 3 | 28 | Routine |
| 098 | PTH83 & Souris River- N, L | 6.28 | 4 | 760 | Primary Arterial | Class A1 | 5.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.7 | | 0.04 | 1 | | Yes | Unknown | Unknown | 2 | 3 | 26 | Inactive |
| 056 | PR359 & Birdtail Creek- W, X | 17.83 | 13 | 30 | Collector "B" | Class B1 | 3.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.1 | | 0.39 | 3 | | No | Unknown | Unknown | 1 | 4 | 24 | Inactive |
| 060 | PR475 & Snake Creek, X | 7.66 | 6 | 110 | Collector "B" | Class B1 | 3.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.0 | | 0.31 | 3 | | No | Unknown | Unknown | 1 | 4 | 24 | Inactive |
| 115 | PTH23 & Elgin Creek, X | 6.69 | 5 | 310 | Collector "A" | Class A1 | 4.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.2 | | 0.01 | 1 | | Yes | Unknown | Unknown | 2 | 3 | 22 | Inactive |
| 072 | PR251 & Souris River- W, X | 26.23 | 20 | 170 | Collector "A" | Class B1 | 3.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.8 | | 0.14 | 1 | | Yes | Unknown | Unknown | 2 | 3 | 21 | Inactive |
| 085 | PR251 & Souris River- E, X | 26.23 | 20 | 170 | Collector "A" | Class B1 | 3.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.8 | | 0.09 | 1 | | Yes | Unknown | Unknown | 2 | 3 | 21 | Inactive |
| 065 | PTH5 & Wilson River | 8.50 | 6 | 1600 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.20 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 075 | PTH5 & Valley River, L | 10.13 | 8 | 1940 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.12 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 083 | PTH2 & Souris River- W, L | 5.38 | 4 | 1640 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.10 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 087 | PTH16 & Snake Creek- S, L | 9.09 | 7 | 1530 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.07 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 099 | PTH1 & Bosshill Creek, X | 3.11 | 2 | 4270 | Expressway (4 Lane) | RTAC | 8.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.03 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 112 | PTH16 & Snake Creek- N, X | 6.62 | 4 | 1530 | Primary Arterial | RTAC | 7.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 10.0 | Yes | 0.01 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 079 | PTH1A & Assiniboine River- N, X | 6.58 | 4 | 7805 | Secondary Arterial | RTAC | 6.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.8 | | 0.11 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 095 | PTH25 & Little Saskatchewan River, X | 3.23 | 2 | 1740 | Secondary Arterial | RTAC | 6.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.8 | | 0.04 | 1 | | No | Unknown | Unknown | 1 | 2 | 20 | Inactive |
| 092 | PTH1A & Assiniboine River- W, L | 4.89 | 4 | 15450 | Secondary Arterial | Class A1 | 6.2 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.2 | | 0.05 | 1 | | No | Unknown | Unknown | 1 | 2 | 18 | Inactive |
| 108 | PTH83 & Bosshill Creek, X | 4.94 | 4 | 990 | Primary Arterial | Class A1 | 6.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 9.0 | | 0.02 | 1 | | No | Unknown | Unknown | 1 | 2 | 18 | Inactive |
| 105 | PTH83 & Thunder Creek, X | 8.03 | 6 | 890 | Primary Arterial | Class A1 | 5.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.9 | | 0.02 | 1 | | No | Unknown | Unknown | 1 | 2 | 18 | Inactive |
| 069 | PR452 & Souris River- E, X | 6.53 | 5 | 40 | Collector "B" | Class B1 | 2.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 5.8 | | 0.15 | 1 | | Yes | Unknown | Unknown | 2 | 3 | 18 | Inactive |
| 110 | PR452 & Souris River- W, L | 6.53 | 5 | 40 | Collector "B" | Class B1 | 2.8 | Unknown | None | Unknown | None | Unknown | None | 3 | 5.8 | | 0.02 | 1 | | Yes | Unknown | Unknown | 2 | 3 | 18 | Inactive |
| 084 | PTH83 & Souris River- S, L | 6.64 | 5 | 760 | Primary Arterial | Class A1 | 5.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.7 | | 0.10 | 1 | | No | Unknown | Unknown | 1 | 2 | 17 | Inactive |
| 090 | PTH83 & Shell River- N2, L | 9.92 | 7 | 670 | Primary Arterial | Class A1 | 5.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.6 | | 0.06 | 1 | | No | Unknown | Unknown | 1 | 2 | 17 | Inactive |
| 106 | PTH83 & Shell River- N1, L | 6.62 | 5 | 670 | Primary Arterial | Class A1 | 5.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.6 | | 0.02 | 1 | | No | Unknown | Unknown | 1 | 2 | 17 | Inactive |
| 097 | PTH21 & Assiniboine River- S, X | 20.47 | 14 | 750 | Secondary Arterial | Class A1 | 5.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.5 | | 0.04 | 1 | | No | Unknown | Unknown | 1 | 2 | 17 | Inactive |
| 064 | PTH45 & Birdtail Creek- E, X | 12.87 | 9 | 810 | Secondary Arterial | Class A1 | 5.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.5 | | 0.23 | 1 | | No | Unknown | Unknown | 1 | 2 | 17 | Inactive |
| 103 | PR257 & Bosshill Creek- W, X | 6.57 | 5 | 1080 | Secondary Arterial | Class B1 | 5.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.1 | | 0.03 | 1 | | No | Unknown | Unknown | 1 | 2 | 16 | Inactive |
| 088 | PTH24 & Little Sasktachewan River, X | 17.94 | 13 | 780 | Collector "A" | Class A1 | 5.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.1 | | 0.06 | 1 | | No | Unknown | Unknown | 1 | 2 | 16 | Inactive |
| 096 | PTH83 & Antler River, L | 4.97 | 4 | 300 | Primary Arterial | Class A1 | 5.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.0 | | 0.04 | 1 | | No | Unknown | Unknown | 1 | 2 | 16 | Inactive |
| 107 | PR257 & Bosshill Creek- E, X | 3.20 | 2 | 1080 | Secondary Arterial | Class B1 | 5.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.0 | | 0.02 | 1 | | No | Unknown | Unknown | 1 | 2 | 16 | Inactive |
| 067 | PTH45 & Little Saskatchewan River, X | 7.33 | 5 | 520 | Secondary Arterial | Class A1 | 5.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 8.0 | | 0.16 | 1 | | No | Unknown | Unknown | 1 | 2 | 16 | Inactive |
| 070 | PR354 & Little Saskatchewan River- N, X | 6.05 | 4 | 520 | Secondary Arterial | Class A1 | 4.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.9 | | 0.15 | 1 | | No | Unknown | Unknown | 1 | 2 | 16 | Inactive |
| 073 | PR257 & Gopher Creek, X | 22.10 | 16 | 690 | Secondary Arterial | Class B1 | 4.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.9 | | 0.14 | 1 | | No | Unknown | Unknown | 1 | 2 | 16 | Inactive |
| 074 | PR250 & Assiniboine River- S, X | 35.10 | 24 | 310 | Secondary Arterial | Class B1 | 4.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.6 | | 0.13 | 1 | | No | Unknown | Unknown | 1 | 2 | 15 | Inactive |
| 080 | PTH24 & Oak River, X | 8.22 | 6 | 570 | Collector "A" | Class A1 | 4.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.6 | | 0.10 | 1 | | No | Unknown | Unknown | 1 | 2 | 15 | Inactive |
| 081 | PTH41 & Snake Creek, L | 6.52 | 5 | 370 | Collector "A" | Class A1 | 4.3 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.3 | | 0.10 | 1 | | No | Unknown | Unknown | 1 | 2 | 15 | Inactive |
| 071 | PR354 & Little Saskatchewan River- N, L | 7.53 | 6 | 665 | Collector "A" | Class B1 | 4.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.1 | | 0.15 | 1 | | No | Unknown | Unknown | 1 | 2 | 14 | Inactive |
| 111 | PTH41 & Niso Creek | 8.20 | 6 | 170 | Collector "A" | Class A1 | 4.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 7.1 | | 0.02 | 1 | | No | Unknown | Unknown | 1 | 2 | 14 | Inactive |
| 078 | PR250 & Little Saskatchewan River- Minnedosa, L | 2.54 | 2 | 270 | Secondary Arterial | Class B1 | 3.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.9 | | 0.11 | 1 | | No | Unknown | Unknown | 1 | 2 | 14 | Inactive |
| 086 | PR455 & Assiniboine River, L | 17.26 | 12 | 200 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.07 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 068 | PR259 & Oak River- 4, X | 9.81 | 7 | 290 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.16 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 093 | PR259 & Oak River- 1, L | 9.81 | 7 | 290 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.05 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 102 | PR259 & Oak River- 2, L | 9.81 | 7 | 290 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.03 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 109 | PR259 & Oak River- 5, L | 9.81 | 7 | 290 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.02 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 113 | PR259 & Oak River- 3, L | 9.81 | 7 | 290 | Collector "A" | Class B1 | 3.7 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.7 | | 0.01 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 094 | PR549 & Assiniboine River- E, X | 16.98 | 12 | 130 | Collector "A" | Class B1 | 3.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.6 | | 0.05 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 100 | PR274 & Wilson River, X | 6.56 | 5 | 590 | Collector "B" | Class B1 | 3.6 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.6 | | 0.03 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 066 | PR251 & Antler River- E, X | 11.51 | 9 | 170 | Collector "A" | Class B1 | 3.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.5 | | 0.18 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 091 | PR251 & Antler River- W, X | 11.51 | 9 | 170 | Collector "A" | Class B1 | 3.5 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.5 | | 0.06 | 1 | | No | Unknown | Unknown | 1 | 2 | 13 | Inactive |
| 101 | PR354 & Oak River- N, X | 14.78 | 11 | 130 | Collector "B" | Class B1 | 3.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.1 | | 0.03 | 1 | | No | Unknown | Unknown | 1 | 2 | 12 | Inactive |
| 104 | PR347 & Souris River | 37.91 | 27 | 90 | Collector "C" | Class B1 | 3.1 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.1 | | 0.03 | 1 | | No | Unknown | Unknown | 1 | 2 | 12 | Inactive |
| 077 | PR256 & Niso Creek, X | 6.57 | 5 | 150 | Collector "B" | Class B1 | 3.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.0 | | 0.11 | 1 | | No | Unknown | Unknown | 1 | 2 | 12 | Inactive |
| 114 | PR542 & Gopher Creek, X | 13.12 | 10 | 50 | Collector "B" | Class B1 | 3.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.0 | | 0.01 | 1 | | No | Unknown | Unknown | 1 | 2 | 12 | Inactive |
| 082 | PR354 & Oak River- S, L | 6.64 | 5 | 130 | Collector "B" | Class B1 | 3.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 6.0 | | 0.10 | 1 | | No | Unknown | Unknown | 1 | 2 | 12 | Inactive |
| 116 | PR359 & Snake Creek, X | 6.37 | 5 | 50 | Collector "B" | Class B1 | 2.9 | Unknown | None | Unknown | None | Unknown | None | 3 | 5.9 | | 0.01 | 1 | | No | Unknown | Unknown | 1 | 2 | 12 | Inactive |
| 076 | PR256 & Gopher Creek, X | 6.94 | 5 | 240 | Collector "A" | Class B1 (Seasonal) | 2.0 | Unknown | None | Unknown | None | Unknown | None | 3 | 5.0 | | 0.12 | 1 | | No | Unknown | Unknown | 1 | 2 | 10 | Inactive |

# Appendix C:

# MITRMS Post-Inspection Results

| Site Identification | | Consequence Factor | | | | | | | | | | | | | | | Probability Factor | | | | | | | | Risk Factor | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Standard Detour | | AADT | Functional Classification | Weight Classification | Primary CF | Nearby Utilities | | Neary Private Land | | Nearby Crown Land | | Seconday CF | Final CF | Does Primary CF + Secondary CF exceed the maximum of 10? | $P(Z < \mu i + \sigma i) \sim N(\mu f, \sigma f)$ | Primary PF | Does Primary PF equal or exceed category 15? | Outcropping Bedrock | Slope Movements | Past Works | Secondary PF | Final PF | Risk | Response Level |
| Site Number | Crossing | Detour Length (km) | Detour Time (min) | | | | | Proximity | Value | Proximity | Value | Proximity | Value | | | | | | | | | | | | | |
| 011 | PTH16A & Little Saskatchewan River- N, X | 3.39 | 2 | 1590 | Primary Arterial | Class A1 | 6.6 | No | None | Yes | Low | Yes | Low | 2 | 8.6 | | 0.997 | 19 | Yes | No | Insignificant | Insignificant | 0 | 19 | 164 | Urgent |
| 008 | PTH83 & Shell River- S, X | 10.75 | 7 | 670 | Primary Arterial | Class A1 | 5.7 | No | None | Yes | Low | Yes | Medium | 3 | 8.7 | | 0.946 | 15 | Yes | No | Considerable | Moderate | 2 | 17 | 147 | Urgent |
| 012 | PR250 & Assiniboine River- N, X | 35.10 | 24 | 310 | Secondary Arterial | Class B1 | 4.6 | Yes | Medium | Yes | Low | Yes | Low | 3 | 7.6 | | 0.944 | 15 | Yes | No | Insignificant | Insignificant | 0 | 15 | 114 | Priority |
| 031 | PR254 & Assiniboine River- S, X | 15.91 | 11 | 100 | Collector "A" | Class B1 | 3.5 | Yes | Low | Yes | Low | Yes | Low | 2 | 5.5 | | 0.962 | 17 | Yes | No | Considerable | Insignificant | 4 | 20 | 111 | Priority |
| 041 | PR259 & Assiniboine River- W, X | 24.49 | 18 | 650 | Collector "A" | Class B1 | 4.4 | No | None | Yes | None | Yes | Low | 1 | 5.4 | | 0.874 | 13 | | Yes | Moderate | Insignificant | 3 | 16 | 87 | Priority |
| 050 | PTH41 & Assiniboine River, L | 5.77 | 4 | 180 | Collector "A" | Class A1 | 4.0 | Yes | High | Yes | Medium | Yes | Low | 6 | 10.0 | Yes | 0.570 | 5 | | Yes | Moderate | Insignificant | 3 | 8 | 80 | Priority |
| 035 | PR259 & Assiniboine River- E, X | 24.49 | 18 | 650 | Collector "A" | Class B1 | 4.4 | No | None | No | None | Yes | Low | 1 | 5.4 | | 0.810 | 11 | | Yes | Insignificant | Insignificant | 1 | 12 | 65 | Routine |
| 018 | PR478 & Assiniboine River- E, X | 30.75 | 22 | 380 | Collector "A" | Class B1 | 4.2 | No | None | Yes | Low | Yes | Low | 2 | 6.2 | | 0.772 | 9 | | Yes | Insignificant | Moderate | -1 | 8 | 50 | Routine |