Development of a Riverbank Asset Management System for the City of Winnipeg

by

Alena James

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Abstract

The City of Winnipeg, located at the confluence of the Red and Assiniboine Rivers, has over 240 km of natural riverbank property. The increased frequency and magnitude of flooding along the Red and Assiniboine Rivers over the past decade appears to have influenced the number of slope failures along riverbank property, resulting in the loss of both public green space and privately owned land. The loss of private and public property adjacent to the river has led to the loss of valuable real estate and public parkland amenities. To ensure that riverbank property is preserved for future generations, the City of Winnipeg wants to increase the stability of certain reaches of publicly owned riverbank property along the Red and Assiniboine Rivers that are prone to slope movements.

Extensive research has been conducted on slope stability problems in the Winnipeg area, but a transparent prioritization procedure for the remediation of riverbank stability problems has not existed. Therefore, a Riverbank Asset Management System (RAMS) was developed for publicly owned riverbank property to prioritize riverbank slope stability problems along the Red and Assiniboine Rivers. The RAMS provides the City of Winnipeg with a rational approach for determining risk levels for specific reaches of the Red and Assiniboine Rivers. The calculated risk levels allow the City to develop recommended response levels for slope stability remediation projects in a fiscally responsible manner with minimal personal and political influences. This system permits the City to facilitate timely and periodic reviews of priority sites as riverbank conditions and input parameters change.

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Chapter 2 – Literature Review

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Chapter 1 Introduction

1.1 Significance of Landslide Risk to the City of Winnipeg

The City of Winnipeg, located at the confluence of the Red and Assiniboine Rivers, has over 240 km of natural riverbank property. The increased frequency and magnitude of flooding along the Red and Assiniboine Rivers over the past decade appears to have influenced the number of slope failures along riverbank property, resulting in the loss of both public green space and privately owned land. The loss of private and public property adjacent to the river has lead to the loss of valuable real estate and public parkland amenities. The City of Winnipeg wants to increase the stability of certain reaches of publicly owned riverbank property along the Red and Assiniboine Rivers that are prone to slope movement, to ensure that the areas are preserved for future generations.

In 1998 a riverbank stabilization program was developed for the City of Winnipeg (City) by the Riverbank Management Engineer and a detailed riverbank stability characterization study for City-owned riverbank property was undertaken. This study was completed by the Waterways Section, Planning, Property and Development Department of the City in 2000. It was compiled to characterize, assess and monitor the stability of the 108 km of City owned riverbank property. The 2000 study indicated that it would cost approximately $80 million to provide stabilization works for all publicly owned riverbank property identified in the report.

The report outlined ”first phase” priority sites, that is the twelve sites that required the most urgent stabilization works. The total cost to provide stabilization works for these twelve sites was around $11.5 million (2000 dollars). At that time, it was also estimated, that approximately $1.0 million worth of publicly owned riverbank property was lost per annum.

The City of Winnipeg’s Riverbank Management Committee provided funding for riverbank monitoring to be conducted in 2002 and 2004. A Riverbank Stability Characterization Study was prepared in 2004 as a result of the additional funds provided for monitoring. It included a comprehensive engineering review, assessment and update of the stability conditions along the riverbanks in the City of Winnipeg (Kingerski 2004). The 2004 report compared the changes in site conditions between 2000 and 2004. The “first phase” priority site list was modified to reflect the changes in stability conditions at the priority sites, based on the changes in site conditions between 2000 and 2004. In 2004, the total cost for stabilization works was estimated to be $12,915,000 (2000 dollars) for the priority site list.

The Riverbank Stability Characterization Studies prepared by the City included detailed site observations and photographs that were collected between 1998 and 2004 for inclusion in the comprehensive engineering review, assessment and update of the stability conditions along the publicly owned riverbanks. This information was used to determine the “first phase” priority sites and the total cost for stabilization works for the priority sites. The main limitation of the ranking system used by the City to generate the “first phase” priority site list was that the ranking system did not explicitly take into account the probability and consequence of slope failure. As such, the ranking of the priority sites was primarily dependent on visual site observations and engineering judgment and experience and did not incorporate weighting factors for the probability and consequence attributes that were determined to affect the stability of public riverbank property.

As identified above, it would cost approximately $80 million to provide stabilization works for the publicly owned sites identified in the 2000 Riverbank Stability Characterization study and $12,195,000 for the “first phase” priority sites identified in 2004. Public riverbank property is considered a valuable natural resource by local Winnipeg residents, so the Riverbank Management Engineer is provided with an annual budget of $1.1 million for the remediation of sites that are experiencing significant slope movement. Despite the annual budget provided for the remediation of public riverbank property, supplementary funds would be needed from the annual City budget to provide the $80 million worth of required stabilization works. On average, the Riverbank Management Engineer can remediate one potential “first phase” priority site with his department’s annual budget. A Riverbank Management Committee composed of elected councillors whose wards are located along the Red and Assiniboine Rivers, reviews and endorses the Riverbank Management Engineer’s proposed “first phase” list of priority sites and the annual remediation plan. The elected officials on the Riverbank Management Committee are responsible for ensuring that public tax dollars are allocated in a transparent and accountable manner for the management and remediation of public riverbank property. Previously, the ranking system used by the City to generate the “first phase” priority site list was based on engineering judgment and experience. Therefore, a 1) documented 2) repeatable and 3) quantifiable system was not in place to determine a potential “first phase” list of priority sites. The City will have a transparent and consistent approach for allocating public tax dollars for the remediation of public riverbank property by developing a ranking system that meets the criteria. This ranking system will provide the most efficient allocation of public funds.

Because of the limitations of the ranking system, in May 2007 the Riverbank Management Committee commissioned the Civil Engineering Department at the University of Manitoba to develop a Riverbank Asset Management System for the City of Winnipeg. Information collected during site characterizations, engineering judgement and asset management principles were utilized to develop the Riverbank Asset Management System. Development of a more comprehensive visualization tool, such as the Riverbank Asset Management System, enables the City of Winnipeg's Riverbank Management Engineer to better prioritize riverbank stabilization projects. This system also allows the City to create a rational approach for determining risk levels for certain reaches of the Red and Assiniboine Rivers. These risk levels allow the City to develop appropriate response levels so slope stability remediation projects can be conducted in a fiscally responsible manner with minimal political influence. The system also permits the City of to facilitate timely and periodic reviews of priority sites as riverbank conditions and input parameters change.

1.2 Past Research

Slope stability research on riverbank property in Winnipeg commenced in the early 1960's. Calculations done by Baracos (1960) using a total stress analysis showed that the average mobilized undrained shear strength of the Winnipeg clay was much less, approximately 1/2 to 1/3, of the recorded laboratory value for undrained shear strength. He documented that the slip surface for riverbank failures was likely a combination of horizontal and rotational movement, and not solely rotational movement as previously believed.

Mishtak (1964) conducted a field investigation along the Red River in the City of Winnipeg to determine: the inclination of naturally stable banks, their degree of stability, slopes at which natural banks failed and slopes at which banks had failed and again became stable riverbank slopes. The results of the investigation of natural riverbank slopes were utilized to design stable side slopes for the construction of the Red River Floodway. Mishtak (1964) concluded that 135 of the 141 riverbanks that he studied were considered unstable and a minimum slope of 6H:1V needed to be achieved before a riverbank on an outside bend was considered stable. He observed that almost every bank on the outside bend of a curve in the river had been previously affected by an old slide, was actively moving or had required slope stabilizing measures (Baracos and Graham 1981).

Freeman and Sutherland (1973) reported on the discrepancies between the measured shear strength of the Winnipeg clays in the laboratory and the performance of Winnipeg clays in the field, based on the research conducted by Sutherland (1966) and Baracos (1960). Some slopes that were calculated to have a factor of safety greater than unity (1), based on the laboratory shear strength data, failed in their natural environment. The discrepancy between the calculated factor of safety and performance, led to further investigations of the proposed mechanism of slope failure for the Winnipeg clays. It was initially assumed that the failure surfaces in Winnipeg clays were circular, but further investigations determined that the failure surfaces might be non-circular, almost horizontal, between the base of the Winnipeg clay and the underlying dense till stratum.

Based on these results, Freeman and Sutherland (1973) measured the shear strength and residual strength parameters of four (4) samples of Winnipeg clays (Freeman and Sutherland 1973). They used the results of their laboratory investigation to analyze the stability of the Winnipeg clays, for circular and non- circular failure surfaces, including an analysis of the anisotropic behavior of the Winnipeg clays. The laboratory results indicated that the shear strength along the direction of the layers was lower than in other directions (Freeman and Sutherland 1973). In addition, Freeman and Sutherland (1973) concluded that using residual strength parameters for the entire failure surface underestimates the factor of safety. Slope stability analyses showed that the lower strength parameters reported across the layers and the non- circular failure surface should be used in the analysis so the minimum factor of safety is achieved. The results of stability analyses conducted by Freeman (1973) indicated that the tendency for the failure surface to be non- circular increases as the slope angle decreases, and is greater when the depth to the hard till stratum is shallow, a weak soil layer is present at the bottom of the slope, and there is a lower shear strength along the layers (Freeman and Sutherland 1973).

Baracos (1978) between 1969 and 1972 monitored the groundwater levels and slope movements at two sites along outside bends. He concluded the largest slope movements occurred when river levels were low and porewater pressures elevated. This situation typically occurred twice a year, before the spring freshet and after fall drawdown. Very little slope movement was recorded when groundwater elevations were low and river levels were high, such as the case during the spring freshet or summer flooding due to large precipitation events. The decreased slope movement is due to the increased hydrostatic forces supporting the bank during high water levels (Baracos and

Lew 2003). Besides river levels, porewater pressure elevations are affected by precipitation, snow melt, service main leaks, runoff from roads and roofs, pipes discharging onto a slope and groundwater pumping from the limestone aquifer. Tutkaluk (2000) demonstrated that for the worst combination of river and groundwater elevations, low river level and high groundwater elevations, attributed to decreased industrial and residential groundwater pumping needs, the factor of safety decrease for a riverbank slope in the City of Winnipeg was around 13% to 17%. This decrease in factor of safety results in significant slope movement in the late fall, in some cases.

Baracos (1960), Mishtak (1964), Freeman and Sutherland (1973) showed that neither undrained shear strength nor effective stress strength alone can accurately predict slope stability problems in Winnipeg clays. Baracos (1980) showed that the peak strength envelope of Winnipeg clay can be represented by three straight lines (Baracos and Graham 1981). At low effective stresses, the clay strength is affected by the clay's highly fissured and nuggety structure, resulting in a low cohesion value and high friction angle. At low effective stresses, the Winnipeg clays behave like a cohesionless and softened material. Therefore, this fact must be carefully considered at the submerged toe of a riverbank face (Baracos and Graham 1981). At intermediate effective stresses, the clay strength is overconsolidated while at high effective stress, the clay strength is normally consolidated and not affected by preconsolidation pressures. To properly design for the stabilization of riverbank property along the Red and Assiniboine Rivers, the residual shear strength parameters for Winnipeg clay are needed. Designers should use, $c_r' = 0$ kPa and Φ_r' in the range 8 - 13º, noting that careful consideration for the worst combination of river and groundwater elevations, should be utilized (Baracos and Graham 1981). A clear understanding of the groundwater conditions is essential.

Baracos and Lew (2003) prepared a report on the causes of riverbank slides and erosional processes on the Red River in the vicinity of Winnipeg, Manitoba for the Federal Government Department of Justice. They concluded that erosion of riverbank property and accretion of alluvial sediment during flood periods are main factors of riverbank slides. Other factors contributing to sliding are:

- Deepening of flood channel and removal of bank toe by high water levels during flooding, compounded by turbulence caused by trees on the slope.
- Ice action against the bank slopes and trees on the bank.
- Loading of the upper sliding mass with overbank deposits from flooding, illegally placed fill, structures, dumped snow and elevated groundwater levels from flooding, rain, snow and lawn watering.
- Progressive weakening of the clay material in the vicinity of new and reactivated slide surfaces.

A transparent prioritization procedure for remediation of riverbank stability problems on publicly owned land did not exist, despite the extensive research conducted on riverbank slope stability problems. Therefore, an asset management system was developed to prioritize riverbank slope stability problems in the Winnipeg area. The research performed by the author has allowed a transparent asset management system to be developed for the City of Winnipeg along the Red and Assiniboine Rivers. The asset management system is an appropriate tool to manage, analyze and prioritize the landslide risk based on risk factors and response levels. The system was developed so it could be easily accessible to both the engineering community and public policy makers.

1.3 Hypothesis

This thesis document will examine the following hypothesis:

Hypothesis: If a ranking system that prioritizes riverbank slope stability problems is based on probability and consequence factors then the ranking order will be inconsistent with a ranking system that is based solely on engineering judgment and experience.

Landslide 'risk' incorporates both probability and consequence factors. Probability and consequence, in the context of this research project, are the probability and consequence of slope movements occurring on public riverbank property. The attributes that were selected to represent probability and consequence factors were assigned weighting factors based on their perceived significance. An attribute determined to have a significant influence on riverbank stability was assigned a higher weighting factor than one determined to have less impact. The probability attributes utilized in this exercise were selected by analyzing the geology and geomorphology of the Winnipeg area, while the consequence attributes were solely limited to the effects on riverbank property and public perception.

The objectives of this research are:

a) Conduct detailed site characterizations for the thirty-six (36) priority sites identified by the City of Winnipeg in the 2000 Riverbank Stability Characterization Study on the Red and Assiniboine Rivers.

b) Develop an asset management system using geospatial visualization tools to assess the risk of landslides on publicly owned riverbank property on the Red and Assiniboine Rivers in the City of Winnipeg.

c) Prepare a “first phase” priority site list for publicly owned riverbank property on the Red and Assiniboine Rivers using the developed asset management system.

1.4 Organization of Thesis

Past research on slope stability research conducted in the Winnipeg area is discussed in Chapter 1. Chapter 2 contains a literature review of risk assessment principles and models, while Chapter 3 provides background information on the study area. Chapters 4 and 5 describe the field component of the research project. Chapter 6 discusses the development and calibration of the Riverbank Asset Management System, while Chapter 7 outlines the Google Earth Application of the Riverbank Asset Management System. Chapter 8 provides conclusions and recommendations.

Six appendices are provided at the end of the thesis on an accompanying CD. The first appendix contains the riverbank observation checklist and the checklist legend. The second appendix contains a description of the terminology used in the riverbank observation checklist and the Riverbank Asset Management System. Photographs are included with each definition, visually demonstrating the characteristics of the landslide probability and landslide consequence attributes and sub-attributes. This allows easy identification of the parameters, when future staff conducts site characterizations. The third appendix contains photographs collected during the site characterizations, conducted on foot and by boat. The fourth appendix includes a user manual and video for the RAMS. The fifth appendix shows the results of the air photo analysis overlain on

Google Earth©. The sixth appendix contains the site characterization assessments for the thirty-six sites investigated during the site characterization program.

Chapter 2 Literature Review

2.1 Introduction

Chapter 2 summarizes the background information and theory required to understand the research program described in the subsequent chapters. Chapter 2 commences with an overview of the application of risk management principles in geotechnical engineering. The Chapter then continues with theory and background information on risk assessment principles and models. This is followed by an overview of the Geotechnical Classification Matrix proposed by Vaunat (1994). Finally, the need for a Riverbank Asset Management System in the City of Winnipeg is presented.

2.2 Application of Risk Management Principles In Geotechnical Engineering

There are many applications of risk management principles in geotechnical engineering. The Riverbank Asset Management System (RAMS) developed for the City of Winnipeg is a combination of various risk management systems. These systems apply to geotechnical projects such as: those in transportation corridors, roadways and railways, pipelines and dams, for example. An overview of these risk management systems is outlined below.

Risk management systems are generally developed using the engineering judgment and experience of professional engineers or geoscientists. Embedded in risk management systems, are probability and consequence factors that are used to determine the 'relative risk' level of a specific site. Probability and consequence factors are assigned weighting factors based on their perceived significance. A probability or consequence factor with a higher perceived significance is assigned a higher weighting factor than a probability or consequence factor with a lower significance.

This chapter, Chapter 2, below demonstrates how probability and consequence factors have been incorporated into the risk management systems used in geotechnical practice today. Risk management is a relatively new component of geotechnical engineering; thus, a standard procedure for developing risk management systems, including the determination of weighting factors for probability and consequence factors, has not been formally established. Therefore, Chapter 2 presents a discussion on the development and utilization of existing risk management systems. Because the principles of the existing risk management systems were utilized to develop the RAMS for the City of Winnipeg, the reader will be able to compare the development of the RAMS and existing risk management systems. The development of the RAMS is discussed in Chapter 6.

To manage and prioritize landslide and geohazard risks better the provinces of Alberta, Saskatchewan and Manitoba have developed landslide and geohazard risk management systems for their highway corridors. The geohazard risk management systems for Saskatchewan and Manitoba were created by expanding the geohazard risk template developed by the Province of Alberta. The landslide and geohazard risk for natural and engineered slopes is calculated by multiplying 'probability' and 'consequence' factors, to obtain a risk level. 'Probability' is defined as the likelihood of a landslide occurring, while 'consequence' is defined as the consequence on transportation corridors and driver safety if a landslide occurred, in the context of this system. Response levels are based on the risk levels. Response levels for the different risk levels were determined by geotechnical engineers. Developing a transparent landslide and geohazard risk management system for provincial highways permits site staff to conduct a comprehensive site assessment. Utilizing the information collected during the site assessment, professional staff can determine the relative importance of existing and newly-formed landslide and geohazard risks. A transparent and defensible risk management system, allows an appropriate allocation of resources, both personnel and monetary, based on calculated risk levels.

A joint research project conducted by the Northern Ireland Roads Service Consultancy and Queen's University Belfast, proposed a risk assessment system for the Northern Ireland Roads Network. The project defined 'probability factor' as the likelihood of slope movement occurring. It is calculated by adding and multiplying probability attributes. Meanwhile, 'consequence factor' is calculated by adding public safety, traffic disruption and property damage attributes (Van Helden 2007). The probability of failure is assigned a qualitative description of poor, average or good, based on the calculated probability factor. A consequence hazard is also assigned a qualitative description of low, moderate or high, depending on the calculated consequence factor. Using these descriptions, a risk matrix was developed based on the descriptive probability and consequence factors. Risk and response levels for a site can easily be determined by using the semi-qualitative risk matrix.

The Muhlbauer Model has been adopted as the framework for risk assessment systems used by railway and pipeline companies (Muhlbauer 1996). Examples of the Muhlbauer Model adopted as the framework for risk management system used by railway and pipeline companies are given in later sentences. The Muhlbauer Model was initially developed as a semi-quantitative risk assessment used by pipeline companies to produce risk values for large segments of pipeline in a wide variety of terrain. The Muhlbauer Model allows an easy comparison of risk values to be conducted along various segments of pipeline. It assigns weighting factors to identified hazards or causal factors by collecting appropriate attribute information through a combination of desk top studies and site characterizations.

Geohazard risk assessment systems for pipeline companies have been developed based on the Muhlbauer Model. The geohazard risk assessment system considers the probability of a geohazard affecting pipeline integrity and the potential that a pipeline may become exposed if affected by a geohazard. This approach has been used successfully by, for example, Esford et al. (2004), Leir et al. (2003), Leir (2004), Porter et al., (2004) and Porter and Marcuz (2006) in the implementation of risk assessment systems for large pipeline companies.

To minimize the risk associated with ground hazards, CN developed a River Attack Track Risk Assessment System (RATRAS), a quantitative risk management system that assesses river erosion and 'river erosion earth slides'. RATRAS was designed utilizing the Muhlbauer Model. Weighting factors are assigned to attributes that are considered to affect the probability of the hazard occurring and the probability that the hazard may cause service disruption or track failure. These weighted attributes are then multiplied to determine the probability of a hazard occurring. System vulnerability, as represented by the distance between the track and the river, are also assigned a weighting factor. To determine the probability of failure, system vulnerability and probability of a hazard occurring are multiplied. RATRAS was calibrated using engineering judgment and failure statistics. The development of RATRAS allows funds to be allocated in an appropriate manner and ensures that proper monitoring and preventative measures are conducted.

In 2007, the Canadian Dam Association outlined Dam Classification Guidelines for a potential dam failure. Figure 2.1 (at the end of this chapter) shows that the Dam Classification Guidelines are based on two factors: population at risk and incremental losses. The incremental loss incorporates the following factors: loss of life, environmental and cultural values, and infrastructure and economics. The dam class, or qualitative risk value, ranges from low to extreme. Typically, the most serious risk factor is solely utilized to determine dam class, as it represents the most serious risk to the public, in engineering practice.

2.3 Risk Assessment Principles

Risk is evaluated by analyzing the likelihood and consequence of a hazard. The Canadian Standards Association (CSA) has outlined three methods for analyzing risk. They are: risk matrix, risk index, and quantitative risk analysis. Table 2.1 (following the figures for Chapter 2) is summarized from Porter et al. (2006).

Porter et al. (2004), Esford et al. (2004), Porter and Savigny (2002) demonstrate how risk matrix and risk index methodologies have been incorporated into risk management programs. These risk management programs are easy to develop and implement; the results are repeatable. The main drawback of these risk estimation methods is that the absolute value of the hazard is arbitrary. It is therefore difficult to make comparisons with other hazards (Porter et al. 2006).

Quantitative risk assessment (QRA) involves estimating the likelihood, consequence, and risk of slope movements occurring. It is typically recommended that QRA be expanded to incorporate risk management. Figure 2.2 shows the progression from hazard identification to risk assessment and finally to risk management. Risk management involves the identification of remedial options to reduce risk (Porter et al. 2007). To develop a risk management system, it is necessary to conduct a cost-benefit analysis to determine what remedial option provides the greatest risk reduction to the public per dollar spent. After the implementation of the preferred remedial option, continual monitoring and re-evaluation needs to be performed to ensure the success of the risk management system. In addition, risk management requires documented, repeatable and quantifiable methodologies (Leir 2004). It is recommended, that risk management systems be (1) clearly documented so due diligence can be performed, (2) repeatable so personal influences will not be introduced, and (3) quantifiable so an objective system is in place.

Risk is assessed quantitatively by using simple mathematical equations. Risk is typically defined by the product of probability (likelihood) and consequence of slope movement occurring as shown in Equation (2.1) below:

$$R = P \times C \qquad \text{Equation (2.1)}$$

Where,

R= Risk value

P= Probability Factor

C= Consequence Factor

Risk is a measure of the probability and severity of an adverse affect to health, property or environment (Leir 2004).

Probability can be defined in a more descriptive manner (Leir 2004) in Equation (2.2) below:

P = P(H) x P(S:H) x P(T:H) Equation (2.2)

Where,

(1) P = Probability of a hazard occurring. Probability of a hazard occurring can be analyzed both quantitatively and qualitatively. Common methods of analysis include: analysis of historical incident data, modeling, and the judgment and experience of professional staff.

(2) P(H) = Hazard, Annual probability of a certain hazard, either geotechnical or hydrotechnical, occurring. This information can be expressed either as an absolute probability (usually ranked between 0 and 1, with 0 being certain not to occur while 1 is certain to occur) or quantitatively, as a frequency. If statistics are not available, observations from past hazards can be incorporated into the risk assessment.

(3) P(S:H) = Spatial Impact, Probability that hazard will impact an element. The spatial impact factor depends on the location of the element relative to the hazard.

(4) P(T:H) = Temporal Impact, Probability of an element being present when the impact occurs. Temporal impact is therefore dependent on how long an element is exposed to the pathway of a hazard.

As shown in Equation (2.3) (Leir 2004), consequence can also be defined as the product of vulnerability and elements.

$$C = V \times E \qquad \text{Equation (2.3)}$$

Where,

(1) C = Consequence Factor. This is defined as the potential outcome arising from a hazard occurring (Leir 2004). Consequence may be expressed either quantitatively or qualitatively. Some typical consequences include: (1) loss of life or injury, (2) loss or damage to property, (3) loss or damage to infrastructure, (4) damage to the environment and (5) litigation costs.

(2) V = Vulnerability, Degree or portion of total loss suffered when hazard occurs (Leir 2004). Vulnerability with respect to property loss is measured in dollar value, while vulnerability with respect to people is measured in loss of life.

(3) E = Element, The feature that may be potentially affected. This can be expressed as population, buildings, engineered structures, utilities, infrastructure, environment and loss of reputation.

By incorporating the variables outlined above, Equation (2.4) below can also be used to calculate risk.

$$R = P(H) \times P(S{:}H) \times P(T{:}H) \times V \times E \qquad \text{Equation (2.4)}$$

In the context of this research project, Equation (2.4) can be modified because some of the variables in Equation (2.4) are constant, and therefore equal to unity (1.0). First, the location of public riverbank property is static, so the probability of temporal and spatial impact is certain. Thus, P(T:H) and P(S:H) are equal to unity. Also, slope movement on public riverbank property negatively impacts the riverbank property, and generally renders it unusable. Therefore, the vulnerability component of the risk equation is also equal to unity. Equation (2.4) can be reduced to Equation (2.5) as shown below, for this research project.

$$R=P(H) \times E \qquad \text{Equation (2.5)}$$

It is essential that continual re-assessment of the hazard, vulnerability and risk takes place, because input parameters and site conditions are dynamic, and thus change over time. Professionals or trained field personnel are required to estimate the hazard, P(H), and note causal factors. Figure 2.3 shows some of the causal factors that should be identified when conducting site characterizations. As the number of causal factors observed in the field increases, so does the probability of landslide occurrence. The cumulative influence of causal factors contributes to progressive deterioration of the hazard to the point of failure (Leir 2004).

2.4 Risk Assessment Models for Landslide Hazards

Many landslide hazard risk assessment models have been developed world-wide. Every landslide hazard model has a different application. Some models were developed to protect vulnerable elements in an urban area, (i.e. people, buildings, environment, public perception), while others were developed to protect the integrity of existing infrastructure in remote regions. Despite the application of the landslide hazards models, they were all created with a similar goal, to provide a framework for anticipating problems, evaluating them, mitigating them in a cost effective manner and accepting the residual risk level and uncertainty (Ho et al. 2000). The following section discusses the criteria and theory utilized to formulate the various landslide hazard risk assessment models.

Abella and Westen (2008) conducted a qualitative landslide susceptibility assessment by applying weighting factors to various attributes that were determined to affect the probability of landslide occurrence (Figure 2.4). If an attribute was determined to have a significant impact on landslide susceptibility, it was assigned a higher weighting factor than if it was determined to have minimal impact. A single value for the landslide hazard was calculated from the various weighting factors assigned to each of the attributes and sub-attributes. A hazard map was created from the single landslide hazard value. It was observed that increased landslide density existed in areas that had higher landslide hazard values. The landslide hazard risk map was used in combination with existing information on buildings and infrastructure, to prepare a qualitative risk map (Abella and Westen 2008).

The Hong Kong Special Administration Region (Ho et al. 2000), published risk guidelines for landslide hazards based on individual and societal risk. The guidelines are based on the frequency (F) of N or more fatalities in a year compared to the number (N) of fatalities. It was concluded that for a new development, the maximum allowable risk to an individual is 10^{-5} while for an existing development the maximum allowable risk to an individual is 10^{-4} per annum respectively. A three-tiered system and a two-tiered system were incorporated into the societal risk guidelines for landslide and boulder fall hazards in Hong Kong (Figure 2.5). The three regions in the three-tiered system are: broadly acceptable, as low as reasonably possible (ALARP) and unacceptable. The two-tiered system is comprised of two regions: unacceptable and ALARP. The two-tiered system was developed with the belief that all possible measures are conducted to reduce the societal risk. If a landslide hazard is found to lie within the ALARP region, further debate about the cost-benefit analysis of risk mitigation procedures is required.

In response to a rapid debris flow that destroyed two homes and resulted in one fatality, The District of North Vancouver decided that a risk management system for potential urban debris flows was necessary (Porter et al. 2007). A risk management system was developed to quantify and manage the loss of life arising from further debris flows and encourage open communication between stakeholders. The risk management system was based on the quantitative risk tolerance criteria developed in Hong Kong as described above. Traditional approaches to managing landslide risks, such as factor of safety calculations, were not considered acceptable forms of risk management, because information such as the probability and consequence of future debris flows was not considered. The risk value, as shown in Section 2.3 above, was calculated by determining the hazard probability, spatial and temporal probability and vulnerability. The risk was estimated for individuals who occupy the property on and above the slopes, in addition to the societal risk for each rapid debris flow. The societal risk was determined by analyzing the number of individuals in homes located beneath each potential fill slope failure. Consequently, approximately twenty percent (20%) of the homes in the hypothetical landslide initiation and run out zones were considered to have an unacceptable societal risk according to the Hong Kong Guidelines. Fifty percent (50%) of the homes in the hypothetical landslide initiation and run out zones were found to lie within the ALARP zone for societal risk. A cost-benefit analysis was then conducted to determine what options were feasible for risk control. Based on this analysis, a remedial action plan was developed and implemented to reduce the societal risks (Porter et al. 2007).

The Canadian Standards Association (CSA), 1991, proposed the framework for risk management shown in Figure 2.6. The Canadian Standard Association (CAN/CSA-Q-850) indicated that risk management should incorporate risk assessment and risk control. Once a risk control measure has been implemented, CSA Guidelines require that an assessment be conducted to determine if the risk control, or the procedure utilized to reduce risk, is successful. Risk estimation and evaluation are continually re-evaluated because of the established guidelines. Risk management systems for pipelines and urban geohazards have been developed using these CSA Guidelines as outlined in Porter et al. (2007) and Ferris et al. (2007).

Morgenstern (2000) indicated that upper and lower bounds between risks and benefits needs to be achieved. The upper limit should never be exceeded. The lower level represents the minimum level, usually the level where it is not practical to reduce the risk further. Between these two levels, lies the ALARP level. Morgenstern (2000) believes that most geotechnical practice falls within the ALARP region and risk associated with geotechnical engineering is best managed by diligent application of the observational method. Figure 2.7 demonstrates the societal risk criteria utilized by BC Hydro, ANCOLD, Netherlands, and UK Health and Safety (Salmon and Hartford 1995). Meanwhile, Figure 2.8 (Bunce 1994) shows the risk of death/damage from a rock fall compared to other activities. Figure 2.9 outlines the f-N Chart for Risk Estimates utilized by the United States Department of the Interior, Bureau of Reclamation (United States Department of the Interior, Bureau of Reclamation 2003).

A sub-committee was formed by the Australian Geomechanics Society (AGS) in 2000 to develop landslide risk management procedures. The policies that were in place prior to the formation of this sub-committee did not quantify the landslide risk, or consider the potential loss of life. The objectives of the sub-committee formed by the AGS were to: establish consistent terminology, outline a framework for landslide risk management, provide guidance on how to conduct risk analysis, and outline acceptable risks for loss of life. Figure 2.10, shows the landslide risk management chart developed by the AGS. The flow chart clearly outlines risk treatment, treatment options, treatment plan, and a monitoring program. The AGS determined that the tolerable risk for the average person for an existing slope is10^{-5}. For a new slope it is 10^{-6}, while for a person most at risk, the suggested tolerable guideline is 10^{-4} for existing slopes and 10^{-5} per annum for new slopes.

The Association of Professional Engineers and Geoscientists of British Columbia released Guidelines for Legislated Assessments for Proposed Residential Development in British Columbia in 2006. As part of these guidelines, a qualified professional engineer or geoscientist must conduct a landslide analysis, and either quantitatively or qualitatively must assess the landslide hazard. This landslide hazard assessment will enable the professional engineer or geoscientist to determine the potential consequences for the elements at risk. Change in site conditions, either natural or anthropogenic, must also be considered in the landslide risk assessment. The landslide risk assessment can either be subjective (engineering judgment) or objective (statistics/mathematical), or a combination of both.

Lacasse et al. (2006) developed a Generalized Integrated Risk Assessment Framework (GIRAF) as a quantitative method for assessing landslide risk. The GIRAF has four steps: data collection, hazard assessment, vulnerability assessment, and risk assessment. The vulnerability assessment includes analysis of the elements at risk, such as people, buildings, infrastructure, environment, material, and reputation. The GIRAF model proposes that vulnerability be a 3-D concept, which incorporates, the magnitude of the landslide (M), scale of the landslide (S) and elements at risk (E). The three components are statistically correlated. The GIRAF system is beneficial because it considers the system as whole at any time, not only during extreme events. However, the uncertainty in the parameters needs to be understood to ensure the assessment is reliable. In addition, expert and engineering judgment is required to ensure the success of the system.

Uncertainty is frequently encountered in engineering design and construction. Morgenstern (1995) identified three sources of uncertainty: parameter uncertainty, model uncertainty and human uncertainty. Parameter uncertainty is due to uncertainty with input variables and the potential of spatial variation of the input variables (e.g. shear strength). Model uncertainty arises from gaps in scientific theory that require predictions to be made on the basis of causal inference (Morgenstern 1995). Finally, human uncertainty simply results from the involvement of humans in design and construction of engineered structures. Morgenstern (1995) stated that risk management is necessary in geotechnical engineering but it will only be successful if sources of uncertainty are understood.

As outlined by Leir et al. (2004) and Aleotti and Chowdbury (1999), there are a number of hazard algorithm frameworks used for landslide susceptibility mapping. These include: index overlay, fuzzy logic, conditional probability models, and multivariate regression techniques. The approaches differ in the way weighting factors are assigned. Weighting factors can either be subjective or objective. The weighting factors can also be applied differently across layers in additive, multiplative or probabilistic operators (Leir et al. 2004). A detailed explanation of the hazard algorithm frameworks and their different approaches is provided by Carrara et al. (1995). Some algorithms, such as conditional probability and retrogression techniques use a probabilistic framework and require a landslide inventory (Leir et al. 2004). However, an updated and accurate landslide inventory is rarely available for most regions in Canada.

2.5 Geotechnical Classification Matrix

In Figure 2.11, (Vaunat 1992), shows a two dimensional, semi-quantitative landslide hazard and risk analysis procedure. It involves an inventory of items, such as triggering or pre-disposition factors, forecast of dangers, assessment of hazards, and evaluation of the risks. For this system to be successful, careful and accurate assessments of the hazards and risks are required. Because the system proposed by Vaunat (1992), Varnes (1978) and Hutchinson (1988) was two-dimensional (2-D), it only incorporated material type and slope movement. Because (1) the classification of slope movement did not incorporate the characterization of the mechanisms from a mechanical viewpoint, (2) the classification was primarily geomorphological, and (3) rarely were geotechnical concepts considered, Vaunat (1994) developed the three dimensional geotechnical characterization of slope movement shown in Figure 2.12. This characterization of slope movement is called the Geotechnical Classification Matrix (GCM). It provides a link between the local material behavior and slope response (Vaunat 2002). By expanding the system from 2-D to 3-D, the four stages of slope movement were introduced.

According to the geotechnical characterization of slope movement (Vaunat 1994), slope responses are classified according to: movement phase, material type, and movement type. Movement phase is divided into: pre-failure (overconsolidated and intact material), failure, post failure and slope reactivation (movement along pre-existing shear planes). As shown in Figure 2.12, Material type is divided into 10 main categories, while movement type is classified according to the geomorphological classification proposed by Cruden and Varnes (1996). Each of these categories is incorporated into a 3-D matrix, as outlined on Figure 2.12. The 3-D matrix is associated with controlling laws and material parameters and a set of triggering factors, pre-disposition factors, revealing factors and consequence factors.

Vaunat et al. (2002) further defined pre-disposition factors, revealing factors, and triggering factors. The pre-disposition factors are initial or boundary conditions that influence the values of the local variables (Vaunat et al. 2002). Stress level is influenced by bank height, bank slope, and water depth, for example. Triggering factors are widely accepted to change over time and therefore, so do the empirical values of the control variables (Vaunat 2002). Strain rate, for example, is related to the rate of erosion at the toe of a slope. Revealing factors show evidence of existing local mechanisms. Slope creep is typically observed because fissures form at the top of the slope, for example. Figure 2.13 shows a characterization sheet outlining how the GCM is employed for a reactivated slide in stiff clay.

Lefebvre (1981) demonstrated that strain rates increase when the stress conditions of a slope are near failure. Pre-failure movement occurs due to increases in shear stress or porewater pressures (Vaunat 1994). An increase in either parameter, results in a decrease in effective stress. Thus, the rate of movement is linked to pre-disposition factors such as slope geometry and water levels. Triggering factors that may result in a decrease in effective stress are: loading at the top of the slope, conditions resulting in porewater pressure increases and toe erosion. Vaunat (1994) indicated that two slopes that have different histories will not react identically to the same triggering factors. Pre-failure movements are generally encountered in an entire soil mass and not confined to a shear zone.

Slope failures result from accelerating pre-failure slope movements. The Mohr Coulomb Criterion, expressed as shear strength parameters, dictates the failure stage of movement. Therefore, friction angle and an empirical cohesion determined from back analysis calculations are the primary pre-disposition factors (Vaunat 1994).

At failure, limiting equilibrium exists between gravity and the shear strength of the soil (Vaunat 1994). During this time, potential energy becomes available. Some of the potential energy will become internal energy that re-arranges and breaks bonds between particles and remolds the soil. The difference between the available potential energy and the dissipated kinetic energy, results in additional slope movement. This slope movement is called post-failure slope movement. The available potential energy depends on slope geometry and the physical properties of the soil mass. In such cases, the liquid limit, remolded shear strength and slope height are vital pre-disposition factors.

Reactivated slope movements are governed by localized creep along one or several sliding surfaces (Vaunat 1994). Regardless of the magnitude of pre-failure slope movements, slope reactivation is not dependent on slope movement history. Reactivated slope movements have pre-existing shear surfaces where residual strength is the controlling pre-disposition factor. Reactivated slope movements depend on applied shear stresses and topography. Therefore, there is a correlation between water levels and rates of movement. In addition, a triggering factor that causes a reduction in effective stress or increases in shear stresses, such as toe erosion, loading at the top of the slope, and increased porewater pressures in the vicinity of the reactivated slip surface, is found during slope reactivation.

Typically, inside and outside bends of rivers are subject to toe erosion, but the amount of toe erosion depends on the location of the site and the magnitude and duration of river flow. A river system is dynamic, and therefore the magnitude and duration of flow is not constant during the year. Like toe erosion, porewater pressures increase in the vicinity of the shear zone and depend on many factors that vary over time. Some factors that affect the porewater pressure in the vicinity of the shear zone are: magnitude and duration of flow, precipitation, antecedent moisture conditions, and whether the river is regulated or unregulated.

2.6 Development of the Riverbank Asset Management System Using Existing Risk Management Systems and Risk Assessment Models

The framework for the Riverbank Asset Management System will be developed using existing risk management systems and risk assessment models, such as those described in Sections 2.3 and 2.5 above. The majority of the risk management systems and risk assessment models used in geotechnical practice were developed by professional engineers and geoscientists in government or the consulting industry. The development of these systems has been described in detail in various conference proceedings. However, very little literature outlining the development of a risk management system or risk assessment model is available in peer reviewed engineering journals.

Section 2.3 illustrates that a risk factor value is traditionally calculated by multiplying the probability and consequence factor (Equation 2.3). 'Probability' is typically defined as the likelihood of a slope movement occurring while 'consequence' is generally defined as the consequence of slope movement to people, property, environment, transportation corridors, infrastructure and utilities. Similar to existing risk management systems used in geotechnical practice, the risk factor value in the RAMS will be calculated by multiplying the probability and consequence factor.

Statistics on the occurrence of slope movements along the Red and Assiniboine Rivers in the City of Winnipeg do not exist. Therefore, the risk assessment model illustrated by Abella and Westen (2008) and risk management systems developed for large pipeline companies based on the Muhlbauer Model will be used as the framework for the RAMS. Probability and consequence attributes and sub-attributes that represent the probability and consequence factors will be identified. The probability and consequence attributes and sub-attributes used in the RAMS will be formulated through a combination of desk-top studies and site characterizations. Similar to risk assessment model developed by Abella and Westen (2008), the probability and consequence attributes and sub-attributes in the RAMS will be assigned a weighting factor based on their perceived significance. Probability attributes or sub-attributes that have a greater influence on riverbank stability will be assigned a higher weighting factor than other attributes or sub-attributes that had a minimal influence or riverbank stability. The landslide consequence attributes will represent specific features affected by slope movements on public riverbank property. Abella and Westen (2008) demonstrated that a probability factor can be calculated by adding probability attributes and sub-attributes. The probability factor in the RAMS will also be calculated by adding the probability attributes and sub-attributes. The same principle will be used to calculate the consequence factor.

The provinces of Alberta, Saskatchewan and Manitoba developed landslide and geohazard risk management systems for their highway corridors to manage and prioritize landslide and geohazard risks. Risk levels and response levels were developed by geotechnical engineers to assess the landslide and geohazard risk for natural and engineered slopes from the calculated risk factor. A technical steering committee composed of geotechnical engineers will also be responsible for developing the risk and response levels used in the RAMS.

A transparent and repeatable RAMS will be developed for the City of Winnipeg by following the same principles used in the development of the risk management systems and risk assessment models discussed in Sections 2.3 and 2.5. The information collected and analyzed in the RAMS, will allow the appropriate personnel to determine the relative importance of existing and newly formed slope stability problems along public riverbank property on the Red and Assiniboine Rivers in the City of Winnipeg.

2.7 Justification for the Development of a Riverbank Asset Management System for the City of Winnipeg

The Riverbank Stability Characterization Studies conducted by the City of Winnipeg for the Red and Assiniboine Rivers between 1998 and 2004 included a comprehensive engineering review, assessment and update of the stability conditions along publicly owned riverbanks. The information was used to determine “first-phase” priority sites and the total cost of stabilization works for the priority sites.

However, the present ranking system used by the City to update and generate the “first phase” priority site list is based on site observations, and does not incorporate the probability and consequence factors that are known to affect slope movement on public property. The ranking system used by the City is subjective and the methodology for ranking the priority site list is not clearly documented, repeatable or quantifiable. At the recommendation of the Riverbank Management Engineer, it was decided by the Riverbank Management Committee, that the existing ranking system needs to be modified and updated to reflect the current risk management standards adopted in engineering practice today.

Development of a more comprehensive visualization tool, such as a Riverbank Asset Management System (RAMS) will enable the City of Winnipeg’s Riverbank Management Engineer to better prioritize riverbank stabilization projects based on risk and response levels for certain reaches of the Red and Assiniboine Rivers. The system will allow the City to create a transparent and rational approach for determining risk levels.

Creation of a RAMS will ensure that the ranking system utilized by the City is documented so due diligence is performed, repeatable so personal and political influences are minimized, and quantifiable so an objective system is in place. Since risk management involves the identification of options to reduce risk, an established RAMS will allow continual monitoring and re-evaluation of public riverbank property as input parameters and site conditions change. In addition, the development of the RAMS, allows funds to be efficiently allocated, to ensure that proper monitoring and preventative measures are conducted. The system will also be easily accessible to both the engineering community and public policy makers, to ensure that all stakeholders will be actively involved in the risk management process.

Dam class	Population at risk [note 1]	Incremental losses		
		Loss of life [note 2]	Environmental and cultural values	Infrastructure and economics
Low	None	0	Minimal short-term loss No long-term loss	Low economic losses; area contains limited infrastructure or services
Significant	Temporary only	Unspecified	No significant loss or deterioration of fish or wildlife habitat Loss of marginal habitat only Restoration or compensation in kind highly possible	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes
High	Permanent	10 or fewer	Significant loss or deterioration of *important* fish or wildlife habitat Restoration or compensation in kind highly possible	High economic losses affecting infrastructure, public transportation, and commercial facilities
Very high	Permanent	100 or fewer	Significant loss or deterioration of *critical* fish or wildlife habitat Restoration or compensation in kind possible but impractical	Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facility, storage facilities for dangerous substances)
Extreme	Permanent	More than 100	Major loss of *critical* fish or wildlife habitat Restoration or compensation in kind impossible	Extreme losses affecting critical infrastructure or services (e.g., hospital, major industrial complex, major storage facilities for dangerous substances)

Note 1. Definitions for population at risk:

None—There is no identifiable population at risk, so there is no possibility of loss of life other than through unforeseeable misadventure.

Temporary—People are only temporarily in the dam-breach inundation zone (e.g., seasonal cottage use, passing through on transportation routes, participating in recreational activities).

Permanent—The population at risk is ordinarily located in the dam-breach inundation zone (e.g., as permanent residents); three consequence classes (high, very high, extreme) are proposed to allow for more detailed estimates of potential loss of life (to assist in decision-making if the appropriate analysis is carried out).

Note 2. Implications for loss of life:

Unspecified—The appropriate level of safety required at a dam where people are temporarily at risk depends on the number of people, the exposure time, the nature of their activity, and other conditions. A higher class could be appropriate, depending on the requirements. However, the design flood requirement, for example, might not be higher if the temporary population is not likely to be present during the flood season.

Figure 2.1 Canadian Dam Association 2007 Dam Classification Guidelines. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

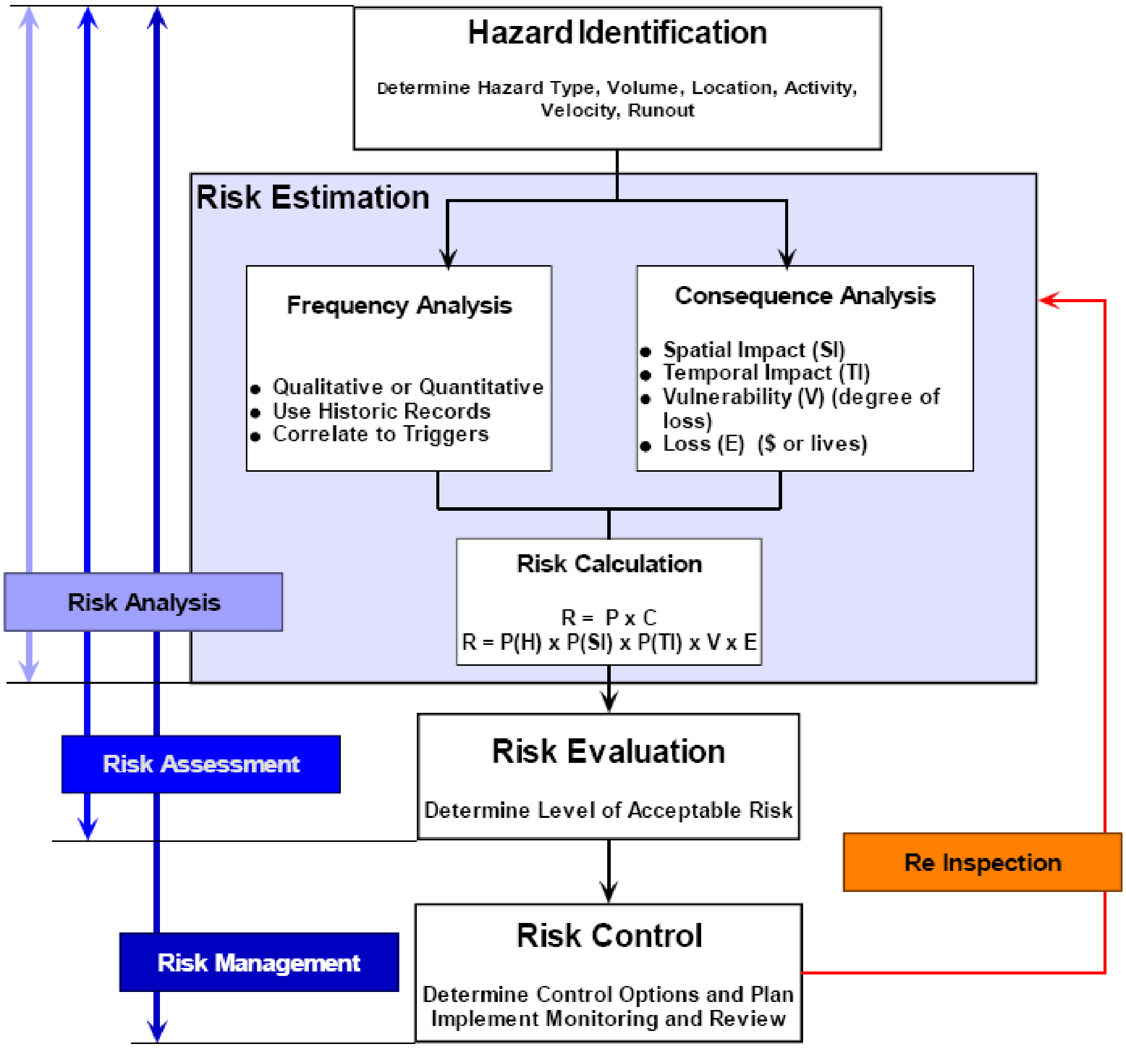


Figure 2.2: Natural Hazard and Risk Management Framework (after Leir et al. 2004). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

Class	Increasing influence on the landslide occurrence/stability →				
Human	-	vegetation removal by forest harvesting	changes to surface water flow	excavation of slope toe	water leakage/diversion
Physical	changes in average rainfall	revegetated landslide scars	groundwater springs present	fresh debris at base of slope	intense rainfall > 10 mm/hr
Morphological	steep slope angles > 20 degrees	Anti-scarp slopes	noticeable joint dilation	fresh tension/ground cracks	-
Geological	closely spaced discontinuities	weathering bedrock	-	-	-

Figure 2.3: A Few Causative Factors that Contribute to the Occurrence of Landslides (after Leir et al. 2004). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

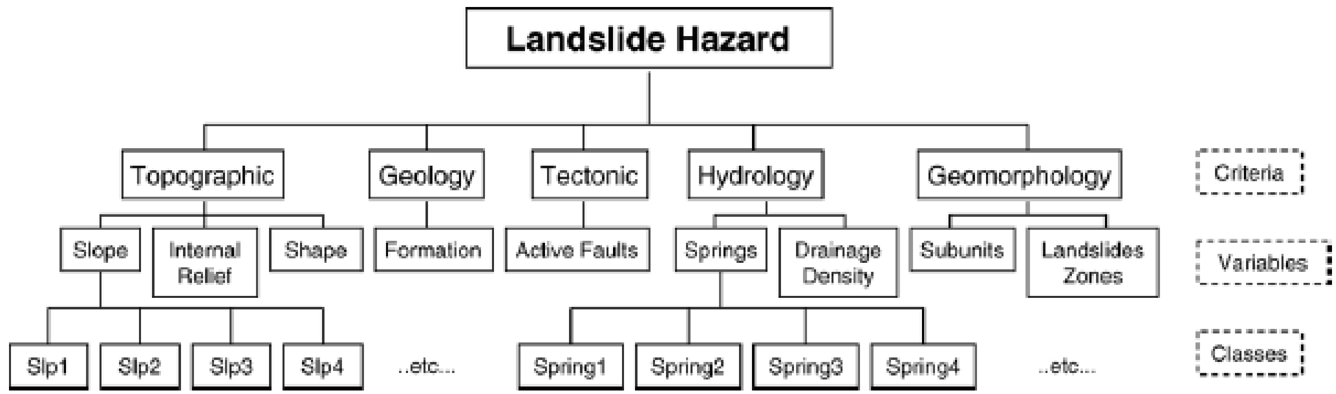


Figure 2.4: Components of Heuristic Landslide Hazard Model (after Abella and Westen 2008). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

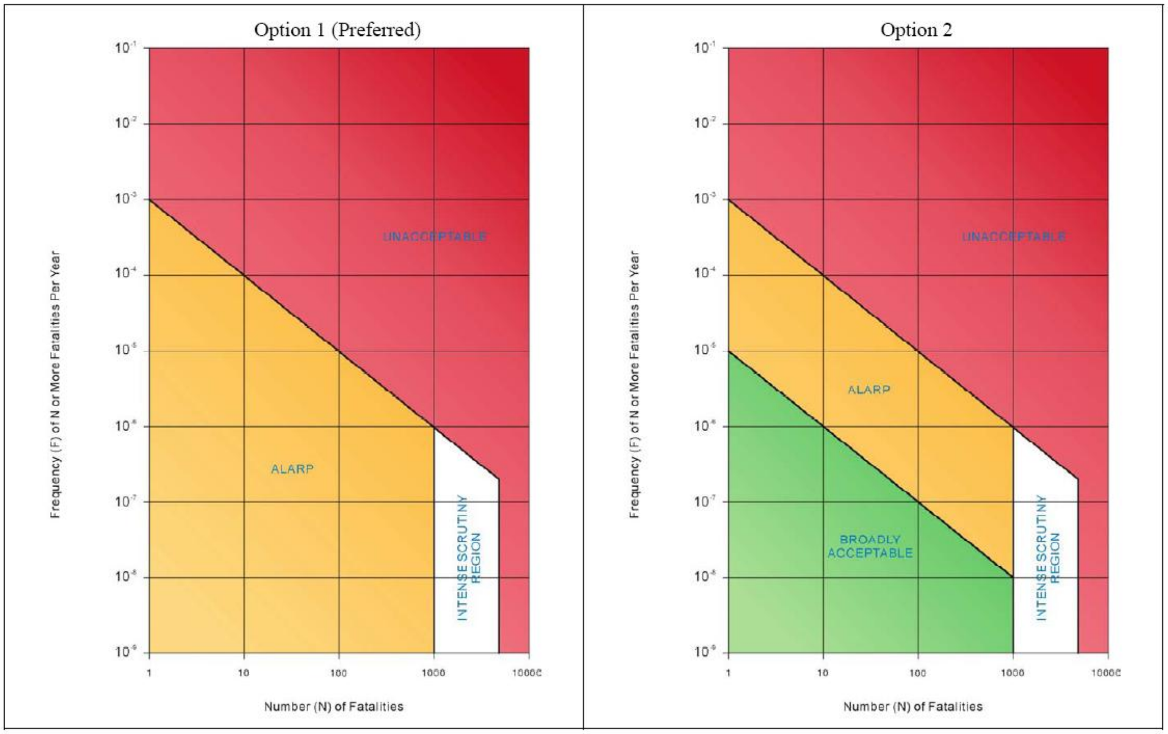


Figure 2.5: Interim Societal Risk Criteria for Landslides and Boulder Falls from Natural Terrain in Hong Kong (after http://hkss.cedd.gov.hk/hkss/chi/studies/qra/Fig2.pdf). Permission for re-use granted. Permission Granted by the Head of the Geotechnical Engineering Office, Director of the Civil Engineering and Development and the Government of the Hong Kong Special Administrative Region. See List of Copyrighted Material for which Permission was Obtained.

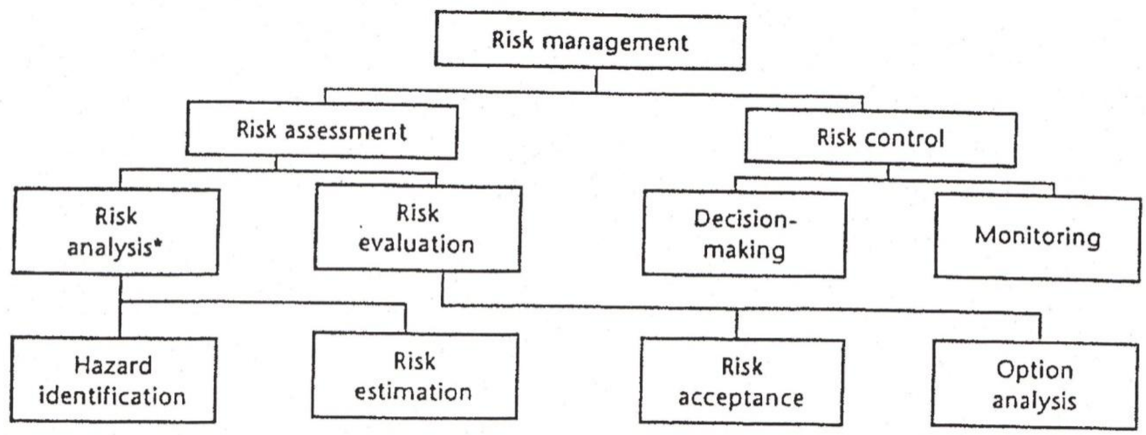


Figure 2.6: Framework for Risk Management (after Canadian Standards Association 1991). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained. While use of this material has been authorized, CSA shall not be responsible for the manner in which the information is presented, nor for any interpretations thereof.

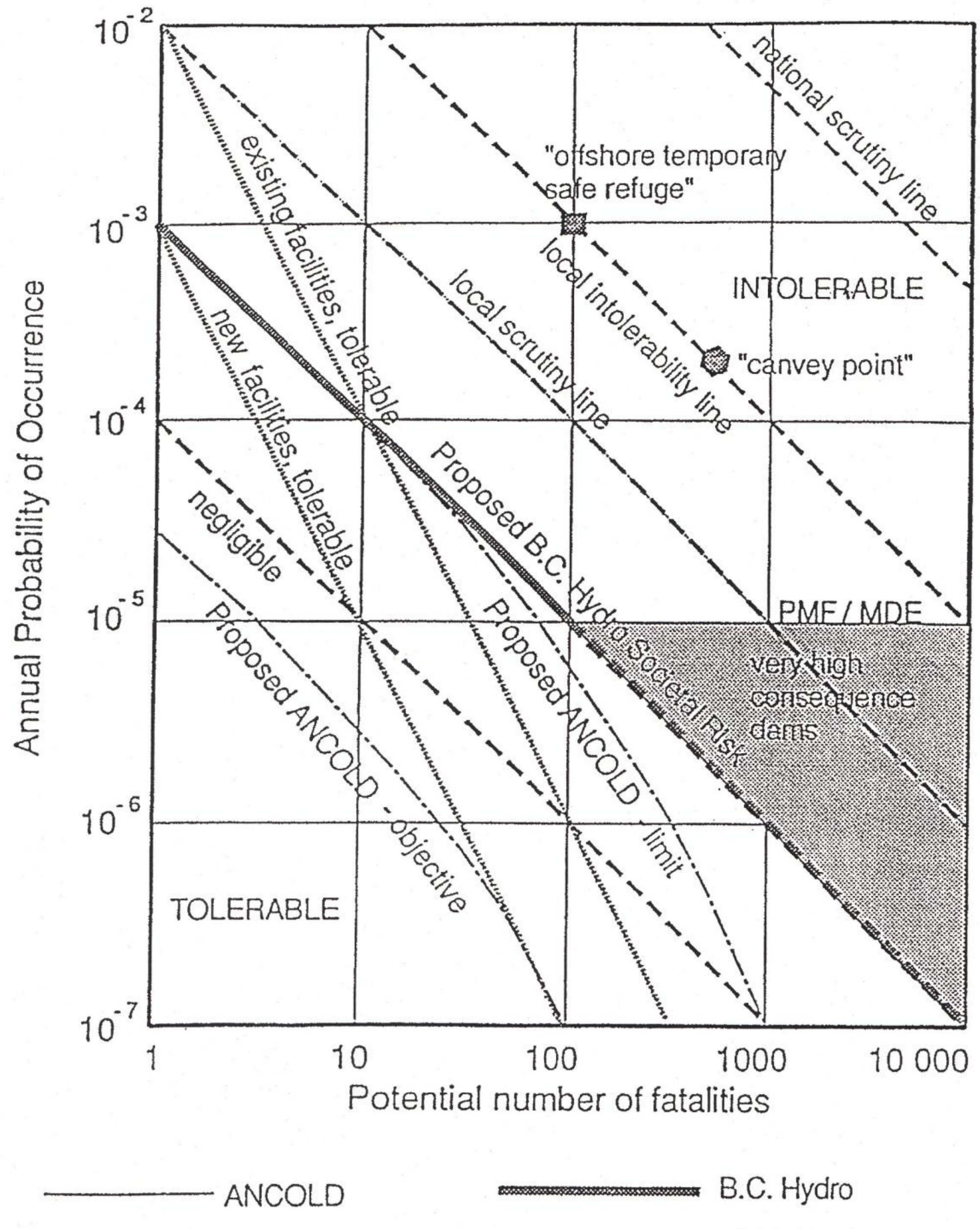


Figure 2.7: Proposed Societal Risk Criteria (after Salmon and Hartford 1995). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

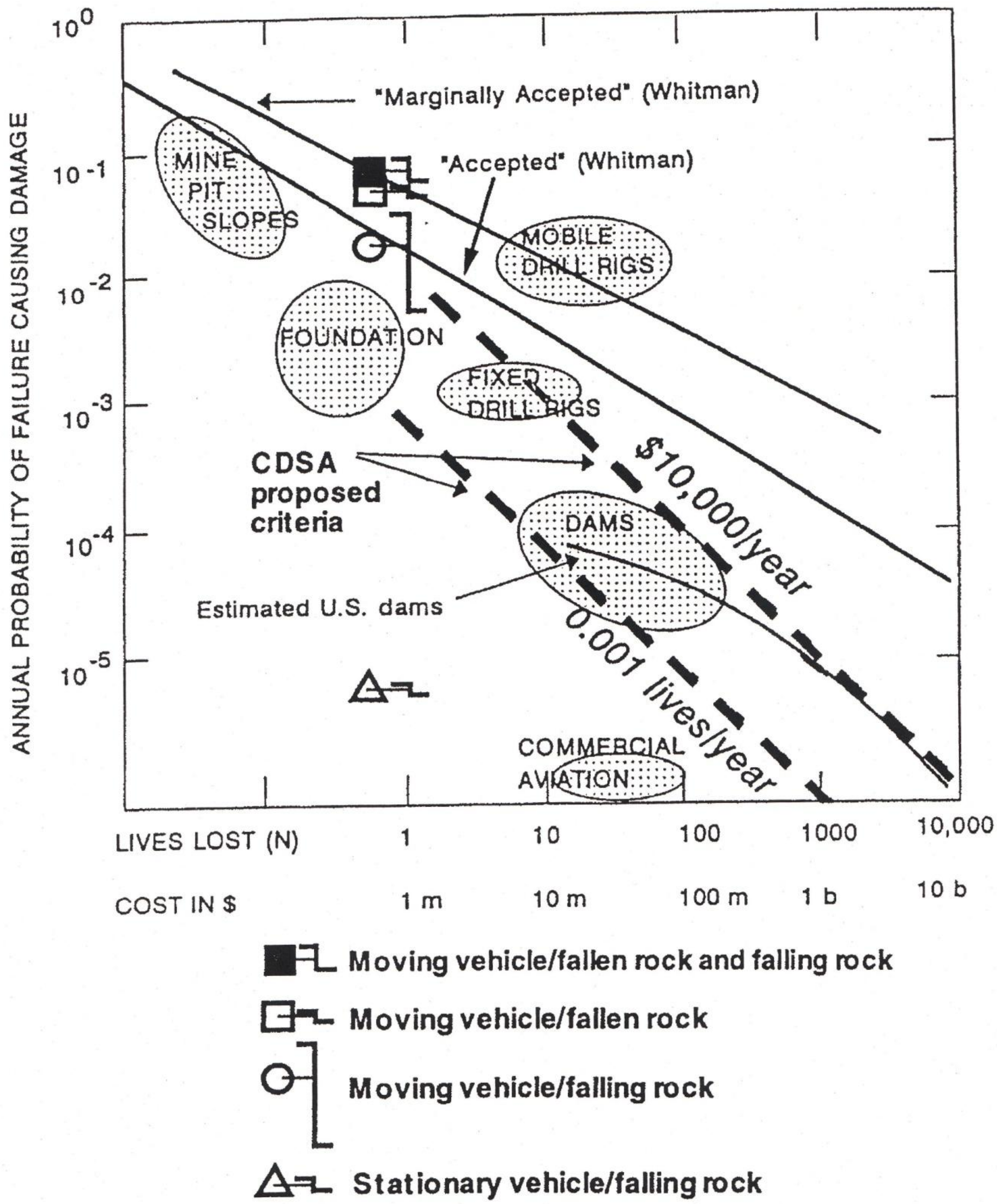


Figure 2.8: Risk of Death or Damage for a Rockfall Hazard Compared with Other Projects (after Bunce 1994). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

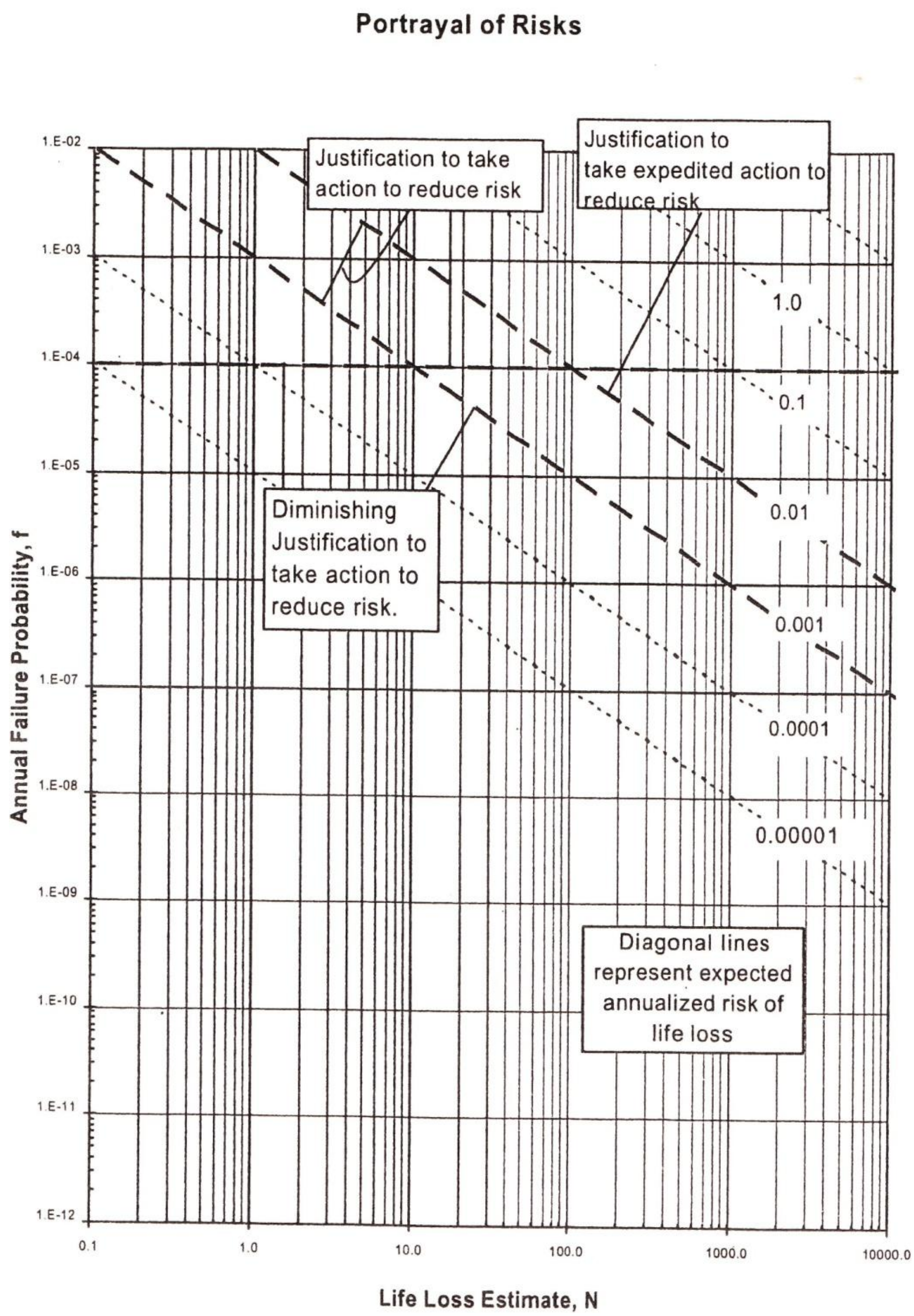


Figure 2.9: The f-N Chart for Displaying Probability of Failure, Life Loss and Risk Estimates. Figure borrowed from the US Department of Interior, Guidelines for Achieving Public Protection in Dam Safety Decision Making. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

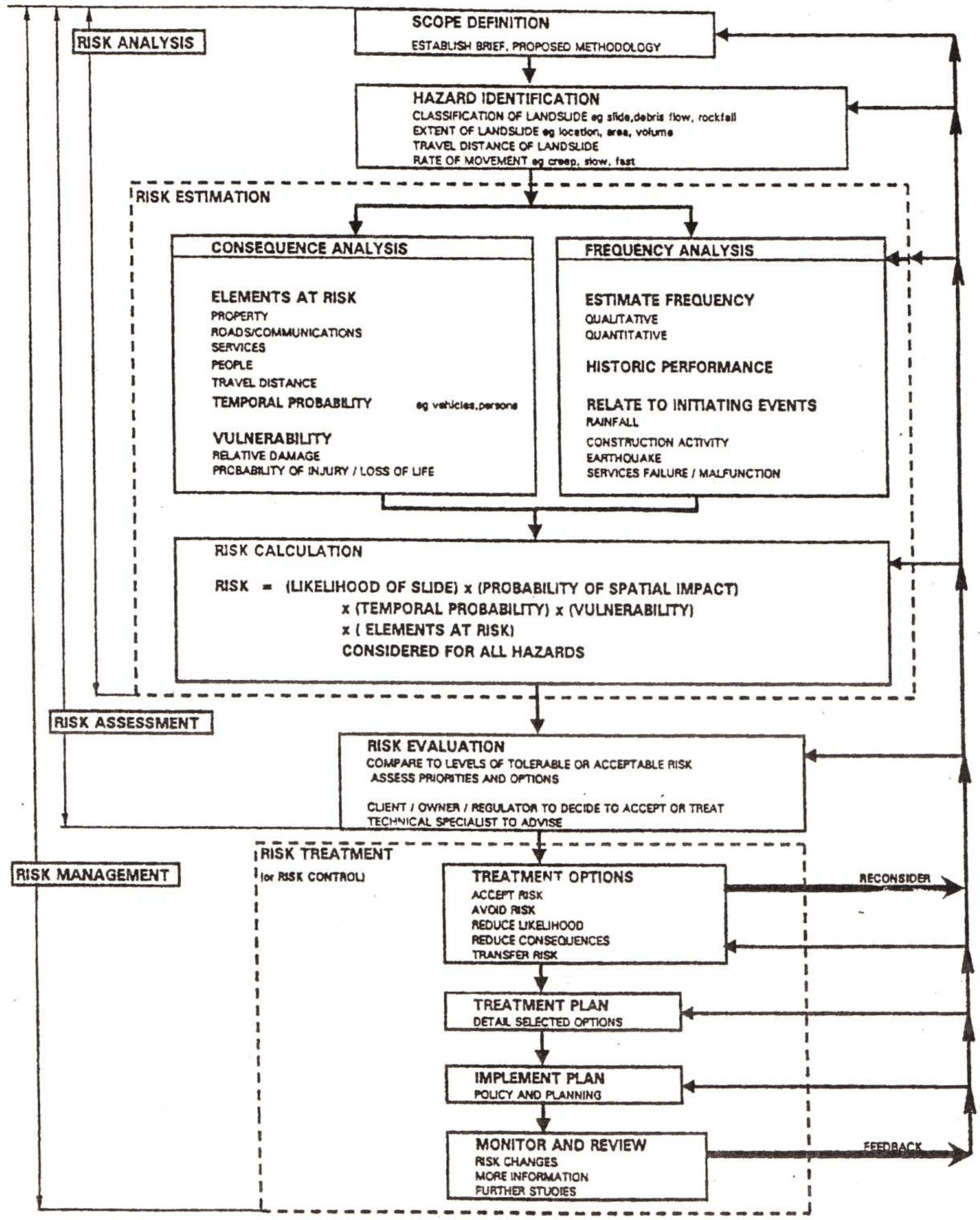


Figure 2.10: AGS Sub-Committee Flowchart for Landslide Risk Management (after AGS Landslide Risk Management Concepts and Guidelines 2000). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

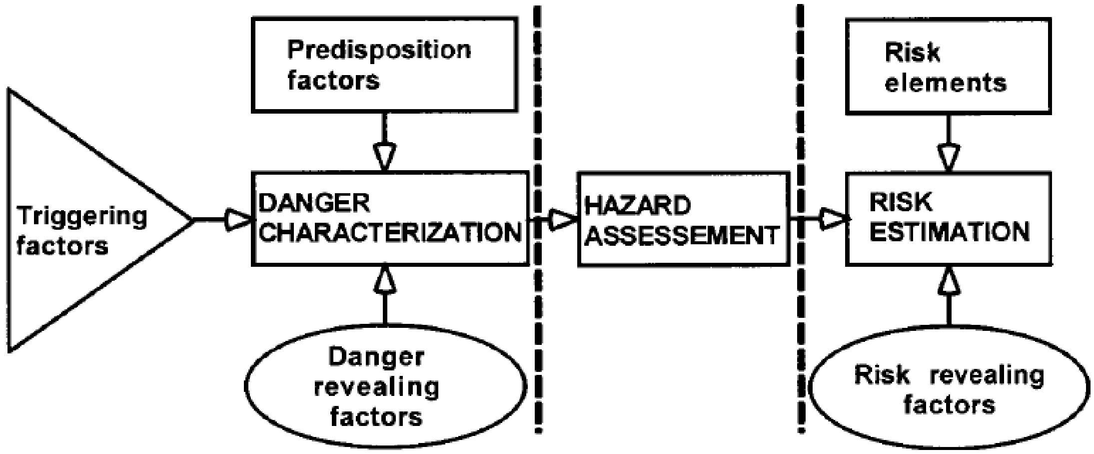


Figure 2.11: Summary of 2-D Landslide Hazard and Risk Analysis Developed by Vaunat (after Vaunat et al. 2002). Permission for re-use granted. See List of Copyrighted Material for which Kind Permission was Obtained.

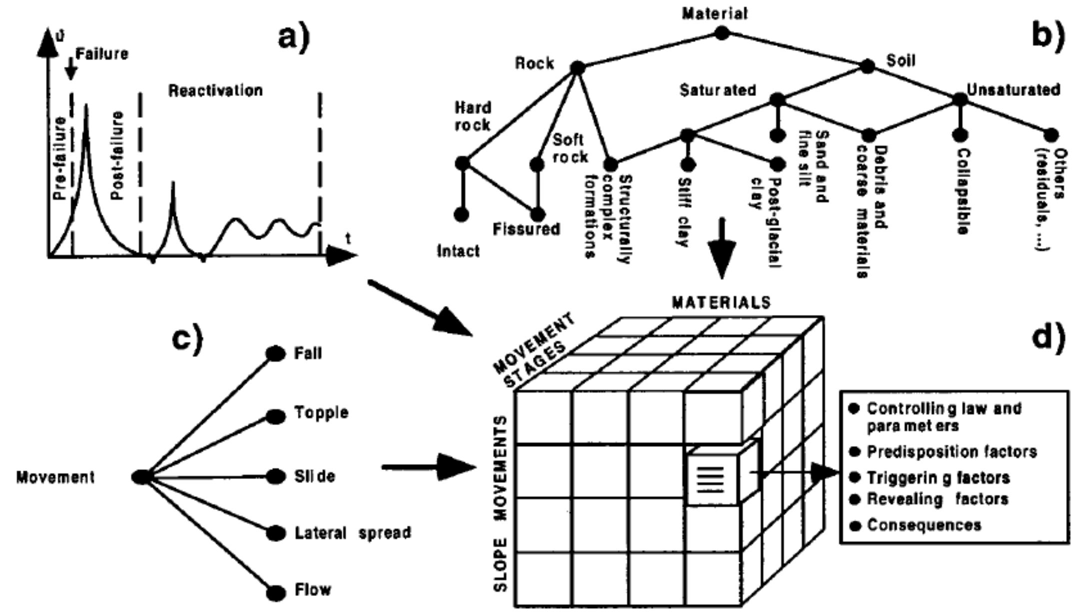


Figure 2.12: Basis of geotechnical classification matrix. A) movement phase B) material types C) movement types D) characterization sheet (after Vaunat et al. 2002). Permission for re-use granted. See List of Copyrighted Material for which Kind Permission was Obtained.

Movement: slide **Stage**: Reactivation **Material:** stiff clays

Controlling laws and parameters

- Residual shear strength: $\tau_f = \sigma'_n \tan \phi'_r$
- Rate of displacement or sliding: $v = A(\tau / \tau_{fr})^n$

Predisposition factors

- Pre-existing shear surface(s)
- Soil particles which can be reoriented

Triggering or aggravating factors

- Increase in pore pressure in the vicinity of shear surface(s)
- Increase in shear stresses by: i) erosion at the toe of the slope or ii) loading at the top of the slope
- Seismic loading

Revealing factors

- Localised displacements on vertical profiles
- Geometry and movements evidencing sliding on essentially rigid blocks

Movements consequences

- Rate of displacement: generally very slow (less than 1 m/a)
- Remedial works can be considered only in some cases

Figure 2.13: Example of Characterization Sheet Utilized for the Reactivation of a Slide in Stiff Clay (Vaunat et al. 2002). Permission for re-use granted. See List of Copyrighted Material for which Kind Permission was Obtained.

Table 2.1: Risk Estimation Methods

Method	Description
1. Risk Matrix	Frequency and consequence of hazard are expressed qualitatively and combinations are outlined in a matrix.
2. Risk Index (Semi-quantitative)	Factors that affect the frequency and consequence of a hazard are assigned values. These values are combined mathematically.
3. Probabilistic Quantitative Risk Analysis	Hazard frequency and consequence are estimated quantitatively and combined using probability theory.

Chapter 3 Background Information

3.1 Introduction

Chapter 3 provides background information on the study area to assist in understanding the research discussed in the subsequent chapters. Chapter 3 commences with a brief overview of the study location, followed by a description of the geological history and stratigraphy of the Winnipeg area. The chapter then proceeds with a summary of the geomorphology and stratigraphy of the Red and Assiniboine River Basins. This is followed by a brief discussion on slope stability problems encountered in the Winnipeg area. Finally, the riverbank characterization used by the City of Winnipeg is reviewed.

3.2 Study Location

Figure 3.1 (Render 1970) shows that Winnipeg, Manitoba, is located approximately 100 km north of the Canada-United States border at the confluence of the Red and Assiniboine Rivers (Baracos et al. 1981). Figure 3.2 (http://www.earth.google.com) illustrates that the City of Winnipeg is located in a broad, flat plain on the former floor of Lake Agassiz in the Red River Valley. Section 3.3 below, outlines the geological history of Lake Agassiz in further detail.

3.3 Geological History of the Winnipeg Area

3.3.1 Introduction

The geological history of the Winnipeg area has been described in detail by Teller (1976), Teller and Fenton (1980) and, Teller and Last (1981).

The late Wisconsin ice sheet advanced to the Winnipeg area approximately 22 to 24 thousand years ago (ka) from the northeast across the Precambrian Shield (Teller and Last 1981). Shortly after this, the Keewatin ice sheet advanced from the northwest over the Paleozoic carbonate rocks (Teller and Last 1981). These two ice sheets were stationary over the Winnipeg area until approximately 13.5 ka; at which time they retreated northward in the direction of Hudson Bay. Lake Agassiz formed between the higher topography in Northwestern Ontario, Minnesota, Western Manitoba, and the northward retreating Laurentide Ice Sheet (Baracos et al. 1983). River flow from the south and west, glacial meltwater, in addition to local rainfall contributed to the formation of Lake Agassiz. Teller and Last (1981) believe Lake Agassiz encompassed the majority of the Red River Valley by 13 ka. At its maximum, Lake Agassiz was up to 213 m deep in the Winnipeg area (Teller 1976). The water level of early Lake Agassiz was controlled by: 1) location of the glacier 2) isostatic rebound and 3) elevation of the overflow channel.

Between 13.5 and 9.9 ka, the Laurentide Ice Sheet advanced and retreated several times in the Winnipeg area. Re-advances of the ice sheet in the Winnipeg area occurred at approximately 13 ka and 12 ka respectively. Between 24 ka and 12 ka, till was deposited on the pre-Pleistocene erosional surface by the advancing and retreating ice sheets. By 11 ka, the ice front retreated from the Winnipeg area due to a warming climate (Teller and Last 1981). After its initial formation at around 13 ka, Lake Agassiz drained southwards through the Mississippi drainage basin. Around 11 ka, Lake Agassiz changed it drainage direction and began draining through an outlet in Northwestern Ontario, to the Lake Superior Basin. Lake Agassiz continued draining eastwards to the Superior Basin until about 9.9 ka when a re-advance of the Laurentide

Ice Sheet in Northwestern Ontario dammed the eastern drainage outlet. The damming of the eastern drainage outlet resulted in the drainage direction being changed from eastwards to southwards, over the dry Lake Agassiz bed bottom in North Dakota and Minnesota. The changed drainage direction caused the water level in Lake Agassiz to again rise. It is estimated that the eastern outlets became ice free again around 9.5 ka.

Radiocarbon dating has shown that sedimentation rates in Lake Agassiz increased in the period between 10.3 and 9.9 ka (Teller and Last 1981). At some time during this period, the level of Lake Agassiz dropped, and the upper glaciolacustrine material formed dessication cracks. Sedimentation rates were constant in Lake Agassiz between 9.9 and 8.7 ka. Around 8.5 ka, Lake Agassiz started draining northwards, and the Lake Agassiz deposits in the Winnipeg area were subjected to dessication, weathering, and water table lowering. Teller (1976) estimates Lake Agassiz waned northwards around 7.3 to 8.0 ka. Lake Winnipeg, Lake Manitoba, Lake Winnipegosis and the Red Lakes in Minnesota are remnants of Lake Agassiz.

Lake Agassiz varied significantly in size and position, as the ice retreated, and drainage channels opened to the south, east, and northwest (Baracos et al. 1983b). At its maximum size, Lake Agassiz was the largest lake in North America. It measured 521,000 km^2 in total area, but the maximum extent at any one time was 208,000 km^2 (Baracos et al. 1983b). Deposition of laminated silt and clay, commonly referred to as glaciolacustrine deposits, occurred for almost 5 ka in the Lake Agassiz Basin. The clay and silt were derived from clay shales and carbonates, to the south and west, and Precambrian bedrock to the east (Baracos et al. 1983b).

Mollard (1983) and Woodworth-Lynas and Guigne (1990) observed reticulate patterns on the floor of Lake Agassiz. The reticulate patterns were carved by ice blocks that were dragged across the valley bottom when water levels in Lake Agassiz were lower than 60 m. It is speculated that post-glacial winds aided in the transport of these ice blocks. The scour marks, or reticulate patterns, that were produced by the ice block scours, were subsequently filled with silt and clay. They are most obvious in the late spring or early summer when the snow cover has recently melted but the land has not dried. Up to 5 m of mostly silt was deposited in these scour holes, in some areas.

3.3.2 Stratigraphy of the Winnipeg Area

The stratigraphy of the Winnipeg area has been described in detail by Baracos et al. (1983a), Baracos and Kingerski (1998), and Tutkaluk (2000).

A typical stratigraphic section in the Winnipeg area consists of the stratified Upper Complex zone overlying glaciolacustrine silty clay. Underlying the glaciolacustrine silty clay is till. Carbonate bedrock is found to underlie the till unit. Figure 3.3 (Baracos et al. 1983a) displays average borehole log information for the stratigraphic units encountered in the Winnipeg area.

3.3.2.1 Upper Complex Zone

The Upper Complex zone consists of stratified silty clay, and silt interbedded with alluvial silt and sand, and occasionally fill. Post-glacial flooding, deposition, erosion, vegetation growth and human activity have resulted in the modification of the near surface landscape in the Winnipeg area (Baracos and Kingerski 1998). The modification of the landscape from these processes has resulted in the deposition of the irregular material known as the Upper Complex zone.

The Upper Complex zone ranges from approximately 0.6 to 4.5 m thick. The silty clay is generally stiff and plastic and has a nuggety structure due to repeated freeze-thaw and wetting-drying cycles. Within the Upper Complex zone, low plastic silt layers may be interbedded with the stratified silty clay. These silt layers are typically found within the top 2 m of the unit and vary in thickness and continuity. Perched water tables are usually found in the silt layers.

3.3.2.2 Glaciolacustrine

Glaciolacustrine material, typically plastic clay containing silt laminations, underlies the Upper Complex Zone. Deposition of the plastic clay during the Lake Agassiz time period masked the underlying topography and has resulted in the extremely flat landscape observed today (Baracos et al.1983a). The glaciolacustrine deposits in the Winnipeg area are typically 9 to 12 m thick, but have been found to range between 0 and 21 m thick and are noticeably thicker further south in the Red River valley. The glaciolacustrine clay in the upper 1.5 to 4.5 m is brown to brown-grey in colour. The 'brown clay' obtained its brownish colour from oxidation. The 'brown clay' is stiff, highly plastic, laminated, and fissured. The frequency of fissures decreases with depth. Gypsum may be encountered as filling in the fissures, or as veins in the 'brown clay'. The clay underlying the 'brown clay' is highly plastic 'grey clay'. The 'grey clay' is firm to stiff and becomes soft at the interface of the till unit. Gravel to boulder sized rock fragments, are found in the lower portion of the 'grey clay' but are seldom encountered in the 'brown clay' (Baracos et al. 1983b). Table 3.1 (Baracos et al. 1983a) shows the typical range of geotechnical properties of the silty clay, glaciolacustrine in origin, encountered in the Winnipeg area.

3.3.2.3 Till

Till generally underlies the glaciolacustrine unit. The till was deposited in a complex series of advances and retreats of the ice margin from the Wisconsin ice age near Winnipeg (Baracos et al. 1983b). The till unit is described by Baracos and Kingerski (1998) as a heterogenous mixture of particles ranging from boulder-size to clay-size, but its grain size is predominantly silt. The contact between the till and the overlying glaciolacustrine deposit is gradational. Till lenses can be encountered in the glaciolacustrine unit and glaciolacustrine inclusions can be found in the till deposit. Frequently, the till encountered at the top of the unit is soft, loose and water bearing. The water-laid till was not compressed directly by ice loading. The lower portion of the till is dense to very dense (Baracos et al. 1983a). Due to the increased density with depth, the moisture content is typically lower at depth and the density is higher. The till unit generally ranges from 3 to 6 m thick, but has been found to range between 0 and 9 m thick. Table 3.2 (Baracos et al. 1983b), demonstrates, the geotechnical properties of the till unit.

3.3.2.4 Bedrock

Paleozoic carbonate bedrock underlies the silty till. The top of the carbonate is a geological discontinuity and the deposit is karstic. The carbonate is a confined aquifer, in the upper 15 to 30 m of bedrock (Baracos et al. 1983b). The bedrock is confined by the silty till above and the less pervious underlying carbonate bedrock below (Baracos et al. 1983b). The upper 7.5 m of the carbonate bedrock is the zone of major hydraulic conductivity (Baracos et al. 1983b). The Upper Carbonate aquifer is characterized by a network of open fractures, joints and bedding planes that provide the aquifer a high hydraulic conductivity (Baracos et al. 1983b). The openings were formed by dissolution of carbonates around pre-existing joints and bedding planes. They decrease in size with depth (Baracos et al. 1983b). The bedrock surface was extensively weathered in pre-glacial times and was subsequently modified during the last glacial period (Baracos et al. 1983). The upper 1.0 m of the bedrock surface is highly fractured and jointed, and often mixed with sand and gravel, that maybe periglacial in origin (Baracos et al. 1983b).

In the early 1900's, the Upper Carbonate aquifer was utilized as an industrial and municipal water source. With the opening of the Lake of the Woods aqueduct in 1919, demand for water decreased in the Winnipeg area. Presently, the Upper Carbonate aquifer is primarily used for commercial and industrial cooling because of its constant low temperature and for the operation of heat pump systems (Baracos et al. 1983). Render (1970) showed that pumping of groundwater in Winnipeg caused a large drawdown cone in the potentiometric surface of the Upper Carbonate aquifer. Because most of the groundwater is pumped by industrial sources for cooling in the summer, the potentiometric surface in the summer can be as much as 5 to 6 m lower than the potentiometric surface in the winter. The potentiometric surface of the Upper Carbonate aquifer has been observed to be higher than low water levels on the Red and Assiniboine Rivers, especially between late fall and early spring. There has been some rebound of the former potentiometric surface, following the closure of some industrial users of groundwater in St. Boniface.

3.4 Geomorphology and Stratigraphy of the Red and Assiniboine Rivers

The Red and Assiniboine Rivers, and their tributary streams, cut sinuous channels inside relatively straight belts through the glaciolacustrine deposits of Lake Agassiz to form their present day configurations (Teller 1976). The height of the riverbanks along the Red and Assiniboine Rivers range from 9 to 15 m. The riverbed depth is typically controlled by the underlying dense till or resistive bedrock outcrops. The sections below provide details on the geomorphology and stratigraphy of the Red and Assiniboine Rivers.

3.4.1 Red River

The Red River originates at the confluence of the Bois de Sioux and Otter Trail Rivers in South Dakota and Minnesota respectively, and flows in a northerly direction to Lake Winnipeg, Manitoba. Figure 3.4 illustrates that the Red River is approximately 885 km in length. The watershed area of the Red River is 290 000 km^2 and this includes the Assiniboine River watershed area, which is approximately 163 000 km^2. Approximately 16% of the Red River watershed is located in Canada, excluding the Assiniboine River watershed. The Assiniboine River is the largest tributary of the Red River, and the confluence of the Red and Assiniboine Rivers is located in Winnipeg, Manitoba.

The mean annual flow of the Red River at Emerson, Manitoba is 98 m^3/s with typically the highest flow recorded during the spring freshet in April or May. Additional peaks in the mean annual flow may occur after periods of heavy precipitation. Within Manitoba, the Red River is a single channeled, meandering river with a sinuosity of 1.1 to 2.3 (Brooks et al. 2000). The Red River has an average valley gradient of 0.0001. The suspended sediment load in the Red River is 90% silt and clay. The suspended sediment load is very similar to the composition of the material encountered on exposed riverbank faces and the floodplain of the Red River. The annual suspended sediment load at Emerson, Manitoba ranges between 0.4 to 1.5 M tonnes (Brooks et al. 2000).

Approximately 51% of the sediment load is transported over a 37 day period in March and April. Thorleifson et al. (1998) describe the Red River as a low-energy, silt and clay alluvial system.

The Red River was incised rapidly about 8200 to 7800 ^{14}C, after Lake Agassiz finally receded from the Winnipeg area (Teller and Last 1981). The Red River is shallow, up to 15 m deep, and 2500 m wide (Brooks and Nielsen 2000). The Red River is prone to flooding because the incised river bed does not have the capacity to contain large flows due to the valley shallowness and low gradient. When the capacity of the Red River is exceeded, its banks are overtopped and floodwater inundates the surrounding flat landscape. Since the surrounding topography is flat, it enables water to travel unimpeded laterally for kilometers. During the ‘Flood of the Century’ in 1997, a 40 km wide ‘Red River Sea’ was formed.

The normal summer water level of the Red River is regulated by St. Andrew’s Lock and Dam (SALD), located downstream from Winnipeg (Baracos and Kingerski 1998). SALD is utilized after the spring freshet has subsided, and the elevation of the Red River measured at the James Avenue Pumping Station, is 223.7 m. When SALD is operational, boat traffic is able to safely navigate the Lister Rapids and continue downstream. At the end of October, SALD is taken out of operation, and the elevation of the Red River recedes to 221.9 m (winter water level). Decommissioning SALD in the late fall, allows the subsequent year’s spring freshet to flow more easily through the City of Winnipeg.

Extremely slow to very slow, rotational to translational sliding of riverbanks is common along the Red River. Earth sliding is especially common along the outside bends of the river where the river is immediately adjacent to Lake Agassiz sediments. However, riverbank failures are not limited to outside bends, and can occur on inside, straight and transition sections of the Red River. The basal rupture surface of earth slides can extend tens of meters into the channel, well beyond the riverbank (Baracos and Kingerski 1998).

Brooks (2005) surveyed 10 profiles along 3 outside bends of the Red River, south of Winnipeg, to determine the thickness of overbank deposits accumulated during the 1999 freshet. As shown in Figure 3.5 (Brooks 2005), seven profiles were located in landslide zones on two shallow sloped (<11^o) outside bends. Three additional profiles were constructed for a moderately sloped (23 to 27^o) concave bank eroding into a floodplain. Brooks (2005) concluded that 20 cm of overbank sediment can be deposited on middle and lower slopes of a shallowly sloped landslide zone within 50 to 80 m of a river channel during a spring freshet. Overbank sediments on a moderately sloped concave bank are much thinner, and are found closer to river channel. During the 1999 freshet, 7 cm of overbank sediment was deposited on the moderately sloped concave bank. The overbank sediments were found within 10 to 30 m of the river channel for the moderately sloped concave bank. Brooks (2005) noted overbank deposit thickness depends on: 1) distance and height from the river channel 2) duration of inundation on the outside bend 3) mesotopography, and 4) vegetation cover. Brooks (2005) concluded that a sediment reworking process is continually occurring on an outside bend. Sediment is initially deposited on an outside bend, likely in a landslide zone. This sediment is then gradually displaced downslope from rotational or translational earth sliding. The displaced sediment is subsequently reworked at the toe of the landslide by the Red River, and eventually transported downstream (Brooks 2005).

Aerial photographs and topographic maps have shown that lateral migration of the Red River over the last 130 years is minimal. A singe phase of lateral migration has occurred in the past however, as ridge and swale topography is evident on the floodplain south of Winnipeg. Brooks et al. (2005) indicated that the river meanders have undergone a slow lateral migration, with most experiencing a single and continuing sequence of expansion and downvalley rotation, since the rapid incision of the Red River at approximately 8 ka. Brooks and Grenier (2001) only encountered eight oxbow lakes and sloughs between Lake Winnipeg and the Canada-United States border. The lack of oxbow lakes over this 170 km distance clearly indicates that the Red River is undergoing a slow rate of lateral channel migration. Figure 3.6 (Brooks 2005) estimates the areas of erosion and deposition along a concave bank over a 100 year period. Figure 3.6 shows that if 4m of lateral translation occurs as a result of river erosion, 26% of the eroded material is deposited as overbank sediment. Brooks et al. (2005) believe that the slow rate of lateral channel migration is due to: 1) low unit stream power of the Red River 2) cohesion of the glaciolacustrine and alluvial deposits, and 3) the large quantity of sediment deposited on a riverbank face and landslide zone during the spring freshet.

Brooks (2003a) showed that two meanders in the proximity of St. Jean Baptiste, Manitoba near the Canada-United States border, have experienced an average channel migration of 0.04 m/yr since 1 ka and an average rate of 0.4 to 0.8 mm/yr since 8 ka. However, Brooks and Grenier (2001) believe that the modern rate of sedimentation has increased, especially since the 1880's. The increased sedimentation is attributed to the introduction of European agricultural practices in the Red River Valley. Nielsen (1993) estimated the vertical sedimentation rate in the City of Winnipeg in the vicinity of two meanders. The first site was located at St. Vital and the second site at St. John's Ravencourt School. It was found that the average sedimentation rates were 1.3 and 2.0 mm/yr respectively.

Brooks (2003b) studied five boreholes along two transects on two inside bends of the Red River near St. Jean Baptiste, Manitoba, in addition to quantifying average channel migration of the Red River along two meanders. Brooks (2003b) observed that average alluvial deposits, were composed primarily of silt, and were 15 to 22 m thick. Deposition or accretion of alluvial deposits along the inside bends typically commenced upstream of the bend apex and continued downstream to the meander inflection point. Figure 3.7 (Brooks, 2003b) demonstrates accretion of alluvial deposits on an inside bend of the floodplain. Brooks (2003b) noted that the accretion of alluvial deposits is thickest closest to the river, and decreases in thickness with increasing distance and height from the channel. Alluvial deposits were found to increase in thickness in swales. In addition, grain size was found to decrease with increasing distance and height from the river channel. Brooks (2003b) recorded that alluvial deposits up to 0.1 m thick were accreted each year, in a 10 to 30 m wide zone extending from the riverbank channel.

Brooks (2003b) determined that a steep inside bend of the Red River experiences net erosion due to fluvial scouring, wave action and slope washing. However, Brooks (2003b) concluded that vertical aggradation on the uppermost portion of the bank face and on the gently dipping inner bank surface is not subjected to such erosion. Brooks (2003b) measured the vertical aggradation of alluvial deposits on an upper bank face between 2000 and 2001. He concluded that the thickness of the alluvial sediment deposited on the inside bend during this time period ranged between 0.1 and 0.17 m. Brooks (2003b) believes the accumulation of overbank deposits further loads an unstable riverbank, causing increased subsidence of the older and deeper deposits. Increased loading on the mid to upper slope, decreases the stability of the riverbank, while increased loading at the toe of the slope, acts as a buttress, increasing the stability of the riverbank. Figure 3.8 (Brooks 2003b), shows three examples of active and inferred rotational bank failures.

Brooks et al. (2005b) indicated that the Red River has lost approximately 60% of its gradient between 8 ka and present due to differential isostatic rebound. The magnitude of isostatic rebound in the northern portion of the Red River Valley is greater than the magnitude of isostatic rebound in the Red River Valley located south of the Canada-United States border. The reduction in the valley gradient has resulted in an enlarged flood zone area. The flood zone area has increased from 1186 km^2 to 1531 km^2 between 8 ka and present.

3.4.2 Assiniboine River

Figure 3.4 shows that the Assiniboine River originates in eastern Saskatchewan and flows in a southeasterly direction, until it joins the Red River in Winnipeg, MB. The Assiniboine River is 1070 km in length and has a 163 000 km^2 drainage basin. The Assiniboine River is classified as a meandering river and it meanders in a single main channel. Its two main tributaries are the Souris and Qu'Appelle Rivers. These two main tributaries represent approximately 110 000 km^2 of the drainage area. The flow of the Assiniboine River is entirely dependent on prairie runoff and the mean annual runoff increases eastward (Ashmore 1992). The average discharge of the Assiniboine River is 45 m^3/s. The Portage Diversion and Shellmouth Dams located near Portage La Prairie are used to reduce peak flows and supplement flows during dry periods. Sixty to eighty percent of the average annual stream-flow occurs between April and June.

Ashmore (1992) describes the Assiniboine River as tortuous, underfit and confined to a large glacial meltwater channel. The glacial meltwater channel is up to 85 m deep and 800 m wide. However, downstream of Brandon, the post glacial Assiniboine River has incised a valley into the Pleistocene Assiniboine Delta (Ashmore 1992). Sand and silt deposits of the Assiniboine Delta are typically exposed on the riverbank face. In addition, numerous vegetated and unvegetated sand bars are encountered along the Assiniboine River in this area. East of the Manitoba Escarpment, the Assiniboine River flows over the Portage ‘floodplain fan’ and then the Lake Agassiz plain (Ashmore 1992). The channel gradient averages 0.0001 upstream of Brandon, increases to 0.0004 through the Manitoba Escarpment and then decreases to 0.0003 east of the Escarpment (Ashmore 1992).

The mean annual suspended sediment load at Russell Manitoba is 0.016 M tonnes while the mean annual suspended sediment load downstream at Holland Manitoba is 0.95 M tonnes. Very little of the sediment input is from the Qu’Appelle and Souris Rivers; therefore, the increase in sediment load is from riparian sources along the Assiniboine River (Ashmore 1992). Eighty percent of the total annual sediment discharge occurs between April and June. It is believed that the Assiniboine Delta is the main source of suspended sediment for the Assiniboine River. Therefore, the Quaternary History and deposits of the Assiniboine River are the dominant influence on the disposition of sediment sources and pattern of sediment yield (Ashmore 1992). The isolation of the Assiniboine River from the prairie system because of the poorly-integrated drainage system and the confinement of the Assiniboine River to a pre-existing meltwater channel are also important contributing factors to the disposition of sediment sources and pattern of sediment yield (Ashmore 1992).

As Lake Agassiz receded from eastern Manitoba around 9.2 ka, the ancestral Assiniboine River carved a route across the flat glaciolacustrine plain created by the former Lake Agassiz. Deltaic and glaciolacustrine sediments previously deposited near the mouth of the Lake Agassiz plain between Brandon and Portage La Prairie, as well as fluvial deposits to the west were entrenched at this time (Rannie et al. 1989). The eastward flowing Assiniboine River into Lake Agassiz led to the formation of the Assiniboine Delta, extending from Brandon to Portage La Prairie. The Assiniboine River had excavated its valley channel by 7.5 ka. In contrast to the Red River, that has experienced minimal lateral channel migration in the last 6 ka years, the Assiniboine River has been very active during the Holocene Period. This has likely contributed to the large number of oxbow lakes observed in the vicinity of the Assiniboine River.

The geological history of the Assiniboine River between 9.2 and 7.0 ka is not well understood. Figure 3.9 (Rannie et al. 1989) illustrates the geological history of the Assiniboine River in the Portage La Prairie area. Based on the results obtained from radiocarbon dating of organic debris, Rannie and Thorleifson (1989) believe that the Assiniboine River originally flowed northward to Lake Manitoba between 6 and 7 ka. Fenton (1970) hypothesizes that the Assiniboine River may have initially drained northwards as this was the direction of maximum isostatic uplift. This became the preferred drainage path, since Lake Manitoba is located north of Portage La Prairie. Due to increased vertical sedimentation rates recorded on the Red River between 5.2 and 4.8 ka, Nielsen et al. (1993) believe the Assiniboine River flowed in an easterly direction during this time period, depositing additional sediment into the Red River. Around 4.8 ka, the flow of the Assiniboine River was once again diverted northwards, to Lake Manitoba. Northward draining paleochannels eventually became filled with sediment, reducing the number of possible drainage routes in the north. Subsequent avulsion exploited lower terrain and steeper gradients, thereby diverting the ancestral Assiniboine River from the Lake Manitoba outlet to the Red River around 3 ka (Rannie et al.1989). The change in flow direction was the result of natural processes affecting a large alluvial fan in the Portage La Prairie area. The large alluvial fan acted as the drainage divide for the Assiniboine River. The Assiniboine River could either flow northwards to Lake Manitoba or eastwards to the Red River. Decreased sedimentation rates in Lake Manitoba at that time, support the hypothesis that the Assiniboine River was diverted to the Red River in the east.

Prior to the eastward diversion of the ancestral Assiniboine River 3 ka, sediment accumulated at a rate of 0.11 cm/year in Lake Manitoba. Sedimentation into Lake Manitoba declined significantly to 0.04 cm/year approximately 3 ka due to the change in drainage direction. Figure 3.9 (Rannie et al. 1989) illustrates that around 3 ka, the flow direction of the Assiniboine River changed, and cut a succession of channels between Portage La Prairie and Winnipeg. When the drainage direction of the Assiniboine River changed from the north to the east, the Assiniboine River flowed to the present confluence of the La Salle and Red Rivers. Despite the warm and dry Holocene period recorded between 9 and 2.5ka, the discharge and sediment loads of the ancient

Assiniboine River are not too different from today. By 1.4 ka, the Assiniboine River had generally established its present day course. However, the higher portion of the Portage La Prairie Fan took until approximately 0.7 ka to develop its present day course.

3.5 Slope Stability Problems in the Winnipeg Area

The 1950 flood not only caused significant damage to infrastructure and buildings in the City of Winnipeg, it also caused extensive damage to both public and private riverbank property. After the 1950 flood, significant slope movements were documented along both the Red and Assiniboine Rivers. In an attempt to prevent future slope stability problems, the Manitoba Government passed the Rivers and Streams Act in 1951. This act required individuals to obtain a permit from the proper authorities before completing work within 46 m of the normal summer water level (NSWL) along the Red and Assiniboine Rivers in the City of Winnipeg. The Rivers and Streams Act prohibited construction on riverbank property or placement of fill at the top of the slope, from the specified distance from the NSWL, unless it could be shown that the action would not detrimentally affect the stability of the riverbank, impede water flow or adversely alter the waterway (Baracos and Kingerski 1998). The act was amended in 1962 to increase the distance from the NSWL to 107 m. In 1963, the act was changed again, to incorporate the Seine and La Salle Rivers. In 1965, the definition of river and stream was modified to incorporate a river, stream, creek, canal, drainage ditch, water channel or any other water course, whether natural or man-made (Baracos and Graham 1981).

Early research conducted by Baracos (1960), Mishtak (1964), Sutherland (1966), and Freeman and Sutherland (1973) documented slope stability problems in the Winnipeg area. Post glacial erosive activities have left the riverbanks in unstable conditions, with oversteepened slopes too high for the low strength cohesive glaciolacustrine material (City of Winnipeg 2000). This has resulted in riverbank failures, generally along the outside bends of the Red and Assiniboine Rivers (City of Winnipeg 2000). However, as mentioned previously, riverbank failures are not limited to outside bends, and can occur on inside, straight, and transition sections of the Red and Assiniboine Rivers. Baracos and Lew (2003) believe that the inherent instability of a riverbank, from new or older deep seated sliding surfaces, lies in the weak clay layers under the riverbank. As more sliding occurs, the clay along the sliding plane becomes progressively weaker.

Brooks (2005) looked at the significance of overbank deposition on an outside bend of the Red River south of Winnipeg. He concluded that the root causes of slope stability problems are: 1) undisturbed strength of the clays 2) loss of strength following slope movement 3) removal of toe support by erosion and 4) generation of high porewater pressures from either river level decrease or increase in Upper Carbonate aquifer levels. Brooks (2005b) noted that overbank sediments typically have dessication cracking. Dessication cracking allows infiltration of rainwater and river water. The weight of overbank deposits on an existing unstable slope, elevated porewater pressures generated after the receding spring freshet, and infiltration of river water and rainwater through the dessication cracks, likely enhance slope stability problems encountered in the Winnipeg area.

Baracos (1978) installed slope inclinometers and piezometers at two test sites, located on outside bends that had slope stability problems dating back to the 1950 flood. He monitored the two sites between 1969 and 1972, and concluded that a decrease in the river level and increased porewater pressure increased the magnitude and likelihood of slope movement. As mentioned earlier, Render (1970) showed that pumping of groundwater in Winnipeg causes a large drawdown cone in the potentiometric surface of the Upper Carbonate aquifer. The drawdown of the Upper Carbonate aquifer is larger near the center of Winnipeg because the demand for water is higher. For example, the potentiometric surface in the Upper Carbonate aquifer at the Perimeter Highway and St. Mary's Road was found to vary by 2.2 m annually, while the potentiometric surface in the Upper Carbonate aquifer at St. Vital, closer to the City centre, was found to vary by 4.5 m annually.

Baracos (1978) showed a correlation between the elevation of the Upper Carbonate aquifer and riverbank stability. The elevation of the Upper Carbonate aquifer's potentiometric surface decreases and the likelihood of slope movement occurring also decreases in the summer when the demand for water is high. However, in the fall when the demand for water is low, the elevation of the Upper Carbonate aquifer's potentiometric surface increases, and the probability of slope movement occurring increases. At this time, too, the river level is drawn down to its winter level, further reducing riverbank stability. A continued increase in the groundwater level through the winter into the spring is regularly observed (Baracos and Lew 2003). Since the elevation of the Upper Carbonate aquifer is affected by human activities, likely a large number of deep seated movements along riverbank property were caused by the upward hydraulic gradient of the Upper Carbonate aquifer prior to the settlement of Winnipeg (Baracos and Graham 1981). Since the residual strength of these soils is very low, deep seated movements are very easily reactivated by erosion or anthropogenic influences (Baracos and Graham 1981).

Slope movement along riverbank property commonly occurs at two times of the year: in early spring before the freshet and in late fall after the drawdown of the Red River. Before the arrival of the spring freshet, porewater pressures are increasing due to snowmelt, runoff, infiltration, and precipitation and the potentiometric surface in the Upper Carbonate aquifer is high because the demand for water is low. River levels are low at this time of year; thus, minimal hydrostatic forces are supporting the riverbank. Increased porewater pressures, an elevated potentiometric surface in the Upper Carbonate aquifer, and decreased river levels contribute to an increased potential for slope movement in the early spring. Tutkaluk (2000) demonstrated that for the worst combination of river and groundwater elevations, low river level and high groundwater elevations, the factor of safety decrease for a riverbank slope in the City of Winnipeg was around 13% to 17%.

In late fall, after the drawdown of the Red River, porewater pressures are high because they have not adjusted to decreased river levels. Clay has low permeability, and therefore, it cannot undergo rapid porewater pressure changes. Therefore, when river levels are receding from NSWL to winter water level, for example, the porewater pressure in the clay cannot immediately respond to the change in the river level. Reduced industrial demand for water in the fall, results in an increased potentiometric surface in the Upper Carbonate aquifer at this time of year. Due to a combination of these factors, the likelihood of slope movement increases in the late fall. Baracos (1978) observed that slope movement typically continues at a decreasing rate throughout the winter. Very little slope movement is recorded when groundwater elevations are low and river levels high, such as the case during the spring freshet or summer flooding. The decreased slope movement is due to the increased hydrostatic forces supporting the bank during high water levels (Baracos and Lew 2003). Therefore, slope failure along riverbank property on the Red and Assiniboine Rivers, is sometimes delayed by the operation of SALD in the late spring, summer, and early fall.

KGS Consulting Group (1994) conducted a study to determine the role of groundwater in riverbank stability. The study looked at the relationship between groundwater levels, river levels, Upper Carbonate aquifer head changes, precipitation, and runoff. Monitoring was conducted for approximately two years and it was concluded that porewater pressure changes were related to river level changes, Upper Carbonate aquifer head changes and precipitation. Porewater pressures in till on the lower bank and the riverbed were related to changes river in level. If the till was confined by the clay and the underlying Upper Carbonate aquifer, porewater pressures in the till responded quickly to pressure changes in the Upper Carbonate aquifer (Baracos and Lew 2003). Porewater pressures in the clay on the lower bank and riverbed were found to have a direct relationship to river levels and till porewater pressure. Upward hydraulic gradients were measured in the clay unit on the lower bank in fall, winter and late spring, due to a combination of carbonate aquifer recharge and low river levels (Baracos and Lew 2003). This relationship is extremely significant as the largest amount of slope movement is recorded during fall, winter and late spring. In the upper bank area, porewater pressures in the clay were not significantly affected by river level changes or changes in the Upper Carbonate aquifer. Upper bank saturation, from runoff, snowmelt, precipitation and anthropogenic influences, play a pivotal role in the porewater pressures measured in the clay unit on the upper bank.

Baracos and Kingerski (1998) noted that rising river levels in the spring lift river ice. Typically, frozen riverbed and riverbank material is attached to the bottom of the river ice. After the ice breaks into sheets and starts moving downstream, it forms packs (Baracos and Kingerski 1998). As the ice progresses further downstream, it gouges the riverbed and lower banks. As river levels continue to rise, additional erosion of the riverbed and riverbank occurs. Baracos and Kingerski (1998) and Baracos and Lew (2003) believe that ice can be a major contributor to riverbank erosion.

Julien and Torres (2006) demonstrated that for a cohesive riverbank, with silt and clay content greater than 45%, flow duration is a major cause of riverbank erosion. Elevated river levels contribute to a deepening of the river channel and removal of toe support at the base of the riverbank. The effects of erosion are magnified by large vegetation along the riverbanks, as the vegetation produces turbulence, which increases the rate of erosion. In addition, vegetation accumulates overbank sediments during periods of high flow, increasing the load on the slope. However, the extensive root systems of some vegetation may have a positive effect on slope stability. This concept has not been examined in detail in the Winnipeg area. Baracos and Lew (2003), and Baracos and Graham (1981) identified loading at the top and middle of the slope, either from deposition of overbank deposits during flood periods, or anthropogenic actions, such as illegal dumping, construction or lawn watering as significant contributors to riverbank stability problems in the Winnipeg area.

3.6 Riverbank Characterization

The Red and Assiniboine Rivers are classified according to the riverbank geometry by the City of Winnipeg. Inside bends generally consist of alluvial sediment, while outside bends are comprised of glaciolacustrine material. Transition sections contain alluvial deposits overlying glaciolacustrine material. Floodplain banks are formed by alluvial deposits.

Failure-controlled banks represent slope failures on outside bends or transition sections of the Red and Assiniboine Rivers, where the slip surface is located in cohesive, low strength glaciolacustrine material. The failures are deep seated, 12 m to 15 m below ground surface, and typically continue to fail until a slope of 6H:1V to 9H:1V is achieved. Outside bends are generally considered stable at a slope of 9H:1V, while transition sections are typically considered stable at a slope of 6H:1V. At these slope angles, it is believed that a quasi equilibrium is reached. History has shown that the potential for slope movement decreases when the slope angle of an outside bend is 9H:1V and the slope angle of a transition section is 6H:1V. Slope movement on a failure-controlled bank, may extend as far back as 80 m from the river’s edge. Consequently, a significant amount of property loss for both the City and private landowners has occurred. The principal factors governing failure controlled banks are: groundwater, river hydraulics, and progressive soil weakening (City of Winnipeg 2000). Figure 3.10 shows a typical failure-controlled riverbank found along the Red River at Canoe Club.

Erosion-controlled banks are located on inside bends of the Red and Assiniboine Rivers. Slope movement is typically shallow. Erosion controlled banks are formed by accreting alluvial sediments, primarily silt and sand. Since alluvial deposits have a higher strength than the glaciolacustrine material, erosion controlled banks are stable at a much steeper slope angle than failure controlled banks. Slope angles for erosion-controlled banks range from 1H:1V to 3H:1V, but a stable slope angle is considered 3H:1V. The principal mechanisms controlling erosion-controlled banks are: river hydraulics, waves, freeze/thaw cycles, drying/wetting cycles, and precipitation (City of Winnipeg 2000). A significant amount of property loss has occurred on inside bends, on both public and private property. Figure 3.11 shows an example of an erosion controlled bank at St. Vital Park.

Transition banks are found upstream or downstream of inside or outside bends and include straight sections (City of Winnipeg 2000). These banks are typically composed of alluvial sediments overlying the glaciolacustrine material. Transition banks may experience deep seated or shallow slope movement, depending on the relative depths of the two soil units. Therefore, significant property loss has also occurred along these banks. A stable slope angle for a transition bank is assumed to be 6H:1V. Figure 3.12 shows an example of a transition bank between Annabella and Mordaunt Streets, immediately downstream of an outside bend on the Red River.

Floodplain banks are located downstream of an inside bend's apex. Predominantly sand and silt, they are deposited on the inner bends of the Red and Assiniboine Rivers as flood plain deposits (Baracos et al. 1983). These banks are typically not as high as erosion controlled banks, and are generally less than 6 m in height. Floodplain banks usually do not experience significant slope movement; therefore, they were not characterized during this research project.

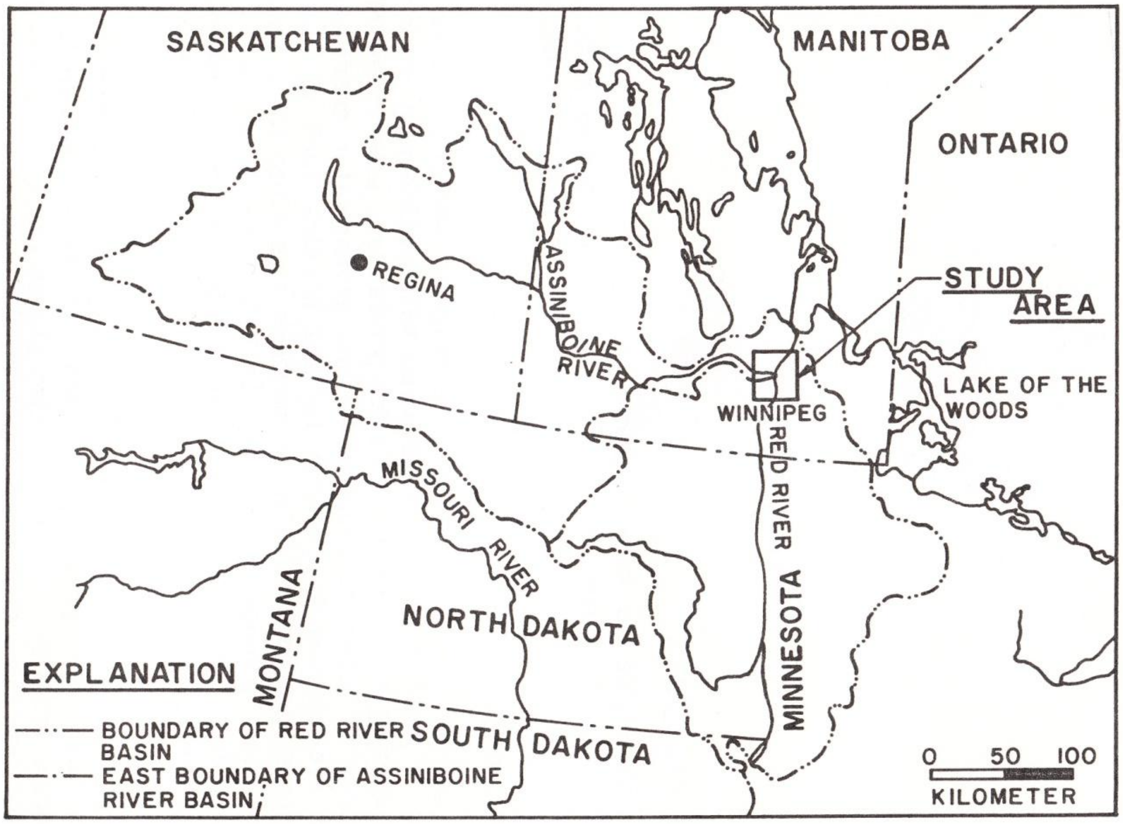


Figure 3.1: Location of Study Area (after Render 1970). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

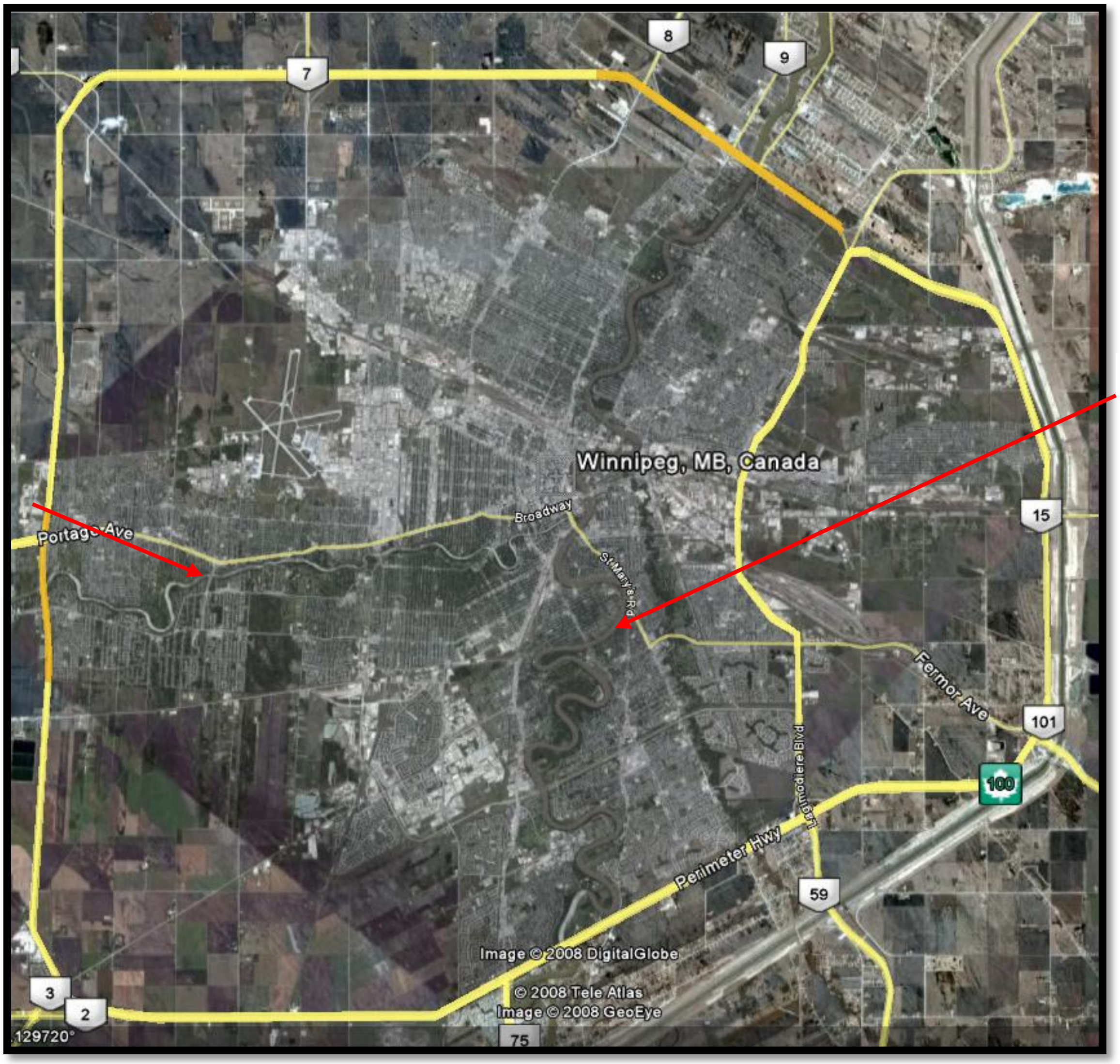


Figure 3.2: Winnipeg is located on the broad, flat plain of the former Lake Agassiz floor in the Red River Valley (after http://www.earth.google.com).

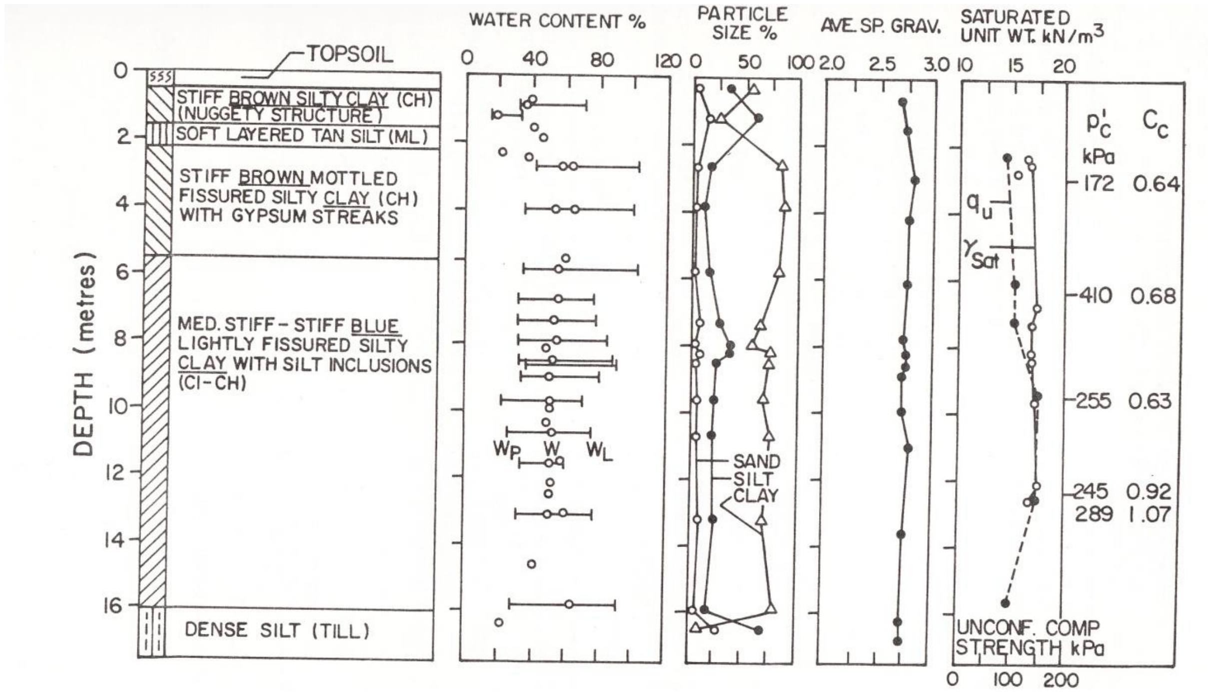


Figure 3.3: Average borehole log information (after Baracos et al. 1983). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

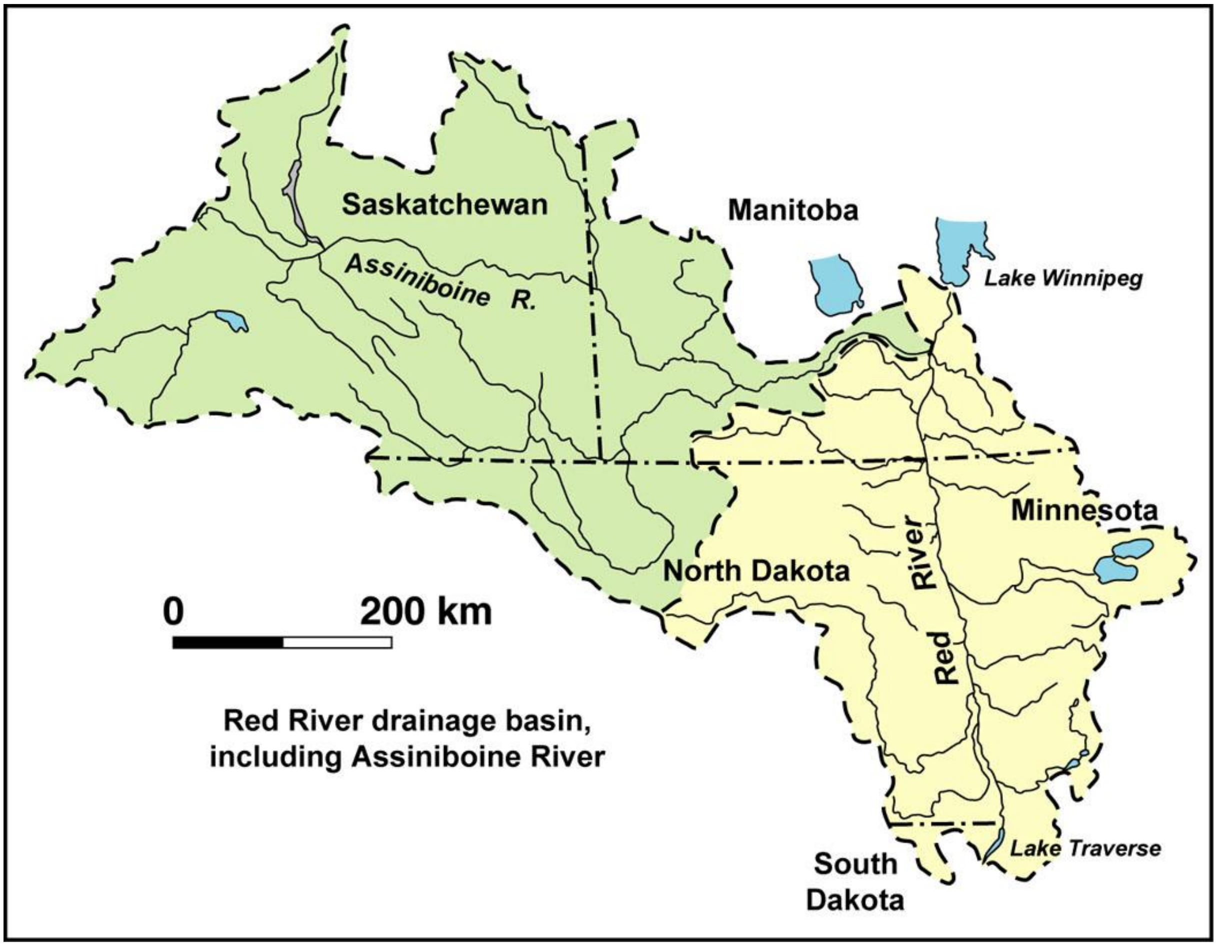


Figure 3.4: Red and Assiniboine River Drainage Basins (after Brooks 2007, http://gsc.nrcan.gc.ca/floods/redriver/geomorphology_e.php). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

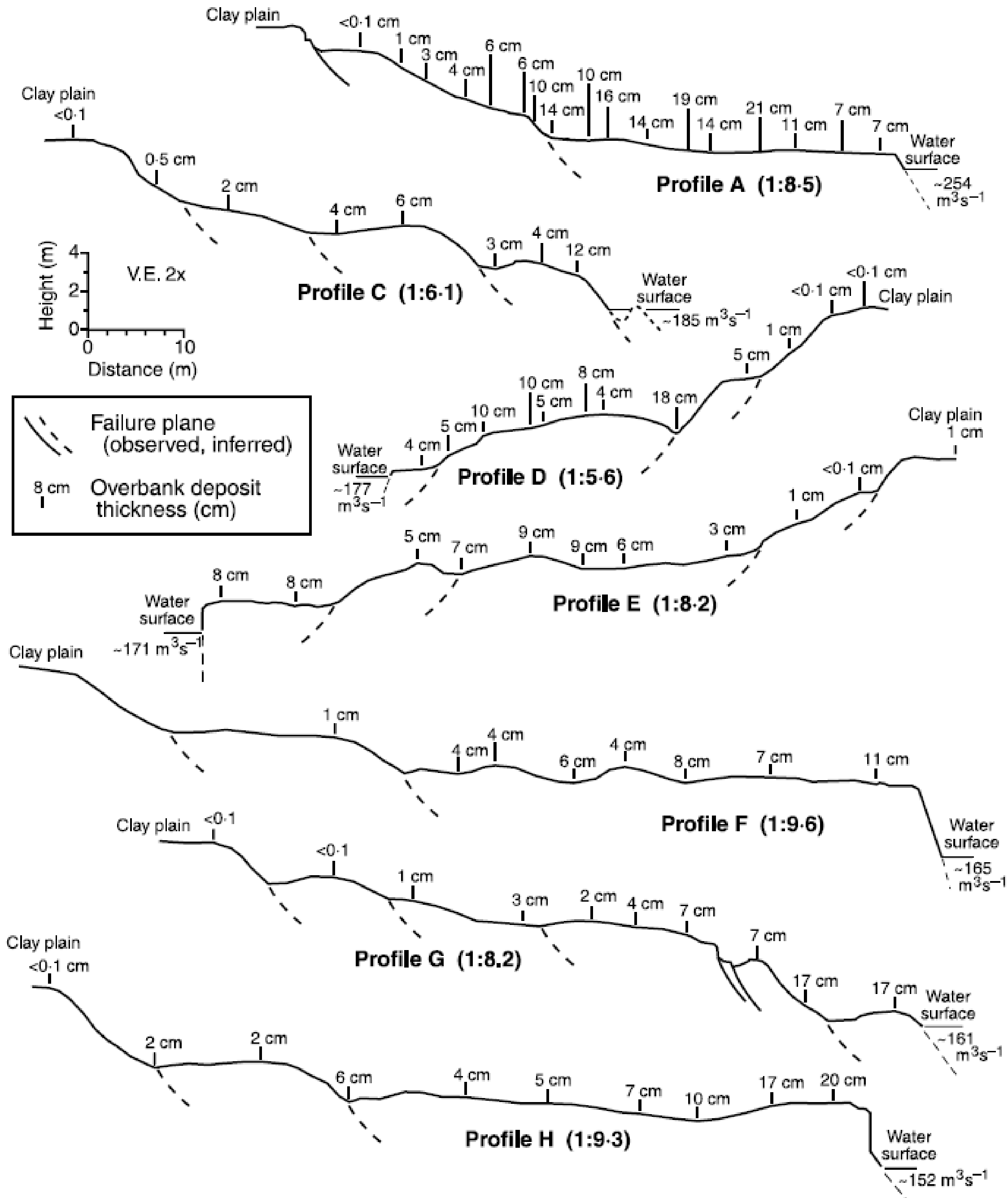


Figure 3.5: Diagrams of seven profiles from landslide zones surveyed in 1999 (after Brooks 2005).The thicknesses of the overbank sediments deposited during the 1999 freshet are shown in addition to the failure planes and height to length ratios. Profiles A, F and H have lateral spreading occurring on the lower bank. Profiles C, D, E and G are rotational bank failures. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

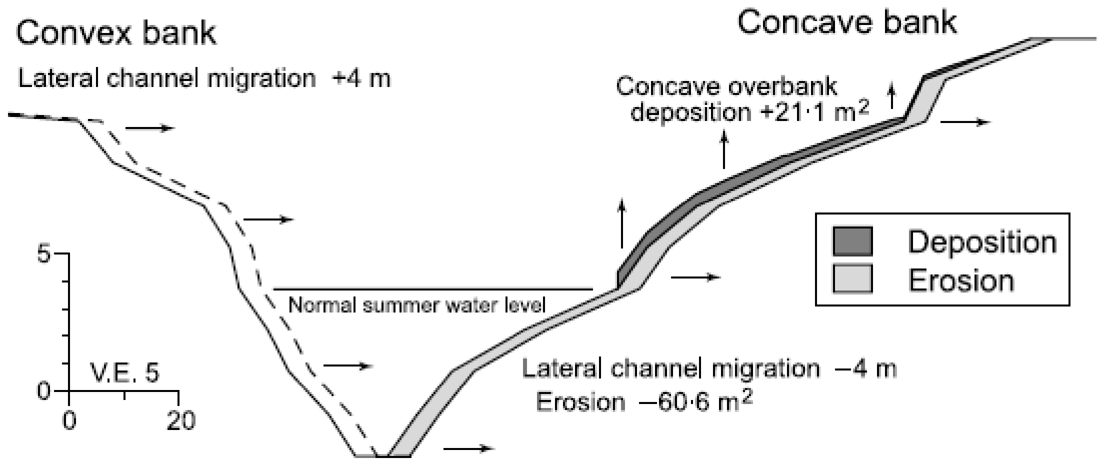


Figure 3.6: Diagram showing the estimate of areas of erosion and deposition over a 100 year interval along the concave bank of the Red River (after Brooks 2005). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

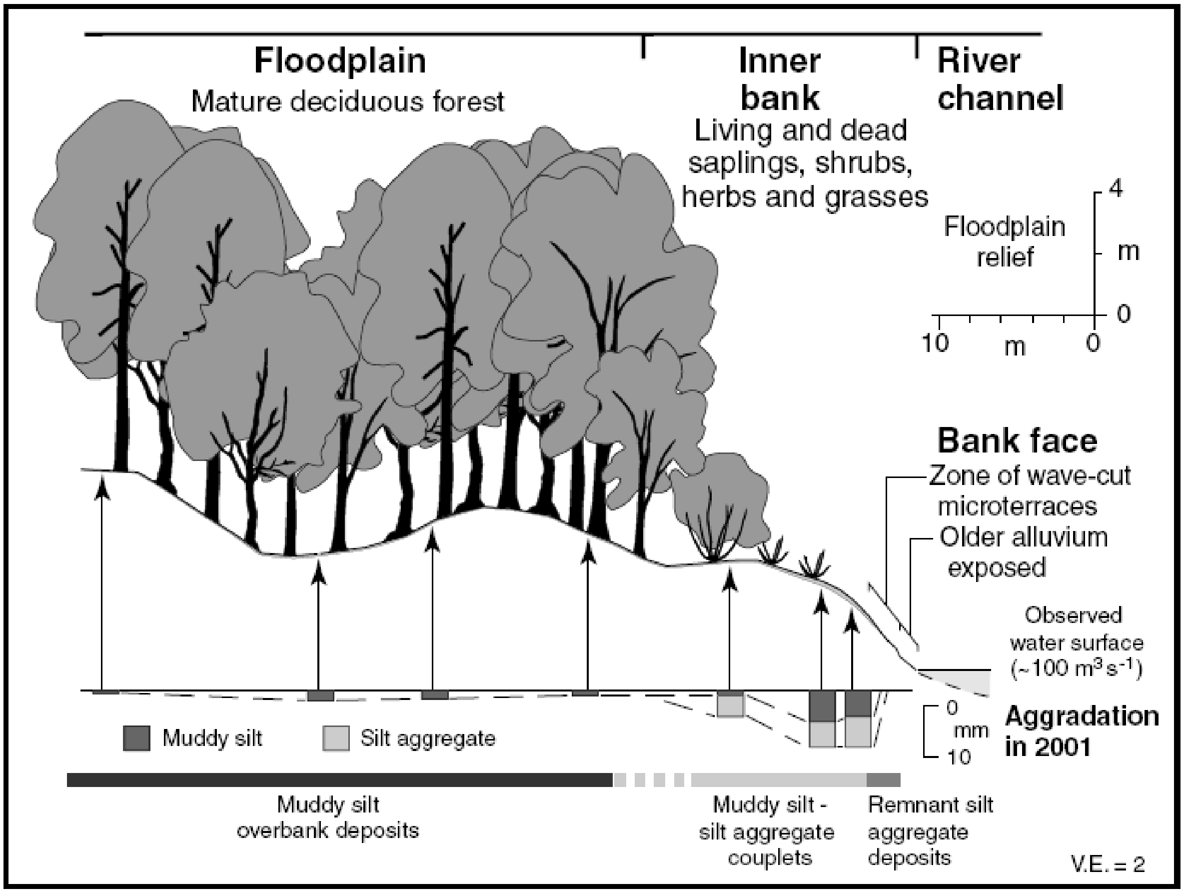


Figure 3.7: Example showing the accretion of alluvial sediments on the inside bend of the Red River (after Brooks 2003).The approximate thicknesses of the alluvial sediments deposited during the 2001 freshet are shown. Note the vertical exaggeration is two times. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

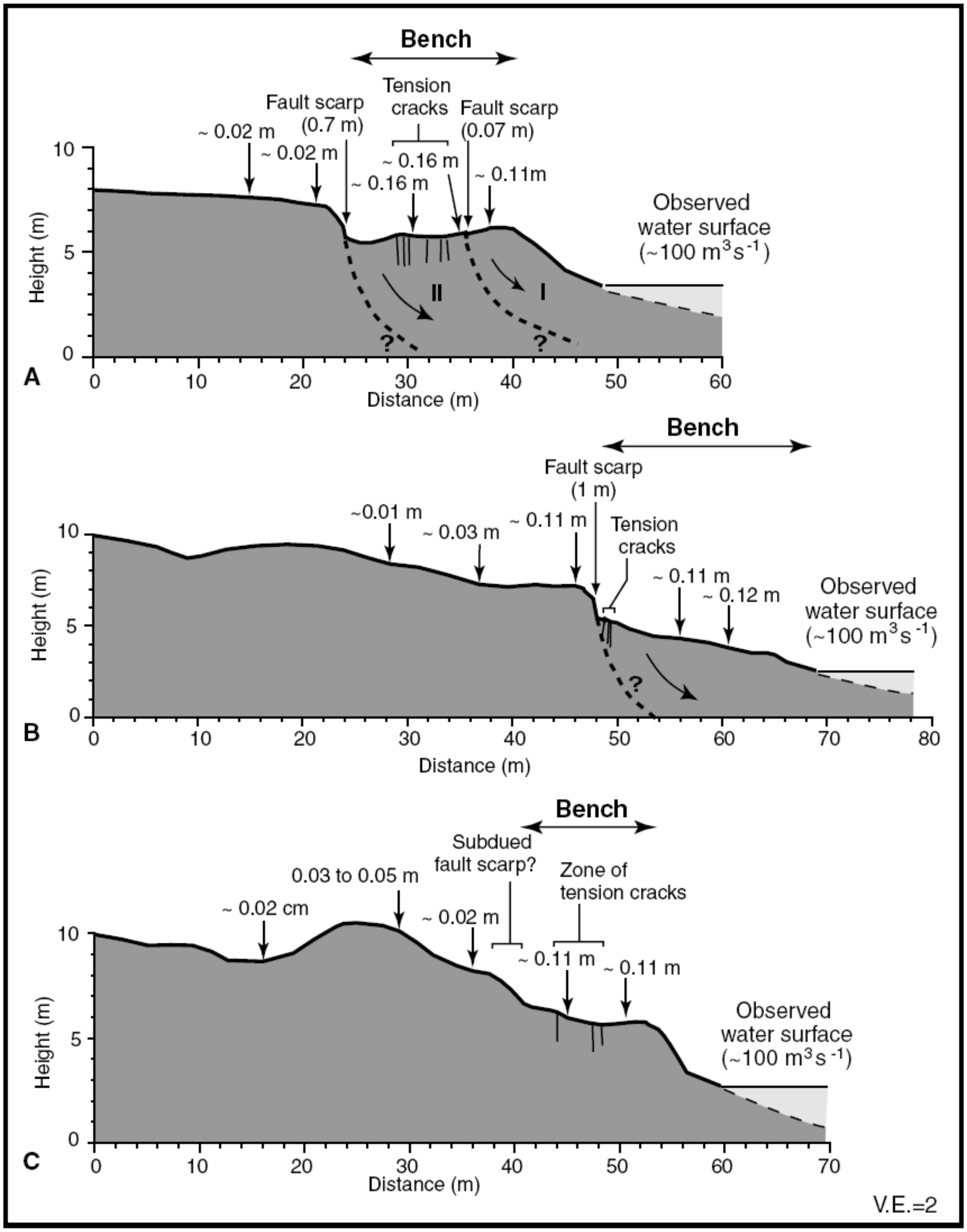


Figure 3.8: Examples of inferred and active rotational bank failures at three surveyed profiles (after Brooks 2003). The arrows on the profiles indicate the thickness of the alluvial sediment deposited during the 2000 freshet. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

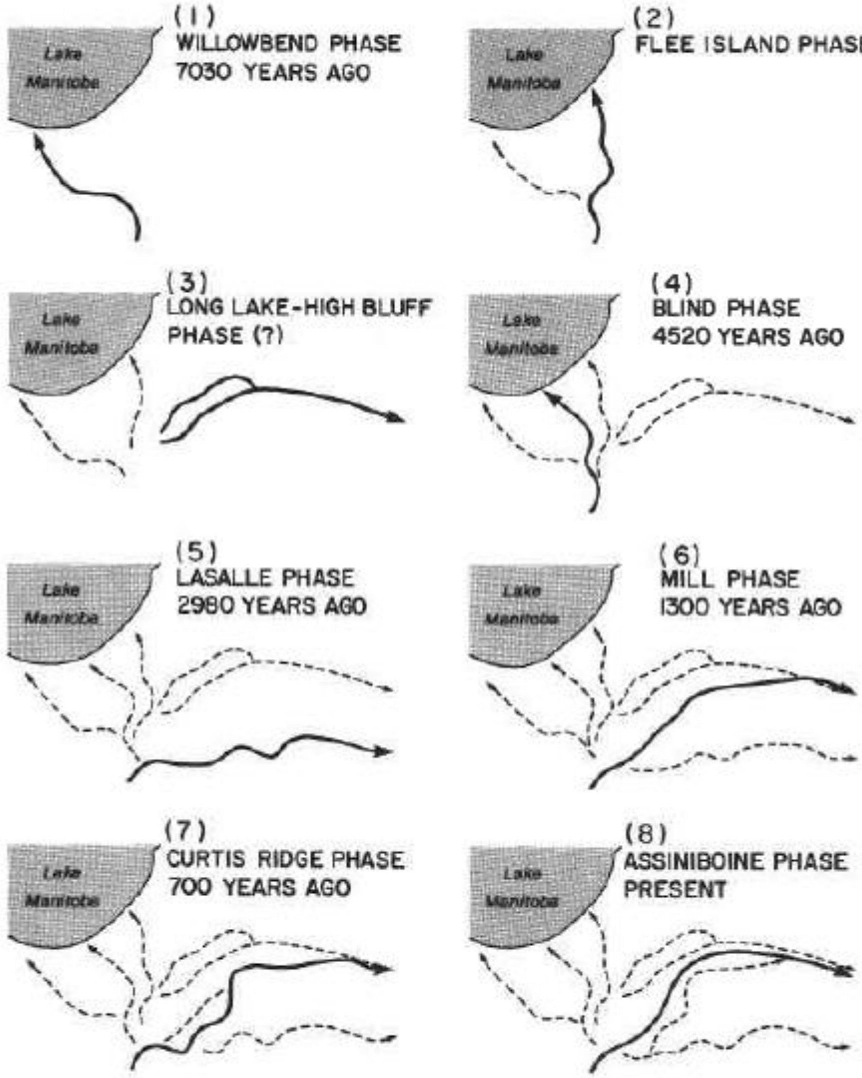


Figure 3.9: Schematic sequence of paleochannel evolution (after Rannie 1989). Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

Figure 3.10: Typical failure controlled bank along the Red River on an outside bend. Note the retrogressing headscarp and shallow slope angle.

Figure 3.11: Typical erosion controlled bank encountered along the inside bend of the Red River. Note the steep riverbank face.

Figure 3.12: Typical transition bank encountered along the Red River. Site is located downstream of an outside bend between Annabella and Mordaunt Streets.

Table 3.1: Geotechnical Properties of Winnipeg Clays.

Soil Properties	Lower Bound	Upper Bound
Deformation Modulus[1]	3.5 MPa	21 MPa
Poisson's Ratio	0.4	0.5
Unconfined Compressive Strength[2]	50 kPa	120 kPa
Undrained Shear Strength[3]	35 kPa	85 kPa
Residual Angle of Friction	8°	12°
Compression Index	0.5	1.0
Swelling Pressure	0	75 kPa
Coefficient of Earth Pressure at Rest	0.6	0.8
Overconsolidation Ratio	1	5
Moist Unit Weight	16.2 kN/m^3	18.2 kN/m^3
Dry Unit Weight	10.2 kN/m^3	13.3 kN/m^3
Liquid Limit	65	110
Plastic Limit	20	35
Plasticity Index	40	75
Sensitivity	2	4

[1] Based primarily on pressuremeter tests.
[2] Based on unconfined compression tests.
[3] Based on a combination of unconfined compression tests, field vane and laboratory vane.

Table 3.1 is based on data from Baracos et al. 1983a.

Table 3.2: Geotechnical Properties of Till in the Winnipeg Area.

Geotechnical Property		**Typical Range**	
		Lower	**Upper**
Unit Weight (moist), pcf			150
Unit Weight (dry), pcf			140
Matrix Material			
	Liquid Limit (%)	13	20
	Plastic Limit (%)	11	13
Gradation			
	Clay Size[1] (%)	10	20
	Silt Size (%)	30	40
	Sand Size (%)	25	35
Pressuremeter Modulus (ksi)			25-35

Notes: [1] Mostly rock flour, with limited clay materials. Information is based on the limited data available.
1 ksi = 6.895 MPa, 1pcf=0.157 kN/m^3

Table 3.2 is based on data from Baracos et al. 1983b.

Chapter 4 Principles of Site Characterization

4.1 Introduction

Before developing a Riverbank Asset Management System (RAMS) for publicly owned riverbank property, it was necessary to review and prioritize the thirty-six (36) priority sites identified in the 2000 Riverbank Stability Characterization Study.[1] This was done to provide a baseline assessment of the risk level for the current priority riverbanks. The review was completed by the author, a graduate student in the Department of Civil Engineering, at the University of Manitoba. The site characterizations were done in the spring, summer and fall of 2007, and the spring of 2008. Comparative site assessments were made, dating back to 2000. Of particular focus, however, were changes in riverbank stability that have occurred since 2004. The 2004 site conditions were documented in the 2004 Monitoring Report, prepared by the Waterways Section of Planning, Property and Development at the City.

The site characterization and monitoring program completed in 2007 and 2008 provided a comprehensive update of visual site inspections and photographic records at each site. The results of the site investigations were used to: 1) assess the stability of each site 2) collect appropriate information to be used in the development of the RAMS and 3) identify potential “first phase” priority sites.

The 2007 and 2008 site characterizations included the following:

[1] Study was prepared by the Waterways Section of Planning, Property and Development at the City of Winnipeg.

- Visual inspection of 36 sites along the Red and Assiniboine Rivers in May and June 2007, October 2007, and May and June 2008. Photographs were taken at each site.
- A completed site observation checklist for each site that can be used in the development of the RAMS.
- Review of the 2000 Riverbank Stability Characterization Study and the 2004 Monitoring Program.
- Comparisons of air photos from 1988, 1998 and 2004 for selected sites.

4.2 Previous Site Characterizations

A Riverbank Stability Characterization Study completed in 2000 by the Waterways Section of the Planning, Property and Development Department at the City, was compiled to characterize, assess, and monitor riverbank stability. The 2000 Riverbank Stability Characterization Study indicated it would cost approximately $80 million to provide stabilization works for forty nine (49) publicly owned riverbank properties. The study listed twelve ”first phase” priority sites, that is, the twelve sites that required the most urgent stabilization works. The total cost to provide stabilization works for these twelve sites was around $11.5 million (2000 dollars).

In May 2000, the Riverbank Management Committee, a committee comprised of City of Winnipeg councillors, provided funding for an on-going riverbank stability monitoring program within the City of Winnipeg. The riverbank stability monitoring program monitors changes in riverbank stability conditions. The monitoring program allows the Riverbank Management Engineer to reprioritize the “first phase” priority sites if riverbank stability conditions change.

The Riverbank Management Committee recognized the importance of maintaining its riverbanks as a valuable resource, and adopted the recommendations provided in the 2000 Riverbank Stability Characterization Report. These recommendations included:

- Obtain low-level aerial photography (air photos) along the waterways in the City every three years. The latest air photos were flown in the fall of 2008.
- Ongoing monitoring of the twelve "first phase" priority sites identified in the 2000 Riverbank Stability Characterization Report. Supplemental monitoring was completed in 2002 and 2004 by the City of Winnipeg. The University of Manitoba completed additional monitoring in 2007 and 2008.

The City of Winnipeg's Riverbank Management Committee provided funding for riverbank stability monitoring to be conducted in 2002 and 2004. As a result of the additional funds provided for monitoring of public riverbank property, a Riverbank Stability Characterization Study, Monitoring Program Report was completed in 2004. The report included a comprehensive engineering review, assessment and update of stability conditions along riverbank property in the City of Winnipeg (City of Winnipeg 2004). Changes in visual site inspections, photographs and airphotos between 2000 and 2004 were analyzed to determine changes in riverbank stability conditions. Based on these observed changes in site conditions between 2000 and 2004, the "first phase" priority site list was modified to reflect the changes in stability conditions of publicly owned riverbank property (Table 4.1). As shown in Table 4.1, the total cost for stabilization works was estimated to be $12,915,000 (2000 dollars) for the "first phase" priority site list developed in 2004.

4.3 Characterizations of Study Sites

Thirty-six (36) of the forty-nine (49) publicly owned sites, identified in the 2000 Riverbank Stability Characterization Study, were inspected by the author during the 2007 and 2008 monitoring program. The scope of the project at this time was limited to developing a RAMS for the Red and Assiniboine Rivers; therefore, only sites located along the Red and Assiniboine Rivers were inspected during the site characterization program. Five (5) sites that have been stabilized since 2000 were inspected and characterized to confirm post construction performance. Tables 4.2 and 4.3 identify the sites inspected along the Red and Assiniboine Rivers during the author's 2007 and 2008 site characterization program. The tables also include relevant information about: 1) bank type 2) stabilization length and 3) preliminary cost estimate for stabilization works.

4.3.1 Purpose of Study Site Characterizations

Site characterizations were conducted in 2007 and 2008 to review, analyze and prioritize the thirty-six sites identified in the 2000 Riverbank Stability Characterization Study. These site characterizations were completed in the spring, summer and fall of 2007, and the spring of 2008. The new characterizations allowed the author to make comparative assessments of riverbank stability conditions between 2004 and 2008 at the various sites. The comparative site assessments were used to: 1) assess the stability at each site 2) collect appropriate attribute information that could be used to develop a RAMS and 3) identify a potential "first phase" priority site list that might or might not be the same as the earlier lists from 2000 and 2004. The site characterizations completed in 2007 and 2008 provide a comprehensive update of visual site inspections and photographic records at each site. The photographic record collection and the updated visual site inspections for each site are located in Appendix C and Appendix F respectively.

4.3.2 Principles for Collecting Study Site Characterization Information

A literature review of the geomorphology and stratigraphy of the Red and Assiniboine Rivers was conducted prior to the development of the riverbank observation checklist. An overview of this review was presented in Chapter 3. Literature sources included: Brooks (2003), Brooks (2005), Nielsen (1993), Brooks (2003b), Brooks (2002), Brooks (2004), Thorleifson et al. (1998), Baracos and Graham (1981), Leir (2004), Esford et al. (2004), Porter et al. (2004), Leir et al. (2004), Leir et al. (2002), and Baracos and Kingerski (1998). These references were utilized to develop a riverbank observation checklist. Engineering judgment and experience of a technical steering committee consisting of the City of Winnipeg's Riverbank Management Engineer, the author and an Associate Professor of the Civil Engineering Department at the University of Manitoba, were also used to develop the riverbank observation checklist. Appendix A contains the riverbank observation checklist and corresponding legend. The Riverbank Management Engineer, at the City of Winnipeg, approved the riverbank observation checklist before it was employed in the field. The river co-ordinate system used by the Waterways Section of Planning, Property and Development, was adopted during the site characterization program for consistency purposes.

The riverbank observation checklist was prepared prior to the site characterizations being conducted so that appropriate and consistent attribute information could be collected for each site along the Red and Assiniboine Rivers. Appendix B provides a manual, with photographic illustrations of the possible input parameters that can be used with the riverbank observation checklist. The terminology used in the riverbank observation checklist was later utilized to develop the RAMS spreadsheet that will be presented and discussed in Chapter 6. To ensure the consistency of collected field attributes, this manual should be referred to before future site characterizations are conducted. A transparent and easy-to-use riverbank observation checklist assures that future site characterizations are 1) repeatable 2) clearly documentable and 3) objective. The riverbank observation checklist can easily be used by both professional and field staff when conducting future site characterizations.

Site specific information such as: bank height, till depth, surficial geology and groundwater are difficult to visually collect in the field. When necessary, engineering reports from the City of Winnipeg's engineering database were used to obtain this information. Numerical values for bank slope and retrogression ratio were obtained from the site surveys conducted in the late spring of 2008. Chapter 5 discusses the results of the site surveys in further detail. Additional site information such as: the extent of bank failure, bank geometry, vegetation cover, surface water, bank drainage, evidence of movement, edge erosion, loading at the top of the slope, accumulation of overbank deposits, existing works, anthropogenic influences and consequence factors were collected during the site characterizations using the riverbank observation checklist.

4.3.2.1 Site Characterizations

As mentioned previously, detailed site characterizations were conducted in May and June 2007, late October 2007, and between May and early June 2008. Due to intense precipitation events in the Red and Assiniboine River watersheds in the spring and summer of 2007, river levels fluctuated significantly during this period. As a result, the time frame for conducting site characterizations of exposed riverbank faces was extremely limited. To collect information that could not be obtained during high water levels, additional site characterization work was conducted in late October 2007 after water levels had receded and SALD was no longer operational for the season. Because the river levels did not fluctuate significantly between May and June 2008, site conditions were conducive for conducting detailed site characterizations and site surveys of the exposed riverbank face between the NSWL and top of the bank.

Foot reconnaissance was conducted on in the spring and fall of 2007 for sites that could be easily accessed by walking. Additional foot reconnaissances were conducted in the spring of 2008. The River Patrol Unit at the City of Winnipeg arranged boat transportation in the spring and summer of 2007 and 2008 so sites that could not easily be accessed by foot, could be observed from the boat. The sites that could not be easily accessed by foot were primarily sub-vertical erosion-controlled banks. Due to the high water levels and strong currents encountered when conducting the boat reconnaissance in 2007, only limited sections of exposed riverbank face could be safely observed. In some erosion-controlled sections along the Red River, namely King's Park and Maple Grove Park the riverbank faces were not exposed. Riverbank faces that could not be observed during the high water levels were re-visited in late October after drawdown and in May and June 2008. Site observations and photographs were taken when the riverbank face was exposed, so an accurate site characterization could be completed.

Site observations were collected for each of the thirty-six sites by filling out the riverbank observation checklist (Appendix A). As mentioned previously, site specific information that could not be obtained in the field, such as depth to till, surficial geology, bank height and groundwater information were obtained from the City of Winnipeg's engineering database. Additional groundwater information, such as installation details of monitoring wells and groundwater levels over the previous ten year period, was provided by the Province of Manitoba. Digital photographs were taken during the site characterization program. The following information was recorded about each photograph: 1) photograph number 2) photograph direction 3) photograph description and 4) location of photograph. The information about each photograph was subsequently input into an Excel spreadsheet (Appendix C) and later transferred into Google Earth (2008)©. Chapter 7 discusses the transfer of the photographs into Google Earth (2008)©.

4.3.2.2 Review of Aerial Photographs (Airphotos)

Low level aerial photographs from 1988, 1998 and 2004 with a 1:5000 scale were reviewed to analyze the magnitude of riverbank slope movement that occurred between 1988 and 2004. Air photos from before and immediately following the 1997 flood were examined to determine if any visual evidence existed of riverbank slope movement caused by this large magnitude flood event. Aerial photographs taken in the fall of 2004, at the time of the air photo review, provided the most up to date aerial information on riverbank property in the City of Winnipeg. The aerial photographs from 2004 were taken after the completion of the 2004 Monitoring Report, so a review of these air photos had not been previously conducted. Selection of sites for air photo analysis was based on the magnitude of slope movements that occurred between 2000 and 2007. The magnitude of slope movement was determined from the site characterizations in the field and from desk top study.

Results of interpretations of the air photos from 1988, 1998 and 2004 were overlain on a Google Earth Pro ©(2008) image of the City of Winnipeg. Appendix E shows the air photo analysis completed for the 1988, 1998 and 2004 air photos. The air photo review for each year was displayed as a separate layer in Google Earth Pro©. By creating separate layers, it was possible to see the changes in stability conditions at a specific site over a sixteen (16) year period. The Google Earth Pro© software also enables a user to compare the present slope configuration to the most recent air photograph interpretation. In this way, it was possible to determine if significant slope movement occurred between 2004 (the most up to date air photographs at the time of the analysis) and present. The results of the air photo analysis were used to provide supplemental information about changes in riverbank stability conditions. The results have been added into the site characterizations. As discussed in Chapter 6, the results of the site characterizations were subsequently used to develop the RAMS.

4.3.2.3 River Level and Precipitation Monitoring

River levels and precipitation were available between March 23, 2007 and August 13, 2007. The river levels at the Bishop Grandin Bridge, James Avenue and Kildonan Bridge were provided by the City of Winnipeg. Precipitation amounts were obtained from Environment Canada's website (http://www.climate.weatheroffice.ec.gc.ca/). The precipitation levels for the City of Winnipeg were recorded at the James Richardson International Airport. Thus, precipitation amounts that fell at the various sites may vary slightly from the recorded values, due to the non uniform precipitation amounts associated with storm cells.

River levels fluctuated significantly between the end of May and the end of June 2007, due to intense precipitation events in the Red and Assiniboine River watersheds. Figure 4.1 illustrates the water elevations at James Avenue Datum, Bishop Grandin and Kildonan Bridges and precipitation amount between March 23 and August 13 2007. Figure 4.2 compares the water elevations at the three locations to the regulated NSWL. Table 4.4 outlines the water level at each site on the date that the initial site characterization was conducted in late spring or early summer 2007. The water level at each site was then compared to the water level at the James Avenue Datum.

4.3.3 Study Site Characterization Assessments

Detailed site characterizations were conducted for the thirty-six (36) sites identified along the Red and Assiniboine Rivers in the 2000 Riverbank Stability Characterization Study completed by the Waterways Section of Planning, Property and Development. Thirty-three (33) sites are located along the Red River while three (3) sites are found along the Assiniboine River. Appendix C shows the site photographs taken while conducting the site characterizations by foot and boat. Appendix F contains detailed site observations for each site. The site observations include a comparative assessment of the riverbank stability at each site and the information collected using the riverbank observation checklist.

Due to a restricted timeline, not all of the detailed site characterizations conducted in 2007 were completed under low flow or leaf free conditions. Therefore, the ground surface conditions in some of the 2007 site photographs are masked by vegetation. The 2008 site characterizations were conducted, under leaf free and low flow conditions.

4.3.4. Priority Site Comparisons and Rankings

Potential “first phase” priority sites were determined by analyzing changes in riverbank stability conditions between 2004 and 2008. The analysis was completed by reviewing: 1) the riverbank observation checklist, 2) site characterization assessments, and 3) air photo interpretation. When the site characterization assessments and air photo analyses were conducted, the approximate time line of the observed slope movement was estimated.

The 2004 Riverbank Stability Characterization Study, Monitoring Report was utilized in determining the changes in riverbank stability conditions between 2004 and 2008. The updated “first phase” priority site list produced in 2004 was also reviewed. If a site was not re-assessed in 2004, a comparison of the change in riverbank stability conditions between 2004 and 2008 could not be completed. Therefore, available information from the 2000 Riverbank Stability Characterization Study was used to make a comparative assessment of the site conditions between 2000 and 2008. Engineering judgment and experience of the technical steering committee were used to ascertain an approximate time line of slope movement between 2000 and 2008, if a site was not re-evaluated in 2004.

Two sites were stabilized during the winter of 2006-2007. A shear key was constructed at St. John’s Park while rock caissons were placed on the lower slope at Pembina Highway and Grandmont Blvd. In addition, St. Vital Park was stabilized in the winter of 2007-2008 by installing rockfill columns, regrading the riverbank and placing an erosion protection blanket. These sites were therefore not considered for the 2008 potential “first phase” priority site list.

Table 4.5 illustrates the “first phase” priority site list generated in 2008. The “first phase” priority sites were determined by conducting comparative assessments between either 2000 and 2008 or 2004 and 2008, depending on the available site information. The comparative assessments were done using historical and present day site characterization information. The primary focus, however, was placed on changes to riverbank stability conditions between 2004 and 2008.

The ranking of the 2008 “first phase” priority site list did not explicitly take into account either the probability or consequence of a riverbank slope failure. Thus, the ranking system for the “first phase” priority sites did not incorporate weighting factors for probability and consequence attributes that affect the stability of public riverbank property. As such, the ranking of the “first phase” priority sites in 2004 and 2008, shown in Tables 4.1 and 4.5 respectively, depended primarily on visual site observations and engineering judgment. Therefore, the ranking of the “first phase” priority sites depends on the individual conducting the site characterizations. Only by reducing the amount of subjective engineering judgment and personal and political influences involved in producing a “first phase” priority site list, can a consistent “first phase” priority site list be generated.

Because of the limitations of the present methodology used to rank the “first phase” priority site list, it was decided that the thirty-six sites assessed during the site characterization program should be analyzed and ranked with a RAMS in Google Earth Pro (2008)©. This formed the basis of the remaining work described in this thesis document. An unbiased “first phase” priority site list can be produced by developing an transparent and consistent RAMS in Google Earth Pro (2008)©. With the development of a RAMS, the City will be able to effectively assess its riverbanks from a risk analysis and management perspective. The RAMS that has now been developed by the author allows and facilitates timely reviews of priority sites as riverbank conditions and input parameters change. This work will be described in the remaining chapters of this thesis document.

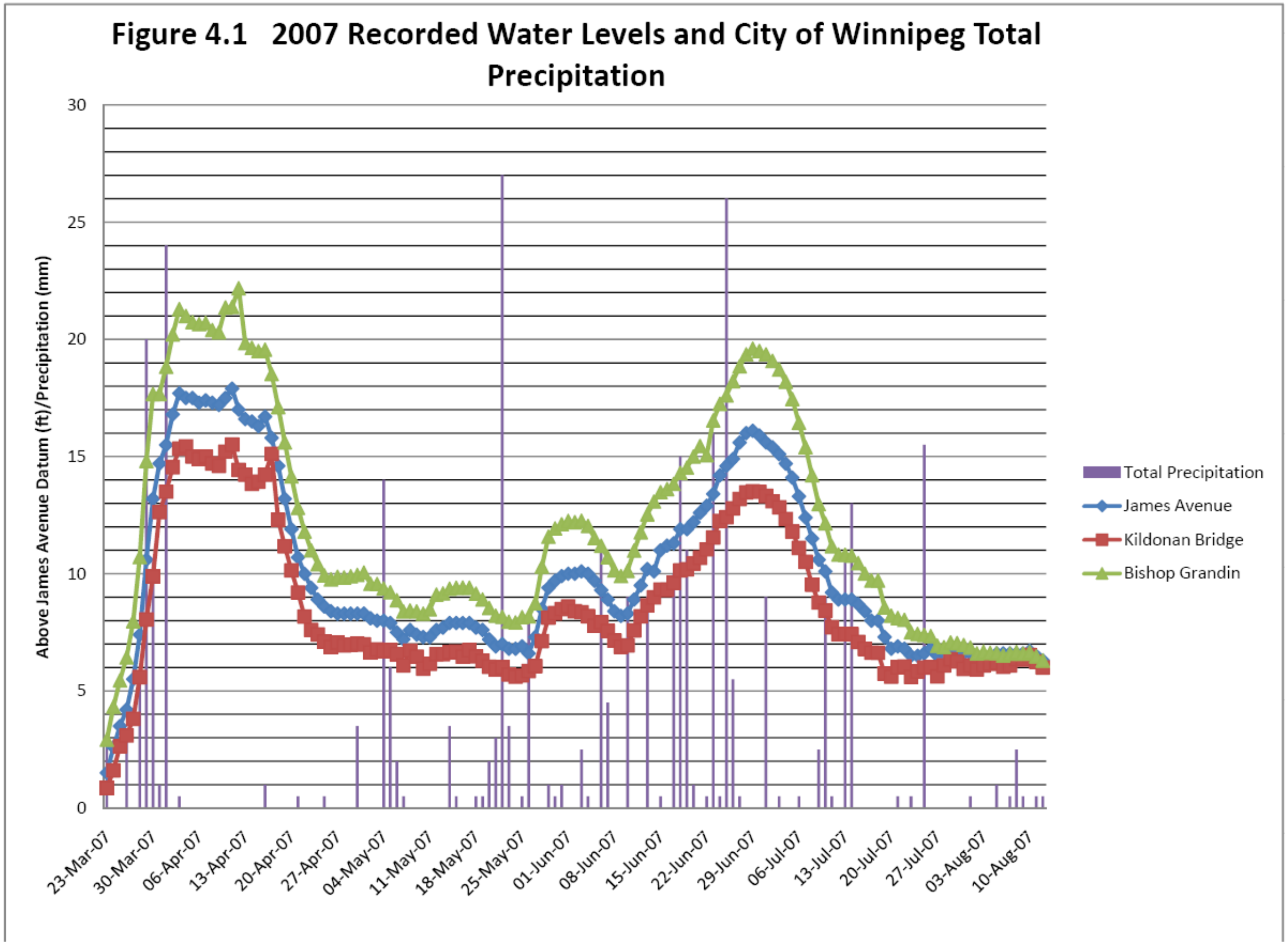


Figure 4.1: 2007 Recorded Water Levels and City of Winnipeg Total Precipitation.

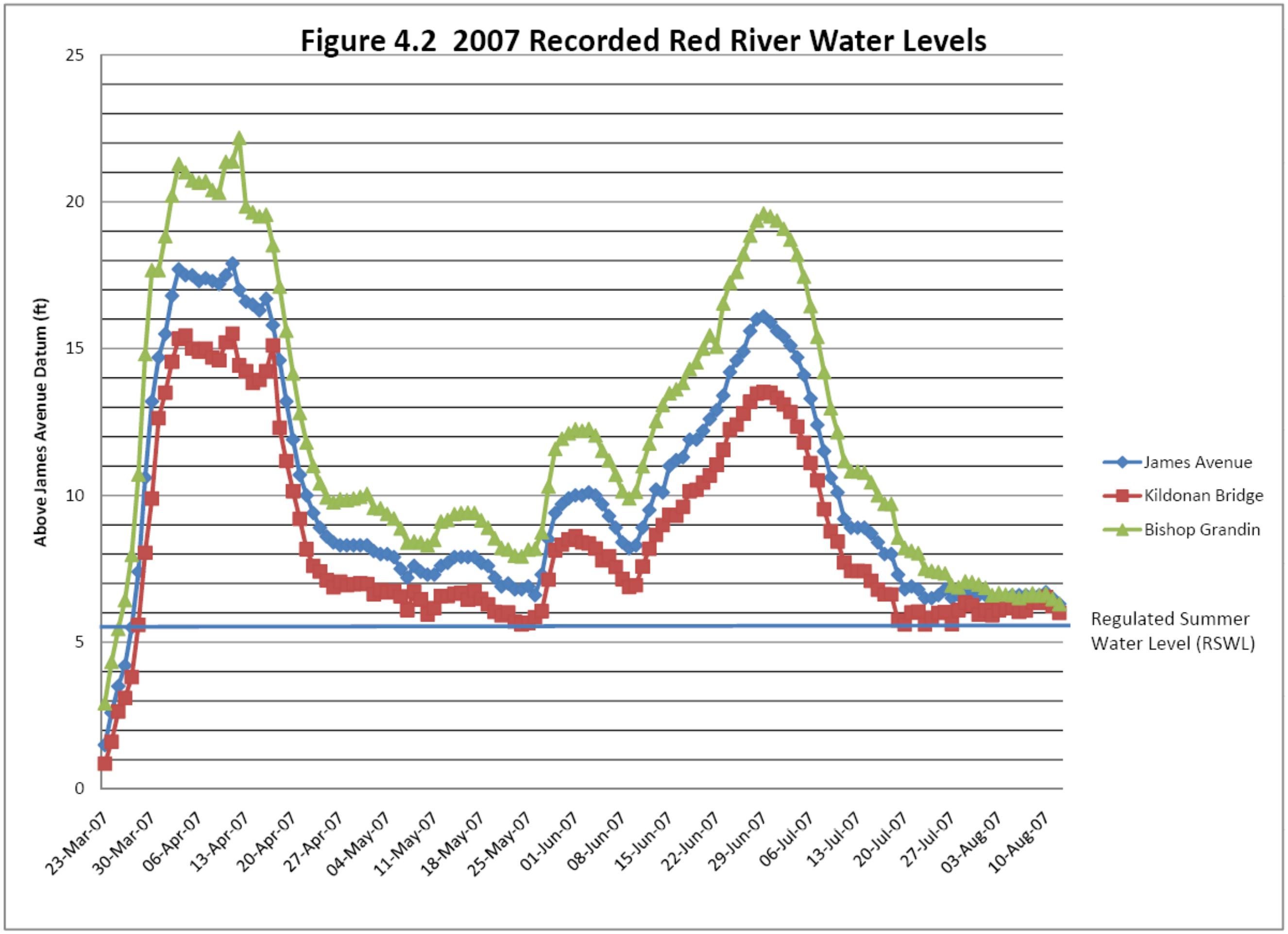


Figure 4.2: 2007 Recorded Red River Water Levels.

Table 4.1: "First Phase": Priority Riverbank Stabilization Sites (2004)

Site	*Preliminary Cost Estimate ($)
Red River – St. Vital	$1,645,000
Red River – Churchill Park	$2,000,000
Red River – St. John's	$600,000
Red River at Bunn's Creek	$165,000
Red River – Lyndale Drive	$1,455,000
Red River – King's Park (Inside Bend)	$450,000
Red River – Crescent Park	$765,000
Assiniboine River – Fort Rouge	$400,000
Red River – King's Park (Outside Bend)	$2,720,000
Red River – End of Minnetonka	$440,000
Seine River – Evans at Cusson Street	$240,000
Assiniboine River – Granite Curling Club	$870,000
TOTAL	**$12,915,000**

*Note: The dollar amount is based on the 2000 Riverbank Stability Characterization Study and does not reflect additional work that may be required if stability conditions have changed.

Table 4.2: 2007 and 2008 Red River Site Characterizations

Location	River Co-ordinates	Bank Type	Stabilization Length (m)	Preliminary Cost Estimate ($)
Red River				
Wardlaw to Brandon	RRR50.81 to RRR52.23	F	820	3,280,000
Kings Park	RRR71.40 to RRR72.08	F	680	2,720,000
Normand Park	RRL69.75 to RRL70.42	F	670	2,680,000
Canoe Club	RRL58.79 to RRL59.34	F	550	2,200,000
Churchill Park -Montague to Cockburn	RRR56.00 to RRR56.50	F	500	2,000,000
Churchill Park -Eccles to Osborne	RRR54.45 to RRR55.53	E	1080	1,620,000
Lyndale Drive - Highfield to Birchdale	RRL51.33 to RRL52.30	E	970	1,455,000
St. Vital Park -Cemetery	RRL64.39 to RRL64.72	F	330	1,320,000
St. Mary's Road	RRL70.66 to RRL71.15	F	330	1,320,000
*Annabella to May	RRR47.82 to RRR48.12	F	300	1,200,000
Norquay Park	RRR44.90 to RRR45.18	F	280	1,120,000
Provencher to LaVerendrye	RRL49.10 to RRL49.37	F	270	1,100,000
River to RIvergate	RRL67.27 to RRL67.53	F	260	1,040,000
Maple Grove Park – D/S Perimeter	RRL73.03 to RRL73.70	E	670	1,005,000
*St. Vital Park	RRL64.00 to RRL64.25	F	250	1,000,000
Mordaunt to Annabella	RRR47.49 to RRR47.82	F	330	825,000
Crescent Park	RRR62.35 to RRR62.86	E	510	765,000
Burrows to Pritchard	RRR44.76 to RRR44.90	F	140	700,000
*St. Vital Park – U/S Apex	RRL63.57 to RRL64.00	E	430	645,000
Darveau to Hebert	RRL48.63 to RRL48.79	F	160	640,000
*St. John's Park	RRR44.15 to RRR44.30	F	150	600,000
Messager to St. Joseph	RRL48.15 to RRL48.53	E	380	570,000
*Pembina and Grandmont	RRR76.28 to RRR76.42	F	140	560,000
Guay Park	RRL53.50 to RRL53.64	F	140	560,000
Churchill Park -Osborne to Montague	RRR55.64 to RRR56.00	E	370	555,000
Maple Grove – U/S Apex	RRL72.15 to RRL72.50	E	350	525,000
King's Park	RRR71.10 to RRR71.40	E	300	450,000
End of Minnetonka	RRL67.00 to RRL67.11	F	110	440,000
Maple Grove – D/S Apex	RRL71.88 to RRL72.15	E	270	405,000
St. Vital Park – D/S Apex	RRL63.25 to RRL63.57	E	320	320,000
Toilers Park	RRR57.09 to RRR57.15	F	60	240,000
*Bunn's Creek	RRL37.10 to RRL37.21	F	110	165,000
End of Grace St.	RRR47.24 to RRR47.29	E	50	75,000
Total Red River			**12,280**	**$34,100,000**

*Note: Sites stabilized between 2000 and 2008. Sites were inspected and characterized to monitor post construction performance. Cost estimates for stabilization works were taken from the 2000 Riverbank Stability Characterization Study. Present day costs may be higher due to inflation or additional required stabilization works. Bank type 'F' denotes a failure-controlled bank while bank type 'E' indicates the bank is erosion-controlled.

Table 4.3: 2007 and 2008 Assiniboine River Site Characterizations

Location	River Co-ordinates	Bank Type	Stabilization Length (m)	*Preliminary Cost Estimate ($)
Assiniboine River				
Granite Curling Club	ARR1.69 to ARR1.90	F	210	870,000
Fort Rouge Park	ARL1.12 to ARL1.24	F	120	400,000
Munson Park	ARL3.20 to ARL3.37	F	170	210,000
Total Assiniboine River			**580**	**$1,480,000**

*Cost estimates for the stabilization works were taken from the 2000 Riverbank Stability Characterization Study. Present costs may be higher due to inflation or additional stabilization works required.

Table 4.4: Red River Water Levels During 2007 Site Characterizations

Site	Detailed Site Reconnaissance Date	Detailed Boat Reconnaissance Date	Geodetic Water Level (ft)	Water Level Above James Avenue Datum (ft)	James Avenue Water Level (ft)	Height Above James Avenue (ft)
Grainite Curling Club	31-May-07		737.89	10.31	9.90	0.41
Fort Rouge Park	04-Jun-07		737.99	10.41	10.00	0.41
Munson Park	04-Jun-07		737.99	10.41	10.00	0.41
Wardlaw	05-Jun-07		737.70	10.11	9.70	0.41
Brandon	05-Jun-07		737.86	10.27	9.70	0.57
Guay Park	05-Jun-07		738.04	10.45	9.70	0.75
Churchill Park Montague to Cockburn	05-Jun-07		738.29	10.70	9.70	1.00
Churchill Park Montague to Cockburn (D/S)	05-Jun-07		738.33	10.74	9.70	1.04
Toilers Park	05-Jun-07		738.39	10.81	9.70	1.11
Canoe Club	05-Jun-07		738.42	10.84	9.70	1.14
Pembina at Grandmont	06-Jun-07		740.33	12.74	9.30	3.44
St. Mary's Road and Perimeter Highway	06-Jun-07		739.66	12.07	9.30	2.77
Normand Park	06-Jun-07		739.50	11.92	9.30	2.62
King's Park	06-Jun-07		739.50	11.91	9.30	2.61
Annabella to May	08-Jun-07		735.80	8.21	8.40	-0.19
Morduant to Annabella	08-Jun-07		735.73	8.15	8.40	-0.25
Norquay Park	08-Jun-07		735.37	7.79	8.40	-0.61
Burrows to Pritchard	08-Jun-07		735.36	7.78	8.40	-0.62
St. John's Park	08-Jun-07		735.31	7.72	8.40	-0.68
Bunn's Creek	08-Jun-07		734.47	6.89	8.40	-1.51
St. Vital Park (63 km)	11-Jun-07		738.35	10.77	8.90	1.87
St. Vital Park (65 km)	11-Jun-07		738.55	10.96	8.90	2.06
Minnetonka Street	11-Jun-07		738.80	11.21	8.90	2.31
River to Rivergate	11-Jun-07		738.83	11.25	8.90	2.35
King's Park (71.4 km)	14-Jun-07		741.16	13.57	8.90	4.67
King's Park (72 km)	14-Jun-07		741.22	13.64	8.90	4.74
Darveau to Hebert	20-Jun-07		740.16	12.57	12.20	0.37
Provencher to LaVerendrye	20-Jun-07		740.31	12.72	12.20	0.52
End of Grace St.		25-Jun-07	741.81	14.22	14.60	-0.38
Messager to St. Joseph		25-Jun-07	742.02	14.43	14.60	-0.17
Lyndale Drive (51.5 km)		25-Jun-07	742.97	15.39	14.60	0.79
Lyndale Drive (52.5 km)		25-Jun-07	743.16	15.57	14.60	0.97
Churchill Park Drive (Eccles, 54.6 km)		25-Jun-07	743.53	15.94	14.60	1.34
Churchill Park Drive (Osborne, 55.6 km)		25-Jun-07	743.70	16.12	14.60	1.52
Churchill Park Drive (Osborne, 55.6 km)		25-Jun-07	743.69	16.10	14.60	1.50
Churchill Park Drive (Montague, 56 km)		25-Jun-07	743.78	16.19	14.60	1.59
Crescent Park (62.5 km)		25-Jun-07	744.77	17.18	14.60	2.58
Crescent Park (63 km)		25-Jun-07	744.84	17.25	14.60	2.65
King's Park		26-Jun-07	746.74	19.15	14.90	4.25
Maple Grove Park (71.8 km)		26-Jun-07	746.86	19.27	14.90	4.37
Maple Grove Park (72.4 km)		26-Jun-07	746.95	19.36	14.90	4.46
Maple Grove d/s of Perimeter (73 km)		26-Jun-07	747.04	19.45	14.90	4.55
Maple Grove d/s of Perimeter (73.6 km)		26-Jun-07	747.13	19.54	14.90	4.64
End of Grace St	04-Jul-07		742.06	14.47	14.70	-0.23
Messager to St. Joseph	04-Jul-07		742.30	14.72	14.70	0.02
Lyndale Drive	04-Jul-07		743.31	15.73	14.70	1.03
Lyndale Drive	04-Jul-07		743.53	15.94	14.70	1.24
Churchill Park Drive Eccles (54.6 km)	04-Jul-07		743.96	16.37	14.70	1.67
Churchill Park Drive Osborne (55.6 km)	04-Jul-07		744.15	16.57	14.70	1.87
Churchill Park Drive Osborne (55.5 km)	04-Jul-07		744.13	16.55	14.70	1.85
Churchill Park Drive Montague (56 km)	04-Jul-07		744.24	16.66	14.70	1.96
Crescent Park (62.5 km)	04-Jul-07		745.34	17.75	14.70	3.05
Crescent Park (63 km)	04-Jul-07		745.41	17.83	14.70	3.13
King's Park	04-Jul-07		747.16	19.57	14.70	4.87
Maple Grove Park (71.8 km)	04-Jul-07		747.33	19.74	14.70	5.04
Maple Grove Park (72.4 km)	04-Jul-07		747.46	19.87	14.70	5.17
Maple Grove d/s of Perimeter (73 km)	04-Jul-07		747.58	20.00	14.70	5.30
Maple Grove d/s of Perimeter (73.6 km)	04-Jul-07		747.71	20.12	14.70	5.42

Note: James Avenue Datum is 727.586 ft

Table 4.5: Potential "First Phase" Priority Riverbank Stabilization Sites (2008)

Site	Preliminary Cost*
Churchill Park Drive (Montague to Cockburn)	$2,000,000
End of Minnetonka	$440,000
King's Park (Outside Bend)	$2,720,000
Maple Grove Park (U/S of Apex)	$525,000
Crescent Park	$765,000
Canoe Club	$2,200,000
Lyndale Drive	$1,455,000
St. Vital Cemetery	$1,320,000
Guay Park	$560,000
Normand Park	$2,680,000
St. Mary's @ Perimeter Highway	$1,320,000
Annabella to Mordaunt	$825,000
TOTAL	**$16,810,000**

*Note: The preliminary cost estimates were based on the 2000 Riverbank Stability Characterization Study. Present costs may be higher due to inflation and additional stabilization works required.

Chapter 5 Site Surveys

5.1 Introduction

Site surveys were conducted by the author between May 27 and June 4, 2008 for twenty-seven (27) of the thirty-six (36) sites identified in the 2000 Riverbank Stability Characterization Study. The site surveys were conducted to assess changes in riverbank slope geometry and riverbank stability conditions.

Sites that were targeted with respect to the implementation of the City of Winnipeg's riverbank stabilization capital works program such as: Bunn's Creek, St. John's Park, Annabella to May Streets, St. Vital Park (U/S of Apex), St. Vital Park (Transition) and Pembina Highway and Grandmont Boulevard did not require additional monitoring as riverbank stabilization measures have been implemented at these sites. Since a local consulting firm has been retained to monitor changes in riverbank stability conditions at the Granite Curling Club, Mr. Don Kingerski, the Riverbank Management Engineer at the City of Winnipeg, decided that the Granite Curling Club did not require additional monitoring to assess changes in riverbank slope geometry. Fort Rouge Park could not be accessed when the site surveys were being conducted because slope re-grading and rip rap placement was taking place at the upstream end of the site. Therefore, a site survey could not be accurately completed at Fort Rouge Park. St. Vital Park (D/S of Apex) was not surveyed because dense vegetation coverage prevented accurate survey readings from being collected.

The site surveys were conducted with a Trimble R8 Global Navigation Satellite System (GNSS) VRS Rover Receiver and Trimble TSC2 Survey Controller. The Trimble R8 VRS Rover is a multi-channel, multi-frequency, receiver, antenna and data-link combined in one unit (http://www.optron.co.za/downloads/datasheets/TrimblesR8VRS_DS.pdf The TSC2 Survey Controller has the capability to operate both Windows and Trimble surveying software. Site information and survey data are stored and saved in the TSC2 Controller. The receiver and controller communicate via an external antenna attached to the rover receiver. The VRS Rover has a GSM cell modem for wireless connection to the internet. Therefore, GNSS data from the Winnipeg base stations can easily be accessed over the internet and no external modem is required. GNSS data such as horizontal and vertical positions, in addition to elevations can be obtained from the Winnipeg base stations. The GNSS data is subsequently transferred from the VRS Rover Receiver to the TSC2 Survey Controller. The horizontal and vertical accuracy of the site surveys is approximately +/-5mm. However, the absolute accuracy of the site surveys depends on: obstructions, satellite orientation, and atmospheric conditions at the time a survey is being conducted.

Prior to conducting each site survey, information about each site, such as site name and location was entered into the TSC2 Survey Controller. Once the VRS Rover Receiver was connected to the Winnipeg base stations via the external modem, a site survey could begin. While conducting a site survey it was possible to enter an identifier code that represents the location where a data point was collected. The top of bank, water level, slope, rip rap, instrumentation, tension cracks, curbs, sidewalks, and tilted trees were delineated during a site survey for this research project. Providing an identifier for each point allows a more accurate generation of riverbank cross sections. At the end of every day, the individual survey files were downloaded into a separate Microsoft Excel file. As explained in Section 5.3 below, the Microsoft Excel files were then used to generate riverbank cross sections.

5.2 Significance of Site Surveys

As mentioned earlier, site surveys were conducted so changes in riverbank geometry and riverbank stability conditions could be analyzed. Site surveys were also performed to outline the extent of slope movement on public riverbank property. The City of Winnipeg provided a digital copy of the 1998 contour information, so a comparison of riverbank geometry between 1998 and 2008 could be performed.

The average slope angle at each site in 1998 and 2008 was of particular interest. The average slope angle was calculated by averaging cross section slope angles. In order to obtain a representative average slope angle, cross sections were created along the entire length of a site. A cross section was not considered in the average slope angle calculation if it did not have a representative number of survey data points in an area where the section was created. The average slope angle was used in all subsequent analyses because it best represented the slope angle for the entire length of the site. A change in the average slope angle may indicate a change in riverbank stability conditions. Section 5.3 will discuss average slope angles in further detail.

As shown in Table 5.1, changes in average slope angles for inside, outside, transition and straight sections of the Red and Assiniboine Rivers were calculated. The change in average slope angle between 1998 and 2008 was analyzed for the following two data sets: 1) average slope angle outlined in the 2000 Riverbank Stability Characterization

Study and 2) 1998 contour data provided by the City of Winnipeg. The average slope angle provided in the 2000 Stability Study was based on 1998 measurements.

By determining the average slope angle in 2008, an up to date retrogression ratio can be calculated for failure-controlled, erosion-controlled, transition and straight sections of the Red and Assiniboine Rivers. Retrogression ratio is defined as the stable slope angle divided by the present average slope angle. The stable slope angle for failure-controlled, erosion-controlled, transition and straight sections of the Red and Assiniboine Rivers was previously determined by the Riverbank Management Engineer at the City of Winnipeg. As identified in Chapter 3, the stable slope angle for a failure-controlled bank is 9H:1V while for an erosion-controlled bank the stable slope angle is 3H:1V. The stable slope angle is 6H:1V, for a transition or straight section. The retrogression ratio calculated from the 2008 site surveys, can be used as an input parameter to calculate the probability factor in the RAMS spreadsheet that has been developed by the author. The representative retrogression ratios calculated for each site are found in Table 5.2.

The expected loss of top of bank was calculated for the average slope angle, in addition to changes in average slope angle. The expected loss of top of bank represents the horizontal distance between the stable slope angle and the present average slope angle. Table 5.2 illustrates the expected loss of top of bank for each site. The expected loss of top of bank, calculated from the 2008 site surveys, can be used as an input parameter to calculate the consequence factor in the RAMS spreadsheet.

5.3 Riverbank Cross Sections

Riverbank cross sections for each site were generated by downloading site survey information from the Trimble TG Office software into Microsoft Excel. Information such as latitude and longitude in NAD83 co-ordinates, elevation of each point in metres, and point identifiers were downloaded into separate columns in Microsoft Excel. The Microsoft Excel data were then imported into Autocad Civil 3D. In Autocad Civil 3D, a surface was created from the data obtained during a site survey. Within the surface, contour lines at 0.25 m intervals were generated for each site.

As mentioned earlier, cross-sections were created at equal distances along the length of a surveyed section. Site specific information obtained from that cross section was removed from subsequent data analysis, if limited survey information existed in an area. This was done to ensure that the most accurate information was used to calculate retrogression ratio and potential loss of top of bank. In addition, the difference in bank height, between the 2008 site survey data and the 1998 contour data was analyzed. An analysis of the difference in bank height between the 2008 site survey data and the 2000 Riverbank Stability Characterization Study could not be completed, because specific bank height information was not provided in the Study. The site specific information obtained from the 2008 site survey was not utilized in subsequent data analysis, if a significant difference in bank height existed between the 2008 survey data and the 1998 contour data. When conducting some site surveys, it was difficult to get accurate readings in dense vegetation. At some locations, it was not possible to get any readings, while in other locations the accuracy of the reading was ±3m. The location was noted, if either of these scenarios presented themselves when conducting a site survey. The cross section information was not utilized in the data analysis, if the data collected in that location was too sporadic for an accurate cross section to be generated.

As noted in Section 5.2, changes in average slope angles for inside, outside, transition and straight sections of the Red and Assiniboine Rivers were calculated. Generally, it was more difficult to compare the change in average slope angle between 1998 and 2008 using the data provided in the Riverbank Stability Characterization Study data. It was sometimes noted that the average slope angle provided in the Study was much different from the average slope angle that was calculated using the 1998 contour data. Therefore, it was determined that the most accurate method to analyze the change in average slope angle between 1998 and 2008 was to compare the 2008 site survey data and the 1998 contour data. Table 5.1 shows the results of the change in average slope angle observed between 1998 and 2008. An increase in average slope angle indicates that the riverbank face is becoming steeper, while a decrease in slope angle indicates that the riverbank face is becoming shallower. Erosion at the toe of the riverbank and accumulation of overbank deposits in the middle of the slope results in the steepening of a riverbank slope. An average slope angle decrease is typically observed when slope movements occur along the riverbank.

Crescent Park and Maple Grove Park (U/S of Apex), both located along an inside bend, showed a significant decrease in average slope angle. The average slope angle at Crescent Park and Maple Grove Park decreased by 25% and 19% respectively between 1998 and 2008. The decrease in average slope angle was not unexpected, as significant slope movement has occurred at both of these sites since 2004. On the contrary, the average slope angle for Lyndale Drive increased by 31% between 1998 and 2008, indicating the riverbank face has become steeper. The average slope angle for Churchill Park Drive (Eccles to Osborne), Maple Grove (D/S Apex) and Messager to St. Joseph increased by 10 % to 15%. King's Park (D/S Apex) and Maple Grove Park (D/S of Perimeter) marginally decreased in average slope angle.

Churchill Park Drive (Montague to Cockburn), located along an outside bend, showed a significant increase in average slope angle. The average slope angle increased by 24% between 1998 and 2008, indicating the bank face has become steeper. The average slope angle at Guay Park decreased by 5% while the average slope angle at Norquay Park and St. Mary's at the Perimeter decreased by 7% between 1998 and 2008. Minimal average slope angle increases or decreases occurred over the ten year period at: Canoe Club, Minnetonka, River to Rivergate, St. Vital Cemetery, and Glasgow to Brandon.

Between Darveau and Hebert Streets, located along a transition section of the Red River, the change in average slope angle was minimal. However, between Mordaunt and Annabella Streets, the average slope angle increased by 7%. On the contrary, the average slope angle at Normand Park Drive decreased by 8%. Between Provencher and LaVerendrye Streets, which is located along a transition to straight reach of the Red River, the average slope angle increased by 4% between river co-ordinates RRL49.28 to RRL 49.37 and decreased by 5% between RRL 49.1 to RRL 49.28.

As noted in Section 5.2, the expected loss of top of bank was calculated for each site with representative site survey data (Table 5.2). When the expected loss of top of bank for an average slope angle is negative, this indicates that the likelihood of significant slope movement occurring is minimal.

5.4 Riverbank Slope Stability Analyses

Stability analyses of riverbanks were conducted for representative cross sections at each site. The cross section data was obtained from the 2008 site surveys. The slope stability analyses were completed in SLOPE/W, modeling software developed by GeoStudio (a product of Geoslope International), using the limit equilibrium (LE) method to calculate the factor of safety (FS). Tutkaluk (2000) provides a synopsis of the various LE methods, including assumptions and limitations for the various methods. Fernando (2007) outlines the benefits and limitations of incorporating finite element (FE) analysis into the LE method. In this research project, FE analysis was not incorporated into LE because groundwater information and soil property information was not available for each site. Therefore, the accuracy of the FE analysis is no better than the LE method in this situation because many assumptions about groundwater conditions and soil properties had to be made.

Factor of safety (FS) is defined as the ratio of maximum available resisting forces to the driving forces in a soil mass. The resisting force and moments depend on the shearing force mobilized along a failure plane while the driving force and moments depend on the soil mass properties and piezometric conditions (Fernando, 2007). When the ratio of resisting forces to driving forces is unity, slope failure is assumed to occur. In Winnipeg, a FS of 1.3 is used to design a ‘stable’ riverbank slope along the Red and Assiniboine Rivers.

SLOPE/W analyses were conducted for representative cross sections during normal summer water level (NSWL) and winter water level (WWL) and flood stage at each site. Flood stage is defined as 3 m above NSWL. Table 5.3 illustrates the location of the representative cross sections, with respect to the City of Winnipeg's river co-ordinate system. The SLOPE/W models were set-up using a Mohr Coloumb analysis. Table 5.4 outlines the soil properties of the alluvial silty clay, glaciolacustrine clay, weak clay layer and till used in the Mohr Coloumb analysis. The soil properties were adopted from Fernando (2007). Tutkaluk (2000) suggested that a weak clay layer, 0.6 m thick, be modeled above the till unit when conducting SLOPE/W analysis. Therefore, this weak clay layer was also incorporated into the SLOPE/W analyses conducted for this research project. Site specific information such as site stratigraphy was determined from previous site characterizations conducted at or in the vicinity of the site. Information required to complete the SLOPE/W analyses was obtained from the City of Winnipeg's engineering database. The following assumptions, taken from Tutkaluk (2000) were also used in the modeling process:

- Slope from NSWL to WWL: 10H:1V
- Slope from WWL to river bottom: 4H:1V
- River bottom elevation: 219 m
- First piezometric line extends 3 m below the top of the riverbank until it intersects the riverbank face. The piezometric line then follows the riverbank face until it intersects the modeled river level.
- Second piezometric line simulates the groundwater levels measured in the till unit. To prevent blowout occurring along the riverbed bottom, the second

piezometric line gradually increases in elevation around mid slope so it intersects the modeled river level at the base of the lower riverbank face.

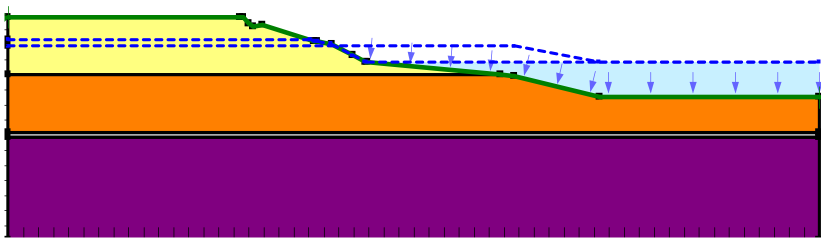
Groundwater information was obtained from engineering reports found in the City of Winnipeg's engineering database or from the Province of Manitoba. The Province of Manitoba has installed monitoring wells around the City of Winnipeg and regularly monitors the elevation of the groundwater levels. The Province of Manitoba provided the University of Manitoba with groundwater levels measured during the previous ten year period for pertinent monitoring wells. At many of the monitoring wells, the average groundwater level over the most recent five year period has been significantly higher than the previous ten year period. The monitoring well information from the last five year period was utilized in the SLOPE/W analysis, if the average groundwater level over the last five year period has changed significantly. The average groundwater levels over the last five years would produce a more conservative, that is, lower, FS in the SLOPE/W analysis. In addition to groundwater levels, the Province of Manitoba also supplied installation details for each monitoring well. The installation details provided a rough estimate of the till and bedrock elevation.

SLOPE/W models were run to determine the FS during three water level stages: NSWL, WWL and flood stage. Representative cross sections for each riverbank location are illustrated in Figure 5.1, while the results for the slope stability analyses are demonstrated in Figure 5.2. The FS calculated from the SLOPE/W models represents an approximate FS for each site. The FS calculated for each site is only an approximation as many assumptions about soil properties and piezometric surfaces were made in order to run the SLOPE/W models. Further site characterizations, with borehole drilling and instrument installation would be required at each site, for an accurate FS to be determined.

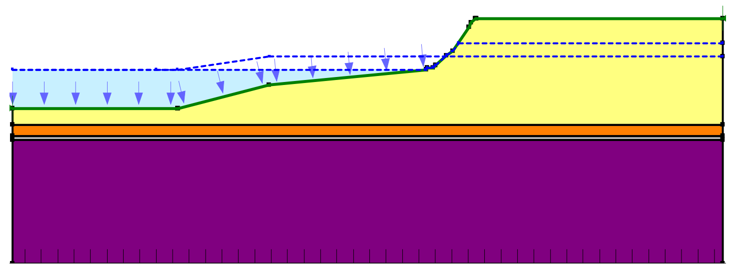
The SLOPE/W analyses showed that during flood stage, the FS at each site was higher than during NSWL and WWL. Baracos and Lew (2003) indicated that a higher FS during flood stage results from increased hydrostatic forces supporting the bank during the elevated river levels. The FS was typically the lowest at WWL. The results of these slope analyses were not unanticipated, as similar results have been reported by Baracos (1978), KGS (1994), Tutkaluk (2000) and Baracos and Lew (2003).

The results of the SLOPE/W analyses for inside, outside, transition, straight and straight to transition sections of the Red and Assiniboine Rivers were compared. The minimum FS calculated for many of the sites along the outside, transition, and straight to transition sections, showed a shallow failure surface in the low strength clay (glaciolacustrine) unit, especially during NSWL and FS. Baracos (1978) has shown that shallow slope movement can occur along a riverbank face, but slope inclinometers installed into the till unit on the Red River, indicate that the largest slope movements occur at the interface of the low strength clay and till units. Therefore, the FS for a slip surface at the interface of the low strength clay and till units was also determined by 'selecting' a representative slip surface in SLOPE/W that encompassed both these units. Generally, the FS for outside, transition, and transition to straight sections is greater for the 'selected' slip surfaces than the 'calculated' slip surfaces. For both the 'calculated' and 'selected' slip surfaces, typically, the slip surface location for the inside and straight sections of the Red River were the same. Figures 5.3, 5.4, 5.5, 5.6, and 5.7 compare the 'calculated' and 'selected' FS for slip surfaces along outside, transition, inside, straight, and straight to transition sections of the Red and Assiniboine Rivers.

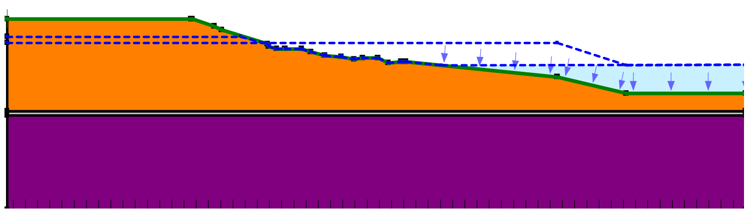
After completing the site characterization program and site surveys, it was possible to proceed with the development of the Riverbank Asset Management System. Chapter 6 will discuss the development of the Riverbank Asset Management System in detail.



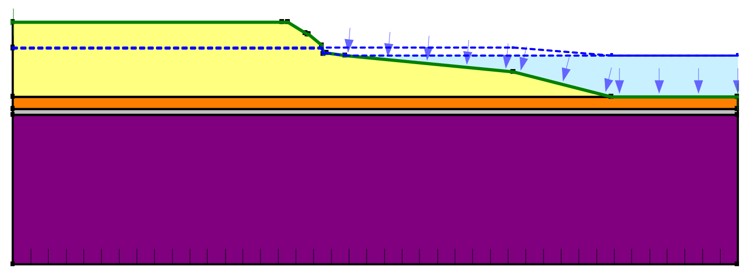
(a) Transition Section (Darveau to Hebert)



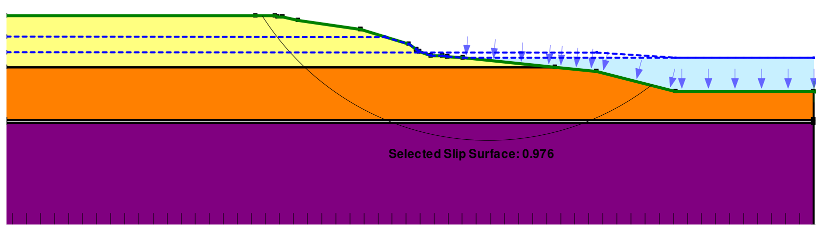
(d) Straight Section (End of Grace Street)



(b) Outside Bend (Canoe Club)

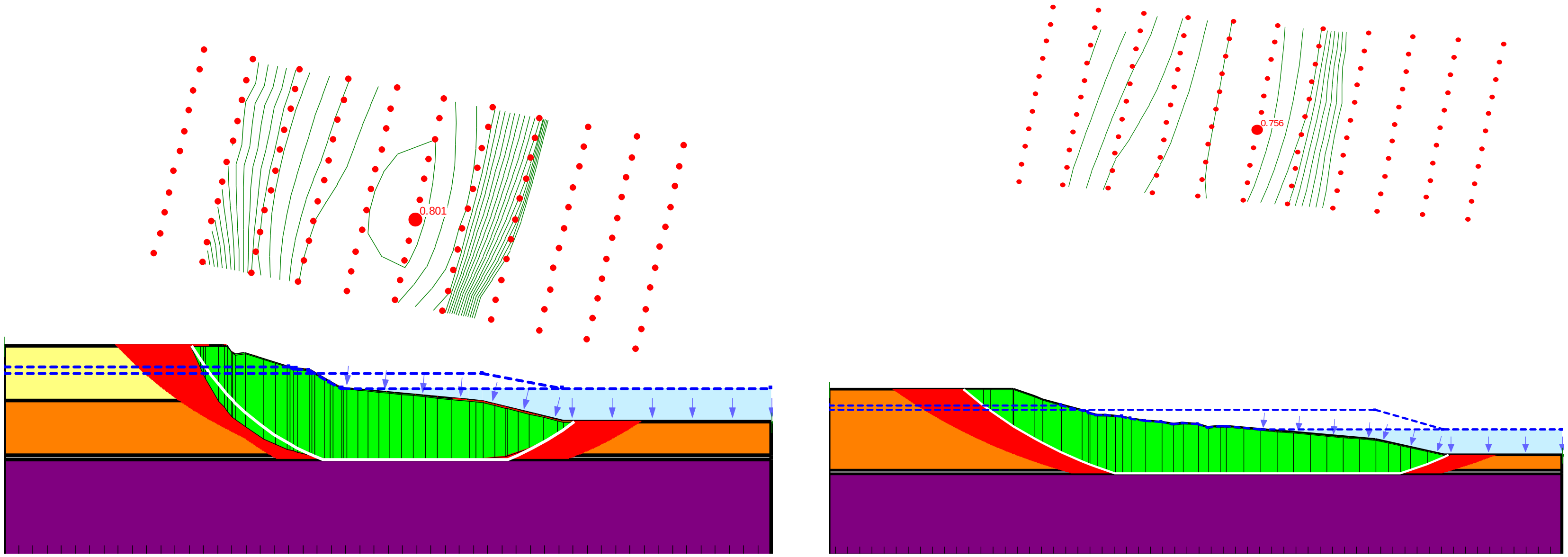


(e) Inside Bend (Lyndale Drive)



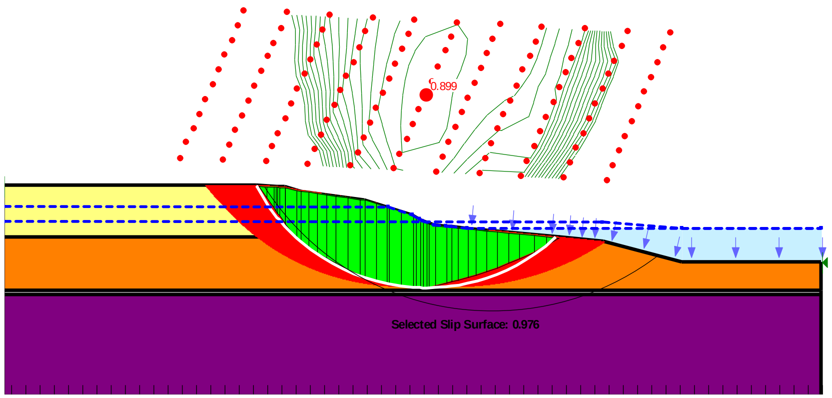
(c) Straight to Transition Section (Provencher to LaVerendrye)

Figure 5.1: Model Cross Sections for (a) Transition Section, (b) Outside Bend, (c) Straight to Transition Section, (d) Straight Section and (e) Inside Bend.

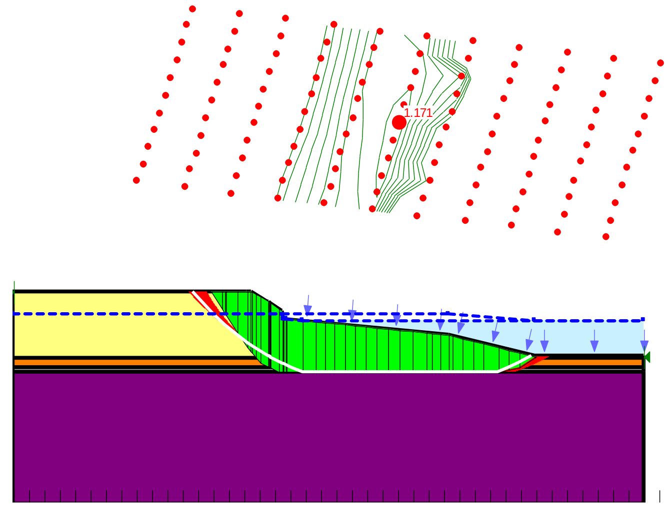


(a) Transition Section (Darveau to Hebert) (b) Outside Bend (Canoe Club)

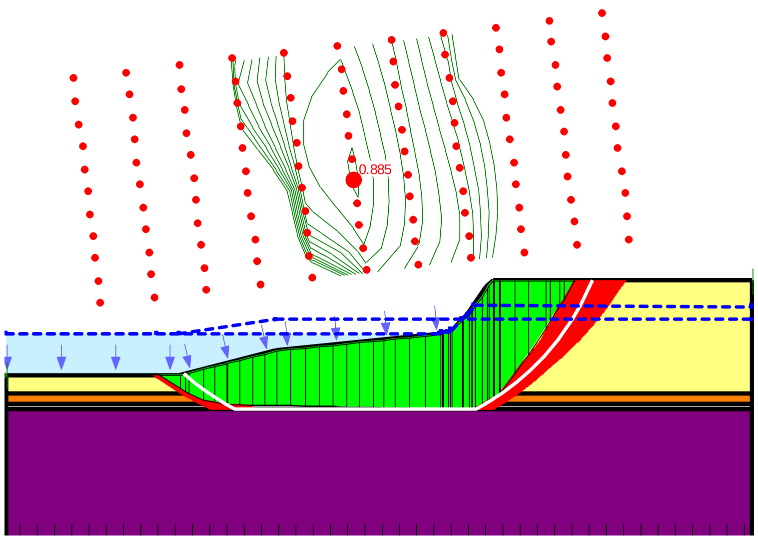
Figure 5.2: Typical SLOPE/W Results for (a) Transition Section and (b) Outside Bend. Continued on next page.



c) Straight to Transition Section (Provencher to LaVerendrye)



(e) Inside Bend (Lyndale Drive)



(d) Straight Section (End of Grace Street)

Figure 5.2: Typical SLOPE/W Results for (c) Straight to Transition Section, (d) Straight Section, and (e) Inside Bend.

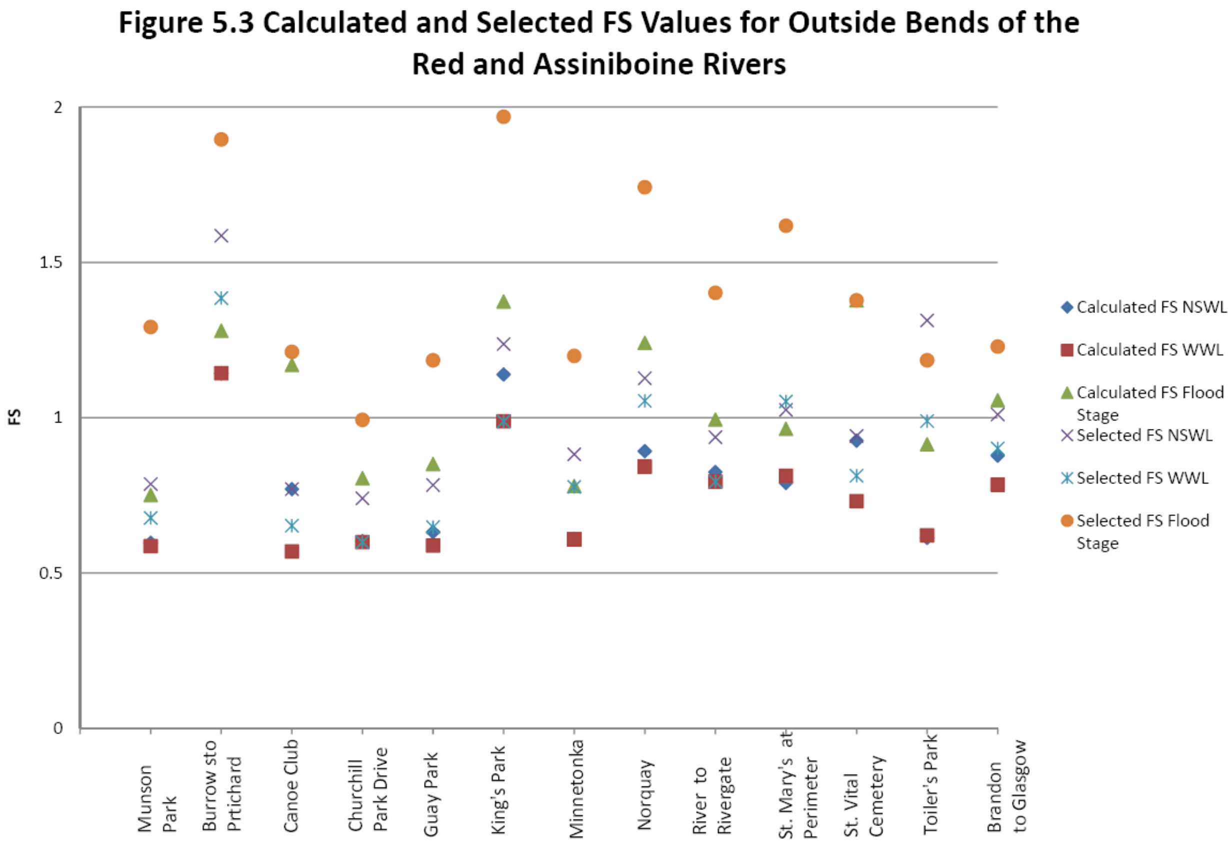


Figure 5.3: Calculated and Selected FS Values for Outside Bends of the Red and Assiniboine Rivers.

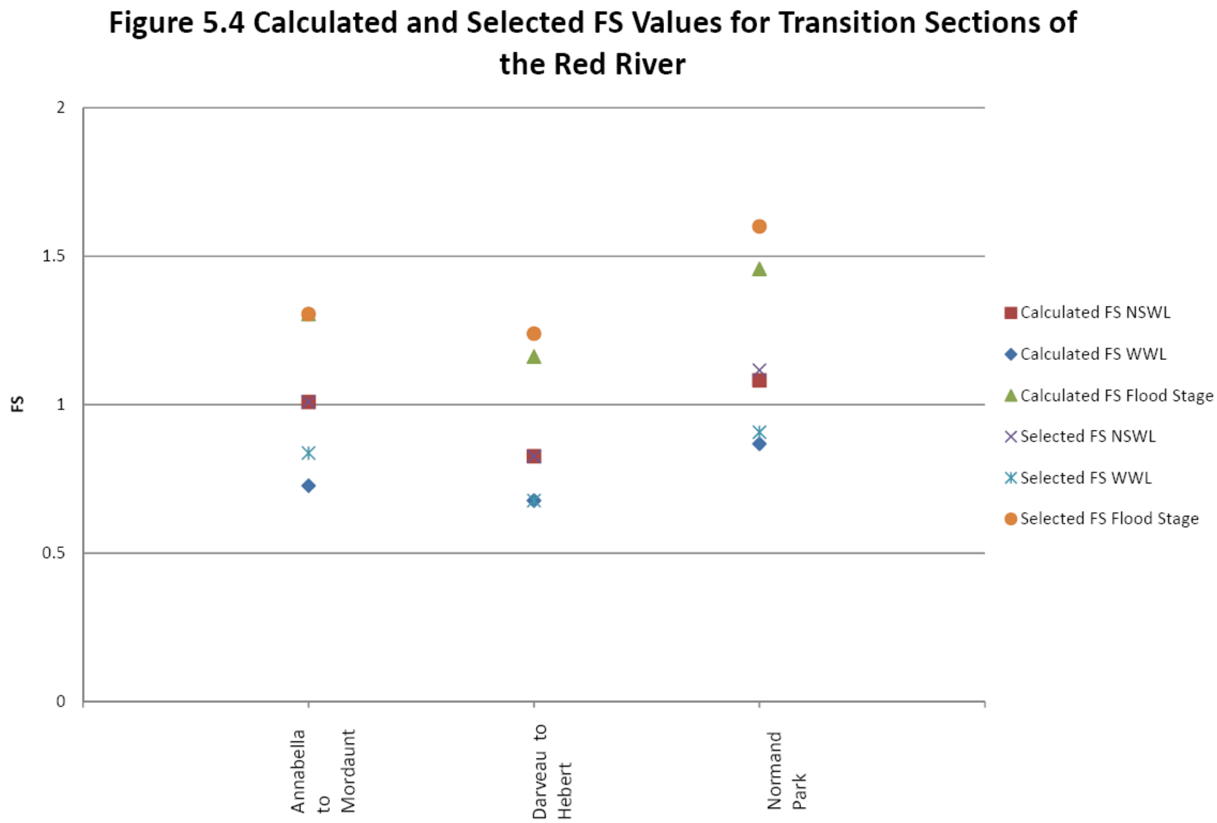


Figure 5.4: Calculated and Selected FS Values for Transition Sections of the Red River.

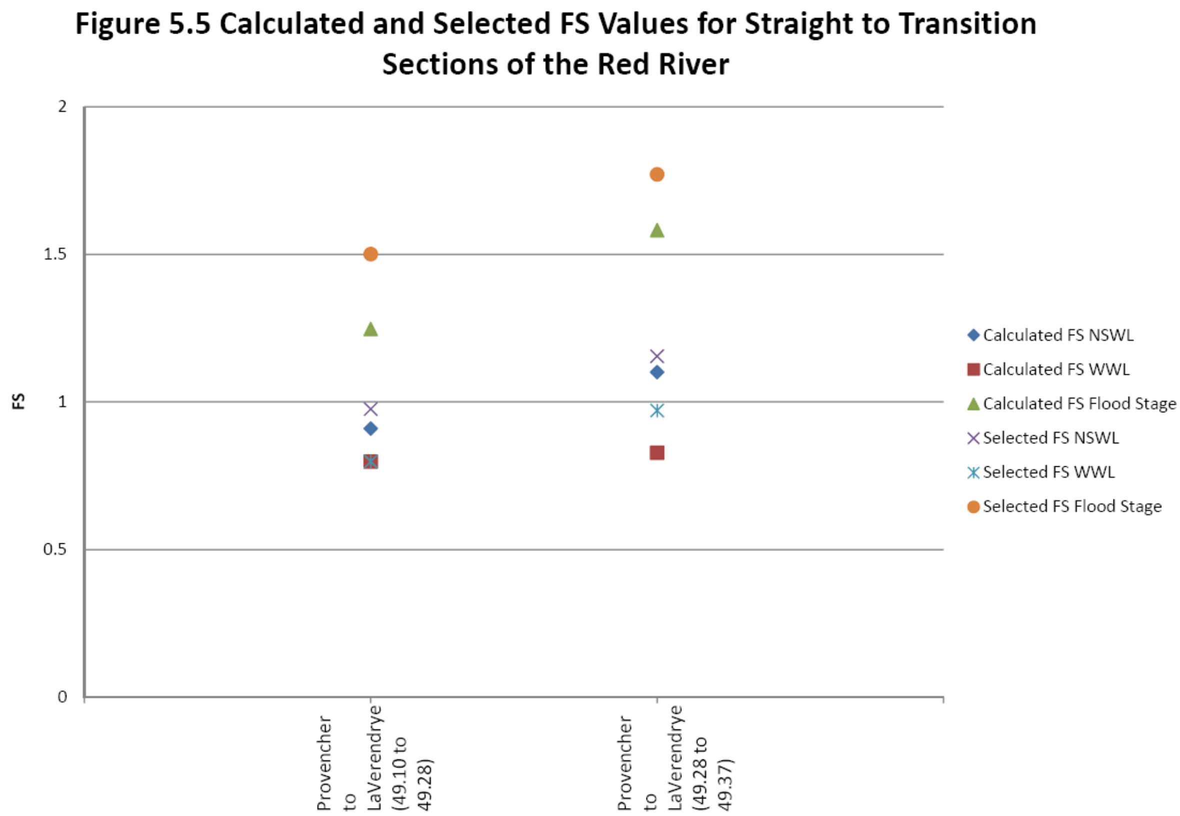


Figure 5.5: Calculated and Selected FS Values for Straight to Transition Sections of the Red River.

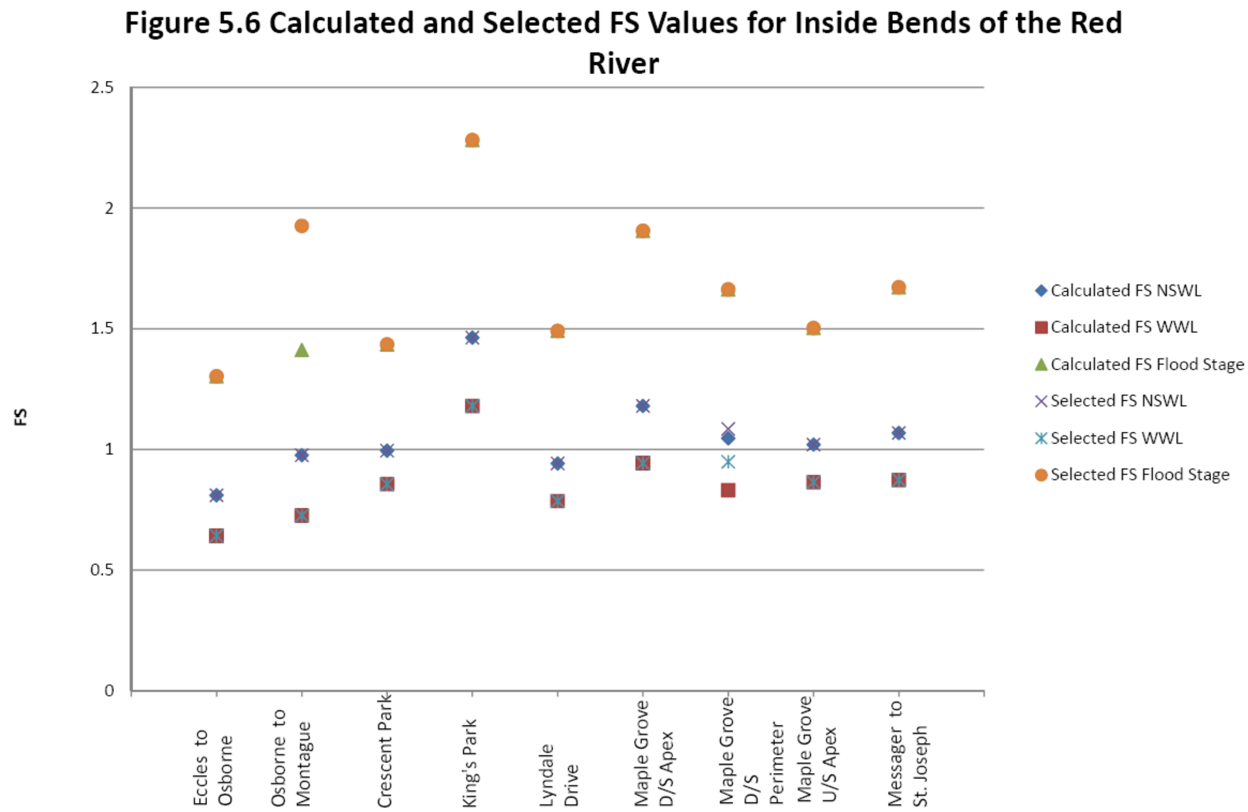


Figure 5.6: Calculated and Selected FS Values for Inside Bends of the Red River.

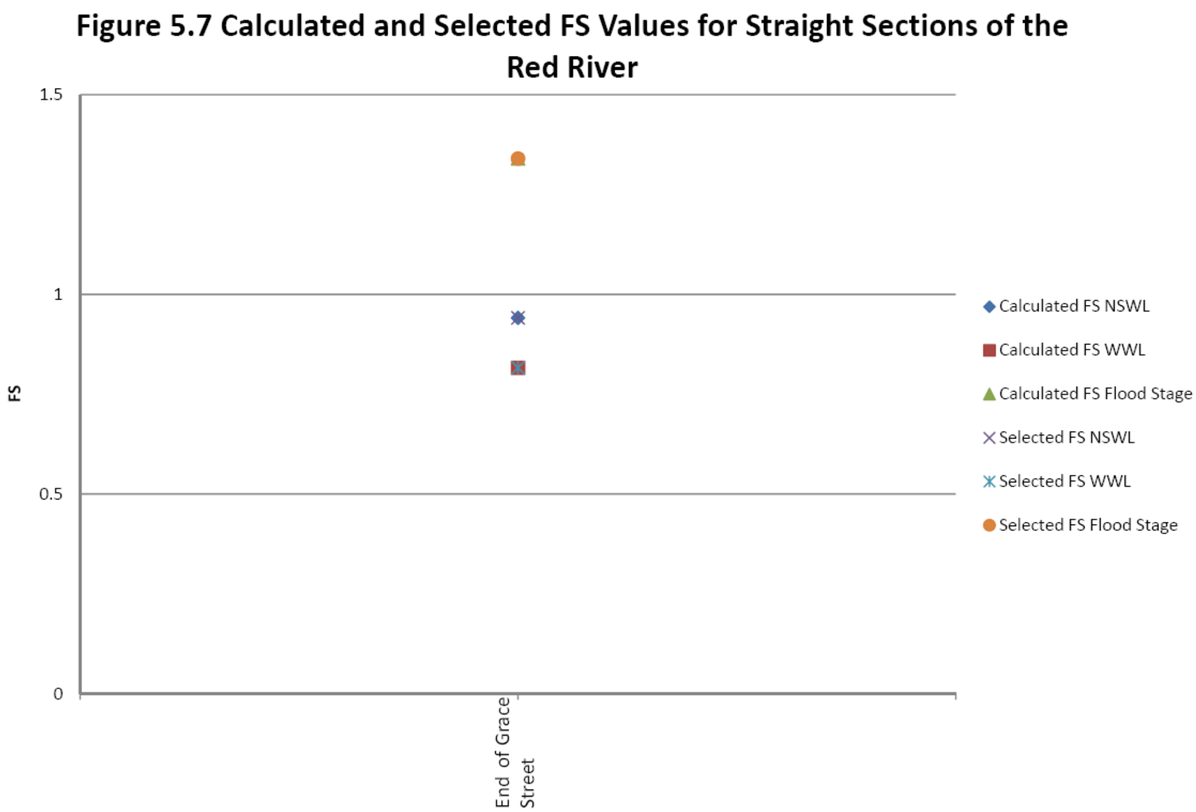


Figure 5 7: Calculated and Selected FS Values for Straight Sections of the Red River.

Table 5 1: Change in Average Slope Angle Between 1998 and 2008.

Site	2008 Slope Angle*	1998 Slope Angle (R)	1998 Slope Angle	Change in Slope Angle	% Change in Slope Angle from 1998	Change in Slope Angle Per Year
Inside						
Red River - Churchill Park Drive (Eccles to Osborne) (RRR54.45 to RRR55.53)	27.45	14.04	24.93	2.52	10.13	0.25
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	60.60	45.00	52.96	7.65	14.44	0.76
Red River - Crescent Park (RRR62.35 to RRR62.86)	29.79	39.81	39.74	-9.94	-25.02	-0.99
Red River - King's Park (RRR71.10 to RRR71.40)	14.33	23.50	14.87	-0.54	-3.64	-0.05
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	43.78	20.32	33.40	10.38	31.07	1.04
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	24.62	37.57	21.70	2.91	13.41	0.29
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	14.56	15.52	14.89	-0.33	-2.21	-0.03
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	30.59	37.57	37.70	-7.10	-18.85	-0.71
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	35.23	8.37	30.95	4.28	13.84	0.43
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	N/A	32.01	N/A	N/A	N/A	N/A
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	N/A	32.01	N/A	N/A	N/A	N/A
Outside						
Assiniboine River - Fort Rouge Park (ARL1.12 to ARL1.24)	N/A	6.95	N/A	N/A	N/A	N/A
Assiniboine River - Granite Curling Club (ARR1.69 to ARR1.90)	N/A	8.37	N/A	N/A	N/A	N/A
Assiniboine River - Granite Curling Club (ARR1.90 to ARR1.98)	N/A	9.62	N/A	N/A	N/A	N/A
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)	N/A	6.48	N/A	N/A	N/A	N/A
Red River - Annabella to May (RRR47.82 to RRR48.12)	N/A	10.12	N/A	N/A	N/A	N/A
Red River - Burrows to Pritchard (RRR44.76 to RRR44.90)	N/A	6.34	N/A	N/A	N/A	N/A
Red River - Canoe Club (RRL58.79 to RRL59.34)	12.37	11.09	12.22	0.15	1.22	0.01
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50	24.57	9.78	19.88	4.70	23.62	0.47
Red River - Guay Park (RRL53.50 to RRL53.64)	20.78	11.77	21.90	-1.12	-5.13	-0.11
Red River - King's Park (RRR71.68 to RRR72.08)	N/A	10.49	N/A	N/A	N/A	N/A
Red River - Minnetonka (RRL67.00 to RRL67.11)	22.16	7.31	22.21	-0.05	-0.21	0.00
Red River - Norquay Park (RRR44.90 to RRR45.18)	7.88	6.34	8.43	-0.56	-6.59	-0.06
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)	N/A	6.63	N/A	N/A	N/A	N/A
Red River - River to Rivergate (RRL67.27 to RRL67.53)	10.86	9.16	10.85	0.01	0.09	0.00
Red River - St. John's Park (RRR44.15 to RRR44.30)	N/A	9.62	N/A	N/A	N/A	N/A
Red River - St. Mary's at Perimeter (RRL70.66 to RRL71.15)	9.81	12.01	10.49	-0.68	-6.50	-0.07
Red River - St. Vital Cemetery (RRL64.39 to RRL64.72)	14.90	13.09	14.34	0.57	3.96	0.06
Red River - Toilers (RRR57.09 to RRR57.15)	25.71	17.88	23.96	1.75	7.30	0.17
Red River - Wardlaw to Cordyn (RRR50.81 to RRR51.37)	N/A	8.88	N/A	N/A	N/A	N/A
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	N/A	10.49	N/A	N/A	N/A	N/A
Red River - Glasgow to Brandon (RRR51.98 to RRR52.12)	10.17	7.04	10.41	-0.24	-2.31	-0.02
Straight						
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	N/A	18.43	N/A	N/A	N/A	N/A
Red River - End of Grace St. (RRR47.24 to RRR47.29)	49.42	27.76	49.67	-0.25	-0.50	-0.02
Transition						
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)	20.36	14.74	20.59	-0.24	-1.15	-0.02
Red River - King's Park (RRR71.40 to RRR71.68)	N/A	20.32	N/A	N/A	N/A	N/A
Red River - Morduant to Annabella (RRR47.49 to RRR47.82)	13.34	12.01	12.50	0.84	6.68	0.08
Red River - Normand Park (RRL69.75 to RRL70.42)	9.62	9.95	10.47	-0.85	-8.13	-0.09
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	N/A	21.04	N/A	N/A	N/A	N/A
Transition to Straight						
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	13.97	9.78	14.72	-0.74	-5.05	-0.07
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)	10.01	6.14	9.61	0.40	4.20	0.04

* Average overall slope calculated

Changes Colour Code Key:

- Between 5-10% change from 1998 slope angle
- Between 10-15% change from 1998 slope angle
- Between 15-20% change from 1998 slope angle
- Over 20% change from 1998 slope angle

Table 5 2: Retrogression Ratio and Expected Loss of Top of Bank for Average Slope Angle.

Site	2008 Average Slope Angle	2008 Retrogression Ratio for Average Slope Angle	Expected Loss of TB for Average Slope Angle (m)
Inside			
Red River - Churchill Park Drive (Eccles to Osborne) (RRR54.45 to RRR55.53)	17.65	0.95	-0.72
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	45.99	3.11	8.14
Red River - Crescent Park (RRR62.35 to RRR62.86)	30.05	1.74	8.39
Red River - King's Park (RRR71.10 to RRR71.40)	24.15	1.35	3.31
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	35.68	2.15	6.91
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	25.96	1.46	5.96
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	15.98	0.86	-3.20
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	31.63	1.85	8.67
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	32.62	1.92	7.62
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	N/A	N/A	N/A
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	N/A	N/A	N/A
Outside			
Assiniboine River - Fort Rouge Park (ARL1.12 to ARL1.24)	N/A	N/A	N/A
Assiniboine River - Granite Curling Club (ARR1.69 to ARR1.90)	N/A	N/A	N/A
Assiniboine River - Granite Curling Club (ARR1.90 to ARR1.98)	N/A	N/A	N/A
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)	N/A	N/A	N/A
Red River - Annabella to May (RRR47.82 to RRR48.12)	N/A	N/A	N/A
Red River - Burrows to Pritchard (RRR44.76 to RRR44.90)	N/A	N/A	N/A
Red River - Canoe Club (RRL58.79 to RRL59.34)	12.16	1.94	33.99
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	21.04	3.46	46.72
Red River - Guay Park (RRL53.50 to RRL53.64)	18.27	2.97	42.40
Red River - King's Park (RRR71.68 to RRR72.08)	14.01	2.25	31.45
Red River - Minnetonka (RRL67.00 to RRL67.11)	20.14	3.30	48.93
Red River - Norquay Park (RRR44.90 to RRR45.18)	7.88	1.25	9.94
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)	N/A	N/A	N/A
Red River - River to Rivergate (RRL67.27 to RRL67.53)	10.52	1.67	26.38
Red River - St. John's Park (RRR44.15 to RRR44.30)	N/A	N/A	N/A
Red River - St. Mary's at Perimeter (RRL70.66 to RRL71.15)	11.73	1.87	35.99
Red River - St. Vital Cemetery (RRL64.39 to RRL64.72)	15.61	2.51	38.49
Red River - Toilers (RRR57.09 to RRR57.15)	21.44	3.53	50.33
Red River - Wardlaw to Cordyn (RRR50.81 to RRR51.37)	N/A	N/A	N/A
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	N/A	N/A	N/A
Red River - Glasgow to Brandon (RRR51.98 to RRR52.12)	11.42	1.82	27.52
Straight			
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	N/A	N/A	N/A
Red River - End of Grace St. (RRR47.24 to RRR47.29)	49.78	7.10	27.32
Transition			
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)	21.11	2.32	18.07
Red River - King's Park (RRR71.40 to RRR71.68)	N/A	N/A	N/A
Red River - Morduant to Annabella (RRR47.49 to RRR47.82)	19.61	2.14	20.11
Red River - Normand Park (RRL69.75 to RRL70.42)	10.02	1.06	2.47
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	N/A	N/A	N/A
Transition to Straight			
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	11.87	1.26	7.57
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)	8.59	0.91	-3.62

Table 5 3: Location of Slope Stability Cross Sections.

Site Name	Location of Cross Section
Inside	
Red River - Churchill Park Drive (Eccles to Osborne) (RRR54.45 to RRR55.53)	RRR 55.215
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	RRR 55.785
Red River - Crescent Park (RRR62.35 to RRR62.86)	RRR 62.700
Red River - King's Park (RRR71.10 to RRR71.40)	RRR 71.100
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	RRL 52.159
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	RRL 71.904
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	RRL 73.405
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	RRL 72.277
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	RRL 48.423
Outside	
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)	ARL 3.309
Red River - Burrows to Pritchard (RRR44.76 to RRR44.90)	RRR 44.734
Red River - Canoe Club (RRL58.79 to RRL59.34)	RRL 58.998
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	RRR 56.187
Red River - Guay Park (RRL53.50 to RRL53.64)	RRL 53.526
Red River - King's Park (RRR71.68 to RRR72.08)	RRR 71.727
Red River - Minnetonka (RRL67.00 to RRL67.11)	RRL 67.021
Red River - Norquay Park (RRR44.90 to RRR45.18)	RRR 45.111
Red River - River to Rivergate (RRL67.27 to RRL67.53)	RRL 67.469
Red River - St. Mary's at Perimeter (RRL70.66 to RRL71.15)	RRL 71.108
Red River - St. Vital Cemetery (RRL64.39 to RRL64.72)	RRL 64.586
Red River - Toilers (RRR57.09 to RRR57.15)	RRR 57.125
Red River - Glasgow to Brandon (RRR51.98 to RRR52.12)	RRR 51.991
Straight	
Red River - End of Grace St. (RRR47.24 to RRR47.29)	RRR 47.259
Transition	
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)	RRL 47.697
Red River - Mordaunt to Annabella (RRR47.49 to RRR47.82)	RRR 48.755
Red River - Normand Park (RRL69.75 to RRL70.42)	RRL 70.169
Transition to Straight	
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	RRL 49.141
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)	RRL 49.298

Table 5 4: Soil Properties Used in LE Analysis

Soil Property	Alluvial Clay	Silty Clay	Weak Clay Layer	Glacial Till
Unit Weight (kPa)	20	17	17	23
Friction Angle	22	10	12	30
Cohesion (kPa)	7	4	3	10

Chapter 6 Development of the Riverbank Asset Management System

6.1 Introduction

The 2008 “first phase” list of priority sites (Chapter 4) was developed by conducting comparative site assessments to determine the changes in the conditions of riverbank stability between 2004 and 2008. The methodology used to create the “first phase” priority site list was based on visual site observations and engineering judgment and experience. Using this methodology to create the “first phase” list of priority sites is subjective. An effective “first phase” list of priority sites should be based on probability and consequence factors.

Because of the limitations of the existing methodology used to rank the “first phase” priority site list, the system needs to be updated to reflect current and acceptable risk management standards used in engineering practice today. Therefore, the thirty-six sites assessed during the site characterization program, described in Chapters 4 and 5, need to be analyzed and prioritized with a consistent assessment procedure. The results of the formal site assessment in Chapters 4 and 5 and the consistent assessment procedure should be broadly comparable. The purpose of this chapter is to ‘calibrate’ or ‘verify’ the riverbank prioritization system. This will be done by synthesizing information collected during the site characterization program and developing a more comprehensive geospatial visualization tool in the form of a Riverbank Asset Management System (RAMS). A RAMS will enable the Riverbank Management Engineer of the City of Winnipeg to create a transparent and rational approach for determining risk levels. From these risk levels, response levels can be developed. The response levels will allow the City to effectively manage their riverbank stability monitoring program. The response levels will prove invaluable during the annual planning process, because appropriate resources, both monetary and personnel can be allocated to manage public riverbank property. The development of a RAMS will ensure riverbank stabilization projects are better prioritized using risk and response levels.

A RAMS will allow site specific information to be easily accessed by the engineering community and public policy makers. This ensures that all stakeholders are actively involved in the risk management process. In addition, the development of a RAMS will permit timely reviews of priority sites as riverbank conditions and input parameters change.

6.2 Probability Factor

To determine the probability of slope movements occurring on public riverbank property, it was necessary to identify specific attributes that may influence the likelihood of slope movements occurring. These specific attributes will subsequently be referred to as 'landslide probability attributes'. Like with the riverbank observation checklist (Chapter 4), the landslide probability attributes were selected by analyzing the geomorphology and stratigraphy of the Red and Assiniboine River Basins. Chapter 3 provided an overview of how these 'attributes' were developed. Engineering judgment and experience of the technical steering committee were also used to help identify potential landslide probability attributes.

A survey was sent to local consultants in the Winnipeg area asking them to provide a relative ranking of each of the landslide probability attributes based on their engineering experience and judgment. The consultants were also requested to provide additional comments or identify other landslide probability attributes that were not previously acknowledged in the survey. The responses to the survey are confidential, but they were used to facilitate the development of the weighting factors in the final probability factor computations. No additional probability attributes were identified by the local consultants.

As shown on Figure 6.1, ten (10) landslide probability attributes were determined to affect the likelihood of slope movements occurring along the Red and Assiniboine Rivers. The attributes include: topography, groundwater, geology, river hydraulics, surface water and drainage, planform geometrics, retrogression ratio, anthropogenic influences (loading at the top of the slope, runoff from roads, paths and leaking services), vegetation cover and altered section.

Table 6.1 illustrates that each of the landslide probability attributes in Figure 5.1 were divided into landslide probability sub-attributes. Information used to properly characterize the landslide probability sub-attributes was collected during the site characterization program. This information was subsequently entered into the RAMS.

The landslide probability attributes and sub-attributes were assigned weighting factors based on their influence on riverbank stability along the Red and Assiniboine Rivers. The attributes and sub-attributes that were determined to have the greatest influence on riverbank stability were assigned higher weighting factors than those attributes and sub-attributes determined to have minimal influence on riverbank stability. The maximum possible weighting factor for a landslide probability attribute is 1.0, while the minimum possible weighting factor is zero. With the exception of vegetation cover, the weighting factors for the landslide probability attributes and sub-attributes were assigned values in 0.05 increments. The weighting factors for vegetation cover were assigned in 0.07 intervals. As shown on Table 6.1, once a weighting factor for a landslide probability attribute is determined, the sum of the weighting factors for the sub-attributes cannot exceed the pre-determined weighting factor. To date, the lowest assigned weighting factor for a landslide probability attribute is 0.21.

Since the primary causes and failure mechanisms for erosion-controlled and failure-controlled riverbanks are different, the weighting factors for the landslide probability attributes and sub-attributes for the two types of riverbank were determined independently of each other. Section 3.5 outlines the primary causes and failure mechanisms for erosion- controlled and failure-controlled riverbanks.

For this research project, it was necessary to determine if a transition section of the Red or Assiniboine River would be classified as a failure-controlled or erosion-controlled riverbank. To make this decision, the lateral extent and thickness of alluvial material in the vicinity of an inside bend was examined. The author decided that for the RAMS developed for the City of Winnipeg, a riverbank along an inside bend would be classified as erosion-controlled from the point of inflection upstream of the apex, to the point of inflection downstream of the apex. This section of riverbank would also be classified as erosion-controlled, if a straight section is located immediately upstream of the apex on the inside bend. The remainder of the riverbanks along the Red and Assiniboine Rivers would be classified as failure-controlled.

Table 6.1 summarizes the weighting factors for landslide probability attributes and sub-attributes for erosion-controlled and failure-controlled riverbanks. Table 6.1 shows that for failure-controlled riverbanks, retrogression ratio, topography, and geology were determined to have the greatest influence on riverbank stability while for erosion-controlled banks, topography, river hydraulics, and planform geometrics were determined to have the greatest influence. The Riverbank Management Engineer at the City of Winnipeg is responsible for approving the final weighting factors for the landslide probability attributes and sub-attributes before the RAMS spreadsheet (Section 6.4.1) is released into the public domain.

6.3 Consequence Factor

To determine the consequence of slope movements occurring on public riverbank property, it was necessary to identify specific attributes that would be affected by the occurrence of slope movements. These attributes will subsequently be referred to as 'landslide consequence attributes'. The landslide consequence attributes were selected by reviewing existing risk management systems. These systems apply to geotechnical projects such as: those in transportation corridors, roadways and railways, pipelines and dams, for example. Engineering judgment and experience of the technical steering committee were also used to identify potential landslide consequence attributes.

Figure 6.2 shows the five landslide consequence attributes that were identified for the RAMS. The five landslide consequence attributes are: transportation and infrastructure, receiving environment, utilities, public property and public perception. However, at this time, only public property and public perception will be considered. The three remaining landslide consequence attributes will be integrated into the RAMS, at a later date. The information required to properly characterize the landslide consequence attributes was collected during the site surveys. This information was subsequently entered into the RAMS.

Public property was chosen as an attribute to represent the potential loss of top of bank. The potential loss of top of bank has been defined here as the horizontal distance between the proposed stable slope angle and the present average slope angle (Chapter 5). Public perception was determined to be based on: 1) foot traffic 2) site access and 3) visualization effects.

The landslide consequence attributes were also assigned weighting factors. The maximum possible weighting factor for a landslide consequence attribute is 1.0, while the minimum possible weighting factor is 0. Presently, it was determined by the technical steering committee that both public perception and public property would be assigned a weighting factor of 1.0. For the landslide consequence attributes, 0.2 intervals were used to differentiate between the input parameters in the RAMS. The three landslide consequence attributes that will be integrated into the RAMS at a later date, were assigned a weighting factor of zero. However, the weighting factors for the landslide consequence attributes may change as additional consequence attributes are incorporated into the RAMS in the future.

Because the angles of stable slopes for erosion-controlled and failure-controlled riverbanks are significantly different, the potential loss of top of bank for a failure-controlled riverbank is typically much greater than for an erosion-controlled riverbank. Therefore, a public property attribute was created for both failure-controlled and erosion-controlled riverbanks to reflect the difference in potential loss of top of bank (Figure 6.3). Table 6.2 summarizes the weighting factors for the landslide consequence attributes for erosion-controlled and failure-controlled riverbanks. The Riverbank Management Engineer is responsible for finalizing the weighting factors for the landslide consequence attributes before the RAMS spreadsheet (Section 6.4.2) is released for public inspection.

6.4 Development of the RAMS Spreadsheet

6.4.1 Probability Factor

A RAMS spreadsheet (Appendix D) was developed to better manage, analyze and prioritize the landslide risk for public riverbank property along the Red and Assiniboine Rivers. In order to determine a landslide risk assessment for the thirty-six sites that were characterized during this research, it was necessary to determine the probability factor or the likelihood of slope movements occurring at each of the sites. Weighting factors assigned to the landslide probability attributes and sub-attributes (Table 6.1) were then used to calculate the probability factor. Section 6.4.1.1 provides detailed discussion on how the probability factors were calculated.

As mentioned above, weighting factors were assigned to the landslide probability attributes and sub-attributes (Table 6.1) for both erosion-controlled and failure-controlled riverbanks. The weighting factors for these attributes can be modified under the *probability*[2] tab in the RAMS spreadsheet (Appendix D). The weighting factor for an input parameter will automatically be adjusted to reflect a change on both the *probability* tab and the main RAMS spreadsheet (*kml* tab), if the weighting factor for a landslide probability attribute or sub-attribute is changed on the *probability* tab. Figure 6.4 illustrates the tabs that were created in the RAMS spreadsheet to allow it to be easily used and managed.

Information required to properly characterize and assess the landslide probability attributes and sub-attributes was collected during the site characterization program and the site surveys (Chapters 4 and 5). Figure 6.3 shows that the site characterization information is input directly into the main RAMS spreadsheet (*kml* tab), under the appropriate landslide probability attribute and sub-attribute columns. Figure 6.3 also illustrates that selection of the input parameters for the landslide probability attributes and sub-attributes are limited by a *drop down menu.* The menu is locked, so only the data in the menu can be entered. However, as input parameters and riverbank stability conditions change, the site data can be changed using the *drop down menu*. Figure 6.5 shows that the sites that were characterized and analyzed during the 2007 and 2008 riverbank characterization program were classified according to riverbank type. Erosion-controlled and failure-controlled riverbanks are categorized separately in the main RAMS spreadsheet.

A user's uncertainty about landslide probability attributes and sub-attributes can be incorporated into the RAMS. The user should enter *uncertain* until site specific information becomes available at a later time, if information about a landslide probability

[2] Words in italics represent a defined term for a location in the RAMS spreadsheet.

attribute or sub-attribute is not available. With input from the technical steering committee, it was determined that an *uncertain* input parameter would have a 50% weighting compared to the maximum possible weighting factor. As more site data become available, the probability factor may increase or decrease. The change in the probability factor depends on data that are collected and inputted.

6.4.1.1 Calculation of Probability Factor

A review of existing risk management systems helped establish an appropriate methodology for calculating probability factors in the RAMS. It was determined that the most suitable methodology for calculating a *probability factor* was to utilize simple mathematical operations such as addition and multiplication.

Equation 6.1 below illustrates the formula used to calculate a *probability factor* in the RAMS. Equation 6.1 shows that nine of the ten *landslide probability* attribute totals are added together. This sum is subsequently multiplied by the attribute total for the *altered section* column. Figure 6.6 outlines the *landslide probability* attributes and their associated sub-attributes. The attribute totals (orange columns) for each *landslide probability* attribute are calculated by adding the values of the input parameters (Figure 6.6).

Probability Factor = Σ (topography + groundwater + geology + river hydraulics + surface water and drainage + planform geometrics + retrogression ratio + anthropogenic influences + vegetation cover) attribute totals x (altered section attribute total)

Equation 6.1

The *probability attribute* total for *altered section* depends on the type of stabilization measures used at a site. A value of 1.0 should be assigned, if no stabilization measures have been utilized at a site. A value of 0.5 should be assigned if a site has been temporarily stabilized, such as slope re-grading or rip rap placement. A value of 0.1 should be assigned, if a site has had extensive stabilization work conducted, such as the installation of rockfill columns, shear key, or rockfill caissons.

It was decided by the technical steering committee that the *landslide probability factor* (Equation 6.1) should be a percentage (maximum possible value of 100%). Therefore, Equation 6.2 is used to convert the *landslide probability factor* to a percentage. The *landslide probability factor* (%) is calculated from the ratio of the probability factor (Equation 6.1) to the sum of the maximum possible weighting factors for the nine probability attributes identified in Equation 6.1. This ratio is subsequently multiplied by 100% to get a percent value. Since the sum of the maximum possible weighting factors for the nine probability attributes is 9.0, the probability factor is divided by 9.0.

Probability Factor (%) = (Probability Factor /9) x 100%   Equation 6.2

Figure 6.7 illustrates the *probability factors* calculated in the main RAMS spreadsheet. The *probability factor* shown is calculated using Equation 6.2. The *probability factor* is highlighted in yellow (Appendix D).

The *Geotechnical Classification Matrix (GCM)* (Figure 2.12), proposed by Vaunat (2002), has been incorporated into the main RAMS spreadsheet, but has not been assigned a weighting factor. Information about the stage of slope movement (pre-failure, failure, post-failure or slope reactivation) can be entered subsequently if extensive monitoring is conducted at a site. At present, because insufficient information is available to accurately ascertain the stage of slope movement, *uncertain* has been entered as the stage of slope movement for the thirty-six sites currently in the RAMS spreadsheet.

6.4.2 Consequence Factor

Previous sections have described a RAMS spreadsheet that was developed to better manage, analyze and prioritize the landslide risk for public riverbank property along the Red and Assiniboine Rivers. In order to calculate the landslide risk, it is necessary to determine the consequence factor for each site. Weighting factors assigned to the landslide consequence attributes are used to calculate the consequence factor (Section 6.4.2.1). These weighting factors are different from those described earlier for calculating the probability factor.

In the present form of the RAMS, weighting factors have been assigned to the *landslide consequence* attributes for both erosion-controlled and failure-controlled riverbanks. The weighting factors for the landslide consequence attributes should only be modified in the future using the *consequence* tab in the RAMS spreadsheet. The weighting factors for the input parameters on the main RAMS spreadsheet (*kml tab*) and the *consequence* tab will automatically be adjusted to reflect the changes, if the weighting factors for the *landslide consequence* attributes are changed on the *consequence* tab.

The information required to properly assess the *public property* attribute was obtained during the site surveys (Chapter 5). The technical steering committee reviewed the public *perception* input parameters for each site. This review was done to ensure consistency in the input parameters used. Sites with high *volumes of foot traffic* were assigned higher weighting factors than those sites with lower *volumes of foot traffic*.

Figure 6.8 shows that the *consequence* data are input directly into the main RAMS spreadsheet, under the appropriate attribute column in *landslide consequence*.

As with the *landslide probability* attribute and sub-attribute input parameters, the input parameters for the *landslide consequence* attributes are limited by a drop down menu. The menu is locked, so only the data values provided in the drop down menu can be entered. As input parameters and riverbank stability conditions change, the consequence information can be modified using the drop down menus.

A user's uncertainty about *landslide consequence* input parameters was incorporated into the RAMS. The user can enter *uncertain* through the *drop down menu,* if information about a *landslide consequence* attribute is not available. It was determined by the technical steering committee that an input of *uncertain* would have a 50% weighting compared to the maximum possible weighting factor. However, as more site specific information becomes available, and *uncertain* is replaced by site data, the *consequence factor* will change.

6.4.2.1 Calculation of Consequence Factor

Since a review of existing risk management systems indicated that it is acceptable to calculate a *probability factor* using simple mathematical operations, it was determined that a *consequence factor* should also be calculated using simple mathematical operations. Therefore, the *consequence factor* was calculated by adding the attribute totals for *public perception* and *public property.* The technical steering committee decided that the *consequence factor* would be assigned a 20% weighting compared to the *probability factor*. The technical steering committee specifically developed Equation 6.3 so that the *consequence factor* would have a 20% weighting compared to the *probability factor*.

Equation 6.3 illustrates the methodology developed by the committee to calculate the *consequence factor*. The *consequence factor* was given a 20% weighting compared to the *probability factor*; therefore, the maximum possible value for the consequence factor is 1.2. The minimum possible consequence factor is 1.0.

$$\text{Consequence Factor} = (\Sigma\ ((\text{public property} + \text{public perception})/10)) + 1) \quad \text{Equation 6.3}$$

As shown on Figure 6.9, the *consequence factor* is highlighted in yellow in the main RAMS spreadsheet.

6.5 Risk Factor

In the context of this research project, risk factor is defined as the product of a consequence and probability factor. From the calculated risk factor, response levels for site monitoring can be proposed. Response levels are interconnected with risk levels. The calculated risk and response levels will allow the City to manage public riverbank property better and to prioritize slope remediation projects along the Red and Assiniboine Rivers.

Figure 6.10 demonstrates the *risk factors, risk levels and response levels* for the thirty-six sites characterized along public riverbank property on the Red and Assiniboine Rivers. Figure 6.11 shows how numerical *risk factors* are converted into non-numerical *risk levels and response levels* for the City of Winnipeg. The ranges for the risk factors, risk levels and response levels are found on the *risk* tab in the RAMS spreadsheet. Like the weighting factors for the probability and consequence attributes, if the ranges for the risk or response levels are modified on the *risk* tab, the risk and response levels in the main RAMS spreadsheet will be automatically adjusted to reflect these changes.

Presently, the response levels provide a suggested timeframe for riverbank stability monitoring. At the time of writing, the Riverbank Management Engineer at the City of Winnipeg needs to approve the proposed risk and response levels before the RAMS becomes a public document.

6.5.1 Generation of a List of Priority Sites

A separate tab, *Top 12*, was created in the RAMS spreadsheet to identify a new "first phase" list of priority sites. The *Top 12* tab displays the risk factor, risk level and response level for each site characterized in the main RAMS spreadsheet. As shown on Figure 6.12, the *Top 12* spreadsheet automatically sorts and updates the risk factor, risk level and response level for each site when a weighting factor or input parameter is changed.

Figure 6.13 shows that a priority site list can be generated by depressing the *priority site list* button in the main RAMS spreadsheet. When the *priority site list* button is depressed, a *Top 12* list of priority sites is created in Microsoft Word. Figure 6.13

illustrates that the list displays risk factor, risk level and response level for each of the Top 12 sites. In addition, the Top 12 sites are ranked in numerical order, from 1 to 12. The site ranked #1 has the highest risk factor value, while the site ranked #12 has the lowest risk factor value of the Top 12 priority sites. The site names and locations are also displayed.

The *Top 12* list of priority sites is programmed to be saved to the C:\directory of any computer. The *Top 12* Microsoft Word file is automatically saved with the file name COWRAMStop12 and the date in which the file was created (day/month/year). Comparing successive *Top 12* lists of priority sites allows a user to analyze changes in riverbank stability. If a *Top 12* list of priority sites is generated more than once a day, the last file that was created will automatically overwrite the previously generated file. However, if the file name is modified just slightly, this will ensure that all *Top 12* lists of priority sites created in one day will be saved.

If the input parameters or weighting factors for a site are changed, the *Top 12* list of priority sites will be automatically updated to reflect these changes. However, if these changes are made, the *priority site list* button needs to be depressed again before Microsoft Word will create a new *Top 12* list of priority sites.

6.6 Calibration of the Riverbank Asset Management System (RAMS)

Calibration of the risk factors generated in the RAMS was performed by the technical steering committee. Calibration involved reviewing the “first phase” list of priority sites, based on probability and consequence factors, and risk factor values for erosion-controlled and failure-controlled riverbanks on public riverbank property along the Red and Assiniboine Rivers. The sites with high risk factors values in the RAMS were then compared with the sites that had been determined to have a high risk factor value during the earlier site characterization program and desk-top study. The weighting factors for the probability and consequence factors were modified until a relative ranking of the risk factor values for the sites was obtained that was acceptable to the Technical Steering Committee. The changes in the probability and consequence weighting factors were based on the engineering experience and judgment of the technical steering committee and an assessment of the riverbank stability conditions at each site.

Calibration of the RAMS is an on-going process. The weighting factors can be easily changed in the RAMS spreadsheet, if additional monitoring and assessment of riverbank stability conditions reveal that the weighting factors for probability and consequence factors need to be modified. This will ultimately result in updated values of the risk factors and the relative risk factor ranking for each site.

6.7 Comparison of the Site Characterization Assessment and RAMS Top 12 List of Priority Sites

Figure 6.14 shows the two *Top 12* list of priority sites that were created from the site characterization assessments and the RAMS. Figure 6.14 clearly illustrates that there are many similarities between the two *Top 12* list of priority sites, but there are also many differences. Churchill Park Drive (Montague to Cockburn) is ranked #1 on both *Top 12* list of priority sites, for example. However, Lyndale Drive is ranked #7 on the *Top 12* list of priority sites that was created from the site characterization assessments, while it is ranked #12 on the *Top 12* list that was generated using the RAMS. The *Top 12* list of priority sites that was created from the site characterizations assessments was based on visual site observations and engineering judgment and experience. The *Top 12* list of priority sites that was developed using the RAMS was based on probability and consequence factors. A ranking system that is based on probability and consequence factors will reduce the subjectivity of the system. A ranking system based on probability and consequence factors is transparent and ensures political and personal influences are minimized in the decision making process.

6.8 Concluding Comments

Chapter 6 discusses the development of the Riverbank Asset Management System for the City of Winnipeg. This research project provides a valuable contribution to the engineering community because it is the first research project that quantifies the risk of slope movements along the Red and Assiniboine Rivers in the City of Winnipeg. The RAMS is a unique risk management tool because it was developed with the capability to automatically update risk factors, risk levels, and response levels if a user changes an input parameter or weighting factor.

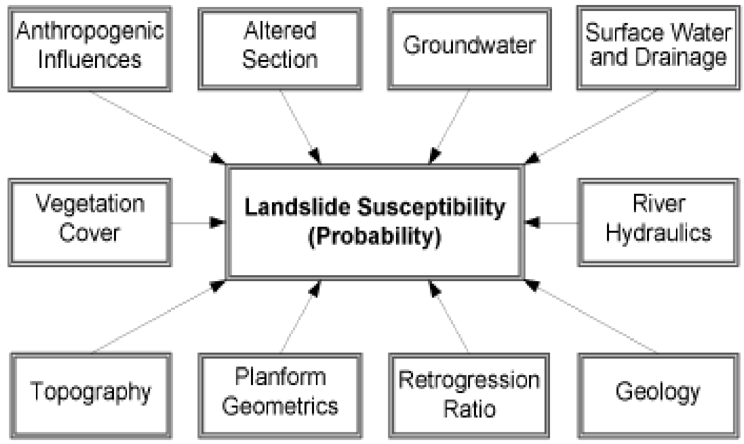


Figure 6.1: Landslide probability attributes. The landslide probability attributes were identified by analyzing the geomorphology and geology of the Red and Assiniboine River basins.

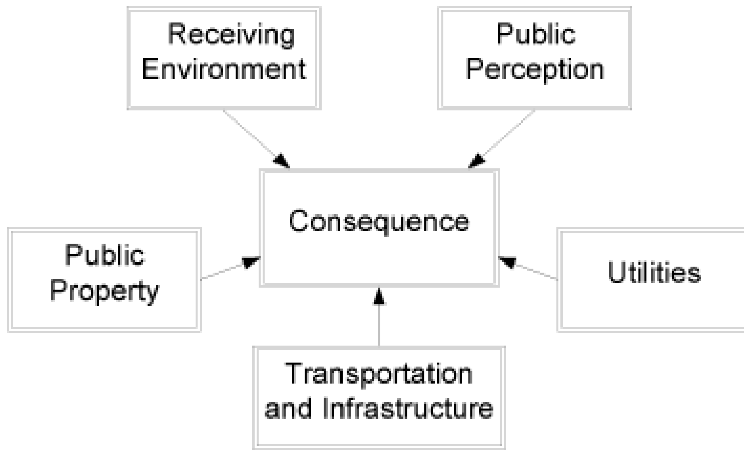


Figure 6.2: Landslide consequence attributes. The landslide consequence attributes were determined by identifying specific features that would be affected by slope movements on public riverbank property.

Site								
	Topography							
Important · Create kml · Priority Site List · Add a Site · Rehide	Azimuth	Value	Bank Height (m)	Value	Slope Shape	Value	Evidence of Slope Movement (Most critical)	Value
Failure Controlled								
Red River - Guay Park (RRL53.50 to RRL53.64)	NE	0.02	7.0 to 8.0	0.32	Hummocky	0.10	Retrogression	0.45
Red River - King's Park (RRR71.40 to RRR71.68)	SW	0.10	7.0 to 8.0	0.32	Hummocky	0.10	Scarp features	0.32
Red River - King's Park (RRR71.68 to RRR72.08)	SW	0.10	6.0 to 7.0	0.28	Hummocky	0.10	Retrogression	0.45
Red River - Minnetonka (RRL67.00 to RRL67.07)	S	0.10	1.0 to 2.0 2.0 to 3.0	0.32	Hummocky	0.10	Retrogression	0.45
Red River - Morduant to Annabella (RRR47.49 to RRR47.82)	S	0.10	3.0 to 4.0	0.28	Uniform to hummocky	0.07	Scarp features	0.32
Red River - Normand Park (RRL69.75 to RRL70.42)	SW	0.10	4.0 to 5.0 5.0 to 6.0	0.32	Hummocky	0.10	Multiple scarp features	0.36
Red River - Norquay Park (RRR44.90 to RRR45.18)	W	0.02	6.0 to 7.0	0.25	Hummocky	0.10	Scarp features	0.32
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)	NE	0.02	7.0 to 8.0 8.0 to 9.0	0.35	Regraded	0.01	None	0.00
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	SW	0.10	6.0 to 7.0	0.28	Hummocky	0.10	Tension Crack	0.45

Figure 6.3: Site characterization information (screenshot). The information is entered into the main RAMS spreadsheet under the appropriate landslide probability attribute and sub-attribute column. The data that can be entered is limited by the drop down menu.

Site	Topography								
Important · Create kml · Priority Site List · Add a Site · Rehide	Azimuth	Value	Bank Height (m)	Value	Slope Shape	Value	Evidence of Slope Movement (Most critical)	Value	Attribute Total
Failure Controlled									
Assiniboine River - Fort Rouge Park (ARL1.12 to ARL1.24)	N	0.02	6.0 to 7.0	0.32	Regraded and hummocky	0.05	Scarp features	0.28	0.67
Assiniboine River - Granite Curling Club (ARR1.69 to ARR1.90)	S	0.10	7.0 to 8.0	0.36	Regraded and hummocky	0.05	Scarp features	0.28	0.79
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)	NE	0.02	6.0 to 7.0	0.32	Hummocky	0.10	Hummocky	0.24	0.68
Red River - Annabella to May (RRR47.82 to RRR48.12)	S	0.10	6.0 to 7.0	0.32	Regraded and hummocky	0.05	Hummocky	0.24	0.71
Red River - Burrows to Pritchard (RRR44.76 to RRR44.83)	E	0.02	5.0 to 6.0	0.28	Hummocky	0.10	Scarp features	0.28	0.68
Red River - Burrows to Pritchard (RRR44.83 to RRR44.90)	E	0.02	5.0 to 6.0	0.28	Regraded	0.01	None	0.00	0.31
Red River - Canoe Club (RRL58.79 to RRL59.34)	SW	0.10	7.0 to 8.0	0.36	Hummocky	0.10	Retrogression	0.40	0.96
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	S	0.10	7.0 to 8.0	0.36	Hummocky	0.10	Retrogression	0.40	0.96
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)	W	0.02	5.0 to 6.0	0.28	Hummocky	0.10	Retrogression	0.40	0.80
Red River - Guay Park (RRL53.50 to RRL53.64)	NE	0.02	7.0 to 8.0	0.36	Hummocky	0.10	Retrogression	0.40	0.88
Red River - King's Park (RRR71.40 to RRR71.68)	SW	0.10	7.0 to 8.0	0.36	Hummocky	0.10	Scarp features	0.28	0.84
Red River - King's Park (RRR71.68 to RRR72.08)	SW	0.10	6.0 to 7.0	0.32	Hummocky	0.10	Retrogression	0.40	0.92
Red River - Minnetonka (RRL67.00 to RRL67.07)	S	0.10	7.0 to 8.0	0.36	Hummocky	0.10	Retrogression	0.40	0.96
Red River - Mordaunt to Annabella (RRR47.49 to RRR47.82)	S	0.10	6.0 to 7.0	0.32	Uniform to hummocky	0.07	Scarp features	0.28	0.77
Red River - Normand Park (RRL69.75 to RRL70.42)	SW	0.10	7.0 to 8.0	0.36	Hummocky	0.10	Multiple scarp features	0.32	0.88
Red River - Norquay Park (RRR44.90 to RRR45.18)	W	0.02	5.0 to 6.0	0.28	Hummocky	0.10	Hummocky	0.24	0.64
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)	NE	0.02	8.0 to 9.0	0.40	Regraded	0.01	None	0.00	0.43
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	SW	0.10	6.0 to 7.0	0.32	Hummocky	0.10	Tension Crack	0.40	0.92
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)	NE	0.02	5.0 to 6.0	0.28	Hummocky	0.10	Multiple scarp features	0.32	0.72
Red River - River to Rivergate (RRL67.27 to RRL67.53)	SW	0.10	7.0 to 8.0	0.36	Hummocky	0.10	Multiple scarp features	0.32	0.88
Red River - St. John's Park (RRR44.15 to RRR44.30)	SE	0.05	6.0 to 7.0	0.32	Regraded and hummocky	0.05	Scarp features	0.28	0.70
Red River - St. Mary's at Perimeter (RRL70.66 to RRL70.77)	W	0.02	8.0 to 9.0	0.40	Uniform to hummocky	0.07	Retrogression	0.40	0.89
Red River - St. Mary's at Perimeter (RRL70.77 to RRL70.93)	W	0.02	8.0 to 9.0	0.40	Regraded	0.01	Scarp features	0.28	0.71
Red River - St. Mary's at Perimeter (RRL70.93 to RRL71.15)	W	0.02	8.0 to 9.0	0.40	Hummocky	0.10	Retrogression	0.40	0.92

kml1 · Top12 · Thesis · Probability · Consequence · Risk

Ready · 85%

Figure 6.4: Tabs located in the main RAMS spreadsheet (screenshot). The tabs were created to ensure the RAMS is easy to use and manage. The tabs are found in the bottom left hand corner of the spreadsheet.

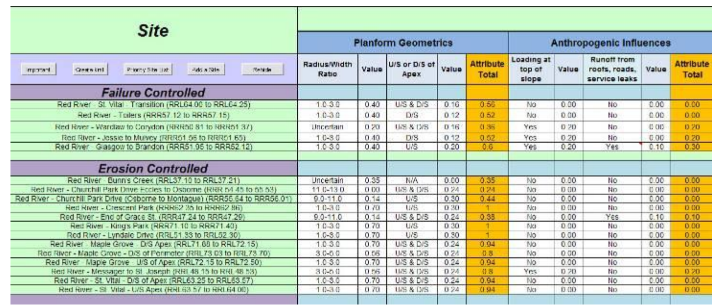
Site
Important · Create kml · Priority Site List · Add a Site · Rehide
Failure Controlled
Assiniboine River - Fort Rouge Park (ARL1.12 to ARL1.24)
Assiniboine River - Granite Curling Club (ARR1.69 to ARR1.90)
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)
Red River - Annabella to May (RRR47.82 to RRR48.12)
Red River - Burrows to Pritchard (RRR44.76 to RRR44.83)
Red River - Burrows to Pritchard (RRR44.83 to RRR44.90)
Red River - Canoe Club (RRL58.79 to RRL59.34)
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)
Red River - Guay Park (RRL53.50 to RRL53.64)
Red River - King's Park (RRR71.40 to RRR71.68)
Red River - King's Park (RRR71.68 to RRR72.08)
Red River - Minnetonka (RRL67.00 to RRL67.07)
Red River - Mordaunt to Annabella (RRR47.49 to RRR47.82)
Red River - Normand Park (RRL69.75 to RRL70.42)
Red River - Norquay Park (RRR44.90 to RRR45.18)
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)
Red River - River to Rivergate (RRL67.27 to RRL67.53)
Red River - St. John's Park (RRR44.15 to RRR44.30)
Red River - St. Mary's at Perimeter (RRL70.66 to RRL70.77)
Red River - St. Mary's at Perimeter (RRL70.77 to RRL70.93)
Red River - St. Mary's at Perimeter (RRL70.93 to RRL71.15)
Red River - St. Vital Cemetery (RRL64.39 to RRL64.72)
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)
Red River - Toilers (RRR57.12 to RRR57.15)
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)
Erosion Controlled
Red River - Bunn's Creek (RRL37.10 to RRL37.21)
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)
Red River - Crescent Park (RRR62.35 to RRR62.86)
Red River - End of Grace St. (RRR47.24 to RRR47.29)
Red River - King's Park (RRR71.10 to RRR71.40)
Red River - Lyndale Drive (RRL51.33 to RRL52.30)
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)

Figure 6.5: Classification of the study sites (screenshot). Characterized sites were classified according to riverbank type. Therefore, failure-controlled and erosion-controlled riverbanks were separated in the main RAMS spreadsheet.

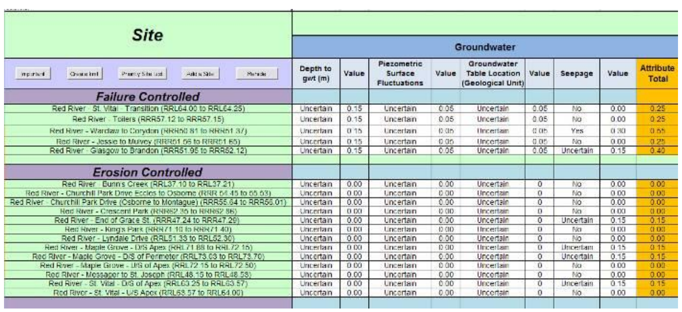
a) Topography

d) Geology

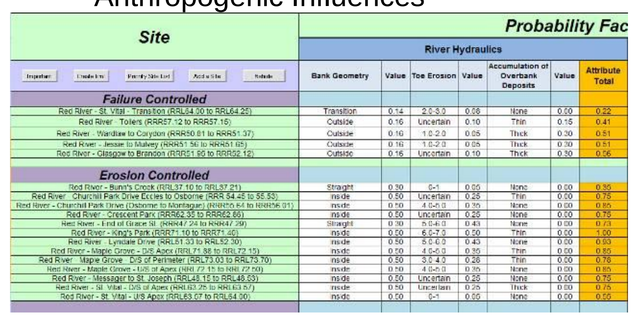
b) Retrogression Ratio



e) Planform Geometrics and Anthropogenic Influences



c) Groundwater



f) River Hydraulics

Figure 6.6: Landslide probability attributes and sub-attributes (screenshot). The attribute total (orange column) is derived by adding the totals for the landslide probability sub-attributes. Continued on the following page.

Site	Bank Drainage	Value	Surface Ponding	Value	Attribute Total
Failure Controlled					
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	Fair to Good	0.09	No	0.00	0.09
Red River - Toilers (RRR57.12 to RRR57.15)	Poor to Fair	0.19	No	0.00	0.19
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)	Uncertain	0.13	No	0.00	0.13
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	Poor to Fair	0.19	No	0.00	0.19
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)	Poor to Good	0.13	No	0.00	0.13
Erosion Controlled					
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	Good	0.05	No	0.00	0.05
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)	Fair to Good	0.09	No	0.00	0.09
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	Fair to Good	0.09	No	0.00	0.09
Red River - Crescent Park (RRR62.35 to RRR62.86)	Fair to Good	0.09	No	0.00	0.09
Red River - End of Grace St. (RRR47.24 to RRR47.29)	Fair to Good	0.09	No	0.00	0.09
Red River - King's Park (RRR71.10 to RRR71.40)	Fair to Good	0.09	No	0.00	0.09
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	Fair to Good	0.09	No	0.00	0.09
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	Fair	0.13	No	0.00	0.13
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	Fair	0.13	No	0.00	0.13
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	Fair to Good	0.09	No	0.00	0.09
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	Fair	0.13	No	0.00	0.13
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	Poor to Fair	0.19	No	0.00	0.19
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	Good	0.05	No	0.00	0.05

g) Surface Water and Drainage

Site	Top of Bank	Value	Slope	Value	River Edge	Value	Site Average	Attribute Total
Failure Controlled								
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	None	0.07	None to Extensive	0.04	Few to Extensive	0.02	0.04	0.12
Red River - Toilers (RRR57.12 to RRR57.15)	None	0.07	None to Few	0.05	Few	0.04	0.05	0.16
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)	None	0.07	Extensive	0.00	Extensive	0.00	0.02	0.07
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	None	0.07	Few to Extensive	0.02	Few	0.04	0.04	0.12
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)	Few	0.04	Few	0.04	Few	0.04	0.04	0.11
Erosion Controlled								
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	None	0.07	None	0.07	None	0.07	0.07	0.11
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)	None	0.07	None to Few	0.05	Few to Extensive	0.02	0.05	0.00
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	None to Few	0.05	None	0.07	None	0.07	0.06	0.00
Red River - Crescent Park (RRR62.35 to RRR62.86)	None to Extensive	0.04	None to Few	0.05	None	0.07	0.05	0.21
Red River - End of Grace St. (RRR47.24 to RRR47.29)	None to Few	0.05	None	0.07	None to Few	0.05	0.06	0.14
Red River - King's Park (RRR71.10 to RRR71.40)	Few to Extensive	0.02	None to Few	0.05	None	0.07	0.05	0.19
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	None	0.07	None to Few	0.05	None to Few	0.05	0.06	0.16
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	Few to Extensive	0.02	None	0.07	None	0.07	0.05	0.18
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	Few to Extensive	0.02	None to Few	0.05	None	0.07	0.05	0.14
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	None to Few	0.05	None	0.07	Few	0.04	0.05	0.18
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	None to Few	0.05	Few to Extensive	0.02	Few	0.04	0.04	0.16
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	Few to Extensive	0.02	Few to Extensive	0.02	None	0.07	0.04	0.14
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	None to Few	0.05	None	0.07	None	0.07	0.06	0.16

h) Vegetation Cover

Site	Stabilization Works	Value	Attribute Total
Failure Controlled			
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	Permanent	0.10	0.10
Red River - Toilers (RRR57.12 to RRR57.15)	None	1.00	1.00
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)	None	1.00	1.00
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	Temporary	0.50	0.50
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)	None	1.00	1.00
Erosion Controlled			
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	Temporary	0.50	0.50
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)	None	1.00	1.00
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	None	1.00	1.00
Red River - Crescent Park (RRR62.35 to RRR62.86)	None	1.00	1.00
Red River - End of Grace St. (RRR47.24 to RRR47.29)	None	1.00	1.00
Red River - King's Park (RRR71.10 to RRR71.40)	None	1.00	1.00
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	None	1.00	1.00
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	None	1.00	1.00
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	None	1.00	1.00
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	None	1.00	1.00
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	None	1.00	1.00
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	None	1.00	1.00
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	Permanent	0.10	0.10

i) Altered Section

Figure 6.6 continued: Landslide probability attributes and sub-attributes (screenshot). The attribute total (orange column) is derived by adding the totals for the landslide probability sub-attributes. Continued from the previous page.

Site	Probability Factor
Important / Create kml / Priority Site List / Add a Site / Rehide	
Failure Controlled	
Assiniboine River - Fort Rouge Park (ARL1.12 to ARL1.24)	34.3
Assiniboine River - Granite Curling Club (ARR1.69 to ARR1.90)	20.5
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)	32.5
Red River - Annabella to May (RRR47.82 to RRR48.12)	20.6
Red River - Burrows to Pritchard (RRR44.76 to RRR44.83)	42.3
Red River - Burrows to Pritchard (RRR44.83 to RRR44.90)	16.1
Red River - Canoe Club (RRL58.79 to RRL59.34)	42.9
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	50.5
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)	43.0
Red River - Guay Park (RRL53.50 to RRL53.64)	48.6
Red River - King's Park (RRR71.40 to RRR71.68)	45.8
Red River - King's Park (RRR71.68 to RRR72.08)	48.9
Red River - Minnetonka (RRL67.00 to RRL67.07)	44.7
Red River - Mordaunt to Annabella (RRR47.49 to RRR47.82)	41.6
Red River - Normand Park (RRL69.75 to RRL70.42)	40.9
Red River - Norquay Park (RRR44.90 to RRR45.18)	40.5
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)	3.6
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	34.6
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)	33.8
Red River - River to Rivergate (RRL67.27 to RRL67.53)	45.7
Red River - St. John's Park (RRR44.15 to RRR44.30)	4.2
Red River - St. Mary's at Perimeter (RRL70.66 to RRL70.77)	39.7
Red River - St. Mary's at Perimeter (RRL70.77 to RRL70.93)	19.4
Red River - St. Mary's at Perimeter (RRL70.93 to RRL71.15)	43.2
Red River - St. Vital Cemetery (RRL64.39 to RRL64.72)	40.3
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	2.7
Red River - Toilers (RRR57.12 to RRR57.15)	33.9
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)	38.1
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	19.9
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)	41.8
Erosion Controlled	
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	8.7
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)	25.0
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	35.4
Red River - Crescent Park (RRR62.35 to RRR62.86)	41.2
Red River - End of Grace St. (RRR47.24 to RRR47.29)	39.8
Red River - King's Park (RRR71.10 to RRR71.40)	39.0
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	41.8
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	41.2
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	33.7
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	39.1
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	38.3
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	35.3
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	2.6

Figure 6.7: *Probability factor* table (screenshot).

Site	Consequence Factor						
	Public Property			Public Perception			Consequence Factor
Important / Create kml / Priority Site List / Add a Site / Rehide	Proximity	Value	Numeric Value	Proximity	Value	Numeric Value	
Failure Controlled							
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	No	None	0.0	Yes	High	1.0	1.10
Red River - Toilers (RRR57.12 to RRR57.15)	Yes	Significant	1.0	Yes	Low	0.2	1.12
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)	Yes	Moderate	0.6	Yes	Low to medium	0.4	1.10
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	Yes	Moderate	0.6	Yes	Low to medium	0.4	1.10
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)	Yes	Moderate	0.6	Yes	Low to medium	0.4	1.10
Erosion Controlled							
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	No	None	0.0	Yes	Low to medium	0.4	1.04
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)	No	None	0.0	Yes	Medium	0.6	1.06
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	No	Moderate	0.6	Yes	Medium	0.6	1.12
Red River - Crescent Park (RRR62.35 to RRR62.86)	No	Moderate	0.6	Yes	Medium to high	0.8	1.14
Red River - End of Grace St. (RRR47.24 to RRR47.29)	No	None Minor Minor to moderate Moderate Moderate to significant Significant	1.0	Yes	Low	0.2	1.12
Red River - King's Park (RRR71.10 to RRR71.40)	No		0.4	Yes	Medium to high	0.8	1.12
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	No		0.6	Yes	Low to medium	0.4	1.10
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	No		0.4	Yes	Low to medium	0.4	1.08
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	No	None	0.0	Yes	Low to medium	0.4	1.04
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	No	Moderate	0.6	Yes	Medium	0.6	1.12
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	No	Moderate	0.6	Yes	Low to medium	0.4	1.10
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	No	None	0.0	Yes	Medium to high	0.8	1.08
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	No	None	0.0	Yes	High	1.0	1.10

Figure 6.8: Consequence attribute table (screenshot). Consequence attribute data is input directly into the main RAMS spreadsheet under the appropriate landslide consequence column. The input parameters for the landslide consequence data are limited by the drop down menu.

Site	Consequence Factor
Important · Create kml · Priority Site List · Add a Site · Rehide	
Failure Controlled	
Assiniboine River - Fort Rouge Park (ARL1.12 to ARL1.24)	1.06
Assiniboine River - Granite Curling Club (ARR1.69 to ARR1.90)	1.10
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)	1.08
Red River - Annabella to May (RRR47.82 to RRR48.12)	1.04
Red River - Burrows to Pritchard (RRR44.76 to RRR44.83)	1.02
Red River - Burrows to Pritchard (RRR44.83 to RRR44.90)	1.04
Red River - Canoe Club (RRL58.79 to RRL59.34)	1.14
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	1.16
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)	1.06
Red River - Guay Park (RRL53.50 to RRL53.64)	1.12
Red River - King's Park (RRR71.40 to RRR71.68)	1.14
Red River - King's Park (RRR71.68 to RRR72.08)	1.14
Red River - Minnetonka (RRL67.00 to RRL67.07)	1.14
Red River - Mordaunt to Annabella (RRR47.49 to RRR47.82)	1.10
Red River - Normand Park (RRL69.75 to RRL70.42)	1.06
Red River - Norquay Park (RRR44.90 to RRR45.18)	1.08
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)	1.06
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	1.06
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)	1.04
Red River - River to Rivergate (RRL67.27 to RRL67.53)	1.08
Red River - St. John's Park (RRR44.15 to RRR44.30)	1.10
Red River - St. Mary's at Perimeter (RRL70.66 to RRL70.77)	1.08
Red River - St. Mary's at Perimeter (RRL70.77 to RRL70.93)	1.04
Red River - St. Mary's at Perimeter (RRL70.93 to RRL71.15)	1.12
Red River - St. Vital Cemetery (RRL64.39 to RRL64.72)	1.16
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	1.10
Red River - Toilers (RRR57.12 to RRR57.15)	1.12
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)	1.10
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	1.10
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)	1.10
Erosion Controlled	
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	1.04
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)	1.06
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	1.12
Red River - Crescent Park (RRR62.35 to RRR62.86)	1.14
Red River - End of Grace St. (RRR47.24 to RRR47.29)	1.12
Red River - King's Park (RRR71.10 to RRR71.40)	1.12
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	1.10
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	1.08
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	1.04
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	1.12
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	1.10
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	1.08
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	1.10

Figure 6.9: *Consequence factor* table (screenshot). The consequence factor column in the main RAMS spreadsheet is highlighted in yellow.

Site	Risk Factor		
Important / Create kml / Priority Site List / Add a Site / Rehide	Risk	Risk Level	Response Level
Failure Controlled			
Assiniboine River - Fort Rouge Park (ARL1.12 to ARL1.24)	36.4	Low	Routine
Assiniboine River - Granite Curling Club (ARR1.69 to ARR1.90)	22.5	Low	Routine
Assiniboine River - Munson Park (ARL3.20 to ARL3.37)	35.1	Low	Routine
Red River - Annabella to May (RRR47.82 to RRR48.12)	21.4	Low	Routine
Red River - Burrows to Pritchard (RRR44.76 to RRR44.83)	43.2	Low	Routine
Red River - Burrows to Pritchard (RRR44.83 to RRR44.90)	16.8	Very Low	Minimum
Red River - Canoe Club (RRL58.79 to RRL59.34)	48.9	Medium	Increased
Red River - Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	58.6	High	Frequent
Red River - Darveau to Hebert (RRL48.63 to RRL48.79)	45.6	Medium	Increased
Red River - Guay Park (RRL53.50 to RRL53.64)	54.5	Medium	Increased
Red River - King's Park (RRR71.40 to RRR71.68)	52.2	Medium	Increased
Red River - King's Park (RRR71.68 to RRR72.08)	55.7	High	Frequent
Red River - Minnetonka (RRL67.00 to RRL67.07)	51.0	Medium	Increased
Red River - Mordaunt to Annabella (RRR47.49 to RRR47.82)	45.7	Medium	Increased
Red River - Normand Park (RRL69.75 to RRL70.42)	43.3	Low	Routine
Red River - Norquay Park (RRR44.90 to RRR45.18)	43.8	Low	Routine
Red River - Pembina and Grandmont (RRR76.28 to RRR76.42)	3.9	Very Low	Minimum
Red River - Provencher to LaVerendrye (RRL49.10 to RRL49.28)	36.7	Low	Routine
Red River - Provencher to LaVerendrye (RRL49.28 to RRL49.37)	35.2	Low	Routine
Red River - River to Rivergate (RRL67.27 to RRL67.53)	49.3	Medium	Increased
Red River - St. John's Park (RRR44.15 to RRR44.30)	4.7	Very Low	Minimum
Red River - St. Mary's at Perimeter (RRL70.66 to RRL70.77)	42.9	Low	Routine
Red River - St. Mary's at Perimeter (RRL70.77 to RRL70.93)	20.2	Low	Routine
Red River - St. Mary's at Perimeter (RRL70.93 to RRL71.15)	48.3	Medium	Increased
Red River - St. Vital Cemetery (RRL64.39 to RRL64.72)	46.8	Medium	Increased
Red River - St. Vital - Transition (RRL64.00 to RRL64.25)	3.0	Very Low	Minimum
Red River - Toilers (RRR57.12 to RRR57.15)	38.0	Low	Routine
Red River - Wardlaw to Corydon (RRR50.81 to RRR51.37)	41.9	Low	Routine
Red River - Jessie to Mulvey (RRR51.56 to RRR51.65)	21.9	Low	Routine
Red River - Glasgow to Brandon (RRR51.95 to RRR52.12)	46.0	Medium	Increased
Erosion Controlled			
Red River - Bunn's Creek (RRL37.10 to RRL37.21)	9.0	Very Low	Minimum
Red River - Churchill Park Drive Eccles to Osborne (RRR 54.45 to 55.53)	26.5	Low	Routine
Red River - Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	39.7	Low	Routine
Red River - Crescent Park (RRR62.35 to RRR62.86)	47.0	Medium	Increased
Red River - End of Grace St. (RRR47.24 to RRR47.29)	44.6	Low	Routine
Red River - King's Park (RRR71.10 to RRR71.40)	43.6	Low	Routine
Red River - Lyndale Drive (RRL51.33 to RRL52.30)	45.9	Medium	Increased
Red River - Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	44.5	Low	Routine
Red River - Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	35.0	Low	Routine
Red River - Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	43.8	Low	Routine
Red River - Messager to St. Joseph (RRL48.15 to RRL48.53)	42.2	Low	Routine
Red River - St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	38.1	Low	Routine
Red River - St. Vital - U/S Apex (RRL63.57 to RRL64.00)	2.9	Very Low	Minimum

Figure 6.10: Risk factor, risk level and response level table (screenshot). The risk factor, risk level and response level for the thirty-six sites characterized along public riverbank property on the Red and Assiniboine Rivers are shown in the table above.

Risk Factors

Response Level

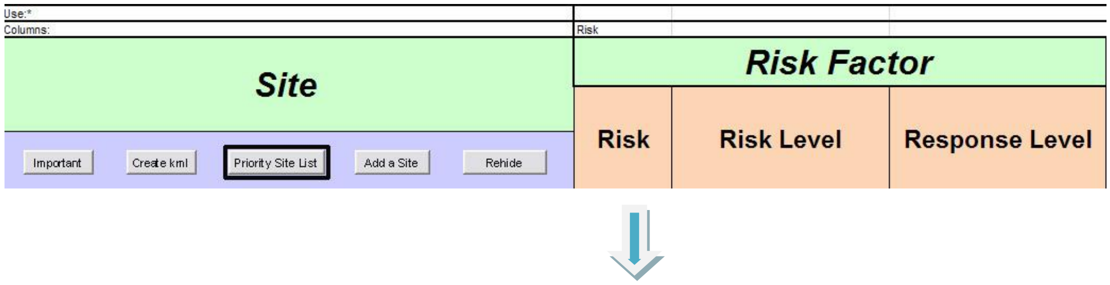
Range		Risk Level	Definition	Response Level
0.00	19.990	Very Low	Inspect once every 3 to 5 years	Minimum
20.00	44.990	Low	Inspect once every 2 to 3 years	Routine
45.00	54.990	Medium	Inspect every 1 to 2 years	Increased
55.00	120.000	High	Insect once to twice per year	Frequent

Figure 6.11: *Risk factor, risk level and response levels* developed for the City of Winnipeg (screenshot).

Top 12 Priority Site List

#	Site Location and Name	Risk Factor	Risk Level	Response Level
1	Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	58.6	High	Frequent
2	King's Park (RRR71.68 to RRR72.08)	55.7	High	Frequent
3	Guay Park (RRL53.50 to RRL53.64)	54.5	Medium	Increased
4	King's Park (RRR71.40 to RRR71.68)	52.2	Medium	Increased
5	Minnetonka (RRL67.00 to RRL67.07)	51.0	Medium	Increased
6	River to Rivergate (RRL67.27 to RRL67.53)	49.3	Medium	Increased
7	Canoe Club (RRL58.79 to RRL59.34)	48.9	Medium	Increased
8	St. Mary's at Perimeter (RRL70.93 to RRL71.15)	48.3	Medium	Increased
9	Crescent Park (RRR62.35 to RRR62.86)	47.0	Medium	Increased
10	St. Vital Cemetery (RRL64.39 to RRL64.72)	46.8	Medium	Increased
11	Glasgow to Brandon (RRR51.95 to RRR52.12)	46.0	Medium	Increased
12	Lyndale Drive (RRL51.33 to RRL52.30)	45.9	Medium	Increased
	Mordaunt to Annabella (RRR47.49 to RRR47.82)	45.7	Medium	Increased
	Darveau to Hebert (RRL48.63 to RRL48.79)	45.6	Medium	Increased
	End of Grace St. (RRR47.24 to RRR47.29)	44.6	Low	Routine
	Maple Grove - D/S Apex (RRL71.88 to RRL72.15)	44.5	Low	Routine
	Maple Grove - U/S of Apex (RRL72.15 to RRL72.50)	43.8	Low	Routine
	Norquay Park (RRR44.90 to RRR45.18)	43.8	Low	Routine
	King's Park (RRR71.10 to RRR71.40)	43.6	Low	Routine
	Normand Park (RRL69.75 to RRL70.42)	43.3	Low	Routine
	Burrows to Pritchard (RRR44.76 to RRR44.83)	43.2	Low	Routine
	St. Mary's at Perimeter (RRL70.66 to RRL70.77)	42.9	Low	Routine
	Messager to St. Joseph (RRL48.15 to RRL48.53)	42.2	Low	Routine
	Wardlaw to Corydon (RRR50.81 to RRR51.37)	41.9	Low	Routine
	Churchill Park Drive (Osborne to Montague) (RRR55.64 to RRR56.01)	39.7	Low	Routine
	St. Vital - D/S of Apex (RRL63.25 to RRL63.57)	38.1	Low	Routine
	Toilers (RRR57.12 to RRR57.15)	38.0	Low	Routine
	Provencher to LaVerendrye (RRL49.10 to RRL49.28)	36.7	Low	Routine
	Fort Rouge Park (ARL1.12 to ARL1.24)	36.4	Low	Routine
	Provencher to LaVerendrye (RRL49.28 to RRL49.37)	35.2	Low	Routine
	Assiniboine River - Munson Park (ARL3.20 to ARL3.37)*	35.1	Low	Routine
	Maple Grove - D/S of Perimeter (RRL73.03 to RRL73.70)	35.0	Low	Routine
	Churchill Park Drive (Eccles to Osborne) (RRR54.45 to RRR55.53)	26.5	Low	Routine
	Granite Curling Club (ARR1.69 to ARR1.90)*	22.5	Low	Routine
	Jessie to Mulvey (RRR51.56 to RRR51.65)	21.9	Low	Routine
	Annabella to May (RRR47.82 to RRR48.12)	21.4	Low	Routine
	St. Mary's at Perimeter (RRL70.77 to RRL70.93)	20.2	Low	Routine
	Burrows to Pritchard (RRR44.83 to RRR44.90)	16.8	Very Low	Minimum
	Bunn's Creek (RRL37.10 to RRL37.21)	9.0	Very Low	Minimum
	St. John's Park (RRR44.15 to RRR44.30)	4.7	Very Low	Minimum
	Pembina and Grandmont (RRR76.28 to RRR76.42)	3.9	Very Low	Minimum
	St. Vital - Transition (RRL64.00 to RRL64.25)	3.0	Very Low	Minimum
	St. Vital - U/S Apex (RRL63.57 to RRL64.00)	2.9	Very Low	Minimum

Figure 6.12: *Top 12 Priority Site spreadsheet* (screenshot). *The Top 12 spreadsheet* automatically sorts and updates the risk factor, risk level and response level for each site when a weighting factor or input parameter is changed.



Top 12 Priority Site List

#	Site Location and Name	Risk Factor	Risk Level	Response Level
1	Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	58.6	High	Frequent
2	King's Park (RRR71.68 to RRR72.08)	55.7	High	Frequent
3	Guay Park (RRL53.50 to RRL53.64)	54.5	Medium	Increased
4	King's Park (RRR71.40 to RRR71.68)	52.2	Medium	Increased
5	Minnetonka (RRL67.00 to RRL67.07)	51.0	Medium	Increased
6	River to Rivergate (RRL67.27 to RRL67.53)	49.3	Medium	Increased
7	Canoe Club (RRL58.79 to RRL59.34)	48.9	Medium	Increased
8	St. Mary's at Perimeter (RRL70.93 to RRL71.15)	48.3	Medium	Increased
9	Crescent Park (RRR62.35 to RRR62.86)	47.0	Medium	Increased
10	St. Vital Cemetery (RRL64.39 to RRL64.72)	46.8	Medium	Increased
11	Glasgow to Brandon (RRR51.95 to RRR52.12)	46.0	Medium	Increased
12	Lyndale Drive (RRL51.33 to RRL52.30)	45.9	Medium	Increased

Figure 6.13: Generation of the *Top 12 Priority Site List* (screenshot). A priority site list can be generated by depressing the *priority site list button* in the main RAMS spreadsheet. When the *priority site list button* is depressed, a Top 12 priority site list is created in Microsoft Word.

Site Characterization Assessment Top 12 List of Priority Sites

#	Site Location and Name	Risk Factor	Risk Level	Response Level
1	Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	_	_	_
2	Minnetonka (RRL67.00 to RRL67.07)	_	_	_
3	King's Park (RRR71.40 to RRR72.08)	_	_	_
4	Maple Grove - U/S Apex (RRL72.15 to RRL72.50)	_	_	_
5	Crescent Park (RRR62.35 to RRR62.86)	_	_	_
6	Canoe Club (RRL58.79 to RRL59.34)	_	_	_
7	Lyndale Drive (RRL51.33 to RRL52.30)	_	_	_
8	St. Vital Cemetery (RRL64.39 to RRL64.72)	_	_	_
9	Guay Park (RRL53.50 to RRL53.64)	_	_	_
10	Normand Park (RRL69.75 to RRL7.42)	_	_	_
11	St. Mary's at Perimeter (RRL70.93 to RRL71.15)	_	_	_
12	Annabella to Mordaunt (RRR47.49 to RRR47.82)	_	_	_

RAMS Top 12 List of Priority Sites

#	Site Location and Name	Risk Factor	Risk Level	Response Level
1	Churchill Park Drive (Montague to Cockburn) (RRR56.00 to RRR56.50)	58.6	High	Frequent
2	King's Park (RRR71.68 to RRR72.08)	55.7	High	Frequent
3	Guay Park (RRL53.50 to RRL53.64)	54.5	Medium	Increased
4	King's Park (RRR71.40 to RRR71.68)	52.2	Medium	Increased
5	Minnetonka (RRL67.00 to RRL67.07)	51.0	Medium	Increased
6	River to Rivergate (RRL67.27 to RRL67.53)	49.3	Medium	Increased
7	Canoe Club (RRL58.79 to RRL59.34)	48.9	Medium	Increased
8	St. Mary's at Perimeter (RRL70.93 to RRL71.15)	48.3	Medium	Increased
9	Crescent Park (RRR62.35 to RRR62.86)	47.0	Medium	Increased
10	St. Vital Cemetery (RRL64.39 to RRL64.72)	46.8	Medium	Increased
11	Glasgow to Brandon (RRR51.95 to RRR52.12)	46.0	Medium	Increased
12	Lyndale Drive (RRL51.33 to RRL52.30)	45.9	Medium	Increased

Figure 6.14: Comparison of the *Top 12 List of Priority Sites* from the site characterization assessments and the RAMS.

Table 6 1: Weighting Factors for the Landslide Probability Attributes and Sub-Attributes for Erosion-Controlled and Failure-Controlled Riverbanks.

Probability Factors

Attribute / Sub-Attribute	Failure Controlled (Average Weighting)	Erosion Controlled (Average Weighting)
Topography	1	1
Azimuth	0.1	0.05
Bank Height	0.4	0.5
Slope Shape	0.1	0
Evidence of Slope Movement	0.4	0.45
Retrogression Ratio	0.9	0.9
Groundwater	0.8	0.3
Depth to groundwater table	0.3	0
Piezometric Surface Fluctuations	0.1	0
Gwt location (Geological unit)	0.1	0
Seepage	0.3	0.3
Geology	0.9	0.45
Soil Type	0.45	0
Depth to Till	0.45	0.45
River Hydraulics	0.7	1
Bank Geometry	0.2	0.5
Toe Erosion	0.2	0.5
Accumulation of overbank deposits	0.3	0
Surface Water & Drainage	0.5	0.25
Bank Drainage	0.25	0.25
Surface Ponding	0.25	0
Planform Geometrics	0.6	1
R/W Ratio	0.4	0.7
U/S or D/S of Apex	0.2	0.3
Anthropogenic Influences	0.3	0.3
Loading at top of slope	0.2	0.2
Runoff from roads, roofs and leaking services	0.1	0.1
Vegetation Cover	0.21	0.21
Top of Bank	0.07	0.07
Slope	0.07	0.07
River Edge	0.07	0.07
Altered Section		
Permanent	0.1	0.1
Temporary	0.5	0.5
None	1	1
Geotechnical Classification Matrix		
Pre Failure		
Failure		
Post Failure		
Slope Reactivation		
Uncertain		

Table 6 2: Summary of Weighting Factors for the Landslide Consequence Attributes.

Consequence Factors

Public Perception

	Average Weighting
Public Perception	1
Uncertain	0.5
Yes	1
No	0

Option	Value	Weight Value (%)	Weighting
None	Public can not access site.	0	0
Low	Site frequented by low foot traffic volumes and has low access potential. Low visual effect.	20	0.2
Low to medium	Site frequented by low to medium foot traffic volumes and has low to medium access potential. Low to medium visual effect.	40	0.4
Medium	Site frequented by medium foot traffic volumes and has medium access potential. Medium visual effect.	60	0.6
Medium to high	Site frequented by medium to high foot traffic volumes and has medium to high access potential. Medium to high visual effects.	80	0.8
High	Site frequented by high foot traffic volumes and has high access potential. High visual effect.	100	1

Public Property (Failure Controlled)

	Average Weighting
Public Property (Failure Controlled)	1
Uncertain	0.5
Yes	1
No	0

Option	Value	Weight Value (%)	Weighting
None	No potential loss of top of bank.	0	0
Minor	Potential loss of top of bank ranges from 0.1 to 10.0 m.	20	0.2
Minor to moderate	Potential loss of top of bank ranges from 10.1 to 20.0 m.	40	0.4
Moderate	Potential loss of top of bank ranges from 20.1 to 30.0 m.	60	0.6
Moderate to significant	Potential loss of top of bank ranges from 30.1 to 45.0 m.	80	0.8
Significant	Potential loss of top of bank >45.1 m.	100	1

Public Property (Erosion Controlled)

	Average Weighting
Public Property (Erosion Controlled)	1
Uncertain	0.5
Yes	1
No	0

Option	Value	Weight Value (%)	Weighting
None	No potential loss of top of bank.	0	0
Minor	Potential loss of top bank ranges from 0.1 to 3.0 m.	20	0.2
Minor to moderate	Potential loss of top of bank ranges from 3.1 to 6.0 m.	40	0.4
Moderate	Potential loss of top of bank ranges from 6.1 to 9.0 m.	60	0.6
Moderate to significant	Potential loss of top of bank ranges from 9.1 to 12.0 m.	80	0.8
Significant	Potential loss of top of bank is >12m.	100	1

Chapter 7: Google Earth Application of the Riverbank Asset Management System

7.1 Introduction

As discussed in Chapter 6, the thirty-six sites that were assessed during the site characterization program and site surveys were analyzed and prioritized using a newly developed Riverbank Asset Management System (RAMS). The RAMS was created to ensure that the City of Winnipeg has a current risk management system that reflects acceptable risk management standards used in engineering practice today. The development of the RAMS has created a planning tool for the Riverbank Management Engineer at the City of Winnipeg. The planning tool can be used to provide improved management of public riverbank property in the City of Winnipeg. The RAMS will allow riverbank stabilization projects to be prioritized using risk and response levels and will therefore minimize subjective personal and political influences from the decision-making process.

The next step of this project document is to display the results of the RAMS, using a comprehensive geospatial visualization tool. Google Earth Pro© was chosen as the medium to display the results of the RAMS because it is easy-to-use, economical, and commercially available software, that provides up-to-date aerial imagery. Of particular interest to this research project, is the incorporation of up-to-date aerial imagery of the Winnipeg area. The main benefit of using Google Earth Pro© (abbreviated to GE in this document) over Google Earth©, a free version of the software, is its ability to import files that can be overlain as separate layers on the aerial imagery.

Google Earth Pro© and Google Earth© can be easily downloaded and operated on any computer world-wide. Therefore, expensive, sometimes difficult to use, propriety software is not required for the RAMS to be accessed and visualized. By creating a geospatial visualization tool in simple to use, economical and easily accessible software, the RAMS can easily be utilized by both the engineering community and public policy makers. This will ensure the success of the RAMS, as all stakeholders can be actively involved in the risk management process.

7.2 Development and Visualization of the Riverbank Asset Management System

As outlined in Chapter 6, the RAMS was initially developed in Microsoft Excel using risk management principles. This meant that results of analysis and prioritization were not presented as a simple and accessible geospatial visualization tool. The author decided that a geospatial visualization tool, such as Google Earth Pro©, should be utilized to ensure that the analysis and prioritization performed in the RAMS is displayed visually. Because it is necessary to convert Microsoft Excel code to Google Earth Pro© code for the RAMS to be exhibited in Google Earth Pro©, it was necessary to develop or access a program that has the potential of converting Microsoft Excel code to Google Earth Pro© code. The Google Earth Pro© educational help desk provided the author, free of charge, a program that has the capability of converting Microsoft Excel code to Google Earth Pro© code. The program was developed in Visual Basic. By using Visual Basic as the interface between Microsoft Excel and Google Earth Pro©, an effective and easy-to-use geospatial visualization tool was created for the RAMS in Google Earth Pro©. The reader is referred to Appendix D, which provides a users manual for the RAMS.

7.2.1 Features of the Riverbank Asset Management System

Many features have been incorporated into the visual component of the RAMS in Google Earth Pro© (GE), to make the RAMS easy to use and manage. The RAMS has been developed so that repetitive data entry and computer programming are not required when additional sites are added or when input parameters and weighting factors change. This ensures that the RAMS can be easily accessed and utilized by all stakeholders involved in the risk management process.

Figure 7.1 outlines the steps that need to be performed so the RAMS can be viewed in Google Earth Pro©. When GE is launched, the program automatically zooms in to the Winnipeg area. Figure 7.1 shows that the thirty-six sites assessed during the site characterization program are then identified by shading. The shading extends from the middle of the river to approximately 107 m inland from the NSWL. The shading represents a site's risk and response level. The sections of the riverbank that were not assessed during the site characterization program remain un-shaded. Twelve "bulls-eyes" displayed during the initial screen loading represent the twelve sites that have the highest risk factor value. The development of the risk factor shading will be discussed in further detail in Section 7.2.2.

Figure 7.2 shows that for data management purposes, it was effective to categorize the sites in the RAMS according to:

- Riverbank Type (failure-controlled or erosion-controlled)
- River (Red River or Assiniboine River)

- City of Winnipeg River Co-ordinate System (ARL, ARR, RRL, RRR and River Stationing between approximately 74 km and 37 km)

The drop down legend, located on the left hand side of the GE screen, allows the user to select the appropriate information, so the location of a site can be visualized in GE.

Figure 7.3 demonstrates the methodology for incorporating additional sites into the RAMS. An additional site can be added by placing the cursor above the row where the additional site is to be added. A users manual is provided in Appendix D. It illustrates the steps required to successfully incorporate additional sites into the RAMS. The user will be prompted to specify the number of sites that need to be added to the RAMS. The columns, which have standard programming, will automatically generate the appropriate code when a site is added. However, specific site information needs to be entered by the user. Figure 7.4 shows that the re-hide button will return the input screen to its original layout once the site information has been entered.

7.2.2 Development of Shading for Risk Factors

As outlined in Section 7.2, the RAMS shows shading that represents the risk and response levels for sites when the RAMS is initially launched in GE. A legend is located in the bottom left hand side of the GE screen (Figure 7.1), demonstrating the shading for the various risk and response levels. As identified in Chapter 6, risk factor is interconnected with response level. That is, a risk factor corresponds to a specific risk and response level. The shading for the risk and response levels at each site have been programmed to change automatically if the user's changes to weighting factors or input parameters result in modifications to the risk and response levels. As new sites are incorporated into the RAMS, the shading for the risk and response levels will be automatically generated in GE.

7.2.3 Creation and Visualization of Google Earth Balloon

A balloon was created in GE for each site, so that data that have been analyzed and prioritized in the RAMS can be easily visualized in one location by the user. This allows the user to bypass the complexities of the RAMS spreadsheet, if additional analysis is not required. The GE balloon is visualized by left clicking the bulls-eye at each site. Figure 7.5 illustrates that the upper half of the balloon displays the following information:

- Brief site description
- Probability and consequence factors
- Risk factor and risk and response levels
- External files

Figure 7.6 shows that the lower portion of the GE balloon provides detailed information about the landslide probability attributes and sub-attributes, and the landslide consequence attributes. Sections 7.2.3.1 to 7.2.3.4 briefly describe the information provided in the GE balloon at each site.

To view the GE balloon for a site that does not have a bull's-eye present during the initial GE screen loading, the link to the GE balloon must be accessed from the drop down menu on the left hand side of the GE screen (Figure 7.2). The user needs to locate the site in the drop down menu by knowing: 1) failure type 2) river name and 3) river co-ordinate. The user will be able to locate a site by clicking boxes in the drop down menu, until the appropriate site is located, if this information is not known. When all of the relevant boxes in the menu have been highlighted, the bull's-eye for a non Top 12 priority site will automatically appear on the screen. The GE balloon can be viewed by clicking on the bull's-eye icon.

7.2.3.1 Site Description

The GE balloon for each site provides a brief description of the site. The description includes specific site information such as: 1) where the site is located with respect to a river meander 2) bank height 3) bank slope 4) retrogression ratio 5) general description about slope movement history and, 6) type of slope movement.

Immediately above the site description, icons are visible that will allow the user to look at the sites immediately upstream and downstream of the site of interest.

7.2.3.2 Probability and Consequence Factors

Figure 7.5 shows that the probability and consequence factors for each site are highlighted in yellow on the right hand side of the GE balloon. Figure 7.6 illustrates that the totals for the landslide probability attributes and sub-attributes and the landslide consequence attributes are displayed in the lower portion of the GE balloon. Changes in the totals for the landslide probability attributes and sub-attributes and, the landslide consequence attributes will automatically occur in the appropriate column, if any of the input parameters or weighting factors are modified. In addition, probability and consequence factors will be automatically updated in the upper portion of the GE balloon if any changes are made to the input parameters or weighting factors. Automation of the RAMS ensures that the input parameters and weighting factors only need to be changed in one location. This triggers automatic changes elsewhere in the RAMS. The automation of the geospatial component of the RAMS provides a unique and valuable contribution to research on slope stability issues in the Winnipeg area as it allows the RAMS to be a user-friendly and easy-to-manage geospatial visualization tool.

7.2.3.3 Risk Factor and the Risk and Response Levels

Figure 7.5 demonstrates that the risk factor and the risk and response levels for each site are highlighted in pink in the middle portion of the GE balloon. Like the probability and consequence factors, changes to the risk factor automatically occur in the GE balloon if an input parameter or weighting factor is modified. In addition, the risk and response level may change if the ‘new’ risk factor is in a different risk and response level category. The risk and response level categories are identified in Chapter 6. Like the other parameters, a change in risk and response level will automatically occur in the GE balloon, if necessary.

7.2.3.4 External Files

External files, such as videos, slideshows and photographs, have been incorporated into the GE balloon at each site. The external files are stored in a *gmail account* that was created specifically for the City of Winnipeg’s RAMS.

Figure 7.5, illustrates an example of a slideshow that was created at each site. Approximately 10 representative photographs were chosen by the author to be displayed in the slideshow at each site. The representative photographs were downloaded into a *Picasa web album*. *Picasa* allows a user to store photographs in a *gmail account*. Description, location and date were entered for each photograph in the web album. After incorporating the photographs into the web album, a slideshow was created for each GE balloon. The slideshow scrolls through the representative site photographs when the GE balloon is opened by the user. Photograph description, photograph location and photograph date are visible during the slideshow.

Figure 7.7 demonstrates that the locations of the photographs can also be visualized by the user when viewing the site image location icon in the GE balloon. The site image location icon is located beneath the external file heading in the GE balloon. The photograph locations are illustrated by a “thumbtack”. Each thumbtack is labelled with the word ‘field’ and a number. The number corresponds to the photograph number assigned during the site characterization program. Appendix C provides photograph numbers and descriptions. As shown on Figure 7.8, if the user left clicks on the thumbtack, the screen displays the photograph, together with its description, location and date. The locations of photographs that were taken during boat tours are too difficult to ascertain exactly and were approximated. The thumbtacks representing the photographs taken from boats have been placed in the display in the middle of the river. The thumbtacks were assigned numbering, IMG 1 through IMG x, where x depends on the number of photographs taken from the boat at a site.

The photograph image, location and information were entered individually into GE at each site. Once the appropriate photographs and photograph information had been input into GE, each site was saved as a separate GE file (.kmz) in *Page Creator*. *Page creator* is available for storing data in a *gmail account*. The files created for each site, were saved with the site’s name to avoid confusion for future users.

Videos taken along the Red and Assiniboine Rivers by the City of Winnipeg were incorporated into the RAMS, if possible. Videos for certain sections of the rivers were available for 1988, 1998 and 2004. The videos were downloaded and stored in the video option of the City's *gmail account*. The videos were incorporated into the RAMS twice. Figure 7.5 shows that the videos for each year, if available, can be accessed from the GE balloon under the external file heading. In addition, the videos can be accessed when the user opens the site image location screen (Figure 7.7).

7.2.4. Embedded Files

Files were embedded in the RAMS to illustrate site specific information such as the site length and type, ownership of riverbank property, and location of public infrastructure and utilities. The information required to produce the embedded files was provided to the author by the City of Winnipeg. The embedded files were created as separate layers in the RAMS and can be turned on and off at the user's discretion. The embedded files are saved as individual GE files in *Page Creator*. Appendix D provides information on embedding files into the RAMS. The files that were embedded in the RAMS to date include:

- Primary dike system for the City of Winnipeg
- Outfall locations along the Red and Assiniboine Rivers
- City of Winnipeg's river co-ordinate system
- Site lengths and types
- Public, private and public property to characterize further

The locations of the primary dike system and the outfalls were provided to the author digitally and subsequently imported into Google Earth Pro©. The locations of the outfalls along the Red and Assiniboine Rivers were created as separate layers in GE. Figures

7.9 and 7.10 outline the locations of the primary dike system and the outfalls in the City of Winnipeg respectively.

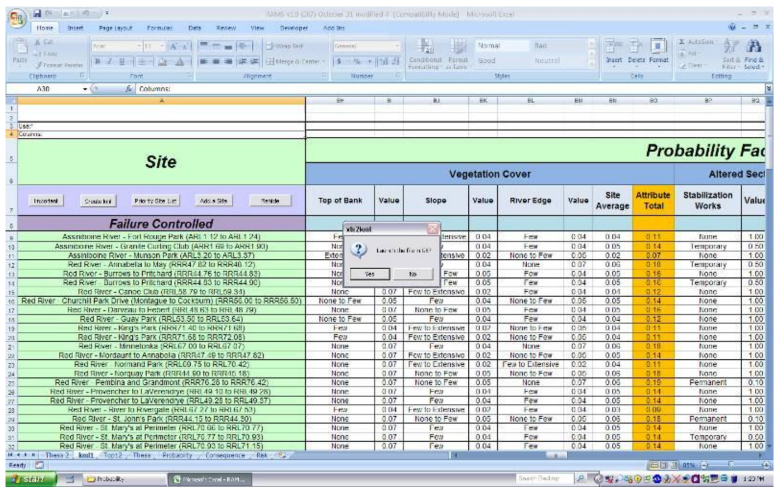
Figure 7.11 illustrates that the City of Winnipeg's river co-ordinate system was imported into GE. The river co-ordinate system is used as a reference system for riverbank location at the City of Winnipeg. It was also adopted as the reference system for the RAMS to ensure consistency when referencing a riverbank location.

Figure 7.12 demonstrates that site length and type were also incorporated as a separate layer in the RAMS. The site lengths were drawn in GE and subsequently saved as an individual GE file in *Page Creator*. A colour coded line was drawn along the toe of the riverbank to delineate site length and type. The City of Winnipeg, in the Riverbank Stability Characterization Report prepared in 2000 used a red line along the toe of a riverbank to designate a failure-controlled site; a green line to represent an erosion-controlled site and a blue line to designate a transition riverbank. The same procedure was used to delineate the site length and type in the RAMS.

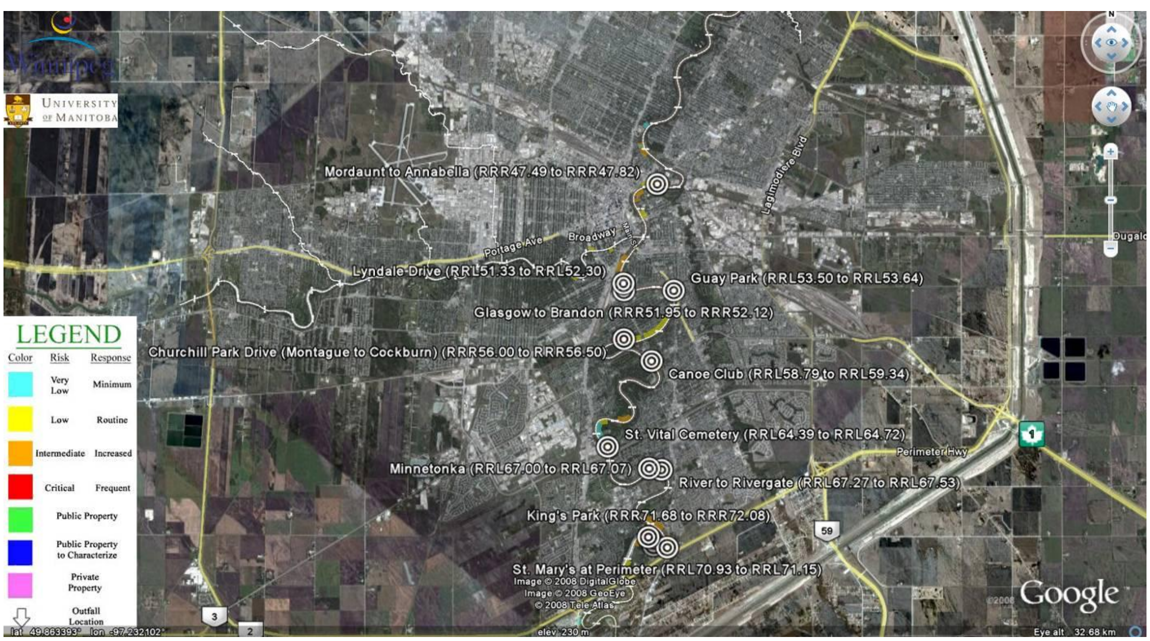
Figure 7.13 shows that a layer was created to differentiate public and private riverbank property. The layer identifies: 1) public property 2) private property and, 3) public property to characterize further. *Public property to characterize* further was defined by the author as publicly owned riverbank property that has a retrogression ratio greater than 1.5. The slope angles for public riverbank property not presently included in the RAMS, were borrowed from the Riverbank Stability Characterization Report prepared by the City of Winnipeg in 2000. The actual average slope angles in 2008 may be slightly different than the earlier ones that have been used in the retrogression ratio calculations.

The author recommends that the City of Winnipeg conduct a detailed site characterization program for the sites that have been classified as *public property to characterize further*. No recommendations are provided at this time for private riverbank property, because the RAMS was created to determine the landslide risk for public riverbank property.

1)



2)



3)

Figure 7.1: Procedure to launch GE from the RAMS spreadsheet. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

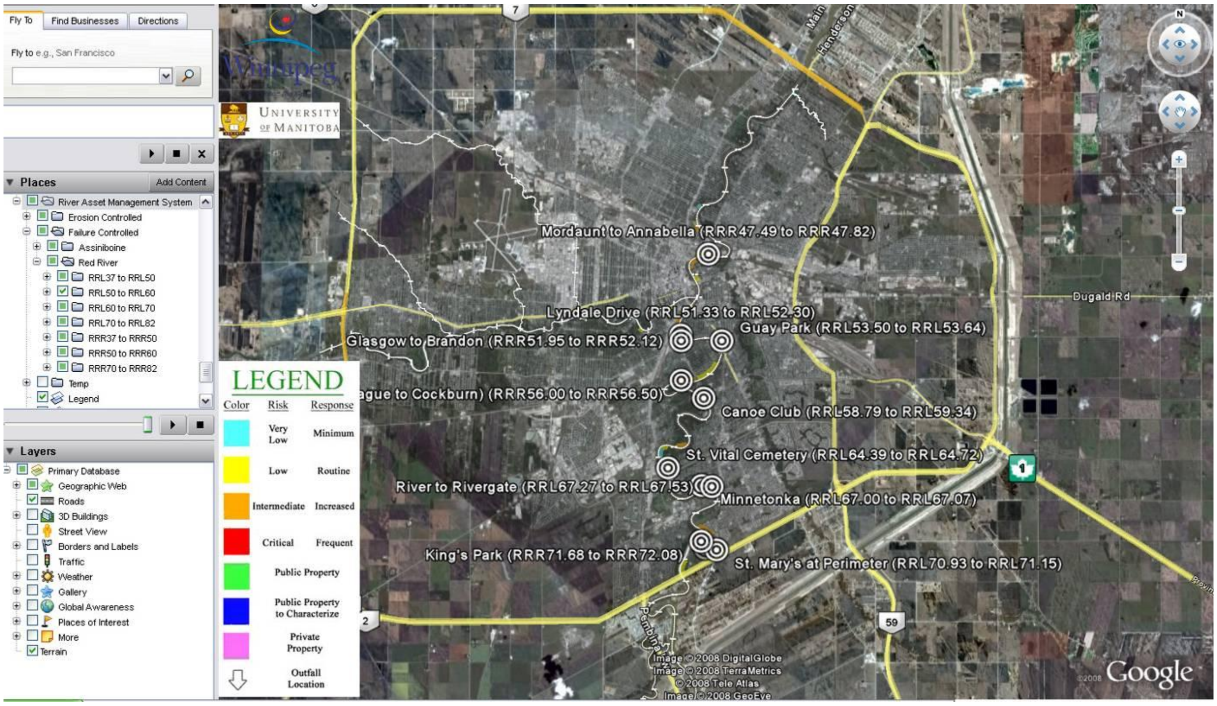


Figure 7.2: Drop down menu used to highlight site of interest in GE. The sites are classified according to: 1) failure type, 2) river name and 3) City of Winnipeg river co-ordinate system. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

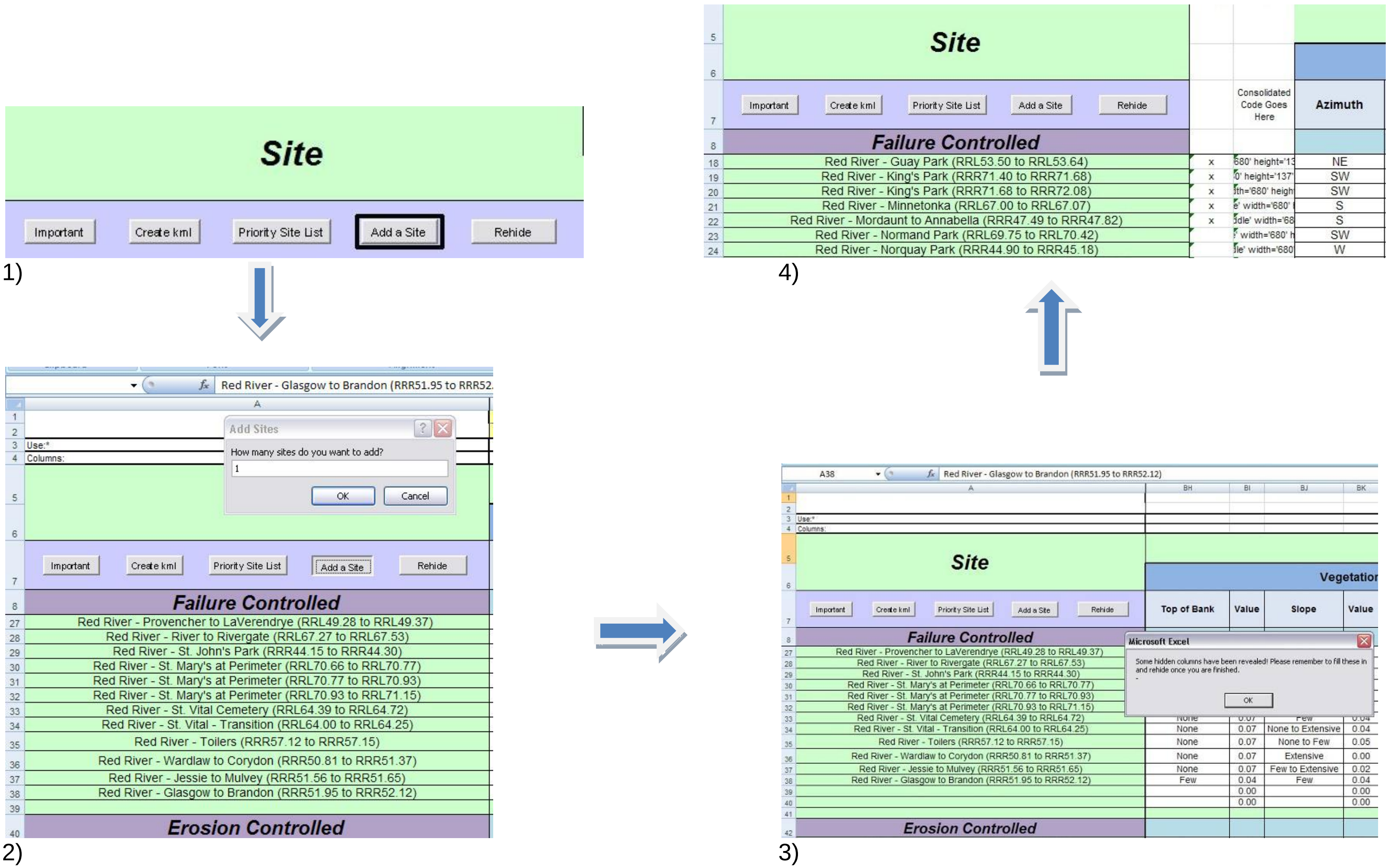


Figure 7.3: Steps required to add a site to the RAMS.

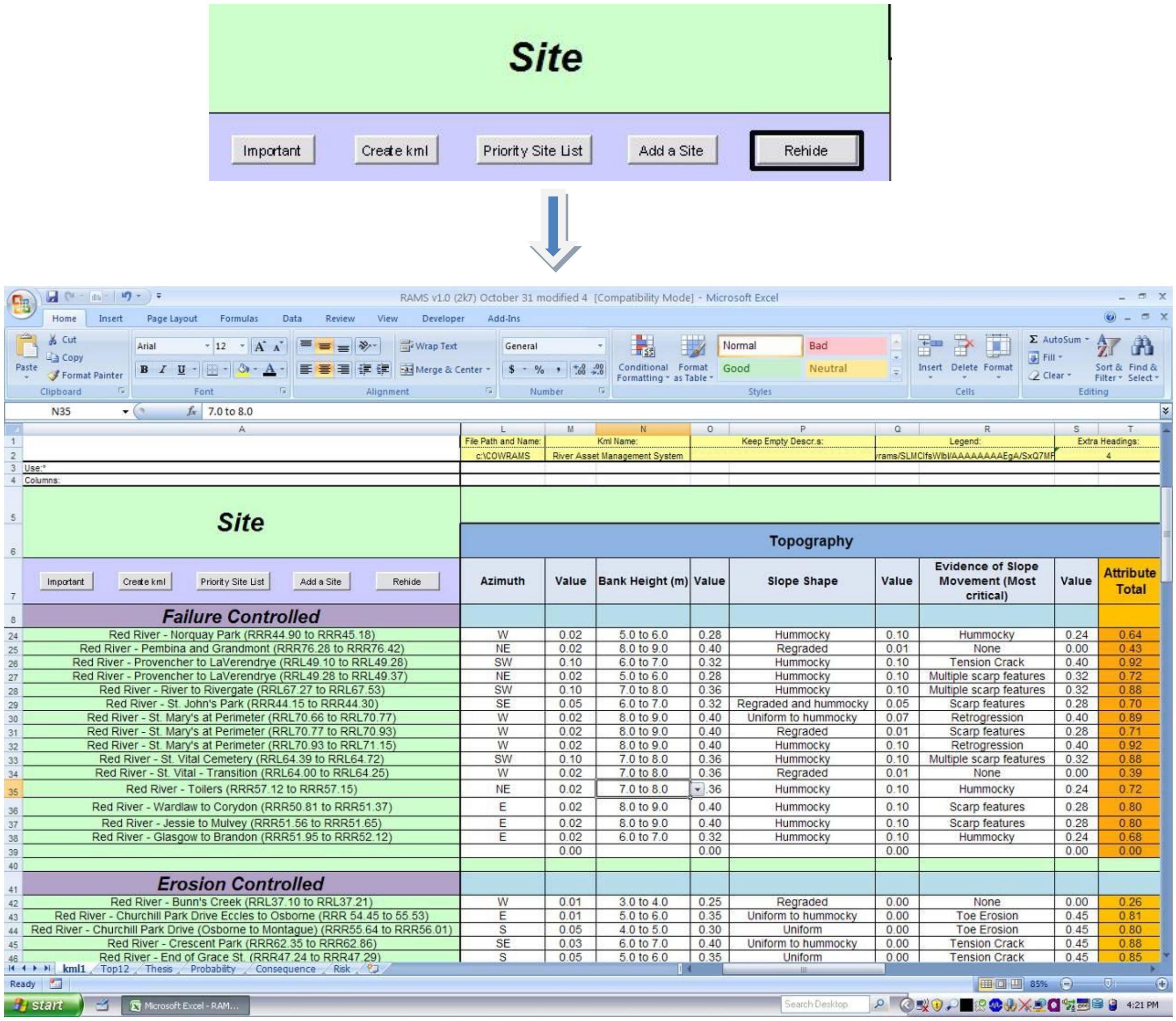


Figure 7.4: Methodology for re-hiding columns after a site has been added.

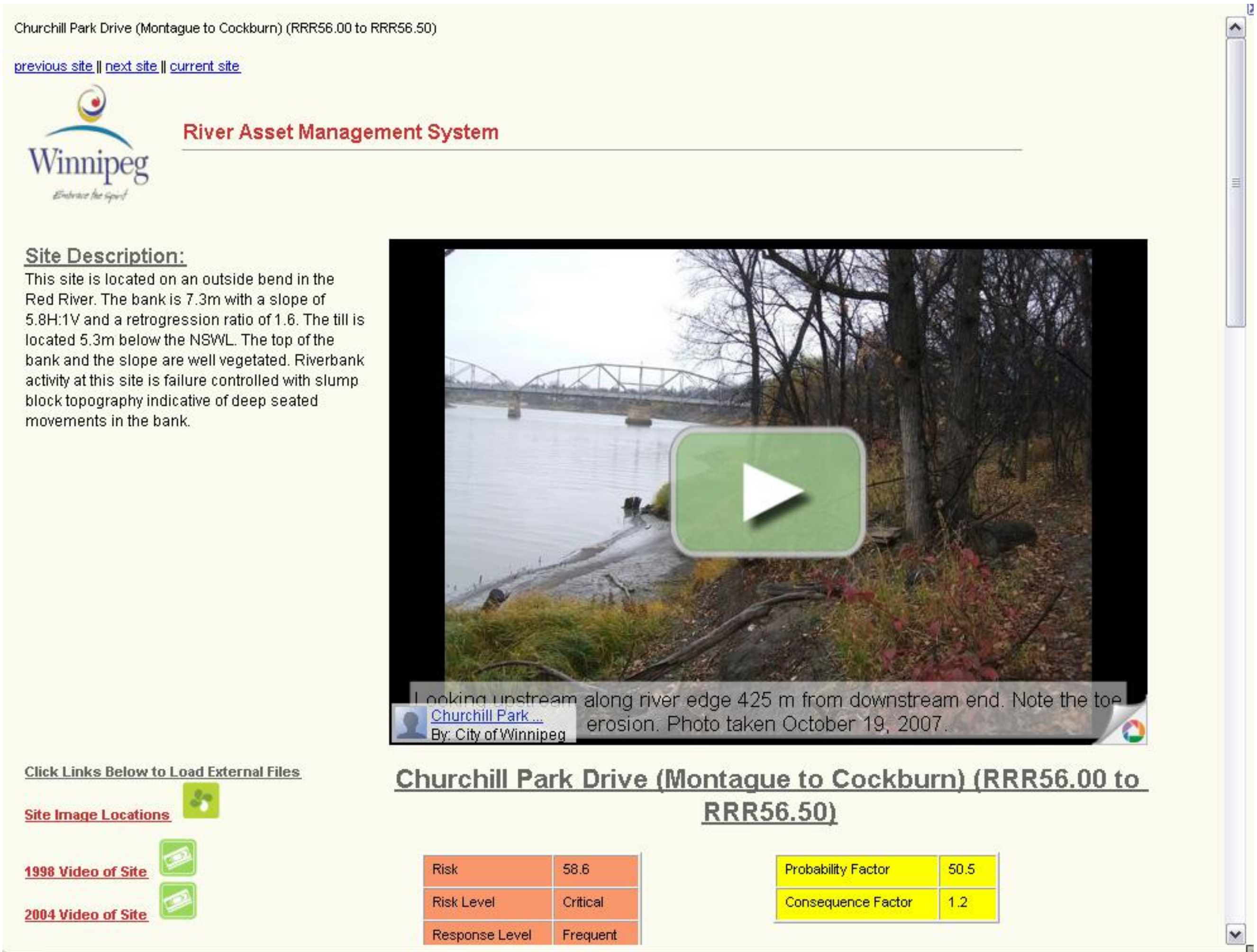


Figure 7.5: Example illustrating the upper portion of a GE balloon. The balloon is generated in GE when the bulls-eye for a site is selected.

Probability Attributes:

Topography

Azimuth	Value	Bank Height (m)	Value	Slope Shape	Value	Evidence of Slope Movement (Most critical)	Value	Attribute Total
S	0.1	7.0 to 8.0	0.36	Hummocky	0.1	Retrogression	0.4	0.96

Retrogression Ratio

Retrogression Ratio	Value	Attribute Total
>3.0	0.9	0.9

Groundwater

Depth to gwt (m)	Value	Piezometric Surface Fluctuations	Value	Groundwater Table Location (Geological Unit)	Value	Seepage	Value	Attribute Total
Uncertain	0.15	Uncertain	0.05	Uncertain	0.05	Yes	0.3	0.55

Geology

Dominant Geological Unit	Value	Depth to Till (m)	Value	Attribute Total
Glaciolacustrine	0.5	7.0-9.0	0.2	0.7

River Hydraulics

Bank Geometry	Value	Toe Erosion	Value	Accumulation of Overbank Deposits	Value	Attribute Total
Outside	0.16	2.0-3.0	0.08	Thick	0.3	0.54

Surface Water and Drainage

Bank Drainage	Value	Surface Ponding	Value	Attribute Total
Poor to Fair	0.19	Yes	0.25	0.44

Figure 7.6: Example showing part of the lower portion of a GE balloon. The balloon is generated when the bulls-eye for a site is selected. Information about the landslide probability and consequence attributes and the landslide probability sub-attributes are displayed.

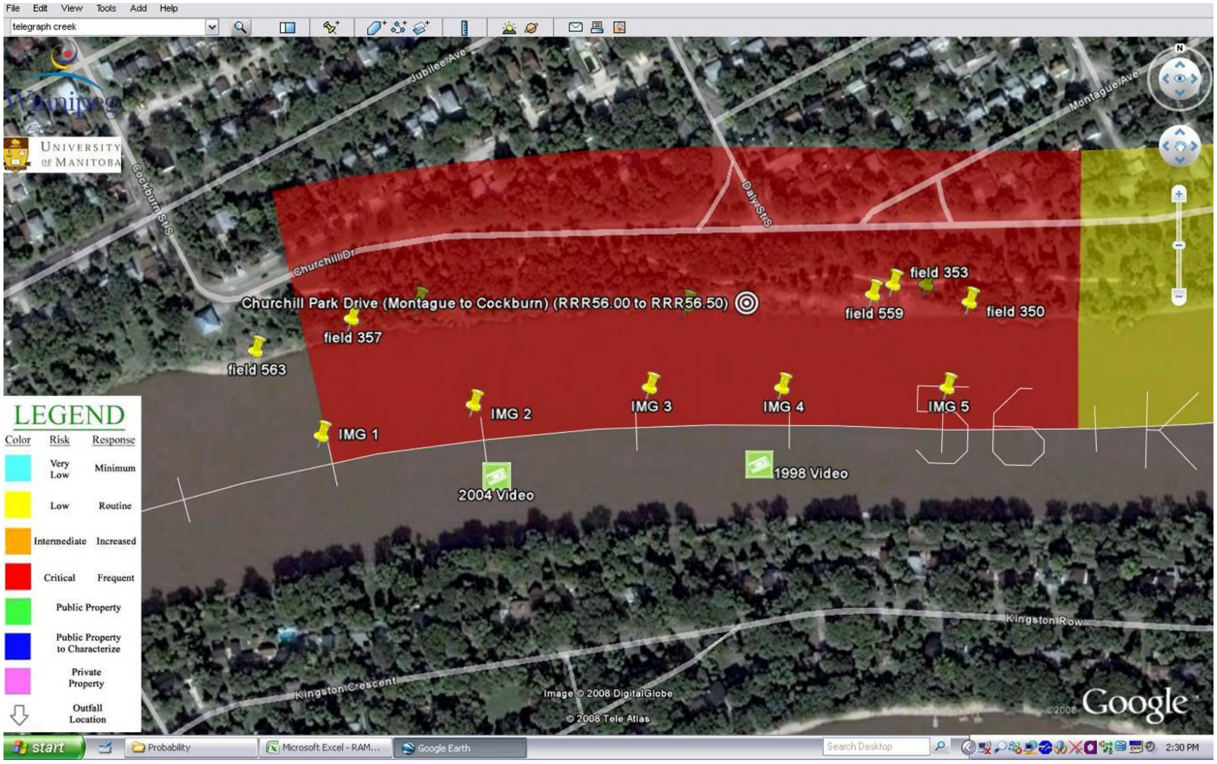


Figure 7.7: Site image location screen. The site image location screen is generated by the site image location icon in the main GE balloon at each site. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

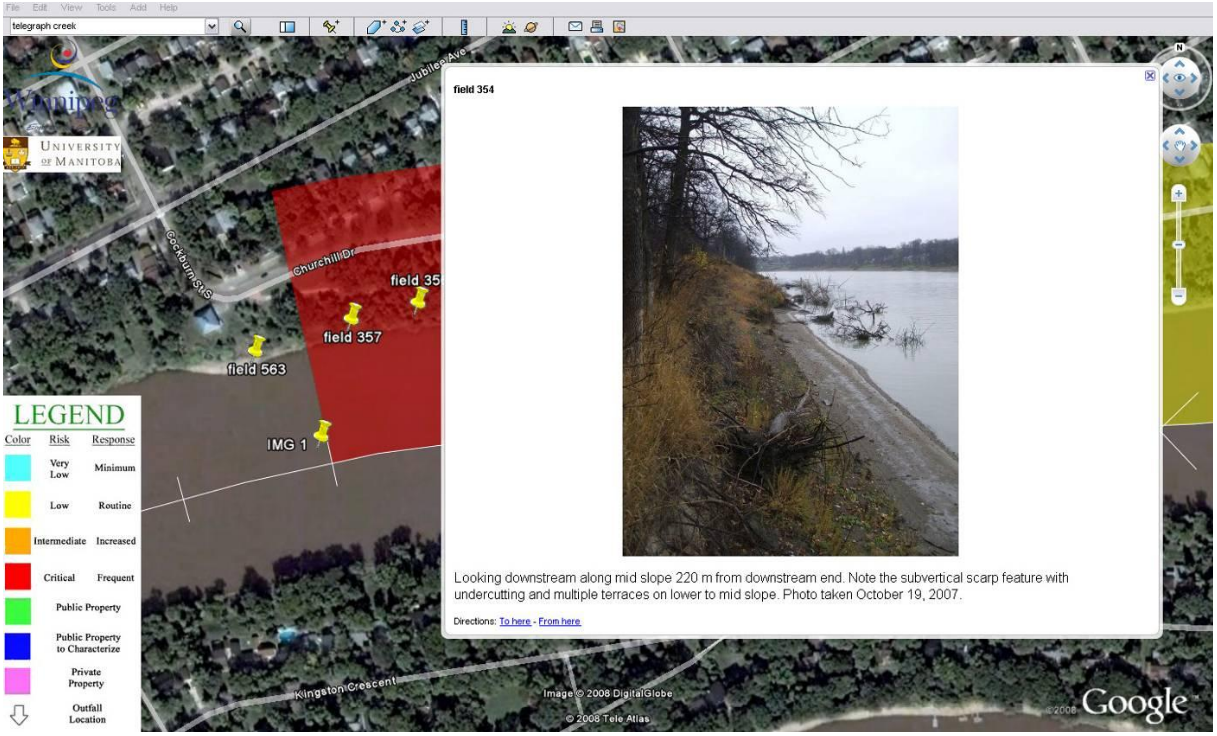


Figure 7.8: Example of a photograph that can be viewed under the site image location. The photograph is displayed by clicking on the corresponding thumbtack. Field 354 corresponds to the thumbtack labelled field 354, for example. Photograph description, date and location are provided. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

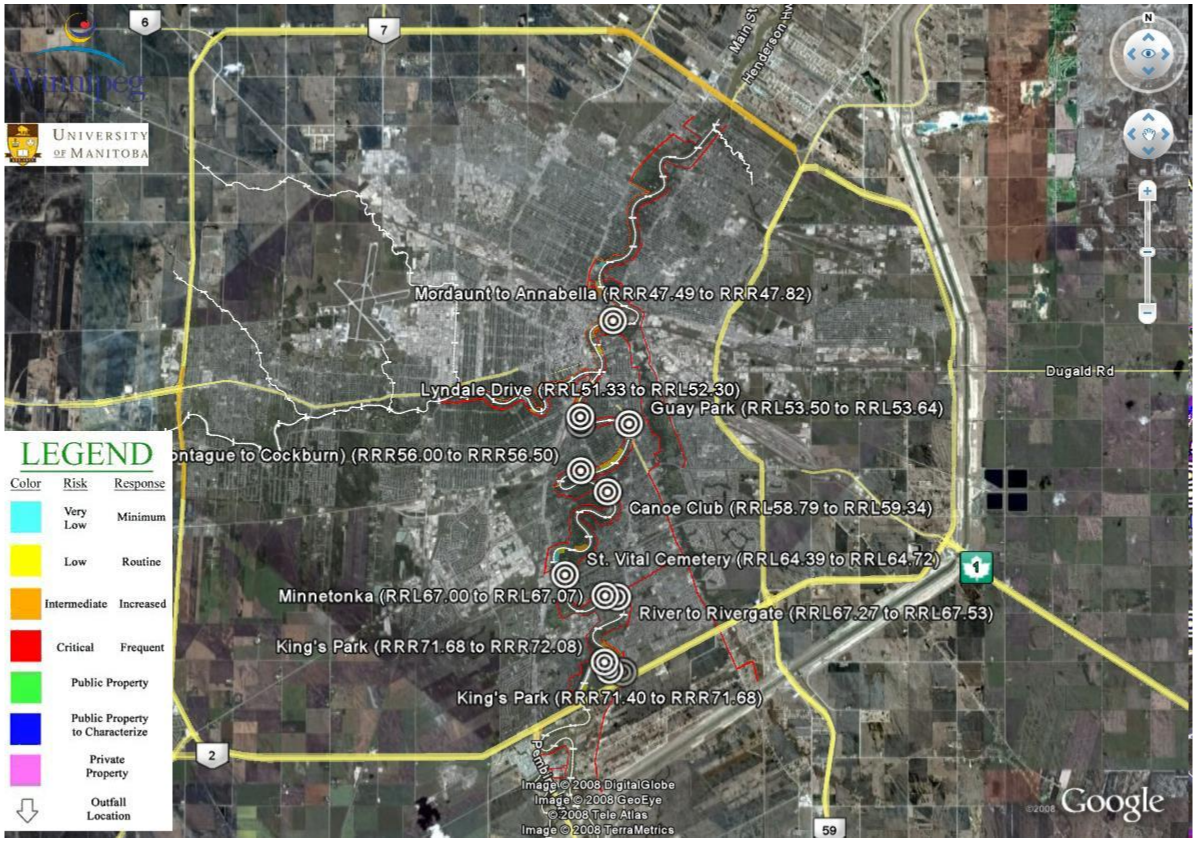


Figure 7.9: Location of the primary dike system in the City of Winnipeg. The primary dike system is created as a separate layer. This layer can be turned on and off at the user's discretion. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

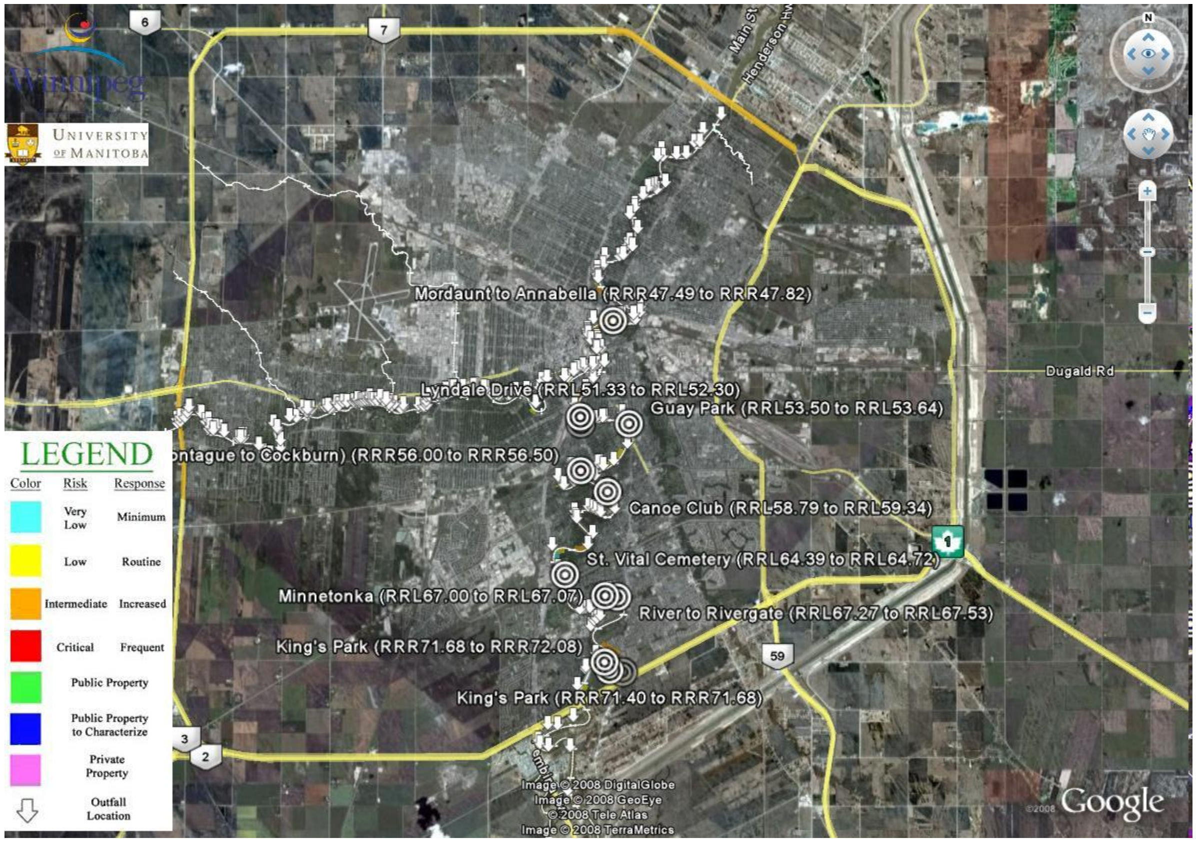


Figure 7.10: Locations of the outfalls along the Red and Assiniboine Rivers in the City of Winnipeg. The locations of the outfalls were created as a separate layer in GE. The layers can be turned on and off, depending if the user would like to view the location of the outfalls. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

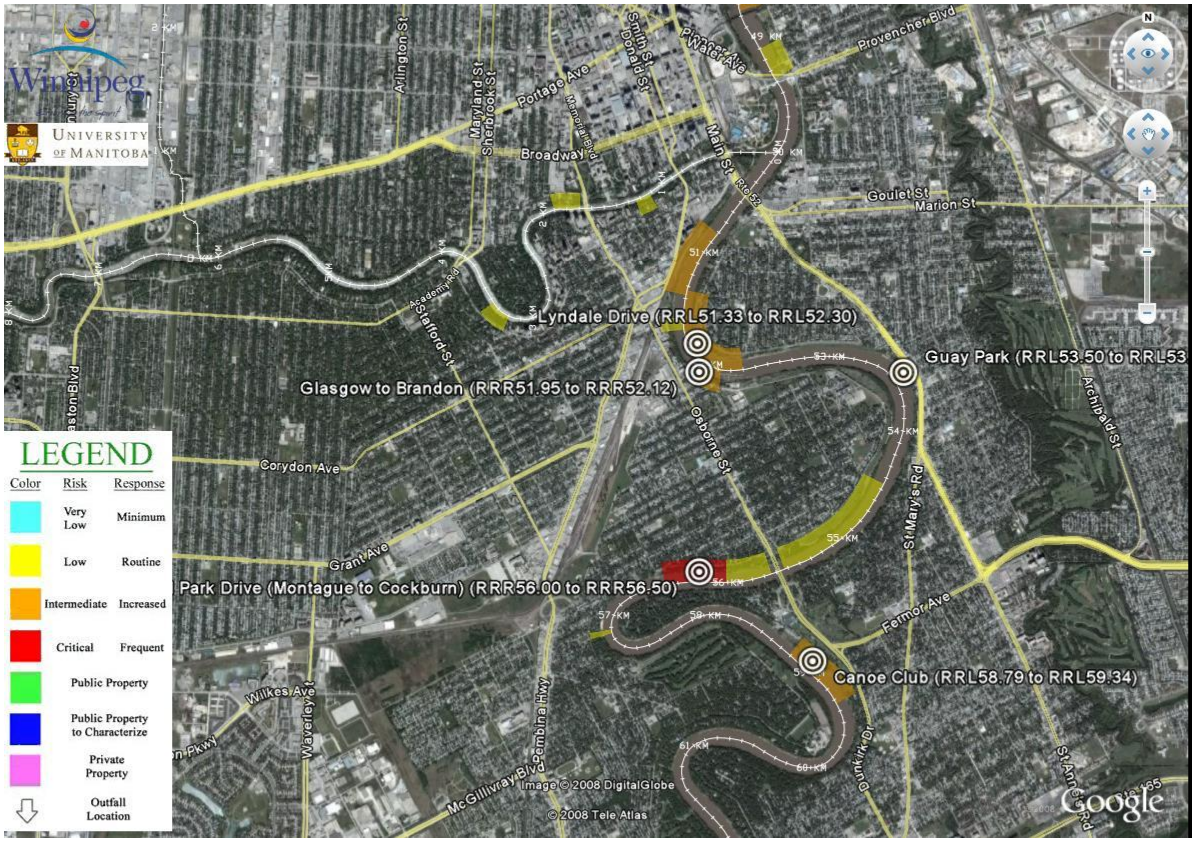


Figure 7.11: Overlay of the City of Winnipeg's river co-ordinate system. The river co-ordinate system was developed as a separate layer in GE. The layer can be viewed at the user's discretion. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

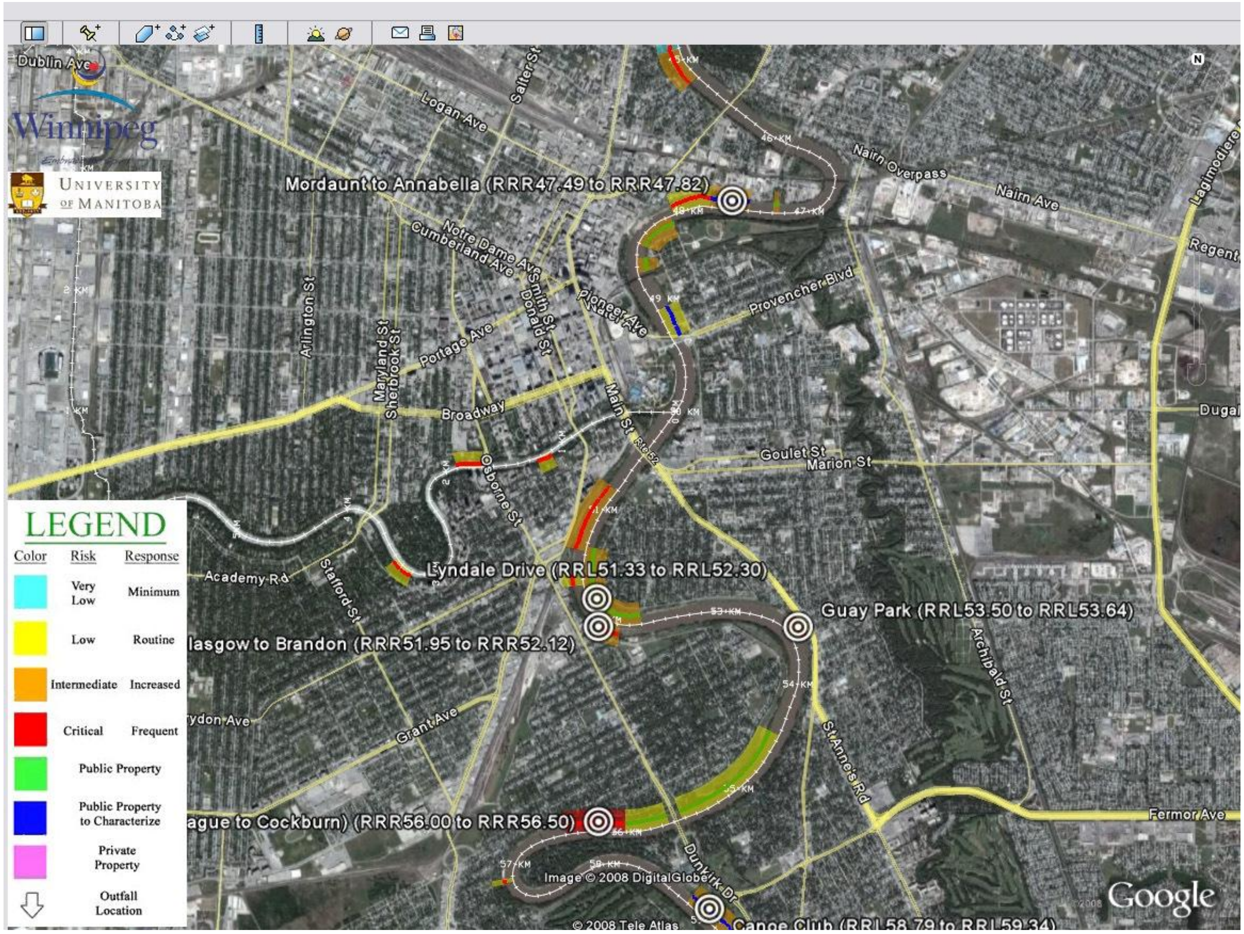


Figure 7.12: Site length and type layer. Site length and type layer is only available for the sites that were investigated during the site characterization program. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

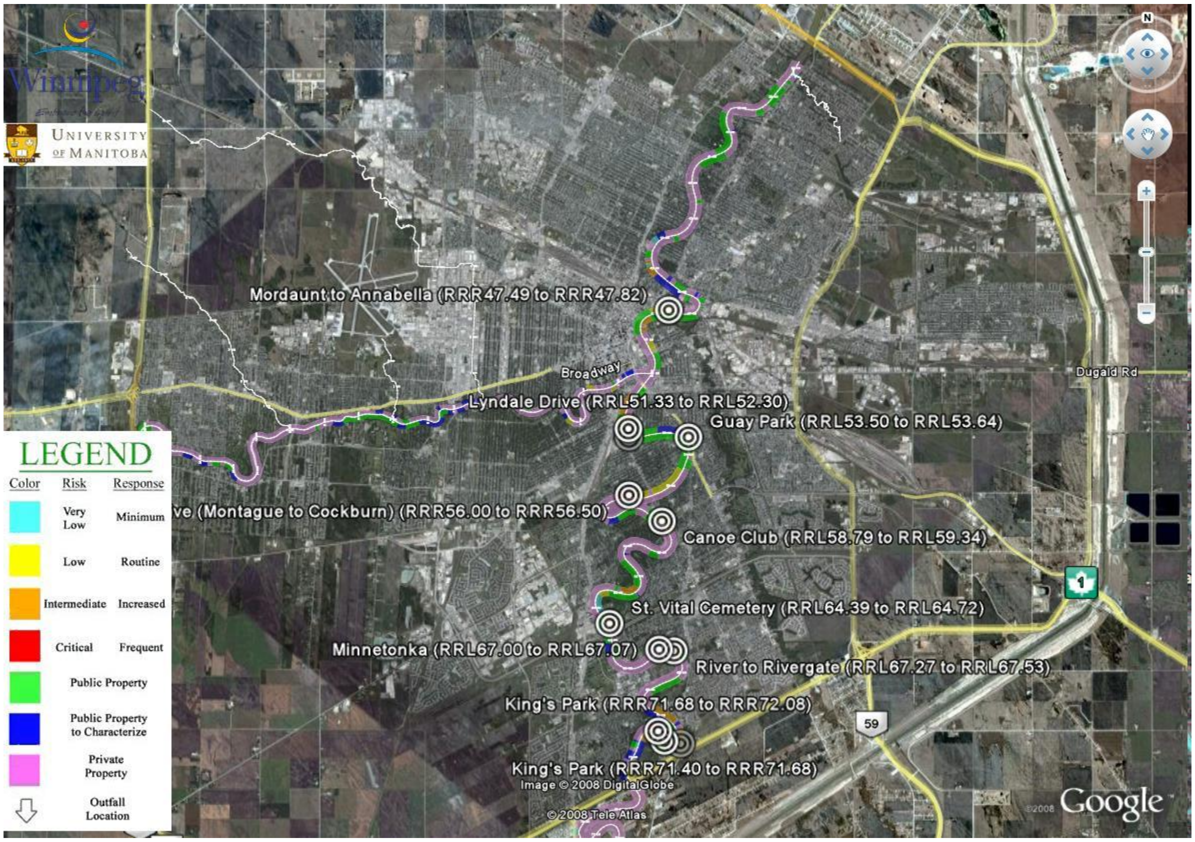


Figure 7.13: Public and private riverbank property. A separate layer was created to differentiate between public and private property. Public property that needs to be characterized further was also identified. Figure provided by ©Google-Map Data ©TeleAtlas. Permission for re-use granted. See List of Copyrighted Material for which Permission was Obtained.

Chapter 8 Discussions, Conclusions and Recommendations

8.1 Introduction

The previous chapters showed that a transparent Riverbank Asset Management System (RAMS) was developed to quantify the risk of landslides along public riverbank property in the City of Winnipeg. The RAMS provides a valuable contribution to research on riverbank stability in the Winnipeg area because it is the first project that quantifies the risk of landslides along the Red and Assiniboine Rivers. The RAMS was developed so that automatic updates of the risk factors, risk levels and response levels occur as input parameters are perceived to have changed. By ensuring that the RAMS is easy-to-use and manage, all stakeholders can be actively involved in managing public riverbank property in the City of Winnipeg. The system can be applied to many asset management issues for jurisdictions all over the world. Chapter 8 commences with a discussion of the benefits of developing a Riverbank Asset Management System. The chapter then continues with some brief conclusions and closes with recommendations for future research.

8.2 Benefits of Developing a Riverbank Asset Management System

The risk of landslides along the Red and Assiniboine Rivers in the City of Winnipeg was previously determined by the Riverbank Management Engineer at the City of Winnipeg by: compiling, characterizing and assessing the stability of public riverbank property. These tasks were completed by comparing changes in riverbank stability conditions at a site over a specified period of time. A “first phase” list of priority sites was generated by analyzing changes in the stability conditions of riverbank properties. The main limitation of the previous ranking system used by the City of Winnipeg to create the “first phase” list of priority sites was that the ranking system did not explicitly take the probability and consequence of failure into account. As a result, the ranking system was subjective, as it was primarily dependent on visual site observations. The procedure for landslide risk assessments in the City of Winnipeg needed to be modified and updated to reflect current risk management standards that are commonly adopted in engineering practice today.

The author developed a transparent Riverbank Asset Management System (RAMS) for the City of Winnipeg because of the limitations of the previous ranking system. The RAMS explicitly takes into account probability and consequence factors. The project identified landslide probability attributes and sub-attributes and landslide consequence attributes that represent the probability and consequence factors. Analyzing the geology and geomorphology of the Red and Assiniboine River basins led to the development of the landslide probability attributes and sub-attributes by the author in consultation with members of the Steering Committee. Probability attributes and sub-attributes were assigned weighting factors based on their perceived significance. Attributes or sub-attributes with a greater influence on riverbank stability were assigned higher weighting factors than the attributes or sub-attributes with minimal influence on riverbank stability. Identifying specific features that are affected by slope movements on public riverbank property led to the development of the landslide consequence attributes. Only public perception and public property are considered at this time. Integration of the other consequence attributes, identified in Chapter 6, will occur at a later date when consultation occurs between the various departments at the City of Winnipeg. The technical steering committee assigned weighting factors to the landslide consequence attributes based on the potential loss of top of bank (public property) and public perception. The committee assigned higher weighting factors to sites that had a greater potential for loss of top of bank than those sites that had a smaller potential for loss of top of bank. The committee also decided that sites with high foot traffic volumes would have higher weighting factors than those sites with low foot traffic volumes.

A riverbank observation checklist was prepared prior to conducting the site characterization program (Chapter 4), to ensure that the appropriate information was collected. The data collected during the site characterization program and the site surveys were subsequently input into the RAMS. The riverbank observation checklist was prepared so that the site assessments are consistent and repeatable, now and in the future. In addition, the riverbank observation checklist will allow professional staff to determine the relative importance of existing landslides along the Red and Assiniboine Rivers.

After implementing the RAMS, the City of Winnipeg will have a ranking system that is: 1) documented so due diligence is performed; 2) repeatable so personal and political influences will be minimized and 3) quantifiable so an objective system is in place. The development and implementation of the RAMS will ensure that the risk of landslides is appropriately managed, analyzed and prioritized along the Red and Assiniboine Rivers in the City of Winnipeg. Since risk management involves the identification of options to reduce risk, an established RAMS will allow continual monitoring and re-evaluation of public riverbank property as input parameters and site conditions change. In addition, the RAMS will allow public funds to be allocated in an appropriate manner, ensuring that proper monitoring and preventative measures are conducted along public riverbank property.

By creating a RAMS that can quantify and prioritize the landslide risk along the Red and Assiniboine Rivers, it was possible to develop a transparent and rational approach for determining risk levels. The risk levels will help the Riverbank Management Engineer develop appropriate response levels so slope remediation projects can be prioritized using risk and response levels. This will ensure that riverbank stabilization projects are conducted in an appropriate time-frame and subjective personal and political influences are removed from the decision-making process. The development of a transparent and defendable RAMS will allow resources, both monetary and personnel, to be allocated in a responsible manner, based on the calculated risk and response levels.

Integrating the RAMS with a geospatial visualization tool such as Google Earth Pro©, is beneficial because Google Earth Pro© is a simple-to-use, economical and easily-accessible program. The integration allows the engineering community and public policy makers, easy access to the risk management system. As a result, all stakeholders can access and visualize the RAMS. This allows them to be actively involved in the risk management process. The author recommends that the RAMS be implemented as a risk management tool in the City of Winnipeg as soon as possible. This will ensure that the RAMS remains current and up-to-date.

The calibration of the weighting factors in the RAMS is an on-going process. The technical steering committee performed the initial calibration. The weighting factors were calibrated from the engineering experience and judgment of the committee and the assessment of riverbank stability conditions at each site. The author recommends that the weighting factors be reviewed, after additional monitoring and assessment of the stability conditions along public riverbank property. The results of the additional site monitoring and site assessments, will determine if the weighting factors need to be modified.

The author recommends that the City of Winnipeg conduct initial site assessments in a timely manner for public riverbank property that was identified in the RAMS as '*to be characterized further'.* Information collected during the preliminary site characterizations will allow the City to determine if detailed site characterizations are required at a specific site. A site can be added to the RAMS, so the landslide risk can be analyzed in further detail, if necessary.

This research project examined the following hypothesis, which was introduced in Chapter 1:

Hypothesis: If a ranking system that prioritizes riverbank stability problems is based on probability and consequence factors then the ranking order will be inconsistent with a ranking system that is based solely on engineering judgment and experience.

The previous discussions have clearly shown that a ranking system that prioritizes riverbank stability problems based on the probability and consequence factors will result in ranking order that is inconsistent with a ranking system that is based solely on engineering judgement and experience.

8.2 Conclusions

The following conclusions can be made from this research project:

- Most of the public riverbank property, in the City of Winnipeg, has experienced slope movement in the past or is currently moving. This has resulted in the loss of public green space and valuable real estate.

- The primary causes and failure mechanisms for erosion-controlled and failure-controlled riverbanks are different.

- The RAMS is an effective tool that provides a transparent and rational approach for assessing riverbanks from a risk analysis and management perspective.

- The RAMS reduces the subjectivity and personal and political influences from the risk management process.

8.3 Recommendations for Future Research

Future additional research activities will benefit the RAMS that has been developed for the City of Winnipeg. The recommendations for future research include extensive site monitoring and expansion of the RAMS. Subsequent sections discuss these recommendations in further detail.

8.3.1 Extensive Site Monitoring

The RAMS was developed by assessing the results of the site characterization program and site surveys for the thirty-six priority sites. The priority sites were previously identified as sites of interest in the Riverbank Stability Characterization Study prepared by the City of Winnipeg in 2000. It is recommended that additional site characterizations and assessments be conducted, by establishing trial sites at various locations on the Red and Assiniboine Rivers.

Data were collected during the site characterization program and site surveys by visual site observations. Site specific information, that could not be collected visually, was obtained from engineering reports at the engineering library at the City of Winnipeg. At some locations, groundwater and geology information was not available. As a result, this information had to be obtained from engineering reports that were prepared for the surrounding area. Since limited data exists for many of the sites, it is recommended that additional instrumentation be installed and monitored on public riverbank property. The instrumentation should be installed at varying distances from the centre of Winnipeg in order to obtain representative groundwater and geology information for different areas of the City.

Since limited groundwater and geology information exists for many of the priority sites, only approximate factors of safety (FS) could be calculated for the representative cross sections that were prepared in SLOPE/W. By obtaining specific information on the groundwater and geology conditions at a site, it would be possible to conduct detailed numerical modeling. The results obtained from numerical modeling, depend on the accuracy of input parameters. More accurate input parameters, will allow the Riverbank Management Engineer to analyze the stability of public riverbank property along the Red and Assiniboine Rivers at various river levels with greater confidence. The results of the SLOPE/W modeling can be incorporated into the RAMS, once the confidence level in the calculated FS is acceptable.

It is recommended that trial sites be established on 1) an inside, 2) outside, 3) straight, 4) transition, and 5) straight to transition sections of the Red River. By establishing different trial sites, it will be possible to quantify the changes in slope geometry caused by toe erosion and overbank deposit accumulations. These changes can be quantified by conducting annual site surveys, site monitoring and site characterizations. Instrumentation should also be installed at the trial sites, in order to obtain detailed groundwater and geology information. From the changes in riverbank geometry, it will be possible to ascertain annual increases or decreases in FS by conducting numerical modelling. As an extension of Fernando's (2007) thesis, the change in FS can be linked to the magnitude and duration of specific river levels, for an outside, transition and straight section of the Red River. The change in FS for the specific river levels can then be incorporated into the RAMS.

The negative effects of vegetation and ice scour were not considered in the RAMS. It is believed, that large vegetation (such as trees) growing in the vicinity of a riverbank face increases the amount of erosion due to turbulence when the river is ice-free and from additional ice scour in the winter months. However, the positive effects of vegetation, such as additional root support, were incorporated into the RAMS. The increased erosion along a riverbank face and toe due to ice scour (when vegetation is not present) was not considered when developing the RAMS. It is recommended that the negative effects of ice scour and vegetation be investigated in further detail and incorporated into the RAMS at a later date.

8.3.2 Expansion of the RAMS

At this time, the RAMS has been developed for the thirty-six priority sites, located along the Red and Assiniboine Rivers in the City of Winnipeg. It is recommended that the RAMS be expanded to incorporate the suggestions outlined below.

The author recommends that the City of Winnipeg expand the RAMS to include sites located along the Seine and La Salle Rivers. Presently, the RAMS is only applicable for regions of Manitoba that are located in the Red and Assiniboine River basins. However, the RAMS could be used as a template to quantify the risk of landslides or shoreline erosion (especially in the vicinity of large lakes), in other regions on Manitoba.

Presently, only two of the five landslide consequence attributes are incorporated into the RAMS. The three additional consequence attributes should be included in the RAMS as soon as possible. When the additional attributes are added to the RAMS, it will be necessary to review the weighting factors for the landslide consequence attributes and the consequence factor.

Triggering factors such as: 1) river level fluctuations, 2) approximate timeframe for ground freezing and thawing, 3) antecedent moisture conditions, 4) extreme climatic events, and 5) rainfall and snowfall totals were not incorporated into the RAMS. Triggering factors contribute to changes in slope geometry and therefore to changes in riverbank stability conditions. It is recommended that the triggering factors be included in future versions of the RAMS.

The mandate of this research project was to develop a RAMS for public riverbank property. It is recommended that the RAMS be expanded to incorporate private riverbank property. The inclusion of private riverbank property in the RAMS, will allow private landowners to assess and visualize the risk of landslides in the vicinity of their property. This will allow them to mitigate future slope movements by constructing stabilization measures in the vicinity of their property, if necessary.

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Appendices