GROUND HAZARD ASSESSMENT USING PROCESS MODELS AND GIS

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RÉSUMÉ
Les lignes de chemin de fer Canadiennes sont exposées à une grande variété de dangers, étant donné la diversité des terrains rencontrés à travers le pays. Keegan (2007) a analysé ces divers dangers et proposé des scénarios de réponse, afin d'évaluer l'influence de ces dangers sur l'opération des chemins de fer. La modélisation des phénomènes a été utilisée afin de développer une méthodologie d'évaluation des dangers associés aux événements pluviaux sévères. Cette même méthodologie a été utilisée par Shi (2006) pour une étude de cas à Port Douglas. Un système d'information géospatial (GIS) a été utilisé pour faciliter le développement de cette méthodologie ainsi que son application pour les événements pluviaux.

ABSTRACT
Canadian railways are exposed to various ground hazards because of the diverse geographic regions of the country. Keegan (2007) analysed these hazards and proposed hazard scenarios to evaluate the influence of these hazards on railway operations. Process modelling was used to develop the methodology for evaluating the hazards associated with a severe rainfall event. The methodology was applied by Shi (2006) to the Port Douglas case study. GIS technology was used to develop the methodology and facilitates the application of the methodology to any rainfall event.

1 INTRODUCTION

The Canadian railways have been exposed to ground hazards since the first transcontinental line was constructed in the late 1800s. Railways have high exposures because of their length and grade limitations. The two national railways in Canada cover on the order of 40,000 sq km, assuming that the track is exposed to a 0.5 km wide hazard zone on either side of the track. In addition, the diversity of soil and rock conditions, the active geomorphological processes associated with the relative youth of the terrain since glaciation, and climate extremes in both precipitation and temperature encountered along rail corridors, increase their risk to ground hazard. As much of the terrain traversed by Canadian railways is sparsely populated, resources available to mitigate these hazards are usually limited. As a result, in Canada there has been a greater need for objective priority setting for mitigative measures by the railway industry. Traditionally, Canadian railways have relied upon experience and subjective assessment for hazard management. Over the last decade there has been increased focus on the risks these hazards pose to railway operations and the management of those risks (Bunce et al 2006). This stems from rising public awareness, greater regulatory scrutiny, increased railway traffic and associated service demands.

Over time, the management of these hazards by the railway industry has evolved from a reactive mode to a more proactive management philosophy. As part of this change in philosophy risk management strategies from other industrial sectors have been evaluated by the railway industry. For example, the “Rockfall Hazard Rating System (RHRS)” was developed by the Federal Highway Administration in the United States for the preliminary evaluation of rock fall hazards and the allocation of priorities for remedial work along highways. The RHRS system was modified by the incorporation of probabilistic algorithms and has been implemented by CN for rock slopes adjacent to its tracks (Abbott *et al.* 1998, Pritchard *et al.* 2005).

Incident reporting of ground hazards is now standard practice for all railways operating in Canada. As a result, a catalogue of ground hazard incidents has been collected across the country, which reflects the types of ground hazards encountered by the railways. As with many linear corridors these hazards are often repetitive geographically, i.e., debris flows occur with a certain temporal and spatial frequency. A proactive management of complex repetitive ground hazards requires technology that can be used to assess the lessons from the past as well as manage the unpredictable nature of future events.

Geographic Information systems (GIS) are well established as a technology that can store and manage data in essentially any form. GIS technology is also widely used as a land mapping tool and Van Westen (2007) notes its increasing use in mapping landslide hazards. However, the application of GIS is typically in the storing and display of data that has been processed and evaluated by other means. To make GIS technology suitable for assessing complex geotechnical hazards requires the development of a process model for each hazard being assessed. In this paper, GIS technology is applied to a process model developed for ground hazards triggered by a severe rainfall event.

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2 HAZARD CHARACTERISATION AND PROCESS MODELLING

A hazard to railway operations can be defined as the potential to directly or indirectly result in track failure or make track unsafe for train traffic at the posted speed. Keegan et al (2007) reviewed the historic CN incident database and concluded that railway ground hazards (RGH) could be broadly classified as landslides, subsidence, hydraulic erosion and snow & ice hazard. The characterisation methodology standardizes the identification of railway ground hazard types by grouping the possible hazard events according to the ground conditions and processes involved into hazard scenarios (Figure 1). Besides labelling the hazard, classifying in this manner provides an immediate understanding of the processes of these hazards.

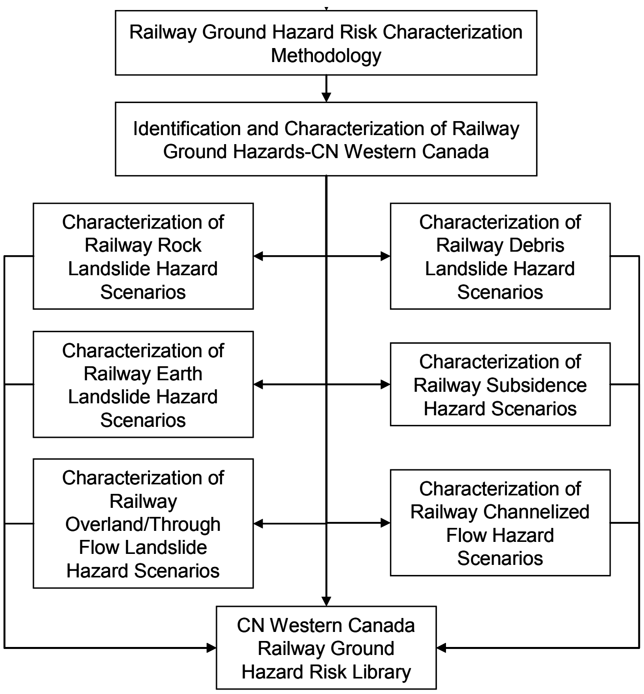

Figure 1: Example of the scenarios used to establish the CN Western Canada Railway Ground Hazard Risk library (modified from Keegan et al, 2007).

As railway ground hazard scenarios typically involve a combination of ground hazard events, Keegan (2007) proposed a simple failure mode and effect analysis (FMEA) logic tree to illustrate the possible events that may be associated with hazard scenarios. In conjunction with this, a nomenclature is adopted to name the railway ground hazard scenarios using the name of the individual ground hazard events with en dash (-) to denote series linkages and forward slash (/) to denote parallel linkages (see Figure 2). The methodology used to develop the FMEA for a particular hazard, involves definition and characterization of the railway ground hazard scenario; identification of the causal factors and attributes; definition and characterization of consequence likelihood factors for track failure, service disruption and derailment consequences and the suggestion of simple and more thorough methods to estimate severity associated with derailment consequences.

While the FMEA logic tree depicts the various events that may occur and impact the railway operations, a process model is required to evaluate the likely occurrence and severity of the event. The term “process modelling” is currently used in many disciplines. Rolland et al (1998) suggested an effective process model in any field should provide a means of communicating complex functions in a form understandable to practitioners in a standardized and repeatable manner, so that personnel can compare and contrast possible outcomes. To develop such a process model requires a complete understanding of the process. A process model of a complex ground hazard must capture the essentials required to meet the objectives of using the model, without including details that are extraneous to these objectives. In geotechnical engineering these objectives can range from ensuring that an engineered structure will perform as intended to managing the risk associated with natural hazards over a larger scale. Establishing the appropriate process is both site and project dependent, and underpins the value associated with the practice of Geotechnical Engineering. Process models in geotechnical engineering for ground hazards have five main components:

1. Generalised description of the ground hazard process
2. Knowledge of the physics that control the process.
3. Evaluation of possible outcome
4. Calibration of the process and outcome with historical data
5. Assessment of the hazard and communication of the risk

In the following sections a process model is examined for two ground hazard scenarios induced by a severe rainfall event: (1) Earth Landslides and (2) Overland/Through Flow Erosion.

3 RAINFALL-INDUCED HAZARDS

Within the Earth Landslide Scenario the Earth (Embankment) Landslide hazard is one that involves the failure of the railway embankment. According to Keegan (2007) railway embankments that are particularly prone to this type of failure generally have a high phreatic surface in a slope made up of loose or contractive, fine, non-cohesive soils. The failure process typically starts with a rapid and sustained overland or through flow of water into the embankment from the upstream side. The resulting landslide typically starts as an earth slide but the slide mass quickly loses cohesion converting to an earth flow. Figure 2 shows a simplified FMEA proposed by Keegan (2007) for Earth (Embankment) Landslide hazard.

Overland /Though flow erosion is a frequent occurrence along railways in relatively low relief topography where the majority of these events were associated with intense rain storms. According to Keegan (2007) the incident database indicate that most if not all of these hazard scenarios involve a culvert which may be blocked, damaged, poorly arranged or under sized. The initial hazard event involves water flowing over or/and through the railway. These flows have a potential to cause seepage erosion, piping or gully erosion which can lead directly to track failure or cause 2nd order events such as an earth slide or collapse failures such as culvert failure or collapse of pre-existing piping voids. All of these hazard events can cause track failure by either removing support from the tracks or by deflecting the track. Figure 3 provides a simplified FMEA for the Overland / Through flow hazard scenario.

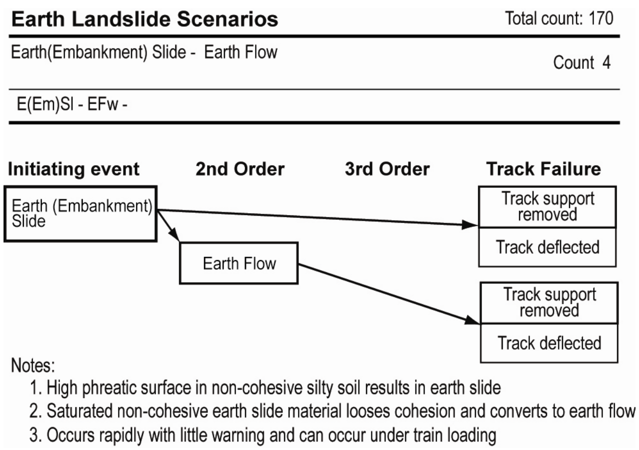

Figure 2: Simplified FMEA for the Earth (Embankment) Landslide scenario, modified from Keegan (2007).

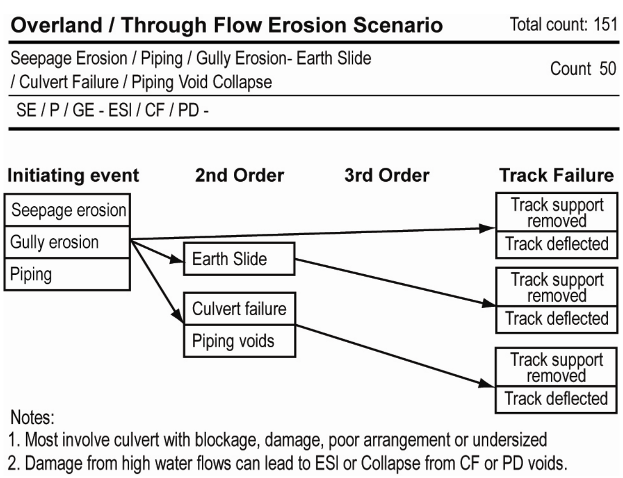

Figure 3: Simplified FMEA for the Overland flow and Through flow hazard scenario, modified from Keegan (2007).

Hydraulic erosion involves removal of soil particles or rock by the action of flowing waters. Keegan (2007) considered hydraulic erosion a hazard if it could result in track failure. As illustrated in Figure 3 the consequence to the railway once Overland/Through flow erosion scenario is initiated, can be quite rapid. In other words there is little time for the railway to react once the process is initiated. Hence the management of this type of hazard can be problematic as evaluating these hazards would require the identification of the magnitude of the triggering event.

Figure 4 illustrates the conditions that must be analysed in considering the scenarios outlined in Figures 2 and 3. In traditional geotechnical analysis the impact of rainfall is normally considered through changes in pore water pressure. From Figure 4 it is evident that the triggering rain event is a key component to the analysis and that to address the possible failure modes identified in the FMEA given in Figures 2 and 3, other types of analyses will also be required. For example in addition to erosion and piping hazards, a rapid drawdown hazard may also exist on both the uphill and downhill sides of the track, depending on the possibility for ponded water on the downhill side. Table 1 illustrates the type of hazards identified in the scenarios given Figures 2 and 3 and a description of the initiating event that must be considered. Also shown in Table 1 is an example of the impact of these events on the railway. In the next section a process model is proposed and the methodology developed that captures the hazards identified in the hazard scenarios including the magnitude of the triggering rain storm event.

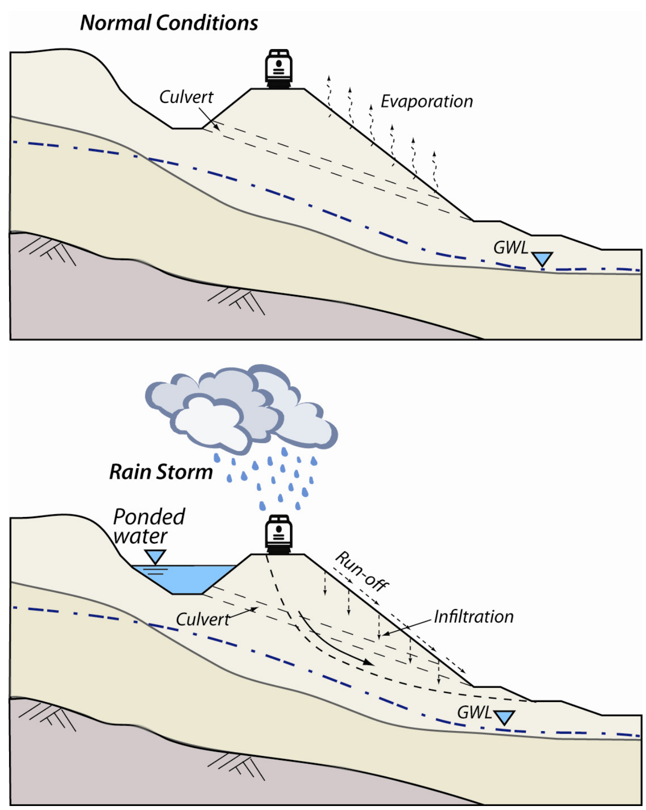

Figure 4: Illustration of the hazards associated with Overland / Through flow and Earth (Embankment) Landslide scenario induced by a rain-storm event.

Table 1: Examples of railway hydraulic erosion hazards and railway embankment earth slide hazard developed by Keegan (2007).

Overland flow (runoff) → *Gully Erosion:* Initiation of a channel on a sloping surface caused by concentrated overland flows. Once water is focused into channels, the channel grows rapidly leading to Gully Erosion. Gully erosion by overtopping of a railway embankment commonly results in catastrophic failure of the rail grade as it involves the sudden release of impounded water comparable to a dam burst scenario.	
Through flow → *Seepage Erosion & Piping:* Seepage Erosion ocurs when exit velocity of groundwater is sufficient to cause particle erosion. Piping occurs when water flowing through material opens a tunnel or pipe that remains open and continues to erode material. Surface erosion and piping are commonly associated with the lost of track support on the downstream side of the track.	
Through flow → *Culvert Erosion:* Processes that result in internal hydraulic erosion around a culvert due to: 1. Water running out of the culvert due to a corrosion or abrasion hole, a pull-apart at a joint or poorly sealed joints. 2. Soil being sucked in through an opening in the culvert by negative pressure from flowing water in the culvert. 3. Water running along the preferential flow path outside of the culvert driven by a surcharge at the inlet of the culvert due to a backup into the culvert caused by debris or ice blockage at either the inlet or outlet, an under capacity culvert or a buoyancy failure of a surcharged inlet.	
Earth Landslide → *Earth (Embankment) Slide Earth flow:* These scenarios involve rapid influxes of water under the track in non-cohesive embankments from either overland flows or through flows. The rapid rise in the phreatic surface or rapid draw down (as occurred in this photo), corresponding steep hydraulic gradient in the lower slope and, on occasion, dynamic train loading causes an earth slide to initiate. The saturated non-cohesive slide mass rapidly converts to a flow. The speed and mobility of the flows depends on the length and gradient of the run out path.	

4 PROCESS MODEL FOR RAIN-FALL INDUCED HAZARD SENARIO

Over the course of several days in June 1999, a section of the CPR Mainline south of Plattsburg, New York endured a severe weather condition resulting in numerous landslides and areas of erosion. This eight-mile section of track was located near Port Douglas on the west side of Lake Champlain (Figure 5). Shi (2006) analysed the events at 34 sites between Mile 143.85 and 155.3 and concluded that 94% of the hazards could be classed as Earth Slides and Overland Flow as described in Table 1. Landslide and erosion volumes ranged from ten to several thousand cubic metres. At the largest event, the destruction of a culvert, at Mile 150.17 near Port Douglas, caused the derailment of a train.

Along this section of west shore of Lake Champlain the track is located 20 to 45 m above the lake shore. It traverses bedrock outcrops; colluvial and dense till side slopes; alluvial sand and silt terraces; and lacustrine silt and clay deposits. The track damage was primarily in the areas of erodible silt and sand fills and natural silt and sand deposits; and in the areas of interbedded lacustrine silts and clays.

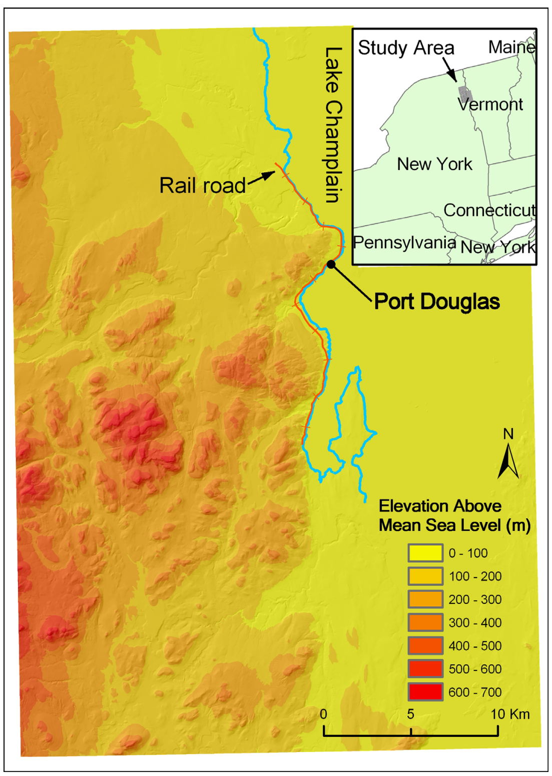

Figure 5: Location map for Port Douglas. The railway is located along the west shore of Lake Champlain.

Shii (2006) analysed the events considering three potential failure mechanisms:

1. The initial failure of the slope was caused by the infiltration of rainwater, resulting in the overall instability of the embankment and damage to the culvert. The reduced capacity of the culvert caused water flow in the stream to overtop the embankment and erode the remaining embankment soils.
2. Local surface failure of the embankment resulted in a blocked culvert, which caused the stream flow to overtop the embankment and to gully the embankment.
3. The failure of the embankment and culvert was due to the high flows generated by the heavy rainfall overtopping the embankment and gullying the embankment soil gradually.

To investigate each of the potential failure mechanics Shi (2006) developed a process model that involved the steps illustrated in Figure 6. Geographic Information System (GIS) technology was used as the main software for analysing and processing the data as shown in Figure 6. As stated by Van Westen (2007), GIS has determined, to a large degree, the current state of the art in mapping ground hazards, particularly for landslide studies that cover large areas. While GIS technology is widely used in attribute studies it is not commonly used in process modelling. The various steps in the process model in Figure 6 are described below using the Port Douglas case study.

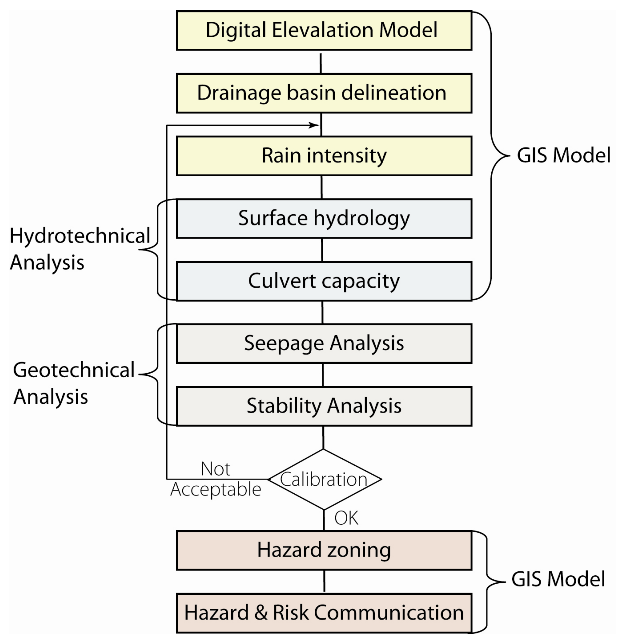

Figure 6: A process model for assessing Overland/Through Flow Erosion and Earth (Embankment) Landslide hazard scenario.

Step 1: Digital elevation model

A digital elevation model is the basic building block in GIS technology. Digital elevation models can be obtained from various sources. A digital elevation model with a 10-meter by 10 meter horizontal resolution for the Port Douglas study site was obtained from USGS online resources (Figure 7). This DEM model was imported into ArcGIS (available from www.ESRI.com) and used as the base model for the processes analysed.

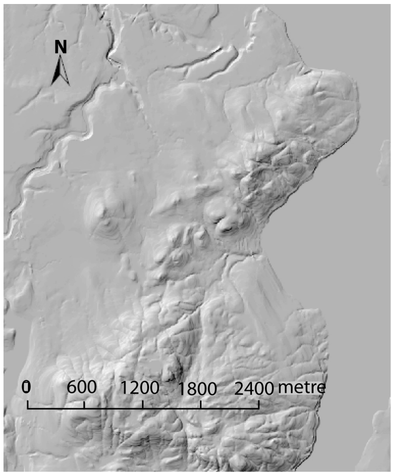

Figure 7: Digital elevation model used in the Port Douglas process model.

Step 2: Drainage basin and stream delineation

The DEM model was used to analyze the hydrologic characteristics of the topography along the railway using the hydrology modeling tools in ArcGIS. Drainage basins were delineated using the Watershed function and direction of the flow was evaluated using the Flow Direction function, built in functions in ArcGIS. The result of the delineation of the stream network and watershed boundaries in the Port Douglas study area and the locations of the major hazard events are provided in Figure 8. It is clear from Figure 8 that a correlation exists between the outlet for the watersheds and location of the hazard events.

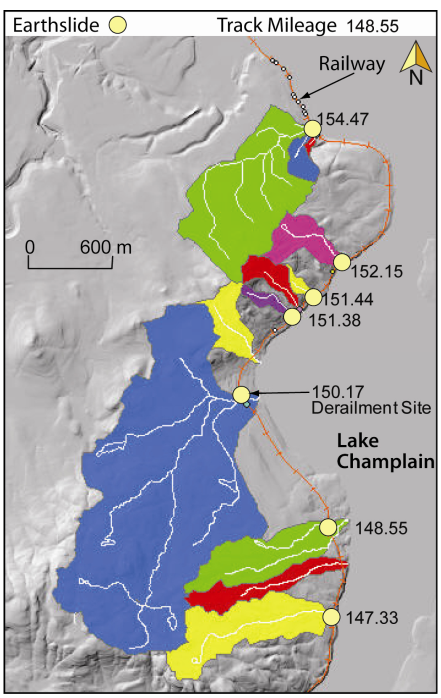

Figure 8: Delineation of the watersheds and streams in the Port Douglas case study superimposed on the digital elevation model.

Step 3:Rain intensity

The precipitation records, before June 26, 1998, of several weather stations near Port Douglas and Port Kent, NY were analyzed. The closest weather stations to the events were located 12 km to the northwest and 16 km to the south and east. Peru, the station to the northwest, recorded precipitation in excess of the 50 year return period for 24 hour duration, and in excess of the 100 year return period for the 2, 10 and 30 day accumulation periods. The stations to the south and east were in the 10-year return period range for the same rainfall durations.

To investigate why the track between Mile 155.3 and 143.8 was so heavily damaged the available weather radar data was analyzed. The results are illustrated in Figure 9 and shows that the precipitation in the area of interest ranged from 0 inches in the northeast to 8 inches in localized areas. Analysis of the radar data suggested that near the Port Douglas site the total accumulation for the month of June was a fairly uniform 13 inches (330 mm). For the month of June the rainfall was greater than 300% of the norm 3.02 inches (77mm). This total accumulation exceeded the 100-year return period by over 4 inches (102 mm) when using the Peru Station's long-term records for comparison. The radar rainfall data was directly imported into ArcGIS and a layer created that provided daily as well as cumulated rainfalls.

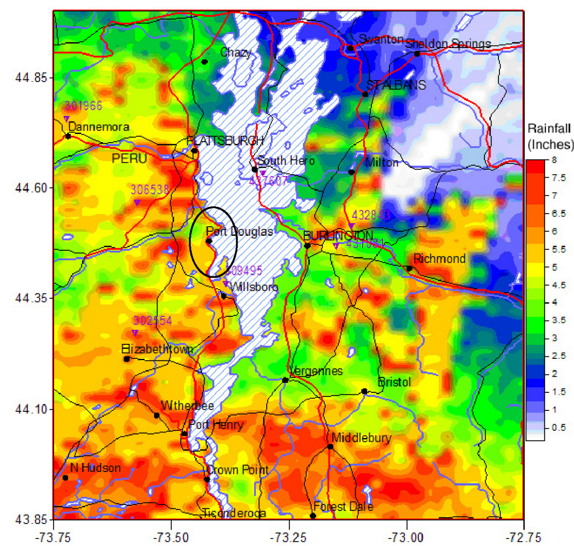

Figure 9: Lake Champlain, NY weather radar precipitation for the month of June 1998 with the track in red along the west shore and an ellipse around the area of damage.

Step 4: Surface hydrology

The watershed and stream network information obtained from the ArcGIS program was used to develop a hydrologic model for a watershed. Most of the input data for the hydrology modeling was also determined with the help of GIS tools. For example, the area of each watershed, the stream length, the cross section and slope of each channel, and, the shape, width and of each channel cross section were determined in ArcGIS. Within a watershed, during a given rainfall event, a portion of the rainfall soaks into the ground, a portion is lost by evaporation, and the rest becomes runoff, which eventually joins a stream and flows out through the outlet of the watershed. The simulation of this precipitation-runoff-routing was carried out using HEC-HMS (available from www.waterengr.com). The GIS enabled software was used to calculate the discharge hydrograph of each watershed within the Port Douglas region.

Step 5: Culvert capacity
In order to assess the capacity of each culvert within the embankments, a hydraulic analysis was carried out for each culvert by using the HEC-RAS program (available from www.waterengr.com). HEC-RAS is an integrated hydraulic analysis program capable of performing steady and unsteady flow water surface profile calculations.

Shi (2006) conducted detailed analysis of all the watersheds intersected by the railway. A summary of the results is given in Table 2 which shows that for watersheds located at Mileage 154.47 and 147.33, the flow capacities of the culverts were less than the peak flows, so overtopping and erosion of embankment may have occurred. However, for watershed 154.44 and watershed 152.15, the culverts were large enough to handle the water flows provided the culvert flow capacity was not restricted.

Table 2: Summary of peak flow and culvert capacity results

Location	Drainage Area (km^2)	Calculated Peak Flow (m^3/s)	Culvert	
			Description	Capacity (m^3/s)
154.47	4.060	14.0	Stone Box 3 ftx4 ft	9
154.44	0.294	1.2	Stone Box 3 ft x 3.5ft	8
152.15	0.746	3.0	Stone Box 3 ft x 4ft	11
151.70	0.145	0.6	No existing culvert	n/a
147.33	2.694	10.6	Culvert pipe 3ft dia.	6

Step 6: Seepage analysis
Seepage analyses were carried out using the GeoStudio software Seep/W. Shi (2006) conducted a series of analysis using fully saturated and partially saturated soils conditions, using the June rainfall as a boundary condition. The results from these seepage analyses were used for the limit equilibrium stability study.

Step 7: Stability analysis
Embankment stability was evaluated by Shi (2006) using the limit equilibrium program SLOPE/W. The results from the stability analysis at Mile 154.47 are summarised in Figure 10. The results suggest that the rain event had essentially no impact of the stability of the embankments until after June 10. As the rain intensity increased the rainfall infiltration wetting front progressed deeper, gradually reducing the stability of the embankment. By June 27 the stability of the embankment was marginal. Shi (2006) considered the stability of the embankment if the soil matrix suction was neglected and found that the factor of safety of the embankment would be 0.95. This finding suggest that the embankment would be unstable if no soil matrix suction existed, indicating that the stability of this type of embankment is very sensitive to severe rainfall events.

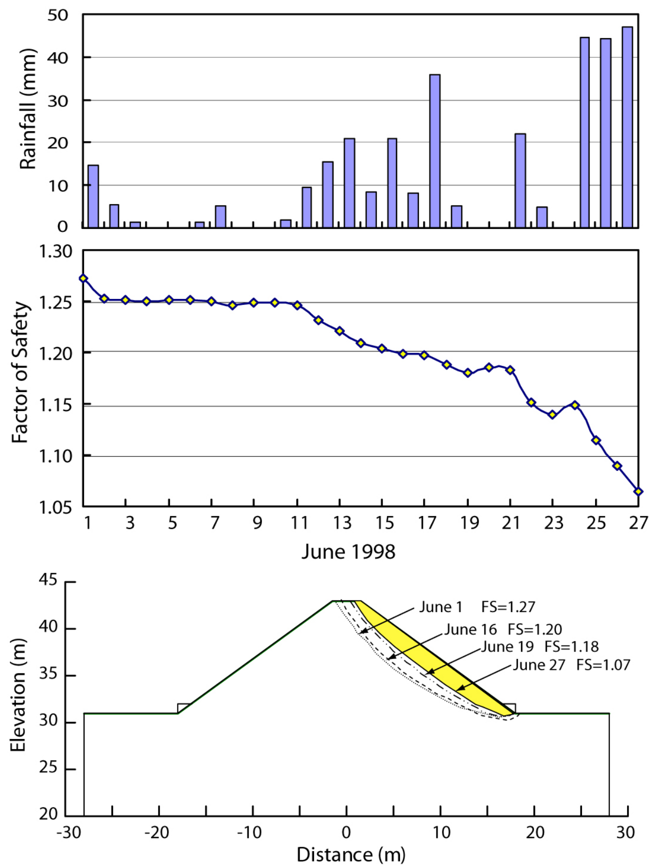

Figure 10: Evolution of critical slip surfaces and the factor of safety at Mile 154.47. (modified from Shi, 2006)

Step 8: Hazard zoning and Hazard & Risk Communication
Once the analyses are completed GIS technology becomes a powerful tool for highlighting the hazard and communicating the risk. Simply delineating the watersheds and displaying where they cross the railway, such as in Figure 8, is a powerful communication tool in planning for future events. The infrastructure with the greatest exposure to these severe events can be readily identified by combining geotechnical analysis and hydrotechnical analysis within a GIS framework.

5 DISCUSSION

In the hazard scenarios presented in Figures 2 and 3 the initiating event is usually an intense rainstorm. Bunce et al (2003) reviewed the records compiled over the past 122 years by Canadian Pacific Railway and concluded that at least 30% of the larger volume hazards occurred synchronous with severe weather events. Severe weather events are defined as climatic conditions including antecedent conditions that develop over months or years that have a return period of at least 10 years. To reduce the impact of these events on the safe and reliable railway operation, the railways retains the service of a weather-information provider. This information comes in three forms: 1) synoptic reporting of current conditions, 2) forecasts of predicted conditions, and 3) Weather warnings (as defined by Environment Canada and the National Weather Service (NWS) in the US).

Class 1 railways in North America use weather information in numerous ways. Temperature information is used to limit train speed during severe cold and hot conditions to reduce the potential for broken rail and rail sun-kinks, respectively. The track, bridge, and structures maintenance personnel also use weather information, such as rainfall amounts, to predict increased potential for damage to the track and structures. Heavy rainfall forecasts frequently prompt increased track and structure inspections. In rare cases trains have been slowed over tens-of-miles of track in response to high rainfall conditions and forecasts. According to Bunce et al (2003) the use of weather is non-systematic and empirical. While maintenance personnel are empowered to invoke multi-mile slow orders, they often need additional climatic information to support their observations and cause for concern. Furthermore, maintenance personnel are not equipped with any means of quantifying or communicating the hazard level. As a result, these severe climatic events are not always responded to in a proactive manner.

A proactive management strategy for rainfall induced hazards requires a forecasting methodology that could evaluate the impact of a severe weather event on the track infrastructure, such as the process model presented in the previous section. Such a methodology must consider, as a minimum, the weather event, the simplified FMEA in Figures 2 and 3, and the processes described in Table 1. Although the specific effects of climate change on climatic events may be poorly quantified at this time it is recognized that climate change will likely affect the return-period for severe weather events. Higher frequency and increased severity of extreme weather events, predicted by some as being a product of climate change, will test the robustness of the railway infrastructure.

6 CONCLUSIONS

The systematic analysis of the ground hazards encountered along the Canadian railways created the framework for developing the hazard scenarios. Process modelling provided the methodology for evaluating the hazard. The Port Douglas case study was used to demonstrate the application of the methodology to assess the hazards initiated by a severe rainfall event. GIS software was the enabling technology that allowed the process model to be developed. Now that the technology has been developed it is apparent how such a process model can be used to assess the hazards along a section of railway from a rainfall event for any return period and perhaps establish more general criteria to guide safe operations.

ACKNOWLEDGEMENTS

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