REGIONAL LANDSLIDE HAZARD SUSCEPTIBILITY MAPPING FOR PIPELINES IN BRITISH COLUMBIA

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ABSTRACT
Terasen Gas Inc. (Terasen) wishes to identify and manage slow, progressive, subsurface ground deformations that could potentially result in an undetected leakage from buried gas distribution piping within any of the 88 British Columbia communities they service. This paper describes the methodology, results, and challenges of a GIS based regional (1:250,000) scale landslide hazard susceptibility mapping project used to rank and prioritise, in a systematic and defensible manner, the communities for more detailed hazard and risk studies. This project utilises international frameworks for probabilistic hazard and risk management, landslide hazard zonation, and simple Fuzzy Logic operators. Methods of aggradation, or assigning a score to each community, are also presented. This paper and presentation should be of interest to those involved in geohazard management and hazard zonation, geoscience data providers, municipal planners, pipeline integrity personnel, insurance professionals, and engineering geology consultants.

RÉSUMÉ

Terasen Gas Inc. (Terasen) souhaite identifier et gérer les déformations lentes et progressives du sol qui peuvent potentiellement causer des ruptures non détectées de ses pipelines desservant 88 municipalités en Colombie Britannique. L'article présente la méthodologie, les résultats et les défis d'un projet de cartographie régionale (1/250,000) de la susceptibilité aux glissements de terrain. L'objectif est d'hiérarchiser et de prioriser, selon une approche systématique et rigoureuse, les municipalités pour des études détaillées de l'aléa et du risque. Ce projet utilise un cadre international pour la gestion du risque et de la probabilité, le zonage de l'aléa, ainsi que des opérateurs logiques de type "Fuzzy". La méthode "d'aggradation", qui consiste à attribuer une cote à chaque municipalité, est aussi présentée. L'article devrait intéresser les personnes impliquées dans la gestion des risques naturels et la cartographie de l'aléa, ainsi que les fournisseurs d'informations géoscientifiques, les planificateurs de l'aménagement municipal, les professionnels du domaine des assurances et les consultants en génie géologique.

1. INTRODUCTION

Terasen Gas Inc. (Terasen) supplies natural gas to over 800,000 homes and businesses throughout the province of British Columbia, Canada. As some portions of Terasen's network of gas distribution piping extend through rugged and varied terrain, Terasen wishes to identify and manage ground movement hazards that could potentially affect the operation of their system. Terasen is specifically concerned with slow, progressive, subsurface ground deformations that could result in an undetected gas leakage. BGC Engineering Inc. (BGC) was contracted to help Terasen determine which communities are susceptible to these types of ground movements.

In accordance with BGC's staged approach to geohazards management (Leir 2004), Stage 1 of this project consists of a regional (1:250,000) scale screening exercise that provides a relative numeric ranking for communities in BC susceptible to ground deformations. It provides Terasen with a systematic approach for identifying which communities warrant further attention and resources for the ongoing proactive management of ground movement hazards.

In this study ground movement hazards are restricted to landslide hazards. As Terasen is primarily concerned with lower intensity subsurface ground deformations impacting their subsurface distribution facilities, landslide subtypes are restricted to;

- earth and debris slides,
- earth and rock flows, and
- earth and rock creep

Earth, rock and debris falls, debris flows, and rock avalanches were not specifically addressed in this study. Specific landslides or discrete landslide susceptible areas within the communities are also not identified.

Lateral spreading and liquefaction triggered by earthquakes, have been addressed through other Terasen initiatives. Ground subsidence caused by piping, soil consolidation, settlement, and bedrock dissolution, are not considered by Terasen at this time to be significant hazards to their gas distribution system.

2. METHODOLOGY

2.1 Overview

Landslide hazard and risk mapping for urban and rural areas is widely performed around the world. A landslide zonation map divides a study area into high, medium, and low zones or varying degrees of stability based on an estimated significance of factors causing instability. When integrated with an inventory of historic landslide incidences, the combined map helps delineate areas susceptible to past, present, and future landslides.

The main factors which influence the occurrence of landslides are discussed in Cruden and Varnes (1996) and Hutchinson (1995). Normally the most important factors are bedrock and surficial geology, slope angle, land use, and hydrologic conditions. The use of more specific factors such as slope aspect, degree of bedrock weathering, or position of groundwater table depends on the type of landslide, objectives and scale of the study, availability of the data, and financial resources for the project.

Quantitative prediction models for landslide hazard utilise map-based databases consisting of several layers of digital information each representing a causal factor for the occurrence of landsliding. Selection of the causal factors is based on expert opinion and availability. The map layers used in this study are described in Section 2.3 below. The methods of combining these layers within the GIS, known as the model, are varied and are akin to layering hardcopy maps on a light table. Areas where unfavourable conditions for landsliding overlay one another are areas where landsliding is more likely to occur. GIS allows this overlaying process to become automated, systematic, and performed at varying resolutions and map scales. The use of the GIS also allows the use of more sophisticated, yet not necessarily more accurate, models.

Soeters and van Westen (1996) and Aleotti and Chowdhury (1999) discuss the analytical methods which can be used to assess the probability of landsliding. Traditional methods of landslide hazard mapping have been based on extensive fieldwork. This is slow, expensive and labour intensive, for any organisation to conduct – especially at national or regional scales. If enough relevant base data is available and affordable, GIS techniques can be combined with field checking to economise the landslide hazard and susceptibility mapping process. Several studies have used GIS and statistics at regional scales to systematically and quantitatively build hazard zoning maps (Guzzetti et al. 1999).

Leir (2003) created a summary of a systematic framework for GIS based geohazard assessment. It allows practitioners to understand what level of hazard mapping (i.e. hazard inventory, hazard susceptibility, or probability based analysis) can be produced for a given level of effort and data availability. In this study, hazard triggers were not considered, thus the focus was only on landslide susceptibility. Without the incorporation of triggers, the project is defined as a hazard susceptibility study.

All GIS landslide models are based on two basic assumptions:

1. Future landslides will occur under circumstances and in locations similar to the ones that have occurred already; and
2. Spatial data representing the causal factors contained in the GIS database can be used to formulate the occurrence of a future landslide.

The first assumption is widely adopted as truth in the geohazards community. The second assumption weakens if the data used in the GIS contains biases, is incomplete, incorrect, or not applicable at the scale of the study.

Like other types of modeling, all available methods for regional landslide assessments have some uncertainties arising from the lack of knowledge and variability in the causal factors. This is because regional landslide assessments are complex and require some generalisations and simplifications. For these reasons, a perfect assessment method for landslide susceptibility does not exist. There will always be some historic landslide locations that the model does not identify. Conversely, some areas identified as susceptible may not have experienced landslides. This is because subtle or localised causative factors cannot be accounted for in the model because they have not been identified or are not practical to obtain at a regional scale.

These uncertainties and oversimplifications are the trade offs to the advantages of using a GIS, namely, facilitation of systematic and quantitative landslide susceptibility mapping that defensible hazard management requires.

2.2 Study Area

The 88 communities serviced by Terasen fall into 8 regions in BC. The location and extent of the regions, which comprise the "study area", are shown in Figure 1. The region boundaries correspond to 1:250,000 scale map sheet boundaries and cover approximately 54,000 sq. km. (86 million cells, each 25 m x 25 m). This project was ambitious as most GIS based landslide studies reported in the literature are 1/5th this size. The study area covers a wide variety of terrain, which negates the use of sophisticated GIS models. In this regard, standard causal factors that were available consistently across all regions, such as bedrock type and slope angle, were used.

Most of the communities are located in the valley floors where slopes are relatively gentle and accumulations of glaciolacustrine, glaciomarine, glaciofluvial and fluvial soils overlie bedrock. Locations where communities are built onto valley sidewalls are expected to have higher susceptibility ratings due to higher slope angles.

2.3 Data Assembly, Reclassification and Scoring

Landslide hazards are a complex phenomenon generally associated with many contributing factors. Once the hazard types are selected then the contributing factors are selected using expert judgement. These factors are classified into two sub categories: causal factors and triggering factors (Vaunat, Leroueil and Tavenas, 1992).

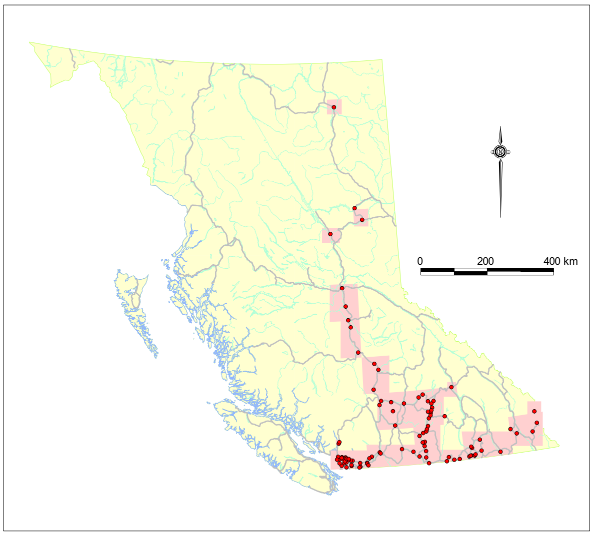

Figure 1. Map of British Columbia showing the location and extent of the 8 regions (shaded areas) that comprise the study area. The study area is 54,000 sq. km is size – over 5% of BC. The 88 communities are shown as dots.

Causal factors are the site characteristics that determine the terrain behaviour when one or more triggers occur. The selection of the causal factors is knowledge-based and is guided in part by the results of a hazard inventory, if available.

Each landslide type will have its own set of causal factors and not every factor needs to be accounted for in the model. Specialised or esoteric factors will not necessarily make the model more accurate.

Some hazards will share causative factors. For example, slope angle is a causal factor for landslides and for piping hazard. The steeper the slope the more likely the hazard could occur. The landslide causal factors used in this study include the following:

- Slope Angle
- Surficial Geology
- Bedrock Geology
- Proximity to Water Bodies
- Proximity to Faults

A number of digital data sources were required to conduct this study. From the outset, a study scale of 1:250,000 was selected because base mapping data was readily available, affordable, and the level of detail and accuracy corresponded well to a Stage 1 study (Leir, 2004). Federal and Provincial Government data warehouses, geological surveys, and other map libraries were searched for resources. Table 1 summarises the data sets collected and their use. Details on the data sets and how they were re-classed are provided below.

Table 1. List of data sets used in hazard assessment

Data Set	Source	Landslides
Topography	TRIM	CF
Hydrology	BTM	CF
Surficial Geology	BCGS	CF
Bedrock Geology	GSC	CF
Faults	GSC	CF
Hazard Inventory	Muni, Public	CB
Gas Distribution System	Terasen Gas	

TRIM – Terrain Resource Inventory Maps; BTM - Baseline Thematic Mapping; BCGS – British Columbia Geological Survey; GSC – Geological Survey of Canada; Muni – Various municipalities in BC, Public – scientific papers, conference proceedings, geohazard guide books
CF = data set is used to asses causal factor(s) for the hazard; CB = used for limited calibration of hazard ratings

2.3.1 The Use of Triggers

Average annual precipitation and zones of peak ground acceleration were considered as candidates for landslide triggers. The inclusion of triggers in the mapping model can provide a better indication of the spatial and temporal occurrence of landslides. Although the information was available at a regional scale, average annual precipitation was not judged to be an effective trigger. Antecedent rainfall and intensity, rather than annual average, is considered to be a more effective trigger (Jakob and Weatherly, 2002). Unfortunately rainfall intensity is not consistently or economically available in BC on a regional scale.

Peak ground acceleration was available at a regional scale but it was also not an effective trigger for generating the types of slow moving slides of interest here. Finally, biogeoclimatic zonation information was considered for estimating vegetation and land use type – two other common causal factors of landsliding. However, in this study, no obvious correlation was apparent because land is often cleared where gas distribution systems are located within communities. As such, biogeoclimatic information was dropped from the study.

2.3.2 Topography

Seventeen 1:250,000 scale topographic maps covering the 88 communities were purchased from Landata BC. As this hazard assessment methodology relied heavily on accurate topography, the 1:250,000 scale digital elevation model (DEM) data was replaced with 1:20,000 scale TRIM DEM data (accuracy +/- 5 metres vertical and +/- 10 metres horizontal) also from Landata BC.

As with many DEM data sets some anomalous elevation points were discovered. The area most affected by these errors was in the District of Langley near the Fraser River.

Filtering was applied to the DEM to minimise the effects of this error on the final hazard ratings.

2.3.3 Hydrology

The presence of creeks, rivers, canals, lakes, and oceans increases the potential occurrence of landslides due to assumed ground water tables near water bodies and hydraulic erosion, such as river down cutting and bank erosion, which commonly occurs at the base of slopes.

2.3.4 Surficial Geology

The use of published surficial geology maps can help identify areas prone to ground movement. Digital 1:50,000 scale terrain stability mapping and soils maps were acquired from the British Columbia Geology Survey (BCGS) in Victoria. These maps show the different soil types and geomorphology within BC using the BC Terrain Stability Mapping Guidelines (Howes and Kenk 1997) or the agricultural soils mapping guidelines from the 1970's. Relevant portions of hardcopy maps were also digitised where digital data maps were not available.

2.3.5 Bedrock Geology

1:250,000 scale digital bedrock geology maps were acquired from the Geological Survey of Canada (GSC) in Vancouver. Certain bedrock types increase landslide susceptibility due to their joint spacing, bedding orientation, and susceptibility to weathering.

2.3.6 Faults

The bedrock map acquired from the GSC also included the location of major faults in British Columbia. Although there are no known active faults in British Columbia, the presence of a fault increases landslide susceptibility because the rocks near the fault have undergone intense shearing and are weaker, and because faults may be associated with anomalous groundwater conditions.

2.3.7 Landslide Inventory

A landslide inventory is a mandatory component to sound hazard and risk assessment. It is used to help characterise the landslide hazards, define the model, and calibrate of the assessment algorithms.

A regional scale landslide hazard inventory was constructed by reviewing hardcopy reports of landslide events found in publicly available community records, scientific papers, journals, conference proceedings and geohazards guidebooks. This search, which spanned approximately three person weeks, resulted in approximately 600 landslides (Figure 2) of which 165 were used in this study for their flow, creep and slide mechanics. All of the slides are represented as single points, which was suitable for a regional scale analysis. Location accuracy of the landslide points varies from ±10 m (hand held GPS) to ±125 m (considerable uncertainty on 1:250,000 scale map).

Apart from resource constraints, there are two reasons why a landslide inventory may under-represent the actual number of landslides. Firstly, landslide incidences are reported in the technical literature on a purely discretionary basis where the author has the interest and the parties affected have the willingness to invest the time in getting the information into the public domain. This means that some, but not necessarily all of the events are recorded in a landslide inventory. Second the literature is biased towards landslide movements with velocities of very slow and greater (i.e. ≥ 16 mm/year). These typically start sometime after municipal development and are recognised and managed quickly because of the implications on structural damage. The landslides in the extremely slow category (i.e. < 16 mm/year) can go unnoticed and, for this reason, are of particular concern to Terasen. These extremely slow events are virtually absent form this inventory.

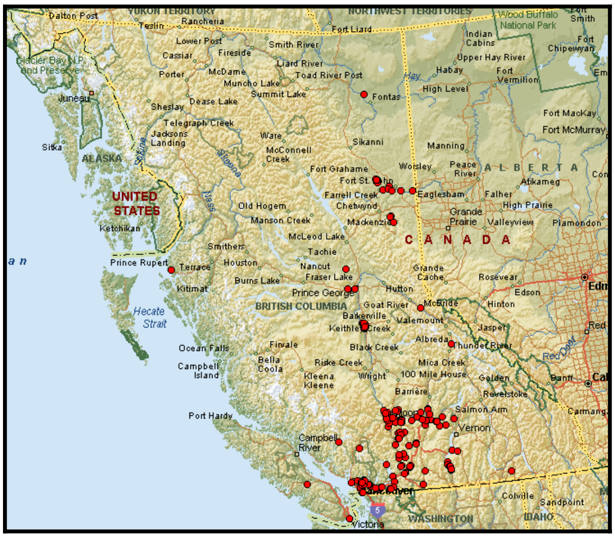

Figure 2. Landslide inventory (red dots) compiled for this study. 165 of the 600 landslides in BC are shown here.

Nevertheless, the inventory was a useful guide for qualitatively calibrating the GIS model and provides some insight into which regions of BC are susceptible to landslides. Due to its obvious geographic and scale bias, the information was used as a guide and not in a systematic or quantitative manner in the model. An excellent case study using a landslide inventory spanning 100 years has been recently documented by Coe et al. (2004).

2.3.8 Pipeline Distribution System

Terasen provided BGC with a vector file of its entire distribution system in BC. The distribution system was buffered by a distance of 50 m to account for future expansion. Each community was assigned a representative proportion of the system and a hazard rating was calculated within these areas.

2.4 Rasterisation

Each map layer is converted from a vector (lines) layer to raster (cells) layer with the following resolutions:

Bedrock Geology	100 m
Surficial Geology	100 m
Faults	100m
Slope	25m

Rasterisation is required so that mathematical computations can be performed across all of the layers using a common cell size. The final landslide susceptibility maps are constructed at 25 m pixel resolution. This resulted in approximately 86 million pixels for all eight regions.

2.5 Re-classification

Re-classification is the process of grouping each causal factor into categories of similar influence. Re-classification also helps simplify algorithm development and data management. For example, the slope angle causal factor that starts as a continuous range of values from 0 degrees to 50 degrees is divided into 5 classes as shown below.

- 0° to 3°
- 3° to 15°
- 15°to 26°
- 26° to 35°
- > 35°

Re-classification was also performed on bedrock, and surficial geology. Faults and hydrology, being represented as lines instead of polygons, are re-classed slightly differently by converting lines to polygons by using buffers.

2.6 Scoring

Once re-classed, each class within the causal factor layer is subjectively scored between 0 and 1 to represent its influence on landslide stability. For example the 5 slope classes are scored as follows:

Table 2. Slope angle scores

Slope Angle (Degrees)	Score
0 to 3	0.0
3 to 15	0.3
15 to 26	0.5
26 to 35	0.9
> 35	1.0

This scoring pattern shown in Table 2 implies that slopes over 26 degrees (score of 0.9) are more susceptible to landslides than slopes less than 26 degrees. These scores are adjusted during the calibration of the algorithm using the landslide database as a guide.

2.7 Algorithm Development Using Fuzzy Logic

Algorithm development follows data assembly. Understanding the limitations of the data, scale of the study, and the hazard types helps with the design, construction, and testing of a suitable algorithm. Calibration, redesign, and refinement of the data scores and algorithm occur iteratively until suitably accurate ratings are produced.

A number of techniques for building hazard rating algorithms are available. The most suitable technique depends on the:

- study objectives,
- study scale,
- available data,
- project resources, and
- participant’s expertise.

There are also a number of GIS based hazard algorithm frameworks to use for landslide susceptibility mapping. In general, they include;

- Index Overlay
- Fuzzy Logic (Chi et al, 2002, Tangestani, 2003)
- Conditional Probability Models
- Multivariate Regression Techniques

Aleotti and Chowdhury (1999) provide a well organised introduction to the types of hazard rating techniques. The approaches differ in the way scores and weights are assigned (subjectively or objectively (Leir, 1994)) and combined across layers (additive, multiplicative, or probabilistic operators) (Carrara, et al., 1995). Conditional probability and regression techniques utilise a probabilistic framework and require a landslide inventory.

The Fuzzy Logic approach was selected for this study because, by virtue of its simple operators (described below), it offered a probabilistic framework (Index Overlay is an algebraic model) without the direct integration of a landslide database (Conditional Probability and Multivariate techniques work best with a landslide inventory).

The idea of using fuzzy logic in landslide susceptibility mapping is to consider the cells on any causal factor layer as susceptible to landslides. Cell values can be gradational and range from 0 (i.e. not susceptible) to 1 (i.e. “susceptible”). Cell values must lie in the range of 0 to 1 but there is no practical constraint on the choice of values. Like Index Overlay scores and weights, values are subjectively assigned to reflect the degree of influence the class has on landslide stability. Due to the framework of the fuzzy operators (see below), the cell values are essentially subjective probabilities. Alternatively these probabilities may be calculated using a relevant landslide inventory by overlaying the landslide locations with each causal factor class.

2.7.1 Fuzzy Operators

The goal is to build an algorithm that combines causal factor layers to produce, in a structured manner, a landslide susceptibility map. An et al. (1991) and Bonham-Carter (1994) discussed five operators which are useful for combining the landslide casual factor layers. The following 4 deserve elaboration as they are used in Figure 5 to describe the algorithm logic.

Fuzzy And The resulting cell value is the minimum of the input cell values.

Hazard Susceptibility Rating = Min (x_1, x_2, x_3,…x_n) [1]

where x_n is the cell value for nth causal factor layer.

This operator always picks the lowest score from a set of layers. It is a conservative operator. For example if a portion of the map has clay (high) but no slope (low), the landslide susceptibility rating will be low. This operator is used when all "bad" causal factors must be present for the susceptibility rating to be high.

Fuzzy Or The resulting cell value is the maximum of the input cell values.

Hazard Susceptibility Rating = Max (x_1, x_2, x_3,…x_n) [2]

where x_n is the cell value for nth causal factor layer.

This operator always picks the highest score from a set of layers. It is not a conservative operator. For example if a portion of the map has clay (high) but no slope (low), the landslide susceptibility rating will be high. This operator is used when only one "bad" factor must be present for the susceptibility rating to be high.

Fuzzy Product The resulting cell value is the product of the input cell values.

Hazard Susceptibility Rating = $x_1 \bullet x_2 \bullet x_3 \bullet \ldots x_n$ [3]

where x_n is the cell value for nth causal factor layer.

This operator always produces a probability less than the input probabilities because of the decreasive effect of multiplying a series of numbers less than 1. This operator is used when the combination of casual factors decreases landslide susceptibility.

Fuzzy Sum The resulting cell value is the sum of the input cell values.

Hazard Susceptibility Rating = $1 - [(1- x_1)\bullet(1- x_2)\bullet(1- x_3) \ldots (1- x_n)]$ [4]

where x_n is the cell value for nth causal factor layer

This operator always produces a probability larger than the input probabilities because of the increasive effect of multiplying a series of numbers less than 1. This operator is used when the combination of casual factors increases landslide susceptibility.

2.7.2 The Fuzzy Logic Algorithm

In this study, instead of using one operator, a "fuzzy inference network" was constructed to simulate the logic of landslide instability at a regional scale. The available components are the causal factors described in Section 2.3 and the fuzzy operators described above. Figure 3 is a diagram of the "fuzzy inference network".

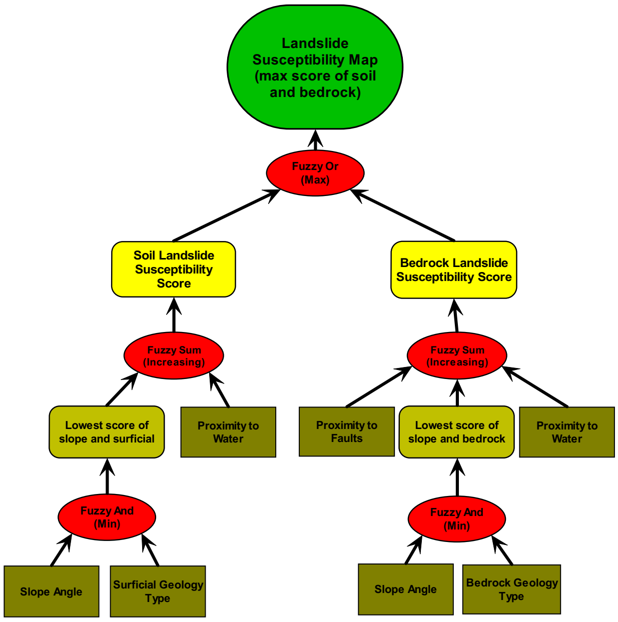

Figure 3. Inference diagram showing use of the fuzzy operators (red) and the causal factors (dark green).

For each pixel in the study area the following algorithm was evaluated to calculate a landslide hazard susceptibility rating:

Select the maximum (highest or worst case) score of Equation 1 or Equation 2:

1 – [(1 – minimum of (slope score, surficial geology score)) x (1 – water proximity score)] [5]

OR

1 – [(1 – minimum of (slope score, bedrock geology score)) x (1 – water proximity score) x (1 – fault proximity score)] [6]

Equation 5 evaluates soil landslide susceptibility. Equation 6 evaluates bedrock landslide susceptibility.

The highest, or worst case, of these two conditions is recorded on the landslide susceptibility map. The bedrock landslide evaluation differs from soil landslide in that bedrock geology is used instead of soil geology and proximity to faults is considered.

An example is provided below:

Select maximum score of:
1 – [(1 –minimum(0.7, 0.9)) x (1 – 0.2)] = 0.76
OR
1 – [(1 –minimum(0.7, 0.6)) x (1 – 0.2) x (1 – 0.4)] = 0.81

In this example, the cell would be assigned a landslide susceptibility rating of 0.81. A bedrock landslide is slightly more likely to be present in the cell than a soil landslide.

The fuzzy logic approach had some advantages over the Index Overlay approach used in the earlier stages of this project. Firstly, the fuzzy logic operators of AND, OR and SUM provide more logical ratings in the areas where the soils or bedrock were susceptible to landslides but very little slope was present. This occurs within the community of Richmond, for example, where soft silts and clays are found but very little slope is present to induce shear stresses. With the use of the fuzzy operators, both poor geology and high slope are required before the susceptibility rating becomes high. The flat areas of Richmond receive a very low rating and do not skew the susceptibility ratings in the study area.

Secondly, the fuzzy operators are built on a probabilistic framework – a framework that is better suited for hazard and risk management investigations.

2.7.3 Calibration of the Fuzzy Algorithm

The landslide inventory was used to help calibrate the effectiveness of the mode by visually comparing with the landslide locations to the locations of the high susceptibility zones. Landslide points were buffered using the estimated accuracy of the landslide location as the radius of the buffer. Approximately 66% of the landslide buffers contained at least one cell with a susceptibility rating greater than the high threshold of 0.54. Most landslide susceptibility models are performing well when they can predict greater than 60% of the observed landslides (Guzzetti et al 1999).

3. PRIORTISATION OF THE COMMUNITIES

The hazard rating methodology described in Section 2 allowed for the calculation of a hazard susceptibility rating for each cell within the study areas. This section describes the methodology for aggregating a rating for each community, which are made up of many cells.

3.1 Defining High Zones Using a Cumulative Frequency Curve

This section describes a simple statistical method that can be used to make the initial selection of candidates for "high" landslide susceptibility zones.

For this method, a cumulative frequency plot of landslide susceptibility ratings is constructed using all 86 million cell values. This plot is shown in Figure 4. The "high" threshold is arbitrarily selected as the 10th percentile. That is, the value where 10% of the cells meet or exceed the threshold and 90% of the cells values are less than the high threshold. Grid cells with ratings above the threshold will then be categorised as "high" (i.e. the ground is highly susceptible to landslide hazards). Conversely, the "low" threshold is the 50th percentile where 50% of the cells have a value less than or equal to 0.16.

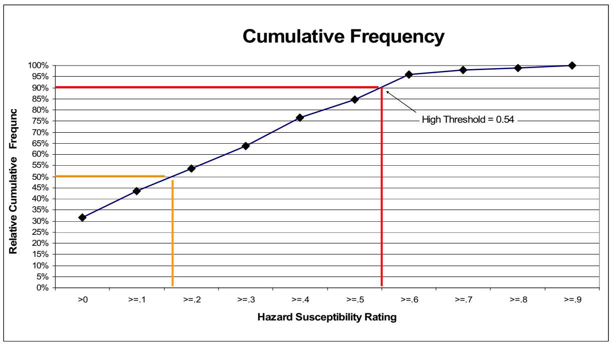

Figure 4. Cumulative Frequency plot of all cells within the study area. This curve is used to set the high (red) and low (yellow) thresholds. The thresholds are used to aggregate the ratings for each community.

3.2 Assigning a landslide susceptibility rating

Now that a landslide susceptibility map has been built and calibrated, a susceptibility rating needs to be assigned to each community. This is called "aggregation by community". To do aggregation, a community is defined as the portion of the 50 m buffered distribution system (from Section 2.6.8) that falls within a community's city limits. Portions of the Terasen distribution system falling outside a community's boundaries (typically occurring in rural areas of BC) were arbitrarily assigned to the nearest community.

For each community the following three statistics are reported:

1. Mean of the high ratings within the 50 m buffered distribution system. This is an indication of how susceptible the ground is to landslides.

2. The percentage of the 50 m buffered distribution system affected by "high" susceptibility ground. This value indicates the amount of distribution system that may be affected by landslides, but in relative terms. The reader is cautioned that small communities may report a high percentage even though there may be only a few hectares of high zone. This number may also be thought of as a basic measure of vulnerability because it quantifies the amount of pipeline exposed to highly susceptible ground.

3. The amount of "high" area within the 50 m buffered distribution system. This value indicates the amount of distribution system that may be affected by landslides, in absolute terms. It may also be thought of as a basic measure of vulnerability.

Additionally, some of the communities have had landslides occur within their municipal boundaries. These communities should not be overlooked as past incidences are often very good predictors of future landslide problems. An approach for including this information in the prioritisation of communities is described below.

3.3 Prioritisation of the Communities

In this study, the communities are prioritised based on the relative or absolute amount of highly susceptible ground (i.e. "high") intersecting the 50 m buffered gas distribution system within the communities' city limits. By inspection of the results, the following 3 approaches are proposed for prioritisation:

1. Mean Susceptibility Rating – Select the communities based on descending mean landslide susceptibility rating. A mean rating is calculated using all of the high ratings intersecting the 50 m buffered gas distribution system. This technique provides a blend of large, small, coastal, and interior communities. This approach may be appropriate for distributing risk management resources across BC and reducing the greatest number of potentially problematic communities with a set amount of resources. If this method is used then the following top five communities are selected:

Table 3. Top five communities selected using Mean Susceptibility Method

Community	"High" Area (km^2)	Mean Rating
Maple Ridge	0.7	0.80
Burnaby	< 0.1	0.75
Kent	0.3	0.74
Cultus lake	0.1	0.71
Mission	< 0.1	0.69

2. Area - Select the communities with the largest area of highly susceptible ground. This technique focuses efforts on the communities with the largest vulnerability, in absolute terms (km^2). The trade off here is that fewer communities are investigated in more detail for a set amount of resources because each selected community has such a large area to investigate. If this method is used then the following top five communities are selected:

Table 4. Top five communities selected using Area Method

Community	Area (km^2)	Mean Rating
Kamloops	2.1	0.61
Creston	1.3	0.65
Abbottsford	1.2	0.64
Chilliwack	1.0	0.63
Castlegar	1.0	0.63

3. History - Select the communities with >4 recorded landslides. This approach considers only the past record of landslides and ignores the results of the fuzzy logic mapping. The reader is cautioned on using this approach exclusively, because, for reasons described in Section 2.3.7, the landslide record does not account for all of the landslides than may have occurred within each community. If this method is used then the following five communities are selected:

Table 5. Top five communities selected using History Method

Community	Area (km^2)	Landslide Count
Kamloops	2.1	18
Quesnel	0.1	16
Coquitlam	< 0.1	9
Surrey	0.0	7
Maple Ridge	0.7	5

4. **Area and History** - Select the communities with greater than 4 known landslides and the largest absolute area. This approach is a blend of historic incidences and future vulnerability. If this method is used then the following top five communities are selected:

Table 6. Top five communities selected using Area and History method

Community	Area (sq. km)	Landslide Count
Kamloops	2.1	18
Penticton	0.8	4
Maple Ridge	0.7	5
Quesnel	0.1	16
Coquitlam	< 0.1	9

4. LIMITATIONS OF THE RATINGS

The landslide hazard rating procedures described above allowed for the calculation of a numerical hazard rating and the ranking of communities relative to one another. This ranking provides a valuable tool for managing landslide hazards, as discussed in greater detail below; however, some words of caution are required.

Hazard ratings are based on imperfect and qualitative data. Therefore, the absolute ranking of one community over another should not be taken literally to the extent that it over-rides engineering judgement. Low ratings do not mean that no hazard-related problems could develop. These communities are simply rated lower relative to other more significant hazard potential sites. It is also important to appreciate that conditions change with time in response to climate change, human activity and significant adverse events such as storms (i.e. triggers). As described above, this study does not incorporate the effects of triggers. Thus, a community that is assigned a low rating at the time of the assessment could be rated higher following activation of a trigger.

Furthermore, a high rating does not infer that failure is imminent. Rather, there is a combination of conditions that indicate the hazard potential is higher than at other communities.

In the future, Terasen may also elect to incorporate consequence into its decision process, such as population density, pipeline size, or throughput volume. Communities with a high population density or high gas consumption may help flag highly susceptible communities for more detailed Stage 2, 3 and 4 studies.

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