

Landslide Susceptibility Mapping for Large Landslides in Saskatchewan

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ABSTRACT

Large landslides are widespread in the Western Canadian Sedimentary Basin and pose a threat to many components of the built environment. Delineation of landslides is time-consuming and subject to human error, particularly where detailed digital elevation models and high quality orthophotos are not readily available. A landslide susceptibility map for large, deep-seated landslides was developed for Southern Saskatchewan using a novel approach with the application of a standard bivariate statistical method (weights of evidence) at a nominal scale of about 1:50,000. Large landslides were mapped within a 500 m buffer of every community in the province, and this inventory served as the basis for statistical analysis. The approach is novel in that the landslide inventory and study area cover a very small proportion of the whole study area but comprise a relatively unbiased and statistically significant representation of the whole, as confirmed through validation by landslide identification in randomly selected locations outside the communities' study area.

RÉSUMÉ

Les grands glissements de terrain sont répandus dans le bassin sédimentaire de l'Ouest canadien et constituent une menace pour de nombreuses composantes de l'infrastructure. La délimitation des glissements de terrain prend du temps et est sujette aux erreurs humaines, en particulier lorsque les modèles d'élévation numériques détaillés et les orthophotos de haute qualité ne sont pas facilement disponibles. Une carte de susceptibilité pour les grands glissements de terrain profonds a été développée pour le sud de la Saskatchewan en utilisant une nouvelle approche avec l'application d'une méthode statistique bivariée standard (poids de la preuve) à une échelle nominale d'environ 1/50 000. Les glissements de terrain ont été inventoriés dans une zone tampon de 500 m autour des communautés de la province, et cet inventaire a servi de base à l'analyse. Cette approche est novatrice en ce sens que l'inventaire et la zone d'étude des glissements de terrain couvrent une très faible proportion de la zone étudiée, mais assure une représentation relativement impartiale et statistiquement significative de l'ensemble, tel que validé par l'identification des glissements de terrain dans des emplacements choisis au hasard à l'extérieur des communautés étudiées.

1 INTRODUCTION

Between 2017 and 2018, a mapping exercise was carried out to identify large, deep-seated landslide features in and around communities in Saskatchewan. This work was conducted to support geohazard characterization and risk assessment for a natural gas distribution pipeline system, operated by SaskEnergy Incorporated (SaskEnergy). The mapping work was conducted for a total of 1101 communities, with the map area encompassing each entire community plus a 500 m buffer. The distribution of communities within the province of Saskatchewan is broad, with communities typically having developed adjacent to railway and highway developments designed to serve a geographically dispersed agricultural industry. Though agricultural townsites are typically located on relatively flat ground, there are also many resort communities on slopes at the flanks of major lakes and river valleys. The distribution of communities is therefore relatively unbiased with respect to geology and geomorphology, as shown in Figure 1.

The scale of the mapping exercise and diverse terrain of the communities assessed provided a strong test set, coupled with publicly available thematic geospatial data, from which to create a landslide susceptibility map. The intent of this map was to help inform the level of

geotechnical input required for new projects in SaskEnergy's natural gas pipeline system. The majority of the communities studied are located within the Western Canadian Sedimentary Basing (WCSB), which is characterized by argillaceous bedrock and is known to contain deep-seated landslides. The susceptibility map is considered valid for only the WCSB area of the Province where these landslide mechanisms are known to be prevalent.

2 METHODOLOGY

The Weights of Evidence Method (Bonham-Carter, Agterberg & Wright, 1989) was used to develop the landslide susceptibility map. This allowed for multiple types of geospatial thematic data to be correlated to the presence or absence of landslide terrain and then combined to form a weighted susceptibility map. The following subsections provide an overview of the Weights of Evidence Method, the thematic geospatial data used, the evaluation of the data and development of weights, the optimization of various susceptibility maps, and the validation of the optimum susceptibility model. The susceptibility map was developed and optimized within the predefined analytical study area of community boundaries (plus a 500 m buffer)

and was then validated within the prediction area outside community boundaries in southern Saskatchewan.

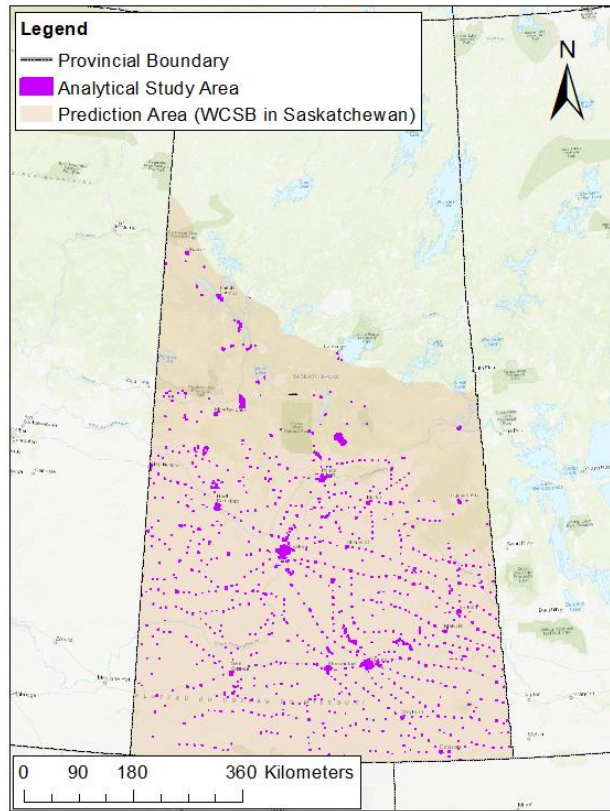


Figure 1. Analytical study area within the Western Canadian Sedimentary Basin in Saskatchewan

2.1 Weights of Evidence Method

The Weights of Evidence Method was used to evaluate the correlation of specific themes¹ to the presence or absence of existing (mapped) landslides. The Weights of Evidence Method is a bivariate statistical approach that combines features of various thematic maps that have some relationship to the incidence of a specific feature, in this case, landslides. For each thematic map, weights are calculated for each individual factor based on the conditional probability (P) of the presence or absence of a landslide, and these individual weights are combined to develop an overall weight map. The process of interrelating thematic data and the landslide inventory is illustrated in Figure 2. The individual thematic positive weights (W_i) are calculated by taking the logarithm of the ratio of spatial probabilities, shown in Equation 1, below. Use of the logarithms for weights, rather than the probability values, is strictly for mathematical convenience, to allow their combination through simple addition. This is mathematically equivalent to multiplication of the conditional probability values.

$$W_i = \log \left[\frac{P\{F_i|L\}}{P\{F_i|\bar{L}\}} \right] \quad [1]$$

Where:

- W_i = The positive weight for the i^{th} thematic factor
- F_i = The presence of a specific (i^{th}) thematic factor
- L = The presence of a landslide
- \bar{L} = The absence of a landslide

Strictly speaking, W_i described in Equation 1 above is the “positive weight” and the formal Weights of Evidence Method also includes consideration of negative weights. Positive weights, W_i , indicate a positive relationship between the presence of a factor and landslide presence, while negative weights indicate a negative relationship between factor and landslide presence. In practice, inclusion of the negative weights adds little or no predictive value to the model, and so they were omitted from the work. This decision was made following careful checking for several model scenarios and was done to make the workflow more efficient.

In the GIS environment, the spatial probabilities in Equation 1 are calculated by summing the number of raster pixels where landslides are present or absent and where a specific factor is also present. Equation 1, using GIS raster algebra, hence becomes Equation 2, below.

$$W_i = \log \left[\frac{A_1/A_2}{A_3/A_4} \right] \quad [2]$$

Where:

- A_1 = The area within the specific factor containing landslides
- A_2 = The total area within the analytical study area containing landslides
- A_3 = The area within the specific factor not containing landslides
- A_4 = The total area within the analytical study area not containing landslides

These weight values are calculated within a specific point, or map pixel, where the i^{th} theme (say, soil type) has a specific value. The A_i values and calculated weight are the same at any other point on the map with the same thematic value, and therefore the number of different weight values for W_i depends on the number of different thematic values (e.g., number of different soil types).

Landslide susceptibility is obtained by combining the thematic weights, W_i , to obtain an overall combined weight, as shown in Equation 3 and Figure 3.

$$W_{\text{Total}} = W_{\text{Soil}} + W_{\text{Bedrock}} + W_{\text{Slope}} + \dots \quad [3]$$

¹ A theme in this context refers to any geospatial dataset which could hypothetically be related to landslide occurrence. Examples could include slope angle, soil type, bedrock geology, or physiographic region, to name a few.

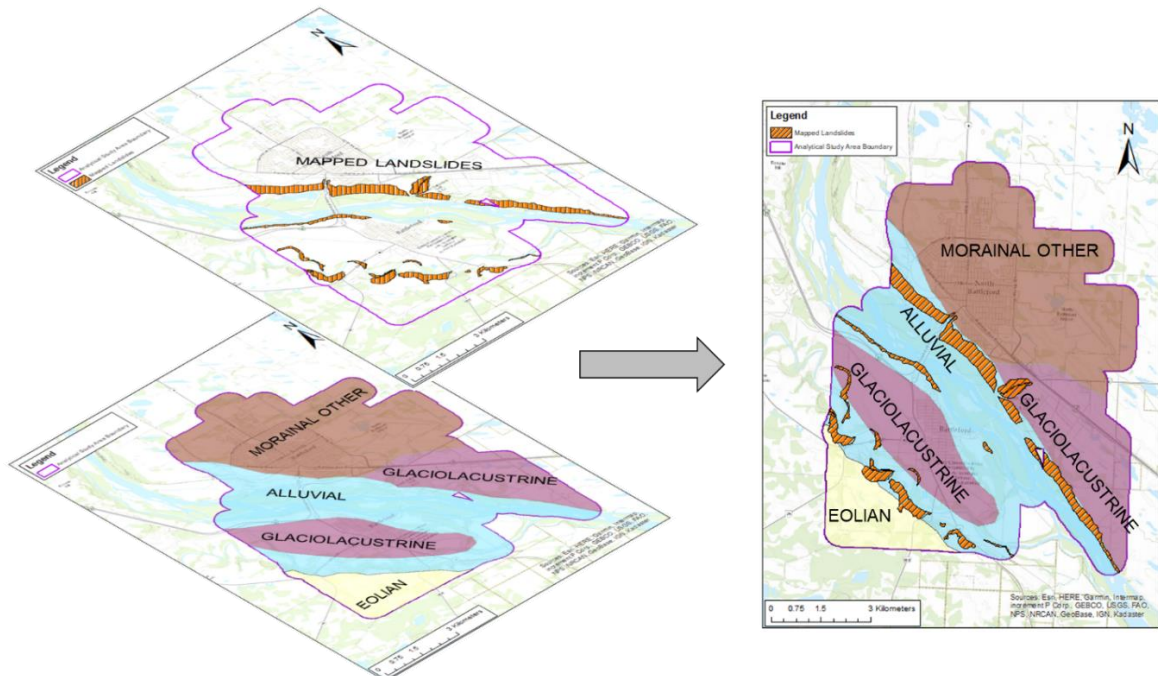


Figure 2. An example of spatially relating thematic maps (surficial geology in this case) and landslide inventory maps.

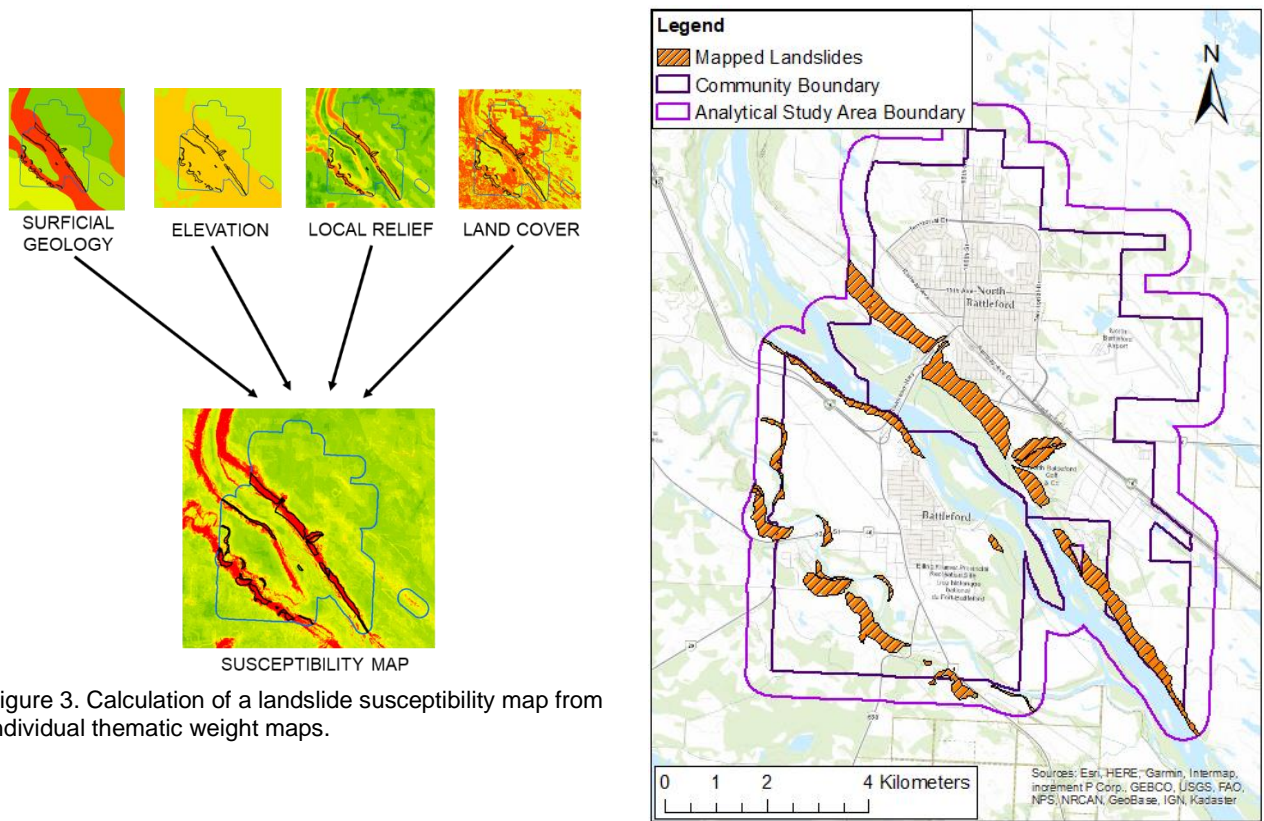


Figure 3. Calculation of a landslide susceptibility map from individual thematic weight maps.

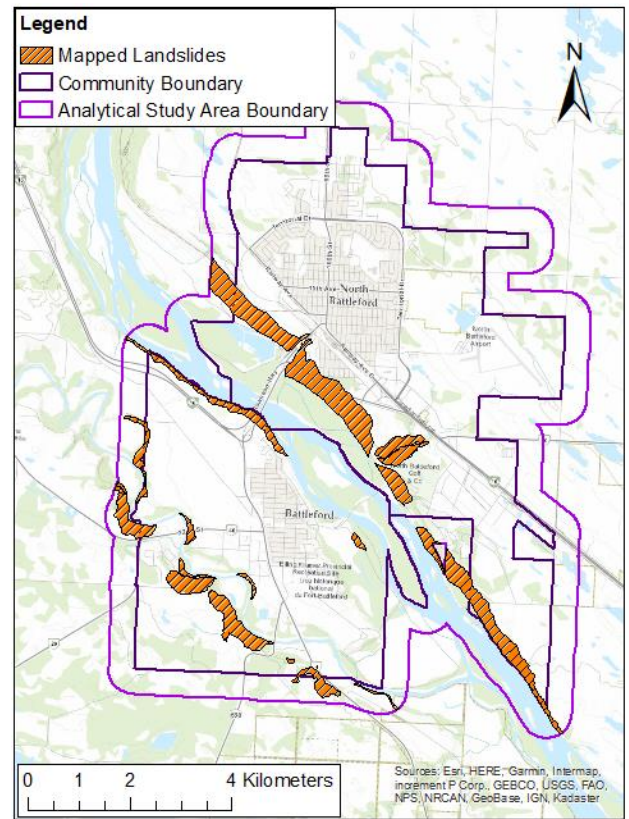


Figure 4. Community boundary (black) with 500 m buffer (purple), and landslide polygons mapped (orange).

The combined map will have numeric values ranging between some low (highly negative) and high (highly positive) values, where higher values represent a higher spatial probability of landslide incidence. The numeric range in this combined map can be divided into smaller ranges representing high, medium and low susceptibility or some similar subdivision. For this map, these subdivisions were related to specific spatial probabilities of landslide presence based on input from SaskEnergy to align with their existing processes for new pipeline construction

2.2 Study Area

The analysis of spatial probability of landslide presence / absence associated with various spatial themes is conducted within a predefined analytical study area within which a complete landslide inventory is available at a consistent scale. For this work, the analytical study area was defined by 1101 community boundaries plus an additional 500 m buffer. This analytical study area contains a complete inventory of deep-seated landslides and landslide terrain (as interpreted at about 1:50,000 scale) and also represents broad geographical coverage of the overall study area of the WCSB in Southern Saskatchewan. An example of a community containing mapped landslides is shown in Figure 4.

2.3 Evaluation of Thematic Data

The Weights of Evidence approach requires a selection of various geospatial themes that may have a correlation to landslide presence. Various geospatial themes were chosen for initial consideration based on experience and judgement, and following a review of recent literature (e.g., Reichenbach, Rossi, Malamud, Mihir, & Guzzetti, 2018). The geospatial themes and the data sources considered for the model are provided in Table 1, below.

Table 1. Thematic data selected

Geospatial Theme	Rationale for Selection
Elevation (Natural Resources Canada, 2015)	May correlate with weak geologic units more prone to landslides or areas with higher precipitation due to orographic effects.
Slope Angle (Natural Resources Canada, 2015)	Certain ranges of slope angles are known to be landslide prone for common geological units in Saskatchewan. The steeper the slope, the greater the driving force for movement.
Slope Aspect (Natural Resources Canada, 2015)	Influences soil moisture.
Local Relief (Natural Resources Canada, 2015)	Local elevation changes are indicative of the scale of terrain features, and the likelihood that driving forces may exist for the development or propagation of landslides. This metric identifies slopes that are either steep or long.

Topographic Curvature (Natural Resources Canada, 2015)	Can indicate sharp breaks in terrain and the shape of the slope breaks (convex vs. concave), and therefore be indicative of landslide morphology. Can influence drainage and/or stresses in the ground, both of which affect slope stability.
Sedimentary Bedrock Type (Morelli, 2010)	Certain bedrock types are more prone to landslides. The dataset was limited to sedimentary bedrock in the WCSB
Surficial Geology (Saskatchewan Research Council, 2018)	Certain soil materials are more prone to landslides.
Glacial Drift Thickness (Simpson, 1997)	Indicates depth to bedrock. Thinner drift is expected along various morphological features such as river valleys which may contain landslides. Thinner drift also implies a greater likelihood of activation of weak layers within underlying bedrock to form landslides.
Land Cover (Arnold, 2008)	Plant cover and land use can be a proxy for surficial geology and may reveal smaller features than observable in available soil mapping.

Many of the geospatial themes used are not fully independent; slope angle and relief are generally related and both likely to impact land cover, for example. The importance of thematic inter-dependence is tested through trial and error, and if inclusion of a theme improves model performance, it is retained in the model. Optimization of the model and final selection of input themes is discussed in the following section.

Geologic judgement was used to evaluate how to group and subdivide thematic data. For discrete-valued data (i.e., polygon vector data like soils and bedrock, and also raster data with discrete values), judgement was used to assess which types can be reasonably combined to create factors with statistical significance while maintaining an adequate range of factors to produce meaningful variation in the calculated weights. Examples include combining geologic materials with similar properties within the surficial geology and bedrock geology datasets. Table 2 shows how factors within the surficial geologic dataset were combined.

Judgement was also used to define some weight values that could not be calculated based on limitations of the analytical study area. As one example, when a factor was not present within any landslide within the analytical study area, the calculated weight (i.e., the logarithm of the spatial probability) is negative infinity, which is not usable within the context of the susceptibility map. For these factors, the weight value was either set to -1 or was set equal to the lowest calculated weight value among other thematic values. As another example, a weight value would be defined or adjusted if a factor was not present within the analytical study area but there was a level of geologic understanding of the factor to assign it a positive or negative weight. An example of this is colluvial soil from the surficial geology dataset. No colluvial soil was present within the analytical study area and thus the calculated

weight was “0,” an indication of no correlation with landslides. However, colluvial soils are landslide-derived, so where colluvial soils are mapped, there should be a high spatial probability of the presence of existing landslides. Thus, colluvial soil was assigned a weight factor equal to the highest positive weight calculated for other values in the surficial geology theme (see Table 2).

Table 2. Surficial geology classes combined from Saskatchewan Research Council, 2018

Environment and Form	Combined Feature
Alluvial	Alluvial
Alluvial Plain	
Colluvial	Colluvial
Eolian	Eolian
Eolian Hummocky	
Eolian Plain	
Eolian Ridged Dunes	
Glaciofluvial Eroded	Glaciofluvial Eroded
Glaciofluvial	Glaciofluvial Other
Glaciofluvial Hummocky	
Glaciofluvial Kame Terrace	
Glaciofluvial Plain	
Glaciolacustrine	Glaciolacustrine
Glaciolacustrine Delta	Glaciolacustrine Other
Glaciolacustrine Plain	
Lacustrine	Lacustrine
Morainal	Morainal and Morainal Eroded
Morainal Eroded	
Morainal Drumlinoid	Morainal Other
Morainal Hummocky	
Morainal Plain	
Morainal Ridged	
Morainal Undulating	
Morainal Veneer	
Organic	Organic
Organic Plain	
Rock	Rock

Some raster thematic data have continuous values, and in such cases, bins were created, assigning discrete values representing ranges of values, to support their inclusion in the analysis. For continuous-valued raster data, bin selection was done to produce a minimal number of statistically significant categories with distinct weight values. Bin assignment can be done in various ways: by selecting bins with even spacing over the range of theme values; by selecting bins based on equal proportion of map area; by selecting bins that divide the proportion of

landslides evenly within each bin; or, by selecting bins to produce evenly divided weight values. Selecting the bins requires judgement and some degree of trial and error. An example of bins selected by dividing local relief values in equal width (i.e., 13 m wide bins) and by approximately even changes in weight values is shown in Figure 5.

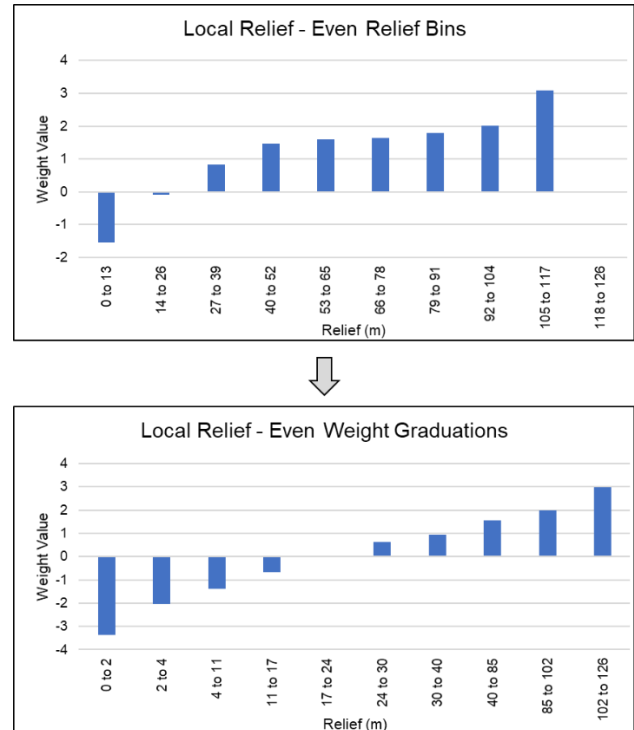


Figure 5. Comparison of bin options for continuous raster datasets

2.4 Optimization and Validation of Susceptibility Models

To build the susceptibility map, the weighted thematic maps were combined in various ways to find an optimized model, one which confined the greatest proportion of mapped landslides to the smallest proportion of the map in the analytical study area. This was done through a combination of judgement-guided trial and error and sensitivity analysis. A perfect susceptibility map would confine all the landslides within the actual area occupied by landslides within the analytical study area as shown in Figure 6, which also shows the performance of the selected susceptibility map.

2.5 Selection of Weight Value Ranges

The optimum landslide susceptibility map is a continuous-value raster over the entire range of calculated weight values. While informative, this data alone is not particularly useful as it is unclear what the weight values represent. The susceptibility map may be more directly useful if the weight values are reclassified into a small number of discrete value ranges that provide some indication of the potential likelihood of encountering landslides within a particular area. For this study, BGC worked with SaskEnergy to classify the weights in a manner that would

be compatible with SaskEnergy’s existing ranking process for new pipeline construction. The weight thresholds were selected to represent specific ranges of spatial probabilities, and final selection was informed by past experience of SaskEnergy at various locations. The final landslide susceptibility map is therefore available in two forms: a continuous-value raster map representing the raw output of the analysis; and, a discrete-value raster map with a small number of bins to help guide new pipeline routing and construction decisions.

3 RESULTS

The optimized landslide susceptibility map was created using weight values from the following themes:

- Slope Angle
- Simplified Surficial Geology
- Local Relief within 256,036 m² (22 by 22 pixel square, with each pixel measuring 23 m by 23 m)
- Elevation
- Land Cover

The map that resulted from combination of the weights of individual theme weights is a continuous-valued raster with combined weights ranging in value from -8.48 to 7.99. The high and low values are associated with the highest and lowest landslide densities while values around zero represent a landslide density approximately equal to that of the overall study area. Figure 6 shows the susceptibility map’s predictive power within the analytical study area. The orange line shows a “perfect” susceptibility map, one which could isolate all existing landslides within the area they actually occupy (i.e., 1.4% of the analytical study area). The dashed black line shows a completely random model with no predictive capabilities. The blue line shows the performance of the optimized model generated as part of this scope. As can be seen in Figure 6, the optimized susceptibility model is expected to constrain 90% of mapped landslides within less than 4% of the study area.

In order to validate the model, 455 points were randomly chosen within the WCSB outside the analytical study area. The weight values were recorded at each point and a blind check of satellite imagery was completed at

those points to document the presence or absence of landslides or landslide terrain. The observed landslide occurrence outside the analytical study area was then compared to what would be expected based on observations inside the analytical study area, as determined from a random sample of 10,000 points. The results, shown in Table 3, show that the percentage of observed landslide area was similar for various weight values both inside and outside the analytical study area (i.e., see final two columns), and that the observed landslide frequency outside the analytical study area was similar to that expected from the model (i.e., see two middle columns).

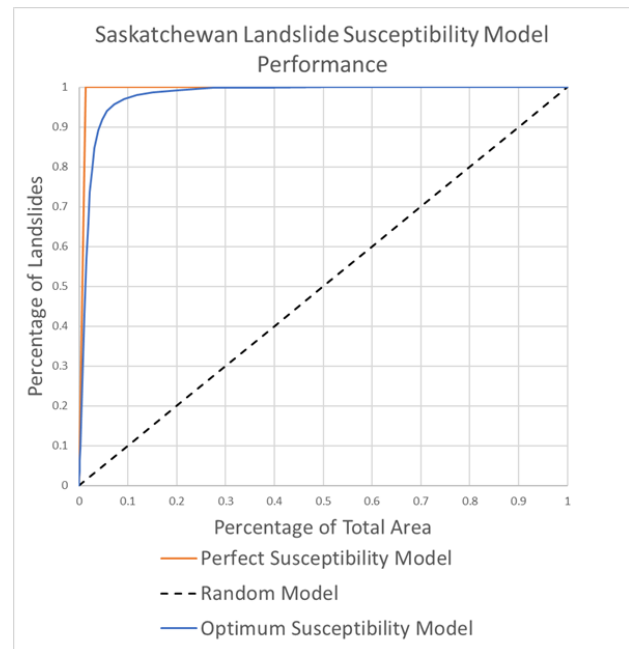


Figure 6. Predictive power of the optimized landslide susceptibility map (blue), plotted against a perfect susceptibility model (orange), and a completely random model (black dashed)

Table 3. Susceptibility map validation results

Map Weight Values	Proportion of Map Area	Validation Comparison - Landslide Presence		Validation Comparison - Percentage of Total Landslide Points	
		Outside the Analytical Study Area (455 points)	Inside the Analytical Study Area (10,000 Points)	Outside the Analytical Study Area (455 points)	Inside the Analytical Study Area (10,000 Points)
> 4.0	1.1%	35.7%	53.8%	60.9%	65.7%
> 1.5	2.1%	21.7%	23.9%	37.1%	29.2%
> - 0.5	4.1%	1.2%	3.3%	2.1%	4.0%
> - 2.5	12.7%	0.0%	0.7%	0.0%	0.8%
> - 3.5	17.0%	0.0%	0.2%	0.0%	0.3%
< - 3.5	63.0%	0.0%	0.0%	0.0%	0.0%

The continuous value raster has been subdivided into weight ranges that represent landslide density thresholds considered useful to the end user, SaskEnergy. The selected weight ranges and their associated landslide density are shown in Table 3. Within Table 3, Weight Limits represent the relative likelihood of an existing landslide of unknown activity being present at a given location. Negative weight values suggest that landslides are less common than the overall study area average; positive weight values suggest that they are more common than average.

Table 3. Susceptibility Classifications Selected for Binned Map

Susceptibility Class	Weight Limits	Expected landslide density (m ² per m ²)
High (H)	> 2.7	> 0.2
Moderate (M)	0.2 to 2.7	> 0.02
Low (L)	-2.5 to 0.2	> 0.001
Very Low (VL)	< -2.5	< 0.001

Due to the resolution of the various data sources, particularly the DEM, the classified weight value map had irregular patterns, particularly near weight threshold boundaries. To remove the irregularities, the "Boundary Clean" ArcGIS tool was utilized to generalize the susceptibility model, with the main result of smoothing transitions between different weight classes. The result of this smoothing process is the elimination of noise, with some potential for loss of information, or introduction of minor spatial error at the transitions between susceptibility classes.

The expected Landslide Density at a given point inferred from the landslide susceptibility model (Table 3) is the spatial density of landslides in the associated weight range and is equivalent to the spatial probability of the presence of an existing landslide. For example, in the High (H) susceptibility map class where landslide density is mapped as > 0.2, there is a greater than 20% chance ($P > 0.2$) that a given map pixel is within an existing landslide. The Very Low (VL) susceptibility map class represents a spatial probability of landslide presence that is about an order of magnitude lower than that of the overall background value across the study area (overall average landslide density in the analytical study area was approximately 0.014). While there surely exist areas of terrain with no possibility of landslide occurrence (i.e., flat ground with strong bedrock at surface), these cannot be identified with confidence at the present scale of mapping. Therefore, the lowest susceptibility class (VL) is judged to have very low, but not zero, likelihood of landslide presence. The final map is shown in Figure 7.

3.1 Limitations

The result of this work is a landslide *susceptibility* model, and this label implies the potential for *future* landslide occurrence. In fact, the landslide susceptibility values at raster pixel locations represent the spatial probability that an *existing* landslide of unknown activity is present at that

pixel, and not, strictly speaking, the probability of *future* landslide development. The map therefore more accurately represents *the spatial probability of the presence of existing landslides of unknown activity*.

The landslide susceptibility model does not provide guidance on landslide activity (i.e., whether a landslide, if present, is active, dormant or relict) as this information is not possible to glean from an interpretation of morphology alone. Determination of whether a landslide is actively moving would require a site-specific field assessment and/or monitoring by means of repeat survey, geotechnical instrumentation such as slope inclinometers, or remote sensing techniques. An assessment of landslide activity was not conducted as part of the mapping exercise and therefore does not carry forward into the susceptibility model.

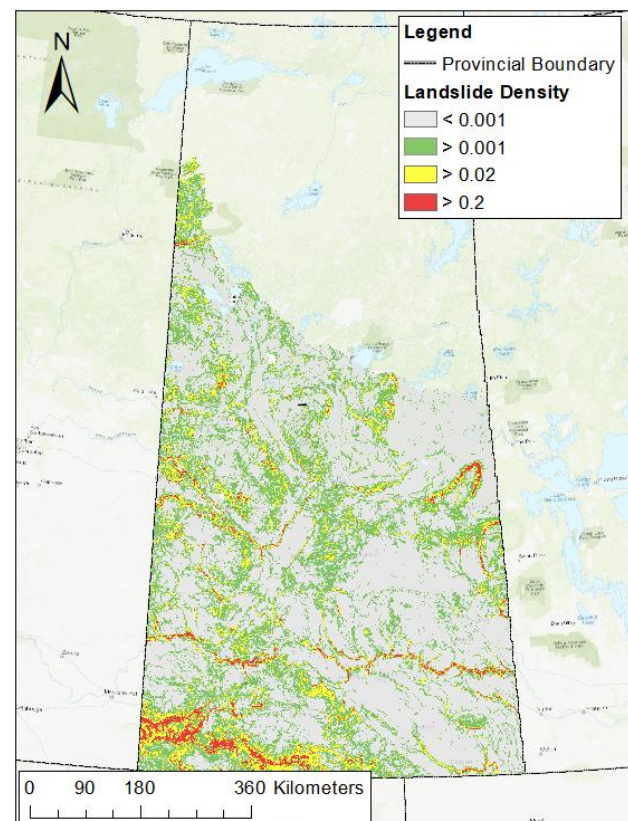


Figure 7. Final optimized map showing susceptibility classes.

4 CONCLUSION

The optimized combination of thematic data used to build the susceptibility map included slope angle, surficial geology, local relief, elevation, and land cover. This optimized model was validated by extending the model to the prediction area of the WCSB of Saskatchewan and selecting 455 random points to compare calculated weights with the presence or absence of a landslide. The model was found to have similar performance in the prediction area as in the analytical study area, suggesting

that it has validity across the WCSB in southern Saskatchewan.

The production of this landslide susceptibility map leveraged two key novel ingredients: (1) a broadly distributed and geographically unbiased test area, and (2) strong communication between the consultants preparing the map and the end user, SaskEnergy. The small but geographically distributed test area allowed the predictive susceptibility map to be produced for nearly the whole province, while specific mapping of distinct landslide features targeted the most vulnerable areas within the province (i.e., communities). This method provides more useful data to the end user than using an arbitrary test area and reduces the chance of missing critical geology packages or morphologies within the test area.

Strong communication between the consultants and SaskEnergy allowed for the creation of a map that was both statistically accurate and served the intended purpose. The classifications shown in Table 2 were determined based on multiple iterations of the susceptibility map, with several meetings between the consultants and SaskEnergy to determine optimal cutoffs between the various susceptibility classifications. The final classification scheme creates a reasonable visual for a layperson reader and is in strong alignment with SaskEnergy's existing practices.

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