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Modelling the spatial distribution of landslide susceptible terrain in the Alberta portions of the Interior Plains and Shield regions, Canada

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ABSTRACT

Landslides on the Alberta Plains are commonly associated with high-relief physiographic elements. Plains landslides are seldom as rapid or spectacular as those of mountainous regions; however, they can be no less disruptive to development as landslide-susceptible terrain may extend for significant distances following high-relief physiographic elements (e.g. river valleys). Therefore, to facilitate high-level planning initiatives or educational objectives, it is important to portray the spatial distribution of landslide-susceptible terrain across the Alberta Plains.

AGS Map 605 is the first provincial landslide susceptibility map of the Alberta Plains (1:1 000 000 scale) produced using a predictive modelling approach in a remote sensing application. The model predicts the degree to which terrain can be affected by landslides based on a statistical procedure that establishes a relationship between the spatial distribution of recognized landslides, and predisposing geological, topographical and climatic factors. Map 605 therefore, represents a predictive statistical model of the distribution of landslide susceptible terrain.

RÉSUMÉ

Les glissements de terrain dans les plaines de l'Alberta sont généralement associés à des éléments physiographiques à relief élevé. Dans les plaines, les glissements de terrain sont rarement aussi rapides ou spectaculaires que ceux des régions montagneuses; cependant, ils peuvent perturber le développement industriel ou urbain, car les terrains sensibles aux glissements de terrain peuvent s'étendre sur des distances significatives après des éléments physiographiques à haut relief (par exemple des vallées fluviales). Par conséquent, pour faciliter les initiatives de planification de haut niveau ou les objectifs pédagogiques, il est important de décrire la répartition spatiale du terrain sensible aux glissements de terrain dans les plaines de l'Alberta.

La carte AGS MAP 605 est la première carte provinciale de susceptibilité au glissement de terrain des plaines de l'Alberta (échelle de 1/1 000 000) produite à l'aide d'une approche de modélisation prédictive dans une application de télédétection. Le modèle prédit la mesure dans laquelle le terrain peut être affecté par des glissements de terrain en fonction d'une procédure statistique établissant une relation entre la distribution spatiale des glissements de terrain reconnus et les facteurs géologiques, topographiques et climatiques prédisposants. La carte AGS MAP 605 représente donc un modèle statistique prédictif de la distribution des terrains sensibles aux glissements de terrain.

1 INTRODUCTION AND BACKGROUND

AGS (Alberta Geological Survey) Map 605 (Pawley et al. 2016a) represents a predictive statistical model of landslide susceptibility of the Interior Plains and Canadian Shield regions of Alberta (Figure 1; 1:1,000,000 scale). The model predicts the degree to which terrain can be affected by landslides based on a statistical procedure that establishes a relationship between the spatial distribution of recognized landslides, and predisposing geological, topographical and climatic factors (Brabb 1984). The map portrays the spatial distribution of landslide susceptibility as a relative ranking from low to high. It does not depict the distribution of known landslides, nor evaluate the probability of landslide occurrence over any specific period of time (Parise 2001). Consequently the map should not be interpreted for the purpose of landslide identification, landslide activity assessment, or landslide hazard appraisal.

Prior to publication of AGS Map 605 (and the model grid; Pawley et al. 2016b) landslide mapping in the Interior Plains of Alberta included only local to regional landslide inventories (e.g. Davies et al. 2003; Morgan et al. 2013) and regional landslide incidence maps (e.g. Cruden et al. 1989). The entire province of Alberta is included in a national landslide susceptibility map (Bobrowsky et al. 2012); however, specific features within the province are difficult to resolve at the published scale of 1:6,000,000. AGS Map 605 represents the first medium-resolution landslide susceptibility model (LSM) of Alberta (excluding mountains and foothills regions) published at 1:1,000,000 scale.

Production of Map 605 was partly facilitated by recent availability of several provincial-scale datasets including provincial bedrock geology (Prior et al. 2013), provincial surficial geology (Fenton et al. 2013), provincial bedrock topography (MacCormack et al. 2015a) and sediment thickness (MacCormack et al. 2015b), acquisition of significant tracts of bare-earth LiDAR imagery by the Government of Alberta, and the release of 1-arc-second Shuttle Radar Topography Mission (SRTM) data covering Canada (U.S. Geological Survey 2014). As such, Alberta represents a relatively data-rich region, and accordingly, we incorporate a wide range of potential landslide predisposing factors into our analysis in order to test their predictive capability.

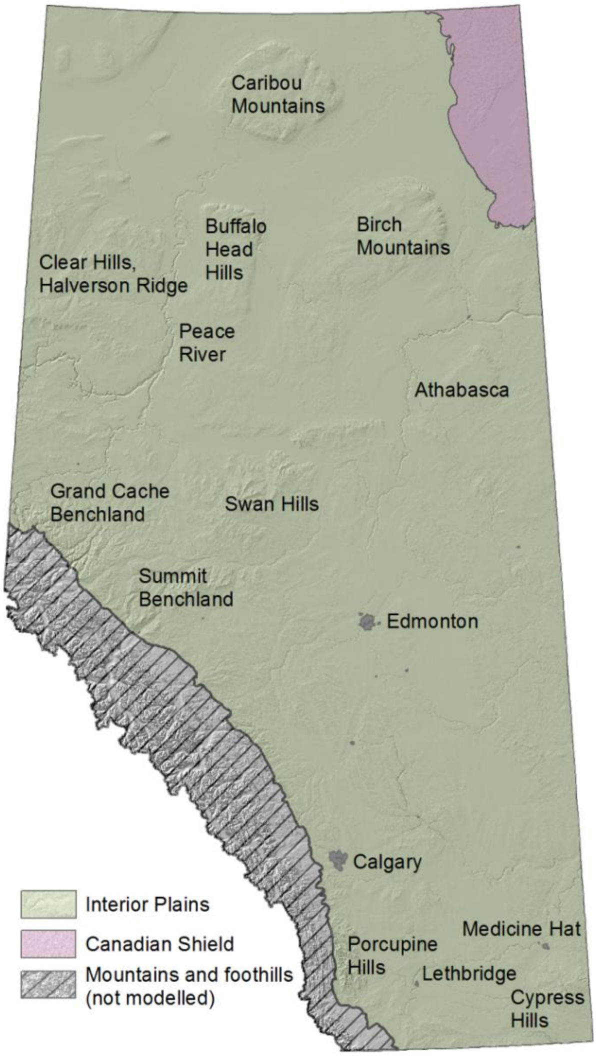

Figure 1. Major physiographic provinces of Alberta (from Bostock 2014).

1.1 Definition

The term “landslide” is defined here as the mass movement of rock, debris or earth down a slope (Cruden 1991), and is identified by the movement itself, as well as the resultant landform (Highland and Bobrowsky 2008). Sinkholes and collapse structures are excluded from this definition. Furthermore, we restrict our evaluation to natural slopes.

Cruden and Varnes (1996) classified landslides according to their constituent material and the type of movement. Movement type classification includes: falls, topples, slides, spreads, and flows. Of these, only slides and flows have been recognized in this model. Composite landslides, where movement evolves downslope from a slide to a flow are common on the Alberta Plains. The dominance of these mechanisms within this model reflects firstly, the characteristic physiography and geology of the Alberta Plains, and secondly, the grid cell size used in the analysis (90 m), which is coarser than the resolution needed to model smaller-scale mass movements such falls and topples.

The terms “landslide susceptibility” or “landslide-susceptible terrain” is defined as the spatial probability that the terrain represented by a given model grid cell is landslide terrain based on the evaluation of its similarity to known landslides across a series of predisposing factors (outlined in Section 2.0 below). The assessment is strictly time-independent (following Parise 2001), and thus does not portray landslide hazard in any way. Terrain exhibiting a high spatial probability of being landslide terrain may include old and presently stable landslides, active landslides, or future landslides. Furthermore, all input data and the model itself are subject to uncertainty (as discussed in Section 2.3.2 below).

1.2 Regional Setting

Landslide susceptibility modelling was performed across the Alberta portion of the Interior Plains and Canadian Shield (Figure 1). This region is comprised of plains, lowlands, isolated uplands (Pettapiece, 1986) and is underlain by flat to gently dipping sedimentary bedrock that is typically mantled by relatively thin sediment cover (~5 m; MacCormack et al. 2015b). Thicker sediment is found overlying buried valleys (30 m to 400 m), within major moraine systems (30 m to 90 m), and rarely where an upland is (at least partially) comprised of sediment (up to 350 m). The main geologic control on landslides within the Interior Plains is rock/sediment strength (Thompson and Morganstern 1974; Mollard 1977; Mansour 2009), and landslides in the region tend to develop via a limited suite of mechanisms (discussed above) irrespective of whether they are seated in bedrock or sediment (Mollard 1977). The relative homogeneity of landslide types facilitates the treatment of the entire model domain with a similar modeling approach. Landslides in the mountains and foothills of Alberta (Figure 1), which are heavily folded and faulted tend to develop via different mechanisms in response to structural control (Mollard 1977), and thus those regions are excluded from the model. While bedrock structure within the Canadian Shield is complex, the small portion of that region within Alberta (Figure 1) has been included mainly because it is a region of low overall relief, thin sediment cover and high rock strength in which landslides are uncommon.

2 METHODOLOGY

2.1 Landslide Inventory

The landslide susceptibility model uses a point-based sampling of landslide and non-landslide terrain. Information regarding landslide distribution was compiled from previously published surficial geology maps, reports, and university theses. These sources included polygon data that delineate the extent of mapped landslides, as well as point data that represent single locations within a landslide. The polygon data were converted to points by randomly sampling the landslide polygons with a density of one point per km2. These data were augmented by sampling new landslide features that were mapped from a number of aerial imagery data sources including LiDAR. The final inventory contains ~23,000 points (Figure 2).

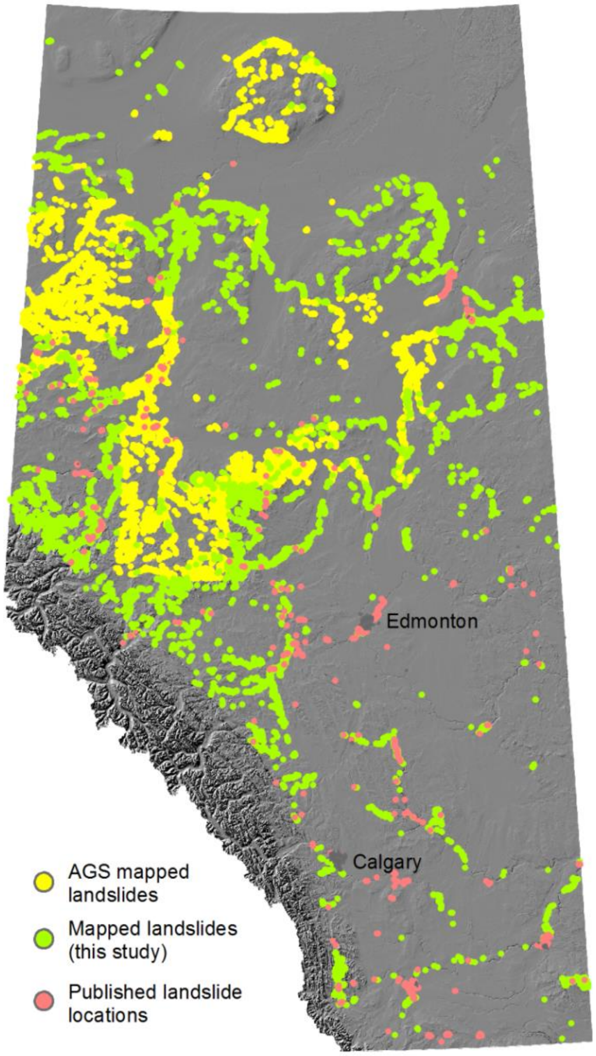

Figure 2. Landslide inventory.

3 LANDSLIDE PREDISPOSING FACTORS

Landslide susceptibility modelling was performed by assessing the spatial likelihood of landslide occurrence on a cell-by-cell basis relative to predisposing geological, topographic and climatic factors. A grid-cell resolution of 90 m was found to optimize model performance. In an exploratory analysis, a wide range of landslide predisposing factors were evaluated for their capacity to predictively model the distribution of landslides in the inventory data. The predisposing factors that exert the strongest influence on the landslide susceptibility are outlined here.

3.1.1 Local Terrain Morphology

The SRTM DEM (U.S. Geological Survey 2014) was used to characterize the geomorphological settings associated with landslide-prone terrain. For this purpose, standard morphometric variables consisting of slope angle (Figure 3), aspect, profile curvature, and tangential curvature were calculated from the SRTM DEM. The variability of the terrain, or topographic roughness, is also useful for characterizing landslide morphology, and was evaluated using the Vector Ruggedness Measure (VRM; Sappington et al. 2007) which assesses the variability of slope and aspect simultaneously (Figure 4).

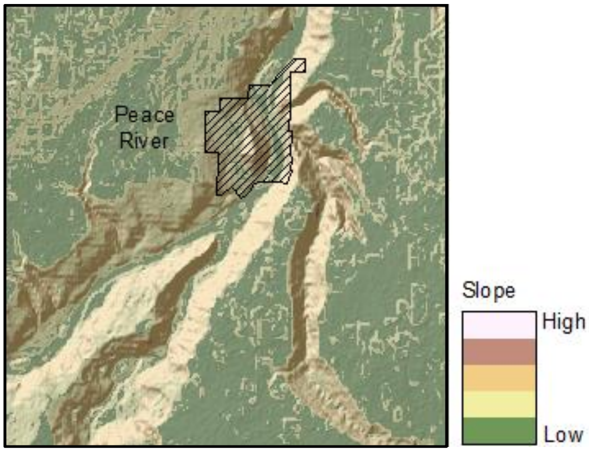

Figure 3. Slope angle.

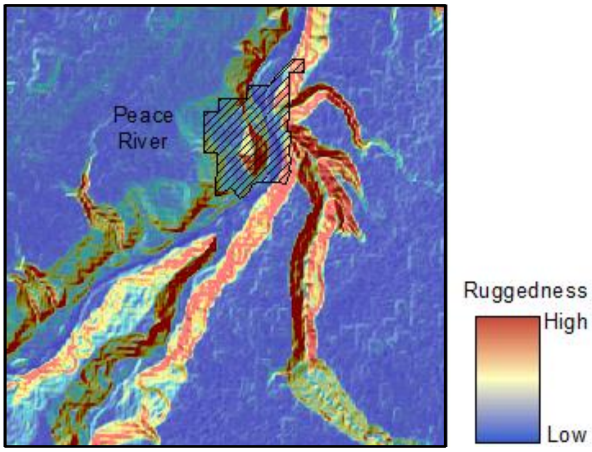

Figure 4. Vector ruggedness measure.

3.1.2 Regional Terrain Morphology

Regional morphometric variables quantify landscape-scale topographic relationships. Topographic openness (Yokoyama et al. 2002) was used to visualize regional topographic convexities and concavities (Figure 5). In the context of landslide susceptibility, topographic openness is related to the maturity of river valleys and gullies, which often represent the foci of landslide activity. The relative slope position of the landscape was also calculated based on the ratio of the SRTM DEM elevation to channel base levels and ridge heights, which results in an estimate of slope height and valley depth (Conrad et al. 2015). Slope height (Figure 6) is related to the driving forces of landslide activity due to the potential energy available for downslope movement. Conversely, valley depth (Figure 7) quantifies the degree of fluvial incision and is particularly relevant for predicting the landslide susceptibility of incised river valley walls.

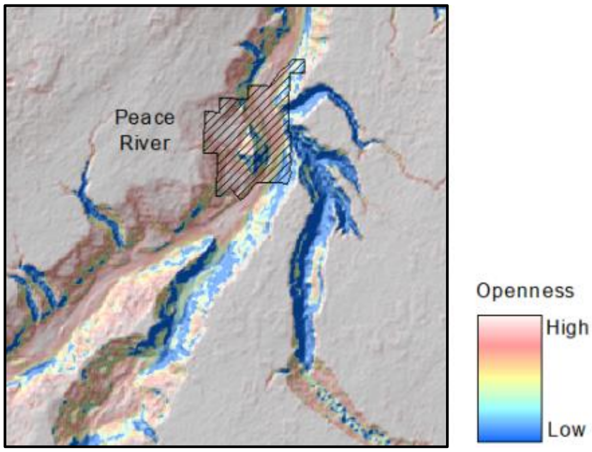

Figure 5. Topographic openness.

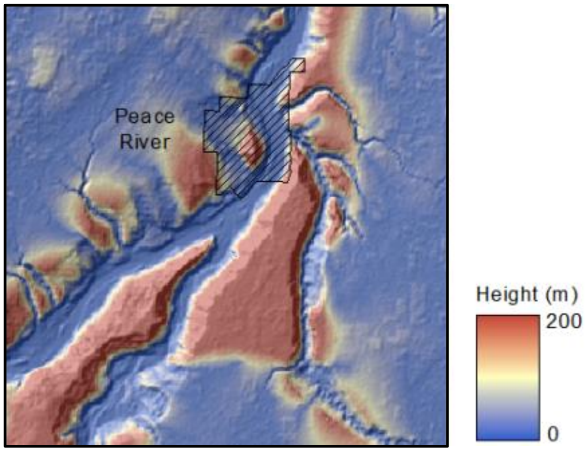

Figure 6. Slope height.

3.1.3 Topographic Wetness

The topographic wetness index (TWI; Figure 8) is a standard calculation for estimating the spatial distribution of soil moisture, based on the upslope contributing area of the DEM and the local slope angle (Boehner and Selige 2006). The TWI provides an estimation of relative moisture in the upper part of the soil profile, and is commonly used as a predisposing factor in landslide susceptibility assessments. Low-relief components of the landscape are typically dominated by high TWI values (wetter surface conditions), and higher-relief landscape components are characterized by lower TWI values (drier surface conditions).

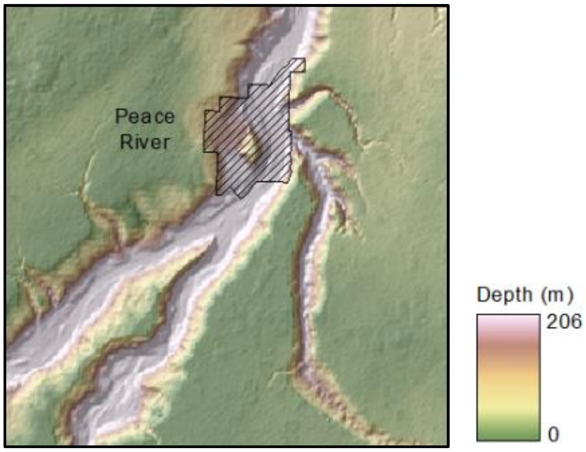

Figure 7. Valley depth.

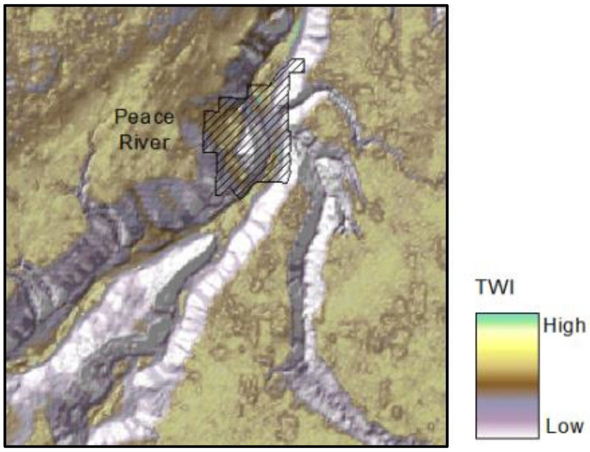

Figure 8. Topographic wetness index.

3.1.4 Physiography and Climate

Fluvial processes and climate represent important agents in landslide susceptibility. River erosion increases landslide susceptibility by undercutting (and thus steepening) valley slopes as a result of meander bend propagation or channel incision. Climate influences groundwater levels, which in turn influence slope stability. The effect of climate is exemplified by the behaviour of slopes comprised of Upper Cretaceous Horseshoe Canyon Formation (a succession of mudstone, sandstone, carbonaceous shales, and bentonite). In the Edmonton region these slopes are highly landslide-prone (Rutter et al. 1998). Conversely, in southwestern Alberta these slopes are relatively stable because the climate is more arid. Climate and precipitation were incorporated

Figure 9. Relative bedrock strength ranking

into the model by calculating the distance to major river features, and by using the average annual precipitation record over a 50-year period provided by Alberta Agriculture and Forestry.

3.1.5 Surficial Geology

Regional geological conditions are one of the most important factors in landslide susceptibility because geology governs the lithology and mechanical properties of rock and sediment. The Surficial Geology of Alberta (Fenton et al. 2013) was used to evaluate the role of surface and near-surface sediment types in the landslide susceptibility assessment. Thirteen genetically-defined classes that are present across the Alberta Plains were used to describe the general surface material characteristics. The thickness of these surface and near-surface sediments is also an important factor in landslide susceptibility, with zones of landslide-prone terrain occurring in regions characterized by thicker sediments (e.g. in areas underlain by infilled palaeovalleys; Miller 2000; Miller and Cruden 2002; Morgan et al. 2012). Data derived from a geostatistical estimation of sediment thickness (MacCormack et al. 2015b) was therefore used in the susceptibility model.

3.1.6 Bedrock Geology

The contribution of bedrock geology to landslide susceptibility was assessed by reclassifying the bedrock geological units of Alberta from Prior et al. (2013) into five classes of relative rock strength (Figure 9) based primarily on the long-established relationship between landslide-prone strata and the depositional environment of geological formations in Alberta (e.g. Thomsen and Morgenstern 1977). In general, high-energy depositional environments result in stronger coarse-grained formations while low-energy depositional environments result in weaker fine-grained formations. The relationship between depositional environment, lithology, and rock strength is complex for formations in which there is significant lithologic variability (e.g. alluvial systems comprised of intercalated sandstone and mudstone units). Therefore, strength classifications were made by considering the bulk characteristics of a formation as a whole. Bedrock strength classifications were reviewed by geologists with significant familiarity with each formation. Where necessary, classifications were adjusted to reflect formational properties beyond depositional environment and constituent lithology. In addition, the potential influence of bedrock structure on these rock properties was included in the analysis by calculating a raster of Euclidian distances to linear structural elements as mapped in the Bedrock Geology of Alberta (Prior et al. 2013).

3.2 Modelling Procedure

3.2.1 Stochastic Gradient Boosting Model for Predicting Relative Landslide Susceptibility

A predictive modelling method termed Stochastic Gradient Boosting (Friedman 2002) was used for the landslide susceptibility assessment. Stochastic Gradient Boosting uses a decision-tree structure to map how the occurrence of landslides relates to thresholds in the predisposing factors using a hierarchy of splits and branches. The terminus of the branches, termed leaves, represents the class labels (i.e. landslide or non-landslide). Data from the landslide inventory represent the landslide cells that were used to train the model. The non-landslide cells were obtained by simple random sampling of the background geological, physiographic, and climatic conditions. The landslide susceptibility estimation represents the probability of membership in either the landslide or non-landslide classes.. Unlike a single decision tree, the Stochastic Gradient Boosting algorithm improves prediction accuracy based on an additive process where additional decision trees are created to model observations that were not accurately predicted by the previous tree. At each iteration, the algorithm determines the gradient in which it needs to improve the modelled fit

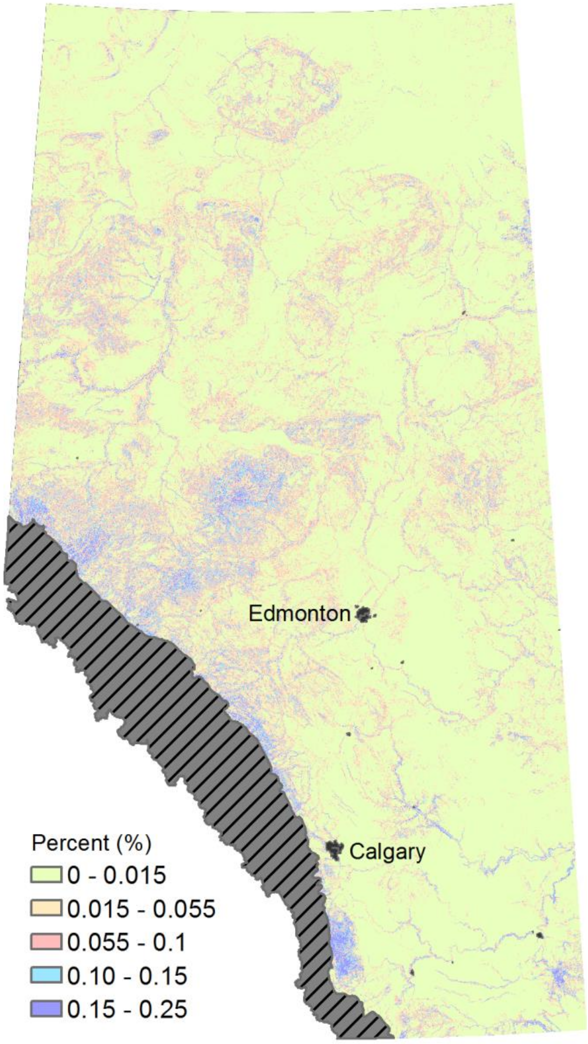

Figure 10. Model uncertainty

to the data, and selects a particular model that is in most agreement with the direction (i.e. the algorithm iteratively fits the model to the residuals). The final model represents a linear sum of the individual decision-tree learners.

3.2.2 Model Uncertainty and Variability

Model accuracy was assessed using a bootstrapping procedure with an ensemble of 20 model replications. These models were constructed by random sampling of the landslide and non-landslide grid cells. For each model replication, 75% of the mapped landslide cells were randomly drawn from the total population and were used to train the model, and the remaining 25% of landslide cells were used to validate the accuracy of the prediction. The final susceptibility map represents the mean of the 20 replicate models. The mean prediction uncertainty is provided in Table 1. The bootstrapping procedure also allows the sampling uncertainty to be visualized geographically, and the standard deviation of the model replicates was chosen as the uncertainty interval (Figure 10). Regions with the lowest uncertainty (less than 5%) occur in the plains and lowlands of the province, or in deeply incised valleys, where the distribution of landslides are well explained by topographic and geological factors. Regions with the highest uncertainty (up to ~25%) occur in some regional uplands including the Porcupine Hills (Figure 1). The higher uncertainty in these regions is due to the distribution of landslides being controlled by predisposing factors that are not evaluated in the model, such as localized geological, geotechnical, or hydrogeological conditions. These conditions may include structurally weak geological strata, or in the case of the Porcupine Hills, more steeply dipping bedding planes that occur near the western margin of the upland (Jackson 2002).

Table 1. Mean predication uncertainty

	AUC[1]	TPR[2]	TNR[3]	Accuracy[4]	Kappa[5]
Mean	96.6%	93.1%	90.1%	91.6%	83.3&
Std. Dev.	0.4%	0.6%	1.0%	0.7%	1.4%

[1] AUC: (area under curve): the area under the receiver operating characteristic curve is based on the ratio of true positives to false positives.

[2] TPR: (true positive rate): the proportion of known landslide cells in the model that are correctly classified as having a high susceptibility.

[3] TNR: (true negative rate): the proportion of non-landslide cells in the model that are correctly classified as having a low susceptibility.

[4] Accuracy: the overall proportion of correctly classified cells.

[5] Kappa: the proportion of correctly classified cells after removing what would be obtained by chance selection.

4 RELATIVE LANDSLIDE SUSCEPTIBILITY OF THE ALBERTA PLAINS

The Stochastic Gradient Boosting model indicates landslide susceptibility across the Alberta Plains is typically associated with areas of higher relief such as valley walls and the flanks of plateaus and uplands (Figure 11). Lower relief areas such as plains and lowlands, broad river terraces and floodplains are less susceptible. Although quite rugged, the Canadian Shield region of northeastern Alberta is not landslide susceptible due to the competent bedrock and thin sediment cover across this region.

The walls of major river valleys and their tributaries comprise the longest contiguous zones of landslide-susceptible terrain across Alberta. These zones are relatively narrow (typically <1 km wide) but can extend along one or both valley walls for 10's of kilometres. Wider zones of landslide susceptible terrain (up to 2 km) occur within the western part of the Peace River valley which, at up to 250 m deep, represents Alberta's most deeply incised valley (Figure 12). Widespread, contiguous zones of landslide-susceptible terrain occur along steep slopes flanking relatively un-dissected plateaus including: the Caribou Mountains, Birch Mountains, Buffalo Head Hills, and the western Clear Hills (Pettapiece 1986; Figure 13).

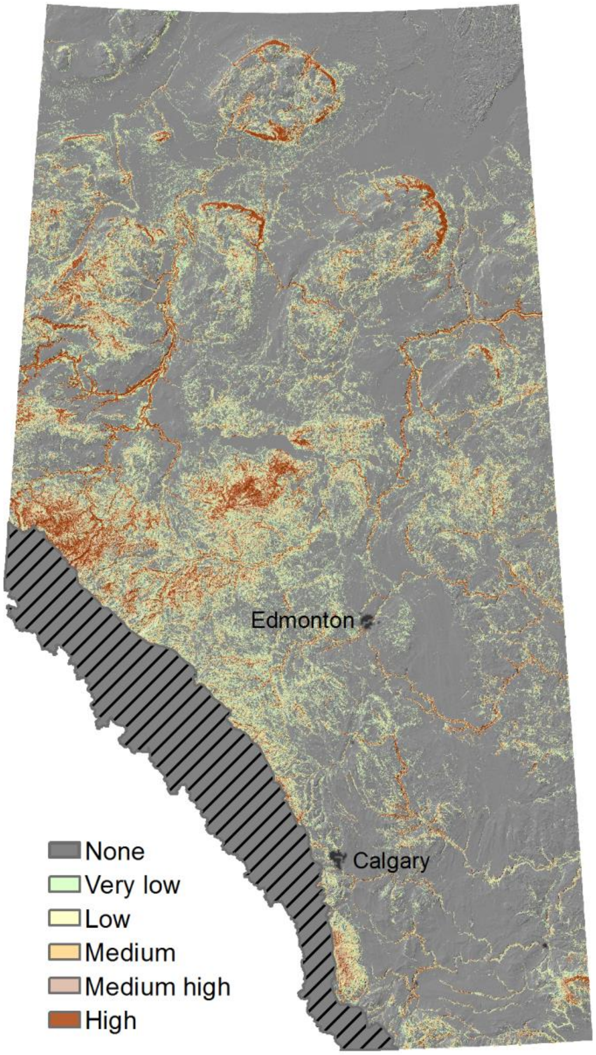

Figure 11. Relative landslide susceptibility.

These zones may be 10's of kilometres long, up to 6 km wide, and up to 500 m in height. Less contiguous zones of landslide-susceptible terrain occur across heavily dissected plateaus or rugged uplands including: the Swan Hills, Grand Cache Benchland, Summit Benchland, Cypress Hills, the eastern Clear Hills and Porcupine Hills (Pettapiece 1986; Figure 14). Collectively however, landslide-susceptible terrain in these dissected regions is extensive.

2 CONCLUSIONS

- AGS Map 605 represents the first medium-resolution LSM covering the Alberta portion of the Interior Plains and Canadian Shield produced at 1:1,000,000 scale.

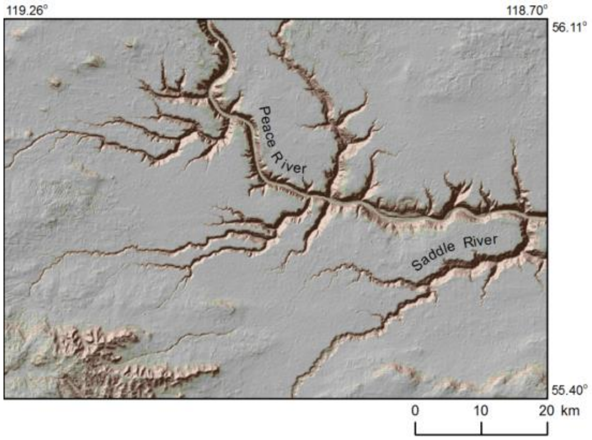

Figure 12. Contiguous zones of landslide-susceptible terrain along the Peace and Saddle rivers.

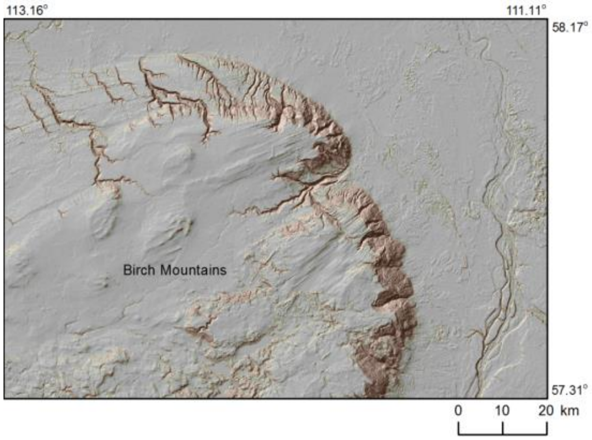

Figure 13. A broad zone of landslide-susceptible terrain on the east flank of the Birch Mountains.

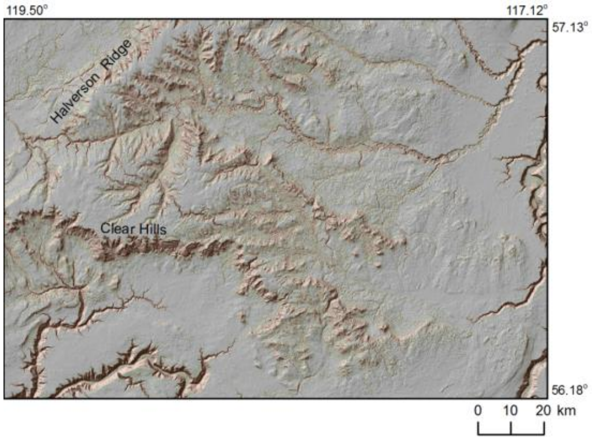

Figure 14. Discontinuous zones of landslide-susceptible terrain distributed across the eastern portions of the Clear Hills and Halverson Ridge.

- The model was produced using a multivariate statistical procedure (Stochastic Gradient Boosting; Friedman 2002) which establishes a relationship between the spatial distribution of recognized landslides, and predisposing geological, topographical and climatic factors on a cell-by-cell basis.
- Model uncertainty is low in plains and lowland regions, and in deeply incised river valleys (typically less than 5%). However, uncertainty is higher (up to 25%) in some upland regions.
- The model results are unsurprising as they reveal that areas with a high spatial probability of being landslide terrain are generally restricted to high-relief physiographic elements including deeply incised valley walls, the steeper flanks of contiguous uplands, and the steeper areas within dissected uplands.
- Being time-independent and of medium-resolution, the model (or map product) cannot be used for landslide identification, landslide activity assessment, or landslide hazard appraisal. Its intention is to facilitate high-level planning and education.

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