

REGIONAL LANDSLIDE SUSCEPTIBILITY MAPPING AND INVENTORYING IN THE MACKENZIE VALLEY, NORTHWEST TERRITORIES

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RÉSUMÉ

La Commission géologique du Canada a entrepris un projet de cartographie régionale des glissements de terrain le long d'un trajet d'un gazoduc dans la vallée du Mackenzie aux Territoires du Nord-Ouest. Plus de 1800 glissements de terrain et d'aléas naturels ont été cartographiés et intégrés dans une base de données développée sur une plateforme SIG. Les résultats de la cartographie indiquent une densité moyenne d'un glissement de terrain tous les 5 km². Les glissements de terrain les plus fréquents sont les coulées rétrogressives dues au dégel (28%) et les détachements dans le mollisol (26%). Environ 47% de tous les glissements de terrain sont survenus dans des dépôts morainiques. La méthode paramétrique qualitative utilisée pour développer la carte de susceptibilité aux glissements de terrain dans la zone pilote du Lac Travailant et la rivière Thunder (TTPS) a conduit à des résultats préliminaires très prometteurs.

ABSTRACT

A regional landslide hazards mapping initiative was initiated by the Geological Survey of Canada to provide information on the types and regional distribution of landslides along a proposed natural gas pipeline corridor in the Mackenzie Valley, Northwest Territories. Over 1800 landslides and other natural terrain hazards were mapped in the study area and integrated into a GIS platform towards the development of a database. Analyses of landslide mapping in the Mackenzie Valley Study Area (MVSA) indicate an average density of one landslide per 5 km² and show that the dominant landslide types are retrogressive thaw flows (28%) and active layer detachments (26%). About 47% of all landslides took place in moraine deposits. The qualitative parametric method used to develop a landslide susceptibility map has produced good preliminary validation with respects to landslide occurrences in the Travailant-Thunder Pilot Site (TTPS).

1. INTRODUCTION

As part of an initiative of a consortium of the Federal Government agencies for filling relevant knowledge gaps for hydrocarbon exploration and development in the Mackenzie Valley (Gartner Lee Limited 2003; C-CIARN North 2004), the Geological Survey of Canada, through the Natural Resources Canada's Northern Energy Program, has initiated a detailed inventory of landslides in the Mackenzie Valley between Inuvik and Tulita (Figure 1). This regional landslide hazards mapping initiative aims at i) providing baseline information on the types, regional distribution, and control of landslides through the compilation of existing and new information and ii) assessing the potential influence of environmental factors on frequency and magnitude of landslides.

This program builds on four decades of terrain studies by Geological Survey of Canada in the Arctic and sub-Arctic regions which have focused on issues such as riverbank stability, terrain disturbance susceptibility and terrain sensitivity (Code 1973a, 1973b; Kurfurst 1973a, 1973b, 1973c; Lawrence & Proudfoot 1976), slope stability problems (Dyke 2000), influence of forest fires and methods of assessing slope stability (Dyke 2004), landslide inventorying (Aylsworth *et al.* 2000); and geotechnical databases (Smith *et al.* 2005).

This paper will present Natural Resources Canada's Mackenzie Valley Project component focusing on regional landslide mapping along a proposed gas pipeline route, between Inuvik (68.35°N, 133.72°W) and Tulita (64.90°N, 125.57°W). Here we present the preliminary results from a regional landslide inventory providing baseline information on types, regional distribution, and control of landsliding will be presented, as well as the results from the landslide susceptibility mapping methodology based on spatial data analysis models.

2. METHODOLOGY

2.1 Study area and the Travailant-Thunder pilot site

The Mackenzie Valley Study Area (MVSA) encompasses a corridor extending 20 km to either side of the Inuvik-Tulita section of the proposed gas pipeline route, for a length of 540 km and an area of about 24,000 km² (dashed line in Figure 1). The MVSA includes the Rampart and the Thunder River regions, both known for widespread landsliding. The study area is characterized by cold winters with low precipitation and mild summers with moderate precipitation (Environment Canada, 2004). The vegetation cover is dominated by coniferous forest (medium to low density) along the southern and central portions of the corridor and wetland/shrub and subarctic boreal forest near Inuvik (Cihlar

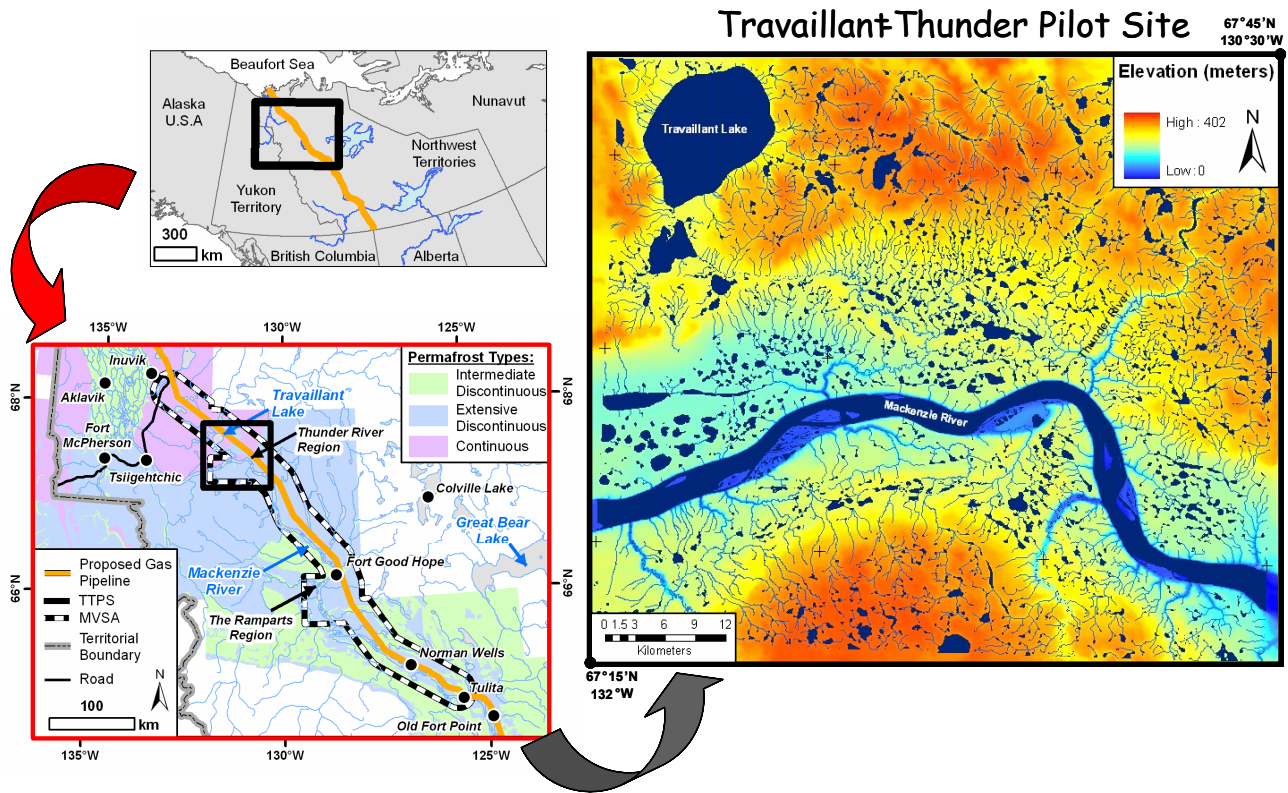


Figure 1. Location map illustrating the study area (dashed line) and the location of the Travaillant-Thunder Pilot Site is indicated (black box).

& Beaubien 1998; Ritchie 1984). The study area is covered by unconsolidated sediments (99%), which are dominated by morainal deposits (60%), and encompasses three zones of permafrost: continuous, extensive discontinuous, and intermediate discontinuous. The permafrost thickness ranges from 0 - 60 m in Norman Wells to 100 - 200 m in Inuvik and the active layer thickness, although highly variable typically ranges from >1.5 m in Norman Wells to 50 cm in Inuvik (Wolfe, 1998).

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From the MVSA, the smaller region of Travaillant-Thunder Pilot Site (TTPS) (black frame in Figure 1) was selected to

test the landslide susceptibility mapping methodology. The TTPS is located 140 km southeast of Inuvik and covers an area of 3,571.5 km². The TTPS was selected as it offers a wide variety of terrain types with respect permafrost conditions, surficial geology, relief and slope, vegetation, and the region is known for widespread landsliding (Figure 2). The TTPS is covered by unconsolidated sediments, which are dominated by morainal and lacustrine deposits (Aylsworth *et al.* 2000). Three types of permafrost were mapped: continuous (90 – 100%), extensive discontinuous (65 – 90%), and intermediate discontinuous (35 – 65%) (Heginbottom and Radburn 1992, Fig.1), which are subdivided into sub-units based on the ground ice content. The vegetation cover is dominated by sparse to open coniferous forest, shrub land (low and tall), and exposed land (Wulder and Cranny 2005). The relief is relatively low with a maximum elevation difference of 402 meters. Numerous lakes, rivers, and streams are present which cover more than 16% of the total area (1:50,000 scale National Topographic System map sheets). Finally, the TTPS is characterized by cold winters (-27.6°C, daily average) with low precipitation (13.8 mm, total precipitation) and relatively warm summers (14.2°C, daily average) with moderate precipitation (33.2 mm, total precipitation) (Inuvik Weather Station, January and July months, Environment Canada 2004).



Figure 2. Photographs of typical landslides mapped in the Travallant Lake-Thunder River region: a) Retrogressive thaw slide-flow which was reactivated in summer 2006; b) large, multiple retrogressive thaw slide-flows along the Mackenzie River bank, near Thunder River; c) Retrogressive thaw slides (L1, L2, and L4) and retrogressive thaw slide-flow (L3); d) Typical circular shape retrogressive thaw flow near Travallant Lake.

2.2 Landslide mapping

The landslide mapping activity included the examination of over 1000 coloured and black & white aerial photographs at a various scales. But most of the airphotos were at the scale of 1:30,000 and acquired in 2004. These aerial photographs covered the proposed natural gas pipeline, i.e. a corridor about 15 km wide along the proposed pipeline route between Inuvik and Tulita, the Ramparts and Thunder River Region, and the main tributaries of the Mackenzie River. The desktop landslide mapping by airphoto-interpretation is accompanied by the development of the Mackenzie Valley Landslide Spatial Database. For each landslide entry in the database, i.e. for each landslide or cluster of landslides mapped on the aerial photographs, the following parameters are recorded: landslide type and size, location, morphological parameters, surface tone and texture, vegetation re-growth in landslide scar, relative age, activity, material type, flight line, air photo number, and topographic

map sheet. Also, collection of several hundreds photographs of landslides, taken while carrying out field campaigns in 2005 and 2006 completes the database (Couture & Riopel, 2007).

2.3 Landslide susceptibility mapping

Qualitative and quantitative methods are used to map susceptibility (Van Westen *et al.*, 1999; Lyle, 2006). Qualitative methods are based on expert judgment (e.g. opinions from scientists familiar with the study region) to produce the map and perform the analysis of the different parameters. The qualitative parametric method was selected because of its: i) flexibility to incorporate data sets from different sources, ii) possibility to evaluate the different data sets as individual parameters, iii) suppleness to combine spatially the data sets, and iv) several GSC scientists are familiar with the study region. However, the limitations in the parametric methods are: i) the reproducibility of results and,

ii) the subjectivity in assigning classes, ranks, and weights to the parameters.

This parametric method developed and used for the TTPS, which is described in detail in Riopel *et al.* (2006), and described by the five steps displayed in the flowchart of Figure 3. In STEP 1, four data sets considered to be the most important physical parameters that contribute to mass movements in the Mackenzie Valley. These datasets are digital elevation models (Duchesne *et al.*, 2006), surficial geology (Aylsworth *et al.*, 2000b), permafrost (Heginbottom and Radburn, 1992), and landcover (Wulder and Cranny, 2005).

In STEP 2, data sets from different sources were compiled and superimposed on the same projection (Universal Transverse Mercator, NAD 1983). The data sets were converted into a common format to enable mathematical integration at the pixel level. The basis format was raster with 25m by 25m pixels. For example, the digital elevation model was resampled from 30m by 30m pixels to 25m by 25m pixels and used to create two new raster layers (25m by 25m pixels): i) slope angle and ii) slope aspect. Also, surficial geology, permafrost type, and permafrost ice content polygons were converted from a vector to a raster format (25m by 25m pixels).

iv) surficial geology, v) permafrost type, and vi) permafrost – ice content. The relative susceptibility to landsliding of each unit within those six layers were reclassified into three (low, moderate, or high) or five (very low, low, moderate, high, or very high) landslide susceptibility classes were selected. The reclassification is based on the judgment of GSC scientists familiar with the terrain and derived from the available knowledge on the influence of the physical parameters on landslide occurrence.

In STEP 4, ranks were assigned to the reclassified units for mathematical computations at the pixel level. The reclassified units of each layer were ranked to a common scale between 1 and 10. A standard class – rank association was applied for the six layers allowing a linear and homogeneous rank value distribution. The 5-class ranking system was given the values 1, 3, 5, 7, and 10 respectively for the classes very low (VL), low (L), moderate (M), high (H), and very high (VH), whereas, the 3-class ranking system was given the values 1, 5, and 10, for L, M, H respectively.

In STEP 5, subjective weights expressed as percentages were assigned to the six layers based on their relative importance -defined by qualitative judgment from experts- in influencing terrain susceptibility to landsliding (Table 3).

A parametric equation (Eq. 1) was built where the six layers were defined as variables and the weights as factors:

$$SI = 0.3S1 + 0.05S2 + 0.30G + 0.05P1 + 0.20P2 + 0.10L \quad [1]$$

The pixels of the factorised variables were spatially added (vertical integration) to obtain susceptibility indices (SI). The resulting susceptibility indices, values ranging from 1 to 10, were classified in three landslide susceptibility zones (low, moderate, and high), by grouping SI values 1 to 3 as low, 4 and 5 as moderate, and SI values from 6 to 10 as high to create the landslide susceptibility map.

3. RESULTS AND DISCUSSION

3.1 Landslide mapping

More than 1800 landslides and other natural terrain hazard features (e.g. karstic sink holes, rock glaciers) have been mapped in the MVSA. Preliminary results indicate an average density of one landslide per 5 km² and show that the dominant landslide types are retrogressive thaw flows (29%) and active layer detachments (26%) where rock falls (10%), debris flows (10%), earth slides (9%), and retrogressive thaw slides (5%) are second order of importance (Figure 4). About 47% of all landslides took place in moraine deposits. The relative age of landslides was estimated based on tone, texture, and vegetation re-growth parameters, where 38% were classified ancient (>50 years old), 40% intermediate in age (10-50 years old), and 22% recent (<10 years old). The reference year is 2004.

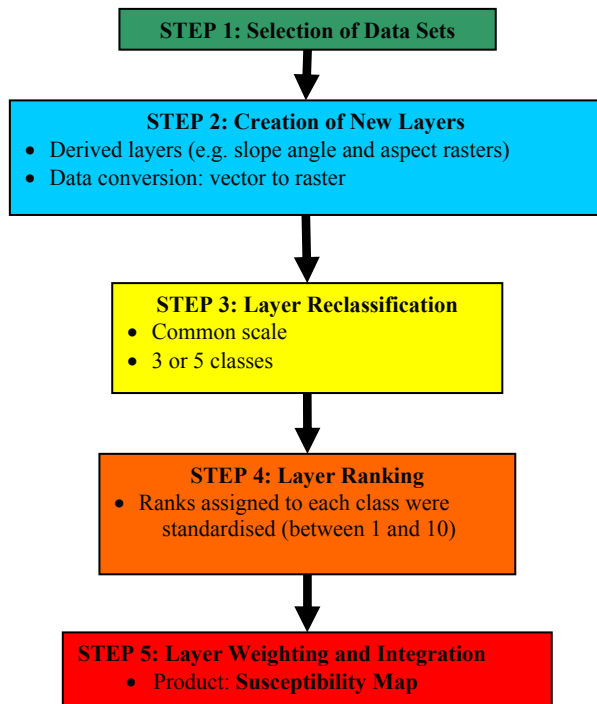


Figure 3. The landslide susceptibility parametric method steps used to produce a landslide susceptibility map.

In STEP 3, six raster layers were selected as inputs in the parametric model, one from the original data sets: i) land cover (vegetation); and five obtained from raster creation and conversion in STEP 2: ii) slope angle, iii) slope aspect,

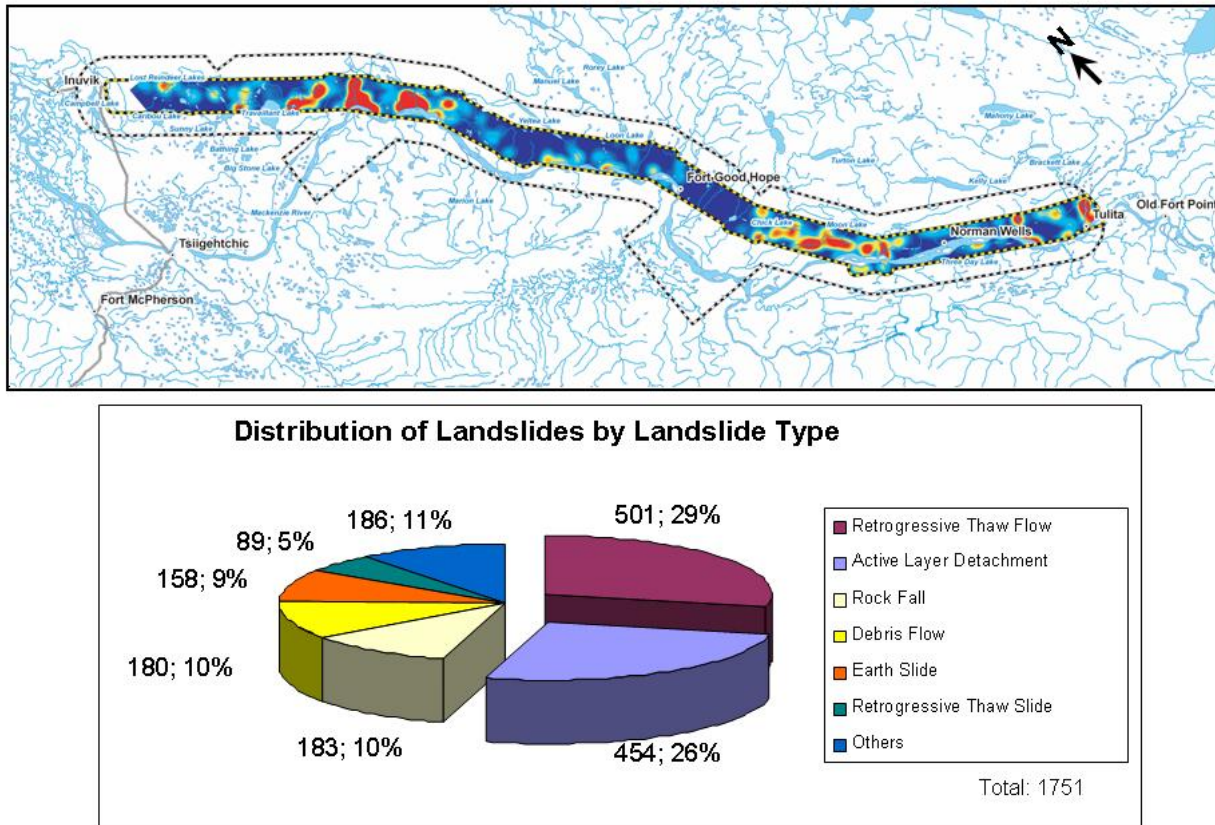


Figure 4. Upper: Landslide density map along the proposed pipeline corridor with some “hot spots” of higher density of landslides. These are situated near Travaillant Lake, Thunder River, Between Fort Good Hope and Norman Wells, and in the vicinity of Tulita (Couture *et al.*, 2007); Lower: Distribution of landslide types in the study area.

The rockslides are by far the largest landslides with an average size (18 ha) almost 10 times larger than all the landslide types, however the number of rockslides is very small (8) compared to the other types of landslides. Although rather small in size, the retrogressive thaw flows cover the largest total area because of greater occurrence, for a total of about 300 ha. It was also observed that the more than 65% of all the landslides occurred in the extensive discontinuous permafrost zone. Within the 3 different permafrost zones, i.e. intermediate discontinuous, extensive discontinuous and continuous permafrost, a vast majority of the landslides have taken place into zones with low to moderate ice content.

Figure 5 shows that 48% of mapped landslides in the study area have occurred on south and southwest facing slopes that have greater exposure to the sun. It was also observed that 57% of the landslides have taken place on gentle slopes, i.e. slope angles lower than 10°.

In the TTPS, 499 landslides were mapped. They cover a total area of 5.5km², or 0.15% of the entire area of the TTPS. Most of the landslides are retrogressive thaw flows (47%) and active layer detachment (28%). Debris flows, earth slides, and retrogressive thaw slides are also encountered (21%). In terms of relative age, about 30% are considered ancient, 60% are intermediate and about 10% are recent. A vast majority of the landslides (62%) occurred in morainal material, whereas about 25% occurred in glaciofluvial deposits, 6% in lacustrine deposits, and 5% in colluvium.

3.2 Landslide susceptibility mapping

Figure 6 shows the TTPS landslide susceptibility map. Susceptibility zones in red, yellow, and green represent areas having respectively high, moderate, and low landslide susceptibility indices. The total areas covered by low, moderate, and high indices are 20%, 56%, and 8%, respectively. Terrain most susceptible to landsliding was located along river banks and lake shores where steeper slopes are present and in areas composed of geological

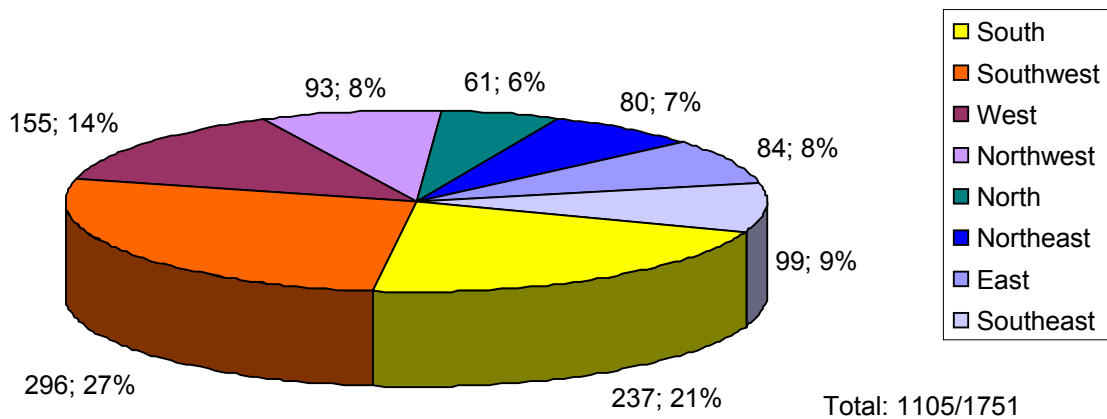


Figure 5. Distribution of landslides by slope orientation. About 50% of landslides occurred on south and southwest facing slopes.

units with fine grained deposits that are more prone to landslides, such as lacustrine plain and morainal deposits. The 499 mapped landslides in the TTPS have been superimposed on the landslide susceptibility map in order to validate the results. Using zonal statistics where the mode of the pixels falling inside each landslide polygon was considered, only 18 (3.6%) landslides fall in the low SI areas, whereas 208 (41.7%) and 273 (54.7%) landslides were found in moderate and high SI areas respectively. It is interesting, and validating for the method, to note that more than 50% of the landslides fall in high susceptibility areas (red zone, $6 < SI < 10$), whereas these areas only covers a very small part of the TTPS, i.e. less than 8%. From all the 273 landslides mapped in the high susceptibility zones (red), about 46% of them are retrogressive thaw flows and 40% are active layer detachments.

A good correlation can be observed between landslide occurrence and landslide susceptibility zones. The preliminary results of the validation indicate that the susceptibility mapping methodology used is proven very effective in identifying zones of low and high zones of landslide susceptibility. However, more refinements are needed in the methodology to sort out the 208 landslides (41.7%) that are falling in the moderate zones (yellow). To our point of view, this percentage appears too high and a larger percentage of landslides should fall in the high susceptibility zone.

The landslide susceptibility methodology used in the TTPS can also be used as land planning tool and for hazards and risk assessment. A rapid examination of the proposed natural gas pipeline route in the TTPS indicates about 6.2km (or 9%), out of the 65.8 km total pipeline length in the TTPS, fall into the high landslide susceptibility zone; whereas 74% and 17% of the pipeline length fall respectively into moderate and low landslide susceptibility zones. The percentage of pipeline route falling into high landslide susceptibility zone could be higher since it is judged that the apparent percentage of landslides in moderate zones is relatively too high versus high susceptibility zones.

3. 3 Next steps

Since these preliminary results are very promising, it is envisioned, firstly, to apply the same qualitative parametric method to the entire Mackenzie Valley Study Area (MVSA). Although, the landslide sample in the TTPS is representative - since it represents about 30% of the total landslides mapped so far and well-distributed within the TTPS - it appears important to validate the methodology with a much larger landslide dataset (about 1800 landslides) as different geological, permafrost, vegetation, amongst others, are encountered elsewhere in the MVSA.

Also, the method can be refined in terms of classes, ranks, and weights, for example by using a non-linear series of ranking values or by adapting the number of classes for each input parameter. Although this may improve the method, it also makes it more complicated. The effort made to improve the precision of the susceptibility map would have to be weighted against the quality of the available datasets.

Finally, additional parameters can also be inserted into the susceptibility index equation. The influence of forest fires appear to be significant in landslide triggering. It has been observed that more active layer detachments occur in areas impacted by forest fires (Dyke 2004). Simultaneously, a more complete landslide inventory is going to be produced by 2007, which may also help in validating the method over the entire MVSA.

4. CONCLUSION

The results from the landslide mapping in the Mackenzie Valley Study Area (MVSA) indicate that an average density of one landslide per 5 km² and show that the dominant landslide types are retrogressive thaw flows (28%) and active layer detachments (26%). About 47% of all landslides took place in moraine deposits.

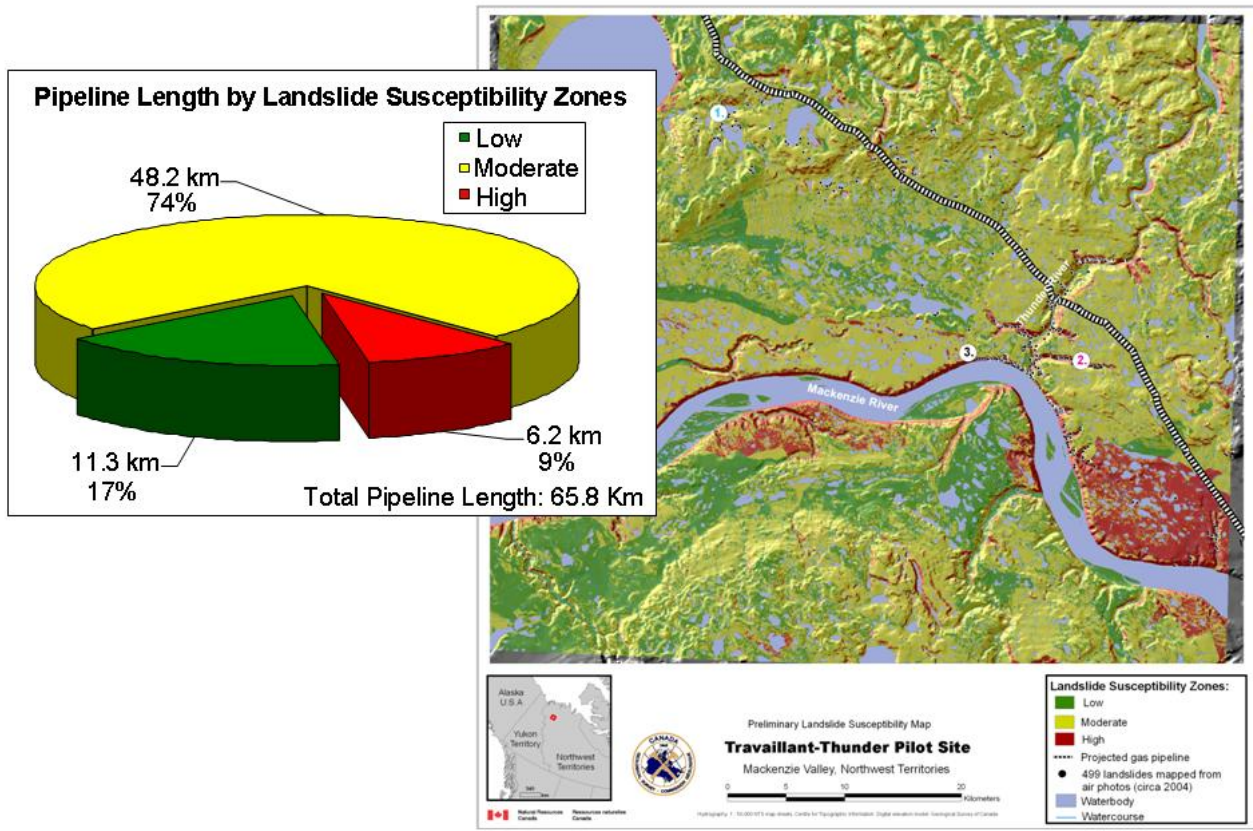


Figure 6. Right: Travaillant-Thunder Pilot Site (TTPS) landslide susceptibility map. Left: Percentage of the proposed pipeline route crossing the TTPS and falling into the 3 modelled landslide susceptibility zones.

The qualitative parametric method used to develop a landslide susceptibility map was proven effective as very good preliminary results were obtained. Comparison between landslide susceptibility zones and mapped landslide occurrences confirms that the applied qualitative parametric method appears a very promising tool for land management and landslide hazards mapping. However, this study has raised some limitations of the method that are associated with the resolution of the GIS datasets.

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