Construction Potential Maps in Support to Climate Change Adaptation and Management Strategies for communities built on permafrost : Case Studies from Northern Quebec

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ABSTRACT

As ongoing climate warming is expected to continue in northern Quebec, the thermal regime and the dynamics of permafrost will be altered. Adequate land use planning must take into account the potential loss of bearing capacity and soil instability due to permafrost degradation.To guide residential and industrial development, an integrated and GIS based geoscience approach was developed to assess permafrost geotechnical properties and map permafrost conditions. Using a multicriteria analysis, terrain sensitive to thaw-settlement, mass movements or other risks related to hazards were then identified. The results are presented as construction potential maps where, for any given terrain category, the suitable foundation types according to the existing engineering solution guidelines are proposed. The high varability of the permafrost conditions across the territory and at the community scale raises specific challenges for land use planning. Using as examples the community of Akulivik and Kangiqsualujjuaq, this paper illustrates the potential of those maps as a tool to support community adaptation and management strategies under a changing climate.

RÉSUMÉ

Avec le changement climatique au Québec nordique, le régime thermique et la dynamique du pergélisol se trouvent modifiés. L'aménagement du territoire doit tenir compte de la perte de capacité portante et des risques d'instabilité des sols qu'entrainent le réchauffement et le dégel éventuel du pergélisol. Pour guider le développement résidentiel et industriel dans ces contextes particuliers, une approche géoscientifique intégrée de cartographie a été développée pour définir les propriétés géotechniques du pergélisol et identifier les terrains sensibles au tassement et aux mouvements de masse. Les résultats de cette analyse multicritère, sous la forme de cartes de potentiel de construction, présentent les types de fondations nordiques appropriées selon les conditions locales du pergélisol. La variabilité spatiale des conditions de pergélisol sur le territoire et à l'échelle des communautés entraine des défis particuliers pour l'aménagement du territroire.En utilisant comme exemples Akulivik et Kangiqsualujjuaq, cet article illustre les résultats obtenus par les cartes de potentiel de construction.

1 INTRODUCTION

Over the past two decades, the mean annual air temperatures in northern Quebec followed the warming trend scenarios long anticipated by the IPCC (Intergovernmental Panel on Climate Change), leading to some negative impacts on the natural and built environments of northern communities (ACIA, 2007; Smith et al., 2010). As the Inuit communities are facing this challenge in their municipal planning work, the rapid population growth in Nunavik (increase of 25% between 1996 and 2006) has also led to a severe housing crisis. In the context of global warming, communities of Nunavik have to deal with the presence of a permafrost in transition in the management of their built environment and in planning their growth. (Allard et al., 2007a, 2007b; ACIA, 2004; Calmels et al., 2008; Smith et al., 2010, L'Hérault et al., 2012). There is an urgent need to identify possible areas of development to build sustainable infrastructures as the climate model predictions indicate a continuation and even an acceleration of the warming trend for the coming decades.

In this project, mapping of surficial geology, permafrost conditions and potential environmental hazards was conducted in 13 Nunavik communities built on permafrost. These maps cover the current built environments and also the areas subjected to the next development needs and beyond. The integration of these maps through a GIS application resulted in the creation of construction potential maps to support the Nunavik authorities in their land use planning.

This paper outlines the methodology of the research work and show examples of application from two communities: Akulivik and Kangiqsualujjuaq.

1.1 Study Sites

Akulivik is located on the west coast of Hudson Bay, about 200 km south of Ivujivik, on a rocky peninsula (60° 48' N -78° 11' W). To the south of this peninsula is the Illukotat River and to the north, a small bay that opens into Hudson Bay (Figure 1). It is home to 615 residents (Statistique Canada, 2014). The mean annual air temperature is between -8,9°C and -6,9°C. The annual precipitations are about 500 mm (Gerardin et McKenney, 2001). Half of the precipitation falls as rain, especially between July and September. The community is located in the continuous permafrost zone (Figure 1) (Allard and Seguin, 1987) and belongs to the bioclimatic domain of shrub arctic tundra (Payette, 1983, 1996). It is built mainly on marine sediments deposited in the post-glacial Tyrrell Sea, which have emerged over the last millennia. Glacial till deposits also over significant areas within the community area. Rock outcrops are also found in town and in its immediate surroundings.

Kangiqsualujjuaq is located in a valley on the east coast of Ungava Bay, 160 km northeast of Kuujjuaq and 100 km west of the Torngat Mountains; it is home to more than 874 inhabitants (Figure 1) (Statistics Canada, 2014). The community is built on the banks of a bay localized in the estuary of the George River, about 25 km upstream from the coast of Ungava Bay. The mean annual air temperature is estimated between -5°C and -6,9°C (Gerardin et McKenney, 2001). Kangiqsualujjuaq is set in the discontinuous and abundant permafrost, at the limit of continuous permafrost zone (Figure 1). The village actually sits on the tree line (Payette, 1983; Gahé et al., 1987). Surficial deposits consist primarily of glaciomarine sediments deposited in the main valley, on the banks of the bay as well as in topographic hollows. Glacial sediments and bedrock are also present, particularly on valley sides and on top of the surrounding shield plateau.

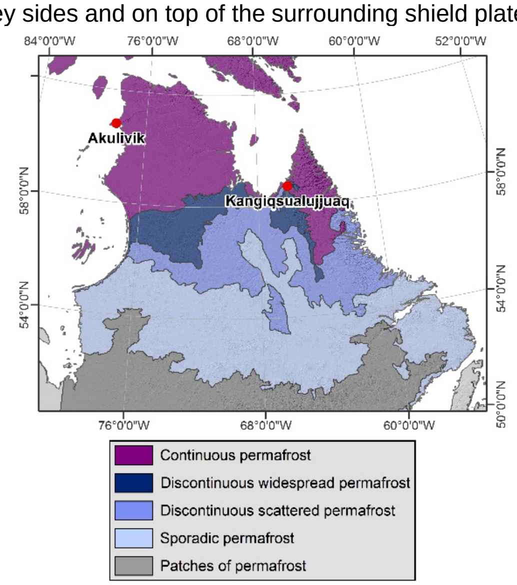

Figure 1: Location of the two communities presented as cases in this study (Akulivik and Kangiqsualujjuaq) and distribution of permafrost in northern Quebec (Allard et al., 2012).

2 METHODS

The methodology used in this project was first developed by Allard and L'Hérault (2010) and improved a few years later by L'Hérault et al. (2013).

2.1 On site observations

Field work was carried out during summers of 2010, 2011 and 2014. For every sites, community leaders and members were met at the beginning of the field work to inform usabout their expectations in terms of future construction and community development. Known permafrost-related issues in the community (e.g., observed settlements, building deformations, difficulties in management of utilities and services) were discussed. These meetings helped guiding field work in order to pay a special attention to permafrost conditions in known priority areas and to ensure complete coverage of sectors targeted for expansion while still ensuring quality mapping for the whole community area.

Field work involved some limited (budget constraints) permafrost core extraction using a portable earth drill (Calmels et Allard, 2005). The drilling sites were selected in order to provide a representative sampling of the different surficial geology units mapped prior to field work.. Many boreholes were drilled to a depth up to 5 meters. The core barrells used allowed the recovery of undisturbed frozen samples with a diameter of 100 mm. In addition, sSeveral test pits with soil sample recovery, , *i.e.* limited to the active layer (shovel, auger or backhoe), were made.

2.2 Surficial geology mapping

The mapping of surficial geology was carried out in order to extend the interpretation beyond the maps previously produced by Allard et al. (2007a) and to provide additional information regarding stratigraphy, depth of bedrock and geotechnical characteristics of the surficial deposits. Geotechnical and stratigraphic informations found in the literature and those acquired during the field work were integrated and archived into a geodatabase. The close association between the sedimentological properties of the Quaternary deposits, patterned ground features and the geocryological properties of permafrost allows for interpreting the spatial distribution of ground ice types and relative abundance (Allard et al. 1993; Allard et Lemay, 2012). Interpretation of 2010 high resolution orthomosaic images and old aerial photographs dating back to ealier times when the communities were very small allow also to map permafrost conditions under the more recently built areas. The aerial photo interpretation was done on stereoscopic numerized images using the SUMMIT EVOLUTION software from DAT/EM Systems International; the interpreted data was automatically loaded into the ArcGIS mapping software and matched with a high resolution DEM built from LiDAR data acquired over the community areas by the Government of Québec in 2010.

2.3 Assessment of permafrost geotechnical properties

During the field seasons, samples from the active layer (unfrozen) were recovered in excavations and frozen samples from the underlying permafrost were extracted as intact cores. The samples were subjected to a sequence of laboratory analyses that started with CT-scanning and imaging (Siemens SOMATOM Sensation 64). This non-destructive method provides a digital high resolution image of the permafrost cryostructure according to a longitudinal plane (sagittal or coronal) (Calmels and Allard, 2004; Calmels, 2005; L'Hérault, 2009). Three-dimensional reconstructions provide internal cryostratigraphic details and volumetric ice contents (Calmels and Allard, 2004).This first step allowed to estimate ground ice types and contents and to select subsamples for the other, destructive, analyses that were: bulk density and water content determinations, grain-size analyses, determination of Atterbeg limits and thaw consolidation tests.

Cryostratigraphic analyses were run on drill-logs based on the CT-Scan imagery of frozen cores. The logs are compiled in the Log-plot™ software.

2.4 Mapping procedure

2.4.1 Multicriteria analysis

The construction potential maps produced are the result of a multicriteria analysis made possible by the use of multiple layers of information (Figure 2). These information layers encompass permafrost conditions, severe constraints to construction and slopes.

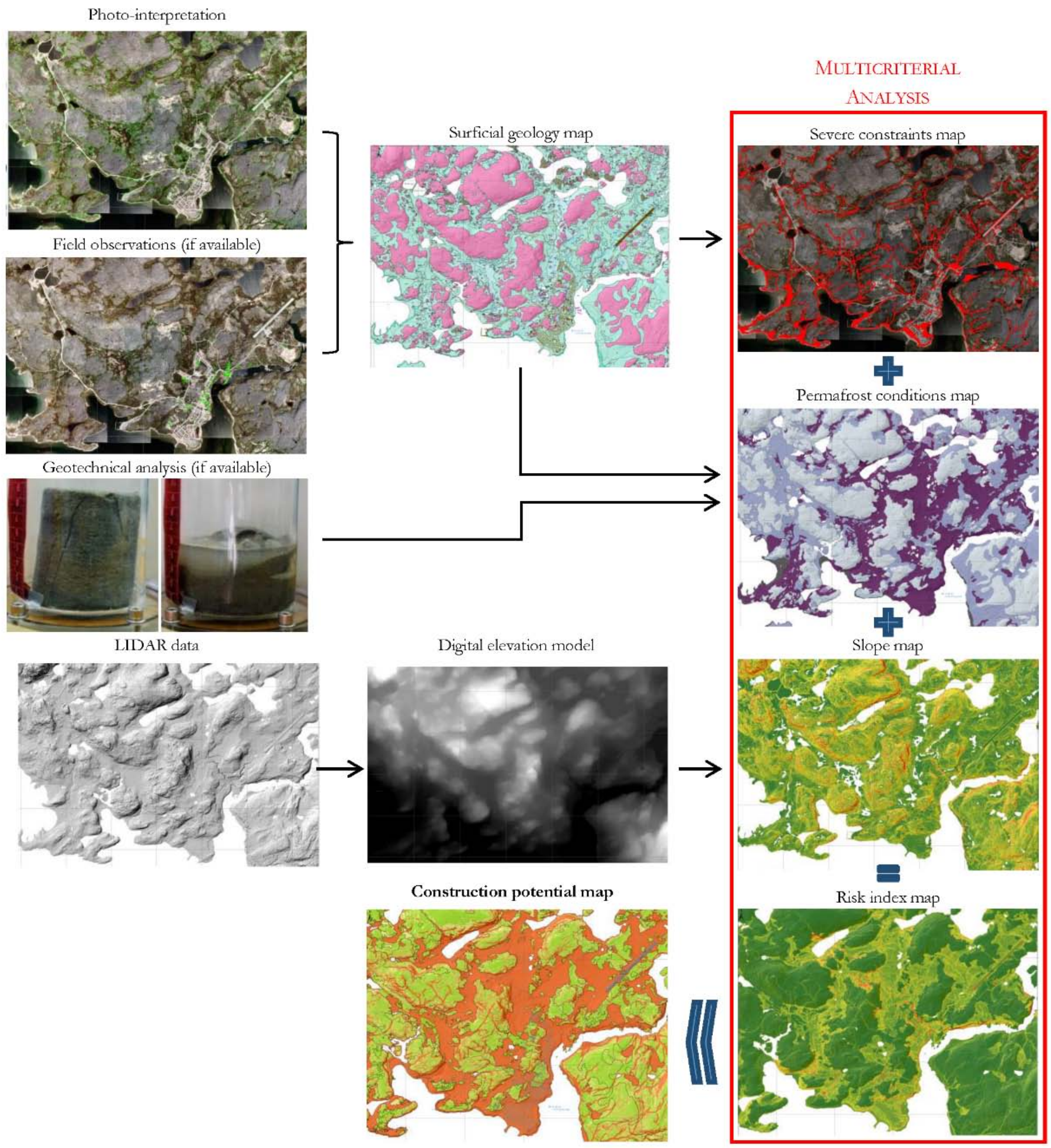

Figure 2: Synthetic diagramme illustrating the integration of mutiples layers of information in order to create the contruction potential maps (Modified from L'Hérault et al., 2013).

Permafrost conditions can be inferred from the surficial geology mapped given that the amount of ground ice and cryostructure are closely associated with the type of geological surficial material (Allard et Lemay, 2012). The surficial geology units mapped were grouped within two classes of permafrost conditions: thaw stable units (bedrock and coarse deposits containing little or no ice) and thaw unstable deposits (ice rich fine-grained sediments). For each class of permafrost conditions, slope values were determined according to the estimated risk based on the nature of the surficial deposit and field processes observed. Beyond a specific critical slope value, a given surficial deposit is considered unfavorable for construction. For instance, for bedrock and thin coarse deposit over bedrock, a 15° slope value was set in order to limit the amount of cut/fill required to accommodate a pad foundation or avoid excessive height of piles foundation (condition 1a and 1b). For tills (condition 2a and 2b), a slope of 8° and more appears conducive to creep (gelifluxion), so likely to cause deformation to infrastructures. In ice-rich clayey sediments (condition 2c and 2d), slopes greater than 2° are considered at risk for active layer detachments. This latter value is the minimum slope onto which an active layer detachment failure with impacts on construction occurred in marine silts in Salluit in 1998.

To these two main classes of permafrost conditions, a third class, which includes the severe constraints to development, is added. These severe constraints to developpement represents natural hazards (wetlands, landslides scars, high and steep slopes with potential risk of snow avalanche, stream bank erosion scars, alluvial flood plains along streams) and periglacial landforms indicating a high ice content or some destructive processes (such as, ice wedges networks, frost blisters, gelifluxion lobes and sheets and thermokarst features).

Quantitative geospatial data, such as slope angles, are easily integrated within a matrix equation. However, qualitative geospatial data such as permafrost conditions and severe constraints need to be weighted to be quantified and integrated into the equation. The weighting of the permafrost conditions was acheived by taking into account the sensitivity of the permafrost to thaw settlement, which is directly proportional to the ice content in the surface deposit and to its thickness. Thus, for different permafrost conditions identified, the settlement sensitivity index (SSI) has been fixed to 0 for bedrock, coarse sediments with a low ice content or glacial deposits (till) less than 2 m thick over bedrock, 60 for thick glacial sediments (till) and 120 for ice-rich fine sediments. Also, a slope coefficient (α) was defined based on the slope threshold value ($R_{maximum\ threshold}$) and the critical slope value previously determined (Sc) for each permafrost conditions encountered.

$$\alpha = \frac{R_{maximum\ threshold}}{Sc}$$

Afterwards, the Hadamard product took the slope coeffient map and the slope map to create a constraint index slopes (CIS). Therefore, for a given cell where the value of the constraint index slopes is greater than 120, *i.e.* when the slope is greater than the critical slope value established for the permafrost condition encountered, it is classified unfavorable for construction.

A risk index is calculated for each cell by adding the settlement sensitivity index (SSI), the constraint index slopes (CIS) and the zones of severe constraints to development (Figure 3).

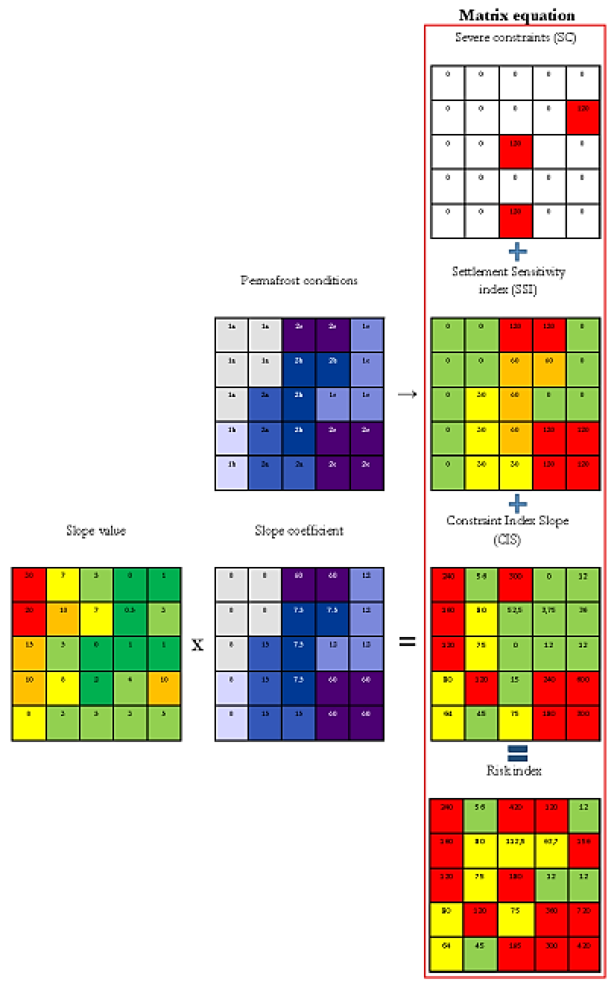

Figure 3: Structure and weighting of the geospatial information use in the matrix equation to calculate the risk index (L'Hérault et al., 2013).

The risk index value can range between 0 and 5640. The higher the index is, the higher is the interaction between the constraints, the permafrost conditions and the slopes which makes the permafrost thaw sensitive and therefore, unfavorable for construction. An arbitrary risk index of 120 was determined has a threshold beyond which the terrain is considered unfavorable for construction. This reclassification aims to classify the field within three categories: 1- terrain manageable for construction, 2- terrain manageable for construction, but may require significant earthwork for setting adapted fondations and 3- terrain either unsuitable for construction or requiring specific engineering adaptations.

3 EXAMPLES

3.1 Akulivik

The construction potential map for Akulivik reveals several thaw stable and suitable areas for developpement of infrastructures (Figure 4). These areas correspond mostly to rock outcrops, but also the well-drained emerged sandy littoral and nearshore Holocene deposits. The western part of the region is essentially rocky, a stable ground for hosting infrastructures with foundations of all types. Test pits made in northeast area of town show the presence of thaw sensitive thin ice rich marine deposits. Their thickness is unknown, but is estimated to be several meters, except for a small land area along the north bank of the Illukotat River. The presence of rock outcrops at this location suggests a shallow thickness of the surficial deposits. Residential development in this sector would require the use of deep foundations resting over bedrock (e.g. piles) or elaborate techniques for site preparation (excavation or pre-melting of permafrost in the surficial deposits) (L'Hérault et al., 2013).

The presence of rather flat extensive rock outcrops offers an interesting potential area for construction on the south side of the river Illukotat, adjacent to the recent housing development although the expansion is limited by thaw unstable areas to the south and north. Further south, the presence of an another important rock outcrop with slopes less than 15 degrees (condition 1a) occasionally covered by a thin layer of coarse littoral sediments (condition: 1b) or till (condition: 2a) is favourable for development. Another suitable area located south-west is characterized by a thick cover of well drained sandy littoral sediments (condition: 1c). Yet special attention should be paid to some poorly drained areas suggesting the presence of potentially ice-rich fine sediments and possible ice wedges (L'Hérault et al., 2013).

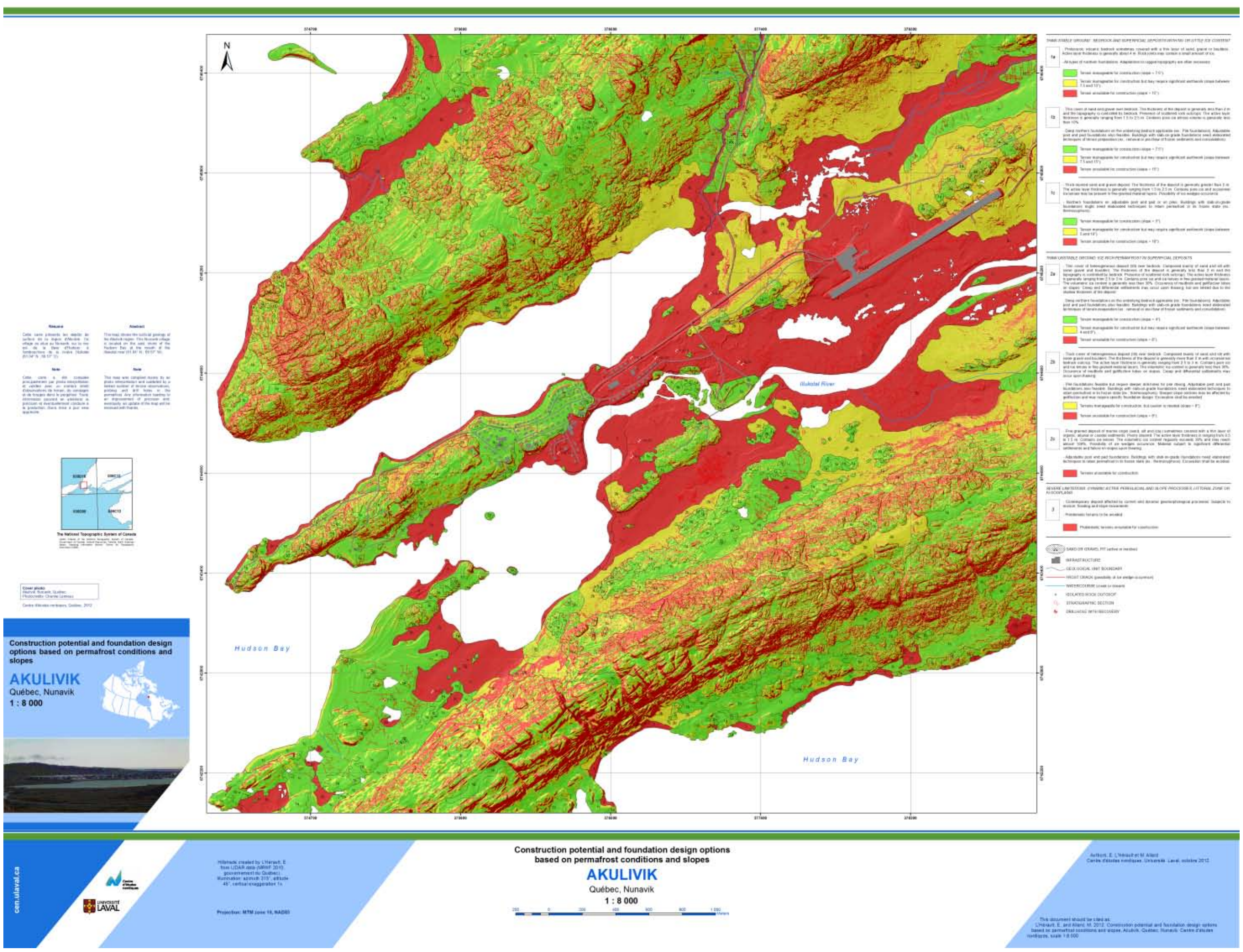

Figure 4: Akulivik construction potential map (L'Hérault et al., 2013). Terrain manageable for construction are represented in green, terrain manageable for construction, but that require significant earthwork for setting adapted fondations are represented in yellow and terrain either unsuitable for construction or requiring specific engineering adaptations are represented in red.

3.2 Kangiqsualujjuaq

The majority of the community is built on glaciomarine intertidal sediments (condition 2d) deposited in the bottom of a valley confined by important rocky cliffs between the airport and the village and in the periphery of the bay where the permafrost appears in the form of ice-rich cryogenic mounds (lithalsas) (Figure 5). This geological unit is poorly drained and sensitive to thawing as shown by road deformations in the valley (L'Hérault et al., 2014). To the west of the village, an area at the base of the cliff is forbidden for implementation of new infrastructure due to high risk of occurrence of avalanches (Carbonneau et al., 2015).

In spite of these problematic terrains some thaw stable areas are identified on the construction potential map of Kangiqsualujjuaq such as the area to the west of the airport. However, this section is already occupied by a pit in glaciofluvial deposits and the water treatment pond. The area behind the new housing development, to the east of the community, also offers a significant potential for construction. The surficial geology unit consist of weathered till (condition 2b) where a few rock outcrops protrude through the till deposit suggesting a rather thin cover. Deep foundations taking support in the bedrock (e.g. piles) could be applied in this sector, as well as floating foundations on pads. Nonetheless, the weathered till possibly contains significant amounts of ice and would be likely to creep. It is therefore strongly suggested to conduct more soil surveys to select the optimal foundation for the permafrost conditions on this frost susceptible material (Carbonneau et al., 2015).

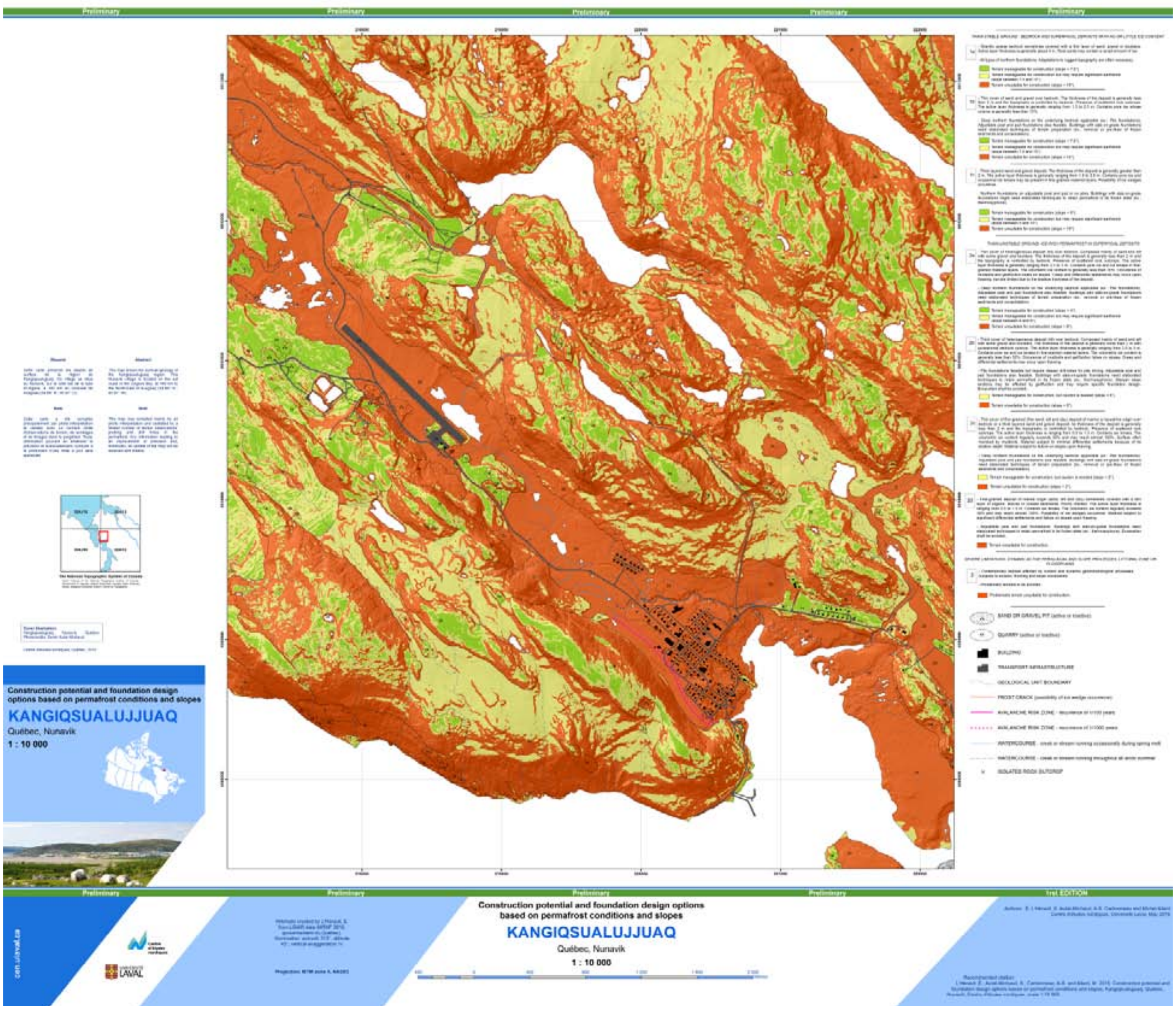

Figure 5: Kangiqsualujjuaq construction potential map (Carbonneau et al., 2015). Terrain manageable for construction are represented in green, terrain manageable for construction, but that require significant earthwork for setting adapted fondations are represented in yellow and terrain either unsuitable for construction or requiring specific engineering adaptations are represented in orange.

4 DISCUSSION

Adaptation strategies to support land use planing decisions in northern community imply to take into account the local variability of permafrost conditions in order to choose the appropriate constructions techniques and foundations types (Allard and Lemay, 2012). Indeed, characterization of surficial deposits provides important baseline information on strategies to be adopted, since bearing capacity of permafrost depends on its sensitivity to thawing, itself being defined by the nature of surficial deposits and ice content. In both Akulivik and Kangiqsualujjuaq, the probability to build on an ice-rich soil is very high. Stratigraphic observations made in these villages, as in many others in Nunavik, revealed that even thin marine sediments, colluviums and some tills may contain high ice content. Within the same geological unit, ice content has important spatial variability both horizontally and vertically. Consequently, the construction potential maps presented in this report are a generalization of specific characteristics observed in the different materials that cover the villages of Nunavik. The construction potential maps are useful tools to support decision making in land management to ensure quality and sustainability of infrastructures. With these maps, used as long-term planning tool, the communities can determine terrain units for construction with types of foundations according to the local characteristic of the permafrost. The foundations proposed are indicative only and were selected from those documented in the litterature and commonly used in Nunavik and Nunavut.

Bedrock (conditions 1a), sometimes covered with thin layer of sand and gravel (conditions 1b), and thick sand and gravel deposits cover (conditions1c), as previously mentioned, contain little or no ice, and is consequently considered thaw-stable (with some exceptions in highly fractured geological settings) . On these types of terrain manageable for construction, northern foundations of all types can be favored, but adaptations to the rugged topography are often necessary. For instance, with presence of a steep slope, it is better to opt for piles foundation to optimize the use of space and limit the amount of cut/fill required to accommodate a pad foundation since the availability of fill granular material is problematic for some communities and can be very expensive to produce and transport.

Thaw-unstable deposits (conditions 2a, 2b, 2c, 2d) contain a significant fraction of fine particles (silt and clay) that allowed the development of segregated ice (e.g. ice lenses) exceeding soil porosity. The thickness of ice lenses can sometimes exceed several centimeters and can affect the stability upon thaw of the permafrost. Mudboils, hummocks, lithalsas and gelifluxtion are commonly found in fine-grained deposits. Moreover, ice-rich sediments are often marked by poorly organized surface drainage networks that may cause formation of frost blisters or icings.

In spite of the presence of ice-rich deposits, some of these terrains remains manageable for construction, but may require significant earthwork and use of adapted foundations. Deep northern foundations resting over bedrock (piles) can be applied when the depth to bedrock is known and not too large. The buildings with slab-on-grade foundations require elaborate techniques of soil preparation (e.g. excavation or premelting of the frozen sediment cover). On the terrain where till cover is important (condition 2b), pile foundations are possible but require deeper drilling for installation.

The ice-rich soils (e.g. marine clays and colluviums) (condition 2c and 2d) are susceptible to active layer detachment and important settlements. In addition, surface runoff can lead to thermal erosion and ditching. These terrains are considered unsuitable for construction, although some foundation types may be feasible, but with caution, despite their fragility. Adjustable posts and pad foundations, if properly dimensioned, offer good support for infrastructures and an adjustment flexibility in case of ground settlement. Nonetheless, climate warming in the coming decades will accelerate and lead to permafrost degradation, so the probable duration of this type of foundation remains a concern for the long term. For infrastructures that require slab-on-grade foundations, elaborate techniques for protection against permafrost degradation, such as thermosyphons, are necessary.

Particular attention should be paid to the design and spatial arrangement of infrastructures, to minimize their impact on natural drainage and accumulation of snow that could accelerate degradation of permafrost. It is recommended when possible to avoid urban developpement in sensitive permafrost conditions 2a, 2b, 2c, 2d and prioritize the rocky thaw- stable bedrock and thick cover of coarse deposits (condition 1a, 1b and 1c).

5 CONCLUSION

For each studied communities, a map of construction potential and foundation design options based on permafrost conditions and slopes, was produced. The permafrost terrain were classified in three categories: 1- terrain manageable for construction, 2- terrain manageable for construction, but that may require significant earthwork and 3- terrain unsuitable for construction. Suggestions relative to potential construction techniques considering existing types of foundations on permafrost, which are commonly used in Nunavik and Nunavut (pad, piles, thermosyphons, removal or pre-thaw of frozen sediments and consolidation, etc.). on terrain classified as "manageable" according to permafrost conditions have been proposed.

Construction potential maps will help residents to participated in decisions related to land use planning by giving them the knowledge and baseline information associated with the characteristics of permafrost. The knowledge transfert to main organizations, policy-makers and managers involved in land use planning decisions is fundamental to ensure sustainable development of villages and establishment of good municipal management and construction practices on permafrost. Doing so, the integration of best practices, by all participants for building maintenance, snow removal and municipal drainage will prevent and minimize the potential damage to existing and future infrastructures related to permafrost degradation.

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