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ASSESSING LAND SUITABILITY FOR RESIDENTIAL DEVELOPMENT IN PERMAFROST REGIONS: A MULTI-CRITERIA APPROACH TO LAND-USE PLANNING IN NORTHERN QUEBEC, CANADA

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Northern Quebec (Nunavik) presents an important intersection between population growth and climate change. The Inuit population of Nunavik has the fastest growth rate in any region of Canada. Land-use planning is an urgent and pressing need for northern communities built on permafrost, where there are considerable risks to development in areas where permafrost may thaw. As northern communities work to adapt to climate changes, they will be in great need of confident recommendations about locations of future development projects. This paper presents a case-study of the community of Tasiujaq and assesses the probability of thaw settlement of the surface, a process seriously affecting infrastructure stability. A method is developed for quantifying uncertainty in the resulting map, expressed as a function of judgmentbased uncertainty in the various factors that can influence eventual map quality. The best estimate of vulnerability and of the confidence in that estimate can be expressed in a single, simple map that allows an analyst to convey both of these vital aspects of the assessment process.

Keywords: GIS; analytical hierarchy process; multi-criteria analysis; permafrost; sensitivity; Nunavik; Monte Carlo.

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Introduction

Land-use planning is an urgent and pressing need in northern regions where there are considerable risks to development in areas where permafrost may thaw, including thaw settlement, thermal erosion, landslides, and other types of mass movements. In the past, the thermal state of the permafrost was nearly stable but climate change scenarios clearly indicate that the North will be more affected by the warming than anywhere else on the planet. As the climate is warming and communities grow, there is an urgent need to reliably find suitable land on which to safely and sustainably build infrastructure (IPCC, 2007). Sustainable development of the North requires that the current and future potential thawing of permafrost be considered for the design life of transport infrastructure and buildings (Canadian Standards Association, 2010). Geohazards related to permafrost degradation need to be evaluated prior to construction to ensure that adequate engineering techniques are applied to counteract the adverse impact of permafrost warming (Remchein *et al.*, 2009). To aid northern communities in their land management, geographic information system (GIS) techniques are applied to identify the potential risks of proposed development areas in four Inuit villages of Northern Quebec (Nunavik): Tasiujaq, Kangirsuk, Puvirnituq and Akulivik. For these villages, key geological, geomorphological and hydrological criteria implicated in the stability of soil and infrastructure in permafrost regions were mapped, including slope, drainage conditions, surface geology, ice content, and other geotechnical and geothermal properties of the permafrost (e.g. ground temperature, thermal conductivity, porosity, permeability).

Like many environmental evaluations using a GIS, a multi-criteria analysis was used to assess the study area based on a set of criteria. This work presents an example of permafrost terrain vulnerability to thaw settlement and subsidence. Potential risk related to thaw settlement process can be reasonably estimated by the analysis of three factors: the surficial deposits (implicitly the potential ice content), the quality of the drainage and the slope of the terrain. Given the complexity of the process under consideration, the Analytical Hierarchy Process (AHP) was used to infer the weights among these factors that can influence this permafrost process and influence site vulnerability (Nelson *et al.*, 2002; Pullman *et al.*, 2007; Fortier and Bolduc, 2008). AHP, a common multi-criteria analysis method, uses one's judgment of the perceived importance of factors in relation to each other, producing a single set of factor weights that are typically used to produce a single map, carefully rendered and submitted to policymakers to support decision-making.

Uncertainties and errors in multi-criteria analysis can originate from many sources, including (1) a limited understanding of underlying processes, (2) poorly conceived models, (3) imprecise datasets, or (4) judgment of the relative importance of factors on a process. Each factor can introduce substantial uncertainty that can translate into weak or imprecise output results. In this paper, the focus is on quantifying and understanding the potential effects of uncertain or inaccurate judgment of the relative importance of factors to a given process.

For GIS to be successfully and reliably integrated into policy decisions, map outputs by analysts must be credible. But analysts are often faced with making difficult and somewhat arbitrary decisions during an analysis that can affect the final output. For example, does a decision to call the contribution of a given soil type or cover class "High" instead of "Very High" drastically influence the output? If so, is the effect the same everywhere, or are there pockets of influence throughout the study area? These questions are currently difficult to address, which is one major reason why map output for a given question is usually comprised of a single "best-estimate" map.

Recent work with AHP has made first steps into understanding the sensitivity of this process to errors or uncertainties in the judgments used when filling the AHP matrix. Chen *et al.* (2009, 2010) developed a method and ArcGIS-compatible tool to perform a one-at-a-time sensitivity analysis of output results to variation in factor weights. That work shows very useful first steps toward understanding the impact of uncertainty in individual input maps on resulting suitability maps. Here, that work is extended in three ways: a novel framework is developed for evaluating and displaying the results, allowing more than one factor to vary at once and allowing factors to be more or less uncertain. The net result is a much more flexible system that is easily understood by analysts and policymakers alike.

This paper illustrates the framework used to evaluate the quality of potential construction sites across an area surrounding the village of Tasiujaq in Nunavik. This multi-year project (2010–2012) involves several summers of sustained field work, the creation of geodatabases and maps of both geophysical and social data, and the estimation of the risk of several geophysical processes (e.g. active layer detachment slide, thaw settlement and infrastructure subsidence, bearing capacity of the permafrost). Because many of these factors are beneath the visible surface, they can only be estimated across a large area with considerable field effort, followed by careful GIS analysis combining field data, aerial photograph and satellite image interpretation, and interpolation techniques.

Each of these parts has an unknowable but important uncertainty in the map, and these uncertainties may vary across the area depending on the factors in consideration. To begin to adequately express the judgment-based uncertainties inherent in this process, a method was needed to quantify the confidence, or lack thereof, in the understanding of the factors influencing a process, the potentially subtle interactions between them, and the basic confidence in the quality of the maps produced for analysis. The objectives of this paper are: (1) to illustrate the framework that was developed for addressing this very complex problem confronted by analysts in many settings where multiple criteria are to be evaluated; and (2) to devise a way, building from the AHP process, in which confidence values can be used to allow analysts both to generate weights for overlaying and to quantify the uncertainty in those weights due to incomplete understanding or map quality. The results of this study should be of interest to others facing a large number of criteria of different importance and map qualities.

Study area

The Nunavik region (Fig. 1), located north of the province of Quebec, is a vast territory encompassing more than $5{\times}10^5\,\text{km}^2$ and inhabited almost entirely by Inuits (Nunavik Tourism Association, 2010). Most of this region lies north of the 55th parallel, on continuous and discontinuous permafrost soils. Defined as soil at or below 0°C for more than two consecutive years (French, 2007) permafrost is greatly influenced and is primarily controlled by surface temperatures. The Inuit population of Nunavik is distributed in 14 villages located along the coast of Hudson Bay, Hudson Strait and Ungava Bay. In 2006, the region had a population

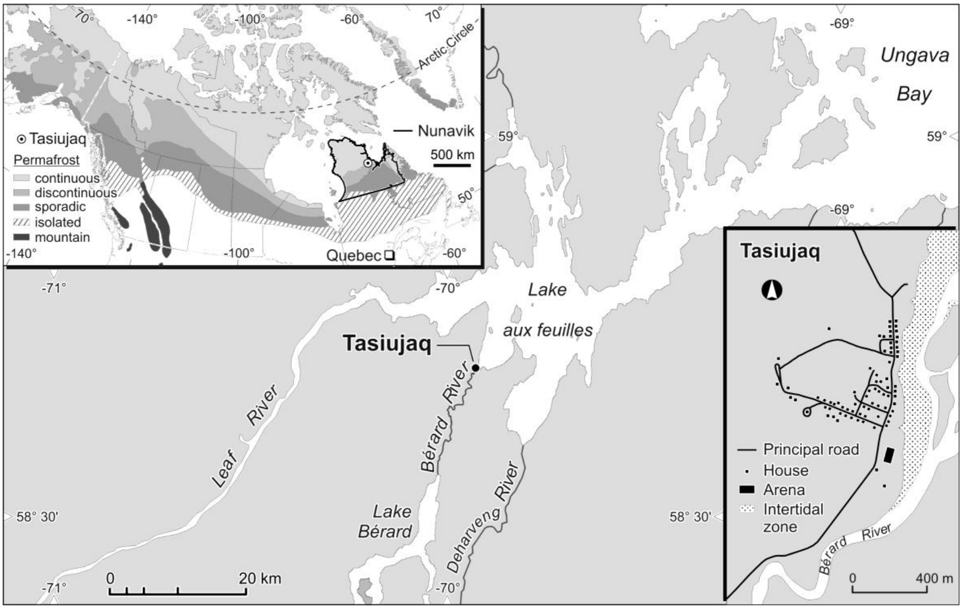


Fig. 1. Localization of Nunavik and the study site.

of just over 9,500 individuals, an increase of 25% from ten years before: this was the fastest aboriginal growth rate in any region of Canada and one of the fastest in the world. During this same period, nearly 50% of Inuit in the region lived in housing that is categorized as "crowded", as opposed to a mere 3% for Canada's non-aboriginal population (Statistics Canada, 2006). The need for new, physically stable housing is urgent and construction projects in villages are initiated regularly.

In recent decades, the climate of Nunavik has warmed considerably (Allard *et al.*, 2002, 2007; Smith *et al.*, 2010). Higher temperatures are already causing lifestyles to change in Nunavik (e.g. length of ice fishing and snowmobile seasons, road/airstrip damage due to degrading permafrost) and leaders of these communities are actively seeking and exploring both short-term and long-term adaptation strategies. Expected effects in coming decades include ground subsidence, increased risk of landslides, formation of sinkholes, thermal erosion due to surface run-off, a reduction in bearing capacity of soils and coastal erosion due to sea level rise and reduction in sea ice cover. Important parameters to be considered in the location of new construction development are thaw depth, permafrost temperature, drainage, the type of sediments to build on and the ice content of these sediments. These parameters strongly influence permafrost degradation processes. Because the physical and mechanical properties of frozen soil are closely related to temperature, the effects are greatest as soil approaches the thawing point (Instanes, 2003). Throughout much of settled Nunavik, leaders and citizens are searching for areas that, even with rising temperatures, will remain stable enough to support structures.

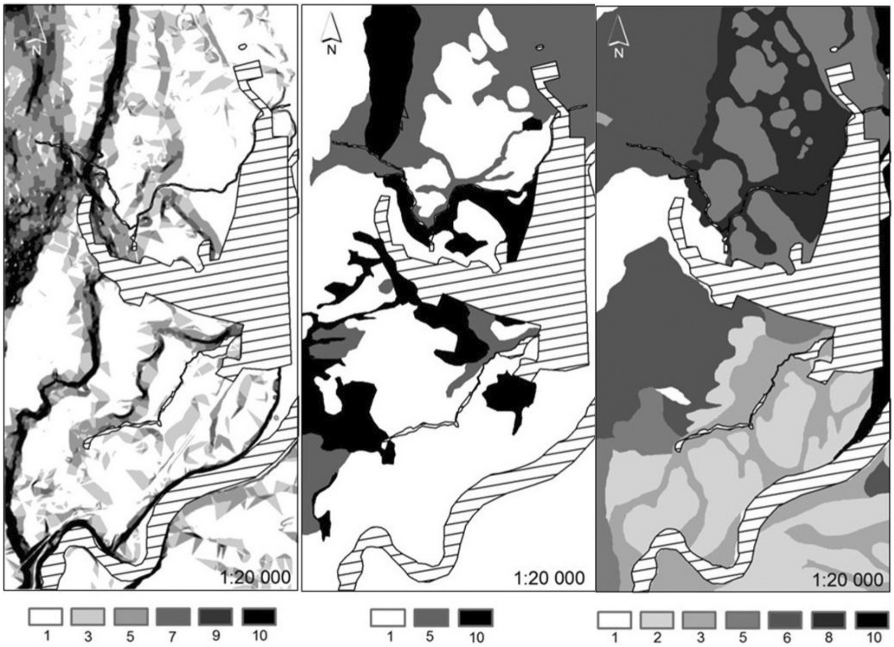
For this paper, a study site was chosen to illustrate the method used to assess the uncertainty related to the use of the AHP process. The study site is located in the village of Tasiujaq (58°42′N–69°56′W) a community of a few hundred people (Statistics Canada, 2007) built on warm permafrost (near zero Celsius), along the banks of the Baie aux Feuilles at the mouth of the Bérard river. The mean annual air temperature for Kuujjuaq, a village located at about 110 km south-east of Tasiujaq was −5.7 for the 1971–2000 period (Environment Canada, 2011). The tidal range is among the largest in the world, regularly exceeding 15 meters, which explains the widespread occurrence of intertidal, fluvial and marine deposits in the village (Allard *et al.*, 2007; Vinet, 2008). Fieldwork carried out in summer 2010 revealed the presence of fine-grained (fine sand, silt, clay) thaw-sensitive sediments (Fortier *et al.*, 2011). These surficial deposits are spatially heterogeneous and mapping the potential thaw-sensitivity risk becomes very complex. A 1×2 km area (with 1 m cells) was selected to illustrate the broad range of variation in terrain conditions within even a small area. The study site comprises a series of marine and fluvial terraces and cliffs, rock outcrops and a narrow coastal plain (where the current village is built) located along the river bank. Considering the physiographic context and the thaw-susceptible nature of the deposits, areas for future development are very limited and special care must be taken for recommendations regarding land use.

Material and Methods

Suitability factors

Thaw settlement related to permafrost degradation can have a significant impact on infrastructure stability, potentially causing foundations to shift and drop and leading to floor and wall cracking. It can induce considerable damages to houses, resulting in high costs of repair or rendering buildings unusable. At the study site, a preliminary assessment of the thaw settlement and surface subsidence potential was conducted. In considering the influence of various factors that could be modeled, it is most important to estimate the volumetric ground ice content. Volume loss resulting from phase change (ice to water) essentially drives the settlement of the surface. This will subsequently be exacerbated by consolidation of the sediments as water is expulsed from the pore space under the weight of the overlying sediments. In the absence of ground ice data (generated, for example, from drilling boreholes to check for ice), surficial deposits can be used as an indirect indicator of ground ice based on the fairly good correlation between the frost-susceptibility of soils and the grain-size distribution of sediments (Andersland and Ladanyi, 2004). The near subsurface stratigraphy (active layer and first meter of upper permafrost) was assumed to be consistent with surficial deposits observations. The following factors for which data were available were considered: surficial deposits, slopes, and the quality of the drainage.

For each factor, a thematic map was digitized with ArcGIS® and ArcMap version 9.3 (by ESRI® software). The slope factor (Fig. 2(a)) was developed from a digital elevation model (DEM) developed by the Quebec Government (Ministère des Ressources naturelles et de la Faune — MRNFQ) and having a 1 meter resolution. Slopes range from 0° to 38°, with the steepest slopes located along a cliff formed by the marine regression in response to isostatic uplift several thousand years ago. This cliff marks the limit of a narrow marine terrace that crosses the western side of the study site. Other steep slopes form the river bluff. The drainage layer (Fig. 2(b)) was digitized from aerial photographs and field observations collected during summer 2010. Three main categories were identified: areas presenting good drainage (coarse grained sediments or terrain along stream/ rivers), medium drainage (mesic) and poorly drained (stagnant water, diffuse drainage). For the surficial deposits (Fig. 2(c)), the nature of the sediments was



(a) (b) (c)

Fig. 2. Maps for the three factors important to the thaw settlement process. Values are drawn with 1 being the least vulnerable and 10 the most vulnerable. See Table 1 for more details of the categories of each factor.

derived from interpretation of aerial photographs, from an extensive field campaign involving numerous shallow excavations in the active layer and from laboratory analysis.

To make the values of these contributing factors both numeric and intercomparable, they were standardized to a common scale of 1 to 10, a typical operation in multi-criteria analysis. Because vulnerability was being modeled, 1 was chosen as a value for a very low contribution to overall vulnerability, and 10 represented high-vulnerability classes (Table 1). For example, a pixel in the study area with a sand/gravel surface (3), moderately well drained (5), and with a slope between 5 and 7 degrees (7) would produce a vulnerability value of $3 + 5 + 7 = 12$, in a case in which all factors (i.e., surficial deposits, drainage, and slope) were equally important factors in influencing a site's vulnerability to thaw settlement. As the next section shows, however, expert opinion about the process indicates that weightings among these three factors should not be equal. The subsequent section illustrates the approach used to treat uncertainty in the maps

Table 1. Factor value ranges and their standardization to a 1:10 scale.

Factors	Class values									
	1	2	3	4	5	6	7	8	9	10
Surficial deposits	Rock	Cobbles, sand, gravel	Sand, gravel		Blocks, gravel, sand	Sand		Sand, gavel, silt		Fine sand, silt
Drainage	Good				Medium					Poorly drained
Slope	0°–2°		2°–3°		3°–5°		5°–7°		7°–9°	〉9°

and in the factor weights that best represented the vulnerability to thaw-settlement in the study area.

Developing a best estimate of vulnerability to thaw settlement

The best estimate of the relationships among the three chosen factors according to their relative importance (Table 2) was identified using the AHP method (Saaty, 1977), which is capable of translating a large number of relative importance estimates among criteria into a clear, mathematically defensible set of weights for each factor. Given a geomorphologist expert's estimates of the relative importance of the factors to thaw settlement, the surficial deposits (factor 1) should be weighted the most heavily (71.4%; Table 3), whereas the drainage and the slopes accounted for less and were of equal importance (14.3% each). The last step in obtaining the final vulnerability map consisted in summing the three thematic maps with respect to their relative weight. The resulting map assesses the vulnerability of the territory to thaw settlement, and represents the usual final output of the multi-criteria analysis. This map serves as a reference for the subsequent steps of analysis and will be referred to as the base map.

Table 2. Scale for comparing factors in the Analytical Hierarchy Process (after Saaty and Vargas, 1991).

1	Equal importance
3	Moderate prevalence of one over another
5	Strong or essential prevalence
7	Very strong or demonstrated prevalence
9	Extremely high prevalence
2,4,6,8	Intermediate values
Reciprocals	For inverse comparison

Table 3. Matrix for executing the Analytical Hierarchy Process (left). Unlike in most AHP studies, in the present study a confidence value is modeled on each of the factor ratios. The ratio estimate of 5 for the ratio of Surficial deposits: Drainage has a low confidence, as described in the text. The weights that follow directly from the base AHP values are shown, in the column marked "Weight". The rightmost three columns indicate the outcome of the sensitivity analysis implied by the variance in AHP values shown on the left. Values and their meanings are described in the text.

Factors	Analytical Hierarchy Process				Sensitivity analysis		
	Surficial deposits	Drainage	Slope	Weight	Mean	Standard deviation	Coefficient of variation
Surficial deposits	—	5 ± 3	5 ± 1.25	0.714	0.660	0.128	0.194
Drainage	—	—	1 ± 0.2	0.143	0.184	0.104	0562
Slope	—	—	—	0.143	0.156	0.033	0.214

Estimating the effect of expert confidence on assessments of site vulnerability

As AHP and multi-criteria analysis are traditionally understood, one or more experts give opinions, weights among criteria are calculated, and the multiple criteria are evaluated to form a single, definitive map of the desired feature: in this case, vulnerability of building construction to future disturbances. Yet variation can be found among experts about which of 9 values to assign to each criteria (Table 2), but also in a single expert's confidence that given criteria ratio ("5", for example), was not a nearby value, such as 4.5, 5.5, 4, or 6. Each of these values can have some unknown but presumably important effect on the final results, with effects that could vary across the study area. Yet it is crucial to these communities to receive advice not only about where to build (the typical output of multi-criteria evaluations using AHP) but also about the effects of analyst confidence in that assessment, especially when dealing with geological hazards. The current conception of AHP does not readily support uncertainty, yet clearly this uncertainty could have a substantial impact on vulnerability estimates. In the spatial domain, an extension to the AHP process can help to understand the impact of analyst judgment uncertainty on spatially explicit estimates of map confidence. This extension is described below.

To understand the impact of a geomorphologist experts' varied confidence in the quality of each factor map and of the inherent importance of each factor with respect to the others, a set of weights was developed summarizing the best estimate using expert opinion, as reflected through the AHP algorithm (Table 3). The weights were calculated based on the estimate and confidence bounds of experts' estimates in the importance of each factor — for example; an expert might say that the surficial deposits factor was 5 times more important than drainage in determining the outcome of the thaw settlement process. Pressed further, the expert might estimate that a standard deviation of 1.25 (i.e. 5 ± 1.25, in lay terms) correctly expressed the confidence in this ratio. Other relative importance ratios, for example, between drainage and slope, might be lower or higher but more confidently so: for example, 1 ± 0.2. Still others might reflect only weak certainty in relative importance of the two factors: for example, 4 ± 3.

Uncertainty in the importance of each contributing factor is only one of several forms of uncertainty in the ultimate output of the MCE process. A second major factor influencing confidence in map output, and perhaps the most tangible for analysts, is the quality of a given map. Even if the weight of a factor should be high given a good map, an analyst might want to express more uncertainty in the final output due to limited available data or a poorly or quickly made map. Depending on the weight of a given factor and the spatial pattern in the maps of that factor, the impact of that uncertainty is not easily quantified. In this method, an analyst adjusts the uncertainty of a factor (e.g. 6 ± 2 instead of 6 ± 1) to reflect that values from that map might be right on average, but should be shown as part of the uncertainty in the process.

Although thaw subsidence is illustrated as a simple combination of three factors, there may be several sub-factors that contribute a factor in subtle or non-linear ways. For example, the surficial deposits factor used here is estimated from values of two sub-factors: ice in the soil; and the nature of the deposits. In this setting, the assessment of these sub-factors generated polygons with nearly identical outlines due to their close relationship. As a result, analysts might choose to model the factors separately, or (as it is done here) to consider them as sub-factors that contribute, perhaps non-linearly, to values of a single grand factor. This can be especially attractive because the combination of sub-factors permits special cases of the sub-factors to exert a stronger influence on the results — for example, a low value of ice content together with an unsuitable surficial deposit (e.g. clay) may be even more vulnerable than a linear combination of the two factors would indicate.

Sensitivity analysis to represent uncertainty

In a multi-factor environment, sensitivity analyses are difficult. As seen in Chen *et al.* (2009, 2010), both the construction and interpretation of maps in an uncertain setting can be challenging. Because the factor weights in a multi-criteria analysis must always sum to 1, a perturbation in one of the weights must be linked to a decline in one or more of the other factors. But which factor? The requirement that weights must sum to 1 means that a set of weights is not independent of each other, which complicates the representation and quantification of uncertainty.

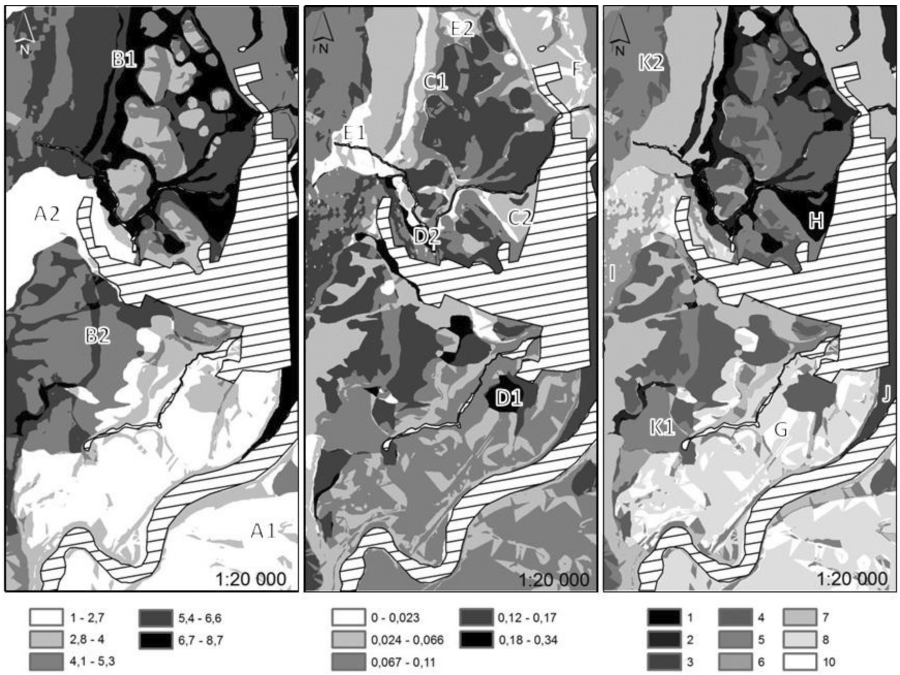
The AHP process provides a framework to perform this sensitivity analysis, by varying the factor ratios (Table 2). But how would each of these estimates and their varied confidences influence the resulting vulnerability map and the assessment of its reliability? The study explored the effect of uncertainty in the three factor ratios that reflected uncertainty in their relative strengths. Scripts were developed to take 500 realizations of each of the three factor ratios and their uncertainties (Table 3) and were fed iteratively into the AHP calculation. Each uncertainty was modeled as being from a normal distribution, meaning that 5 ± 1 .25 represented a normal value of 5 and a standard deviation of 1.25. In that case, this meant that about 68% of 500 iterations used a value for this factor between 2 and 7. In this case, the relatively high uncertainty meant that an expert's best estimate was that one factor exerted a "strong" importance relative to the other, but that the true relationship might be "moderate" or "very strong" (Table 2).

To generate weights with systematic variation that always summed to unity, values for the three ratio values in Table 3 were sampled according to their mean and standard deviation, and input these values to the AHP calculation. The effect was to generate 500 estimates of the three factor weights that reflected the uncertainty of the expert's judgment. The base run of AHP was built from the best estimates of each factor's importance (the values 5, 5, and 1 from Table 3) and gave layer weights 0.71, 0.14, and 0.14 (Table 3). The uncertainty among the weights (e.g. 5 ± 1.25) meant that one of the 500 iterations might have weights of, for example, 0.65, 0.17, and 0.18. Allowing these factor ratios to vary, it allowed for the exploration of the effect of judgment-based uncertainty on the layer weights and thus, to express the effect of this uncertainty on the map result. With the uncertainties described above, the 500 runs of AHP gave the following characteristics for the weights of each factor. Surficial deposits: expected value 0.66, coefficient of variation 0.2; Drainage: expected value 0.18, coefficient of variation 0.56; Slope: expected value 0.16, coefficient of variation 0.21. Thus, the estimate of the influence of drainage on thaw settlement was the least certain (as reflected in its high variation).

Results

A Single Multi-Criteria Analysis: the Base Map

Using the best estimate of weights on the three selected factors influencing thaw settlement (Table 3), a base map was produced (Fig. 3 Panel a) through the



(a) (b) (c)

Fig. 3. Understanding the uncertainty of a vulnerability map. Panel (a) shows the vulnerability map computed by mulli-criteria analysis. Data are on a scale of t to 10, with lower numbers having less vulnerability to thaw seltlement. Panel (b) shows the coefficient of variation in each pixel, calculated from a set of 500 runs with imprecision in factor ratios represented as in Table 3. Panel (c) shows the combination of these two aspects of the assessment of site vulnerability. Letters denote important features mentioned in the text.

multi-criteria analysis using values from Table 1, the column marked “Weights” in Table 3, and the spatial patterning of Fig. 2. Areas of differing vulnerability to thaw settlement can be easily identified. The areas presenting the lowest vulnerability are mainly located in the southern portion of the site (A1) as well as to the west of the site (A2) where a large rock outcrop is visible. The vulnerability is more varied and pronounced in the northern part of the study area, where many vulnerability classes are represented in close proximity to each other. It is also possible to identify the cliff that emerges in the west part of the site (B1 and B2), which, in combination with deposits that are of moderate- to high-susceptibility to thaw settlement and medium drainage conditions, makes this area moderately to highly vulnerable to development.

Variability Map: Viewing Uncertainty

The sensitivity analysis described above made it possible to express, for each pixel, a measure of the variability of that pixel's vulnerability value across the 500 sensitivity runs. For example, a pixel with vulnerability values having a mean of 5 and consistently between 4.8 and 5.2 would have a lower variability than a nearby pixel with a mean value of 5 but with individual values spread widely between 3 and 7. To account for the fact that larger means have larger variances, each pixel's standard deviation was divided by its mean to get the coefficient of variation (Fig. 3 Panel b) of each pixel. (The map of the means of vulnerability estimates was mostly indistinguishable from that of the base run of Panel a). The coefficient of variation was used to compare the relative spread of high and low vulnerability values. The coefficient of variation is interpreted as an expression of the confidence, given the uncertainties specified above, of a pixel's calculated vulnerability value.

On average, areas of high vulnerability present a moderate to moderately-low variability over the 500 runs (Fig. 3 Panel b, area C1 and C2). Locations that vary the most (D1, D2) are small in size. There are only few areas (E1, E2) showing very low variation across the sensitivity runs. The variability pattern does not exclusively follow the pattern shown in the base map. For example, area F on the variation map not only shows a general medium-low variation, but is also punctuated by some low-variation spots, whereas on the base map, the same area is characterized by a uniform class of medium vulnerability. A more systematic analysis of the base and variation maps together is described in the next section.

Combining the Base Map and Variability Map

To obtain a visual representation of the vulnerability of the site and its associated confidence, the base vulnerability map (Fig. 3 Panel a) and the map of the coefficient of variation (Fig. 3 Panel b) were combined. After simplifying the continuous range of values of each map to be Low, Medium, and High, the nine combinations could be easily calculated (Table 4). Using the combinations, it is possible, for example, to identify areas that are unsuitable, with the most certainty of this judgment (Fig. 3 Panel c, area H).

The patches identified from class 10 (Fig. 3 Panel c, area G) show areas where it can be concluded with great confidence that the vulnerability of the terrain to thaw settlement is low. They are very fragmented and scattered over the study site. Interestingly, they are all contained within moderately stable areas of low vulnerability. Areas indicating a high vulnerability and low variability (area H) can be understood with great confidence that they are vulnerable to the process of thaw settlement. In the base map, they were classified as highly vulnerable, and turned

Table 4. Combining the base map and variability map. This shows the pixel counts of the vulnerability estimate (Low, Medium, and High) versus the coefficient of variation (Low, Medium, and High) identified through the 500 sensitivity analysis runs. The first value in a given cell indicates the percentage of pixels in the study area having a given combination of vulnerability and confidence. For example, the best areas for construction, located in pixels with low estimated vulnerability and low variation in that result, comprised 6.4% of the study area. The second value in a cell shows a ranking of these combinations on a ten-star scale. Thus this combination, because it is the best place identified to build for which the confidence is high, gets 10 stars. See panel 3c for the map of these values.

	Calculated Vulnerability			
	Low	Medium	High	Total
Variation				
Low	64% (10)	22.1% (7)	4.7% (1)	33.2%
Medium	20.6% (8)	16.5% (5}	4.8% (2)	41.9%
High	3.4% (6)	19.4% (4)	2.1% (3)	24.9%
Total	30.4%	58.0%	11.6%	

out to be relatively stable over the 500 runs, which suggests that these areas should definitely be avoided for construction. Areas that combine low vulnerability and high variability (area I) shows that even though an area can be classified as very low vulnerability on the base map, these patches should nonetheless be considered cautiously because the certainty of this assessment is low. There is one main spot (area J) where the combination of high risk with high variation is depicted and it is located at the far east of the map, in the foreshore section. Although the deposit map classified this region as highly vulnerable, it shows a large variability over the sensitivity runs, which suggests that more studies might be undertaken to confirm the actual vulnerability of the area.

There are important aspects to this step that are subject to control by the analyst. In this case, the objective was to have a large number of pixels reclassified as “Low Vulnerability”, and set the vulnerability break point accordingly. For other assessments, an analyst might want the “Low Vulnerability” class to be highly restrictive. For the present assessments, the focus is mostly on identifying areas that either present a high or low vulnerability or a high or low confidence. There are many patches scattered all over the site that present those intermediate characteristics. Areas of medium vulnerability and medium variation (Fig. 3 Panel c, area K1 and K2) do not provide clear indications as to whether future investigations should be carried out in those areas.

The analysis presented here allows for the identification of not only the vulnerability, but also the confidence in that vulnerability. A major advantage is that it allows an analyst to realize that not all pixels evaluated as vulnerable should be considered equally strongly. In this example, although a vulnerability assessment indicates that 30% of the study area can be considered low vulnerability, the analyst can be highly confident of only about one-fifth of those pixels. Overall, the coefficient of variation map and the vulnerability and confidence map allow an analyst to see beyond the results that were obtained by producing the base map. They add the dimension of the analyst's uncertainty to the vulnerability results and provide a better estimation of the areas that should be further investigated.

Discussion

As northern communities work to adapt to climate changes, they will be in great need of confident recommendations built on high-quality, high-resolution data. Yet such recommendations, even if created with the utmost care, carry uncertainties introduced during many steps of the analysis process. It is essential to be able to convey some sense of these uncertainties to stakeholders to give them a fair sense of the confidence of experts in the result. The method developed in this work allows for the quantification of uncertainty in the resulting map, expressed as a function of uncertainty in the various factors that can influence eventual map quality.

Although this method is intended to quantify some of the many effects of uncertainty on the assessment process, there are many sources of uncertainty that are not directly modeled here. This can include, for example, the fact that some values of a factor might be delineated more or less confidently than others. Bare rock, for example, can be very easily identified on aerial photo, whereas most surficial deposits are not as easily delineated. In this sense, further work should explore a way to quantify different levels of confidence in different values of a single factor, rather than assigning a single confidence value to a factor in its entirety. Although there are numerous ways that might be accomplished, it is outside the scope of the work presented here.

This project highlights the use of GIS techniques combined with the AHP process as a valuable tool for land-use planning. Some limitations, as well as strengths, of the AHP process arose during the realization of this project. In many instances, the AHP's demand for an ordered evaluation of class categories did not adequately capture the importance of several key factors. In this instance, communities are well served if they are able to build upon solid rock. In all but the most extreme slopes, the suitability of rock sites is, for practical purposes, vastly better than any alternative. To treat this important fact implied by the structural geomorphology, the resulting could be taken map from the process described above and be marked with all the locations presenting visible rock as having maximum suitability, regardless of the weighting of value of those pixels for other factors. In effect, this would "burn in" a high suitability for certain land types, regardless of what its other factor values might have been. Such an approach would also be suitable for marking some areas "unsuitable" regardless of the suite of values, but instead driven only by the value of a certain layer. This would be useful for, for example, clayey soil where building is strongly discouraged in warm permafrost areas.

The process described here should not be misconstrued as an effort to replace the judgment necessary when providing an environmental assessment. It is intended to aid, not supplant, the important expertise that can best be gained from field effort. The goal is to give experts an added tool to express the inevitable uncertainty inherent in making estimates of geomorphological characteristics, their relative importance to a process of interest, and the delineation of these areas using maps, aerial and satellite photos, and field work. Evaluating uncertainty for risk-assessment products is crucial due to the inherent large consequences to people related to triggering of geological hazards.

Conclusion and Future Developments

Northern communities built on permafrost will be increasingly affected by climate warming. Warming and thawing of ice-rich permafrost is already triggering several geomorphological processes such as thaw settlement of the surface, mass movements and thermal erosion that can significantly impact landscape and infrastructure stability. These growing communities are facing unprecedented land-management and land-planning challenges, and GIS can be used as a living, interactive tool for land-use planning and crucial decision-making. This work demonstrated how GIS techniques were used to identify the potential risks of proposed development areas for the village of Tasiujaq in Nunavik. A base map was created in the usual manner of a multi-criteria analysis, using the AHP to determine the ranks and weights for the selected criteria. With a single, best-estimate calculation based on those weights, a single map was created, showing the best estimate of vulnerability to thaw settlement of the surface, a process seriously affecting infrastructure stability. A method of quantifying and incorporating uncertainty in the resulting map was developed to express these results to stakeholders of the communities in terms of level of confidence in risk assessment products. In this study, the base map was used in conjunction with the confidence map to indicate not only the analyst's estimate of vulnerability, but also the certainty of that estimate.

In remote locations like Nunavik, where reliable field data are scarce and gathering additional data is especially costly, environmental assessments must necessarily work in an environment where the best information will always contain considerable uncertainty. In such settings, the ability to convey one's confidence in a work product, which may vary around the study area, is extremely valuable. By highlighting the locations in the study area where the best estimate indicates that it is a good area for construction, but where the certainty of this estimate is only of low or moderate confidence, this approach can help target future field studies. By focusing precious field effort in such areas, one can identify locations in the study area where more information might best help to diminish the uncertainty in the estimate.

Future development will include technical efforts to refine these approaches, field work to improve the quality of factor maps, and interactions with the community to incorporate human and social factors into final products. Additionally, work will be done to incorporate at least several more factors influencing site vulnerability, as well as to incorporate processes in addition to thaw settlement that also strongly influence construction suitability.

Planning decisions in these communities are quite complex and have aspects that are spatial, social, and temporal. As an aide to the initial spatial planning of expansion of these communities in the near future, it was found that the ability to offer more than a single map aids the process immensely. The approach and case study developed here will hopefully aid others working to use spatial data and GIS as tools that can greatly advance environmental assessments.

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