Development of a quantitative approach for evaluating and managing the risk associated with large retrogressive slides

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ABSTRACT
Since 2003, the Ministère des Transports du Québec has been mapping zones that are vulnerable to landslides in areas underlain by clayey soil in many regions of Québec. This paper presents the landslide risk management method that is used in the province of Québec and its application to a specific case study.

In the St. Lawrence Lowlands, large retrogressive slides (flowslides or lateral spreads) represent the highest risk because of the very large areas that they can affect within a few minutes and the high population density in these areas. In order to facilitate management of the areas that are vulnerable to this hazard, a quantitative approach to risk evaluation was recently developed, based on the results of mapping work carried out for the landslide-prone zones. This approach proposes that these areas be classified according to the probability of occurrence of a large retrogressive slide (hazard) and the severity of the potential consequences. The risk maps and the accompanying monitoring plan make it possible to develop a regional risk-management framework for the areas that are already developed. These tools are essential to urban planners in terms of managing the risk of landslides.

RÉSUMÉ
Le ministère des Transports du Québec effectue depuis 2003 la cartographie des zones exposées aux glissements de terrain dans les secteurs de sols argileux de différentes régions du Québec. Cet article présente la méthode de gestion des risques de glissements de terrain dans la province de Québec et son application à un cas particulier.

Dans les basses-terres du Saint-Laurent, les glissements fortement rétrogressifs, de type coulée argileuse, représentent le danger le plus important en raison des très grandes superficies qu'ils peuvent affecter en quelques minutes et en raison de la très grande densité de population de cette portion du territoire. Dans le but de faciliter la gestion des zones exposées à ce danger, une approche quantitative de l'évaluation du risque a été développée récemment, en s'appuyant sur les résultats des travaux de cartographie des zones exposées aux glissements de terrain. L'approche proposée classifie les zones de façon relative en fonction de la probabilité que survienne un glissement fortement rétrogressif (aléa) ainsi que de l'intensité des conséquences potentielles. Les cartes de risque, ainsi que les plans de surveillance qui les accompagnent, permettent de constituer un cadre régional de gestion des risques pour les secteurs déjà bâtis. Ces outils s'avèrent indispensables pour les gestionnaires lorsque vient le temps de prendre des décisions concernant ces risques.

1 INTRODUCTION

In Québec, more than 85% of the population lives on clayey soils, primarily those that were deposited in post-glacial seas along the St. Lawrence and Outaouais Rivers and in the Saguenay region (Figure 1). These soils are conducive to the development of landslides that usually occur on the clayey banks of watercourses, often caused by the bases of the slope being undercut by erosion within meanders. Cases of rotational, superficial, and deep landslides are very frequent (Demers *et al.*, 1999a and b). Although most landslides are on the order of several tens of metres in size, they can still cause a great deal of damage in terms of property and infrastructures.

Rotational landslides sometimes trigger a large retrogressive movement that can create gigantic scars called "flowslides" (Figure 2) in only a few minutes. These flowslides can reach dimensions of several hundred metres, and can cause significant loss of life and property. The analysis, evaluation, and management of the risks of this type of landslide are included in the global landslide risk management plan for Québec (Demers *et al.*, 2008).

This paper describes a quantitative approach that has been developed for the evaluation and analysis of the risk associated with the potential for the occurrence of large retrogressive landslides of the flowslide type.

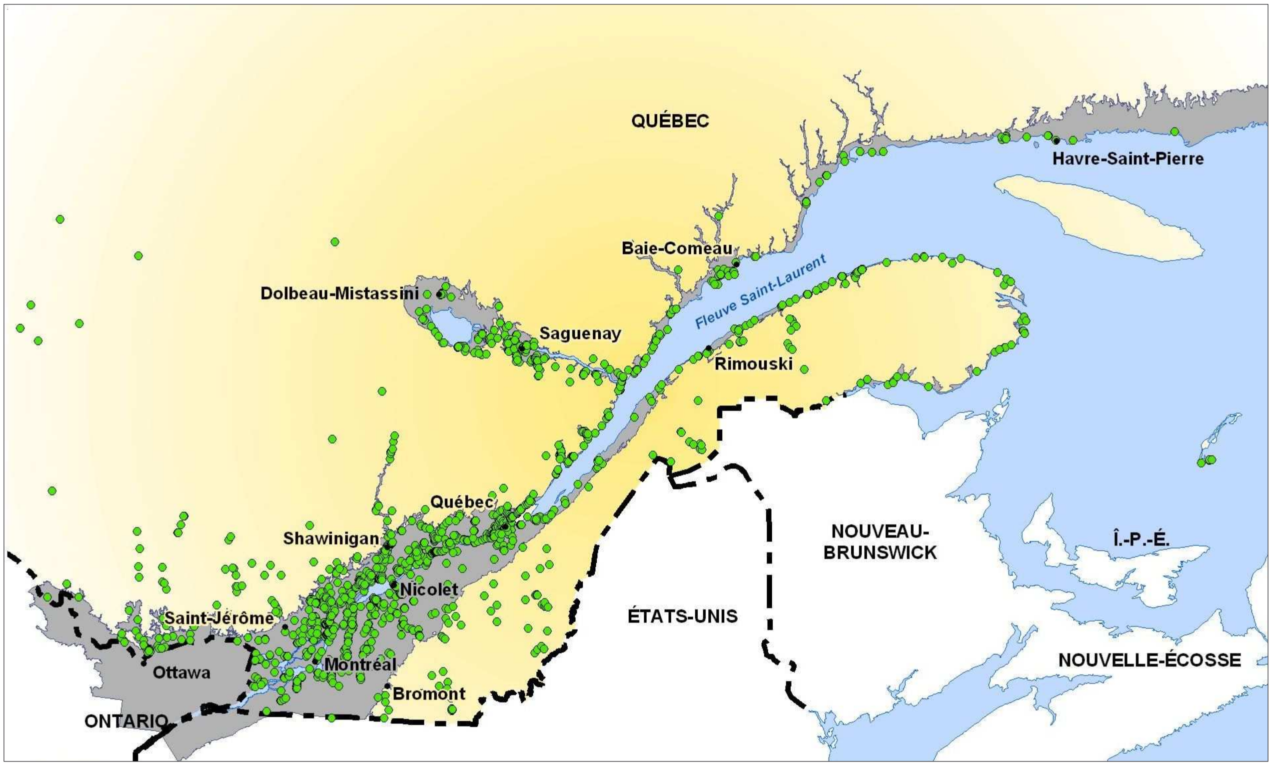

Figure 1:Distribution of post-glacial marine deposits (shown in grey) and distribution of data from the MTQ's mass movement inventory (green dots)

2 GLOBAL LANDSLIDE RISK MANAGEMENT PLAN FOR QUÉBEC

As mentioned by Demers *et al.*, 2008, the Québec government produces thematic maps of zones that are vulnerable to landslides. These maps form part of the global landslide risk management plan, and they allow for the acquisition of detailed knowledge of the territory, along with the application of a management and regulatory framework.

Mapping is based on a regional approach. The fact that a site is located within a vulnerable zone does not mean that a landslide on this site is inevitable, but rather that this site presents a set of characteristics that predispose it to this type of event to a certain degree. A landslide can occur naturally, or it may be triggered by factors of human origin.

The information that is available for a given territory consists of three thematic maps prepared at 1:5,000 scale (1:2,000 for a highly urbanized location). The first of these maps is called a "documentation map". It contains most of the basic data that is used to define the zoning. The second map is called a "map of zones susceptible to landslides" (Figure 3), and is used to identify the zones where unconsolidated sediments are potentially exposed to the dangers of landslide. Certain geological and geomorphological characteristics are classified as being revealing, predisposing, or aggravating factors. The presence and intensity of these factors are used to evaluate how susceptible a site is to the development of a landslide. The size of these zones is essentially based on the inventory of large retrogressive landslides prepared during mapping using the method proposed by Lebuis et *al.*, 1983. Finally, the third type of map represents the zones where various regulations respecting land-use are applied, which is called a "map of restricted zone related to landslides."

Figure 2: Photo of a flowslide scar (Saint-Jean-Vianney, 1971)

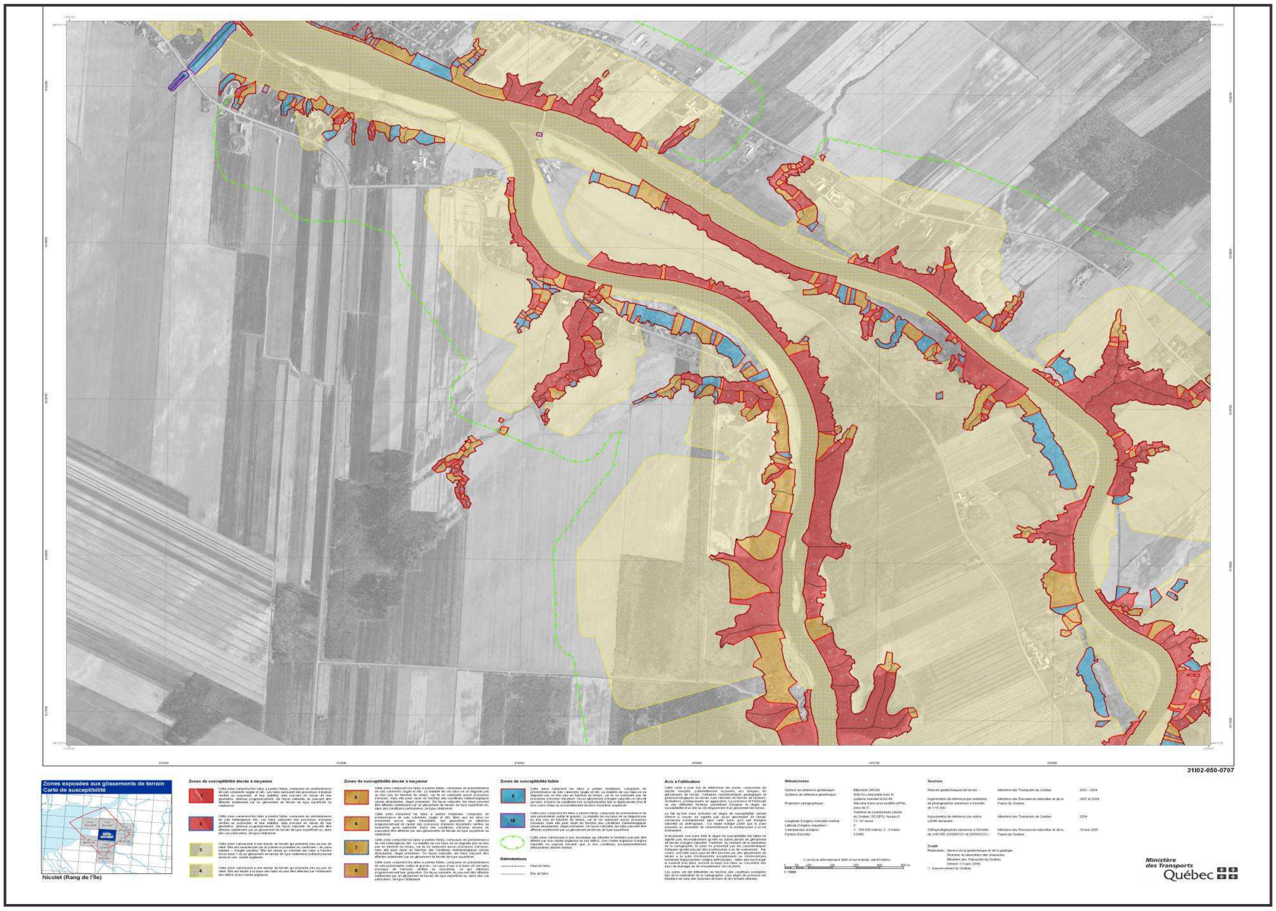

Figure 3: Example of a landslide susceptibility map

In the case of already developed land that is located within zones that are subject to landslides, the risks may already be at unacceptable levels, and therefore, they require immediate or short-term action (Figure 4). In these cases, it is best to evaluate the level of risk to people and property. Risk evaluation and analysis are conducted at the regional level for the entire territory of a municipality or for a watershed of a major watercourse. A "risk map" is prepared for a given type of hazard, such as the occurrence of a large retrogressive landslide, taking into account the consequences of a landslide in terms of hazards to people and property. The risk management method that is presented in the following paragraphs applies only to locations where susceptibility maps indicate zones that are potentially threatened by the occurrence of large retrogressive slides of the flowslide or lateral spread type. It allows for the quantification of this danger and its consequences in terms of loss of life at a given site.

The risk evaluation process is based on the quantitative risk assessment (QRA) method (Fell, 2005; Australian Geomechanics Society, 2000; Porter, 2007). The approach that is used to attribute a risk value to a given site takes into account each potential event.

Figure 4:Example of a site where stabilization work was carried out on an emergency basis because of a very high risk level.

3 RISK ASSESSMENT

3.1 Hazard Analysis

The first step in the risk evaluation consists of quantifying the probability that a large retrogressive landslide will occur at a particular site. This analysis is based on the generally recognized fundamental principle (Lefebvre, 1996) that a large retrogressive flowslide follows an initial deep rotational slide that has left a main scarp sufficiently high and inclined to trigger the retrogressive process. Therefore, the probability of a retrogressive process being triggered is conditional on the probability of the initial slide occurring at a given location, which is referred to as the "triggering zone" of the slide. A triggering zone generally appears in the form of a slope that is located along a watercourse and subject to erosion.

The regional probability of "$P_{Région\text{-}fr}$" is determined first. This is defined as the probability that a large retrogressive slide has occurred within a watershed according to an inventory covering a 100-year period. The probability of such an event occurring for a specific mapping sector "$P_{Secteur\text{-}fr}$" corresponds to the regional probability divided by the number of possible events within the mapped sector "$N_{Ép}$".

$$P_{Secteur\text{-}fr} = P_{Région\text{-}fr}/N_{Ép} \qquad [1]$$

The total number of possible events is calculated by dividing the watercourse section into geotechnically homogeneous segments, and then measuring the total length of zones within each of these segments that are susceptible to developing this type of slide, as indicated on a susceptibility map, taking care not to count any segment more than once. This total length is then divided by the average width of scars of large retrogressive landslides, as inventoried within the studied sector. The sum of the number of events for each of the segments gives the number of possible events for the entire sector studied.

However, not all triggering zones present the same capacity for the occurrence an initial landslide and not all have the same potential for the occurrence of a large retrogressive landslide. In order to take these variations of susceptibility into account at each potential triggering zone, the probability of a large retrogressive slide occurring must be weighted by a general coefficient that expresses the likelihood of an initial rotational landslide "K_{Rot}" occurring and a general weighting coefficient that expresses the likelihood of starting a retrogressive process "K_{Fr}", according to the following equation:

$$P_{Site\text{-}fr} = P_{Secteur\text{-}fr} \times K_{Rot} \times K_{Fr} \qquad [2]$$

Table 1 presents the factors and the partial weightings of these factors that are taken into consideration in comparing the triggering zones to each other and calculating a general weighting coefficient as a function of the degree of influence of each of these factors on the susceptibility of an initial rotational landslide occurring. For each of the zones that are likely to be affected by a large retrogressive landslide, the slope that exhibits the lowest level of stability is used. As expressed in equation 3, the product of all of these partial coefficients gives the global weighting coefficient "K_{Rot}":

$$K_{Rot} = K_H \times K_I \times K_F \times K_W \times K_S \times K_E \qquad [3]$$

where:

- K_H: coefficient representing the maximum height of the slope
- K_I: coefficient representing the average angle of the slope
- K_F: coefficient representing the general form of the slope
- K_W: coefficient representing the groundwater flow conditions
- K_S: coefficient representing the presence of signs of instability
- K_E: coefficient representing the degree of erosion at the base of the slope

Table 1. Example of calculation of K_{Rot}

Factors	Range	Partial weighting coefficient
Height of slope (K_H)	10 to15	1
	15 to20	1.25
	20 to25	1.5
	25 to 30	1.75
Inclination (K_I)	20 to 25	1
	25 to 30	1.25
	30 to35	1.5
Form of the slope (K_F)	concave	0.75
	rectilinear	1
	convex	1.25
Groundwater condition at base of slope (K_W)	i -	0.5
	i = 1	1
	i +	1.5
	i ++	2
Erosion (K_E)	moderate	1.25
	strong	1.5
	severe	2
Signs of instability (K_S)	yes	1.5
	no	1
Global weighting coefficient for landslides (K_{Rot})		**Min = 0.47 Max = 19.7**

* The values associated with each of these factors may vary slightly from one region to another.

Although the importance of all of these factors has been recognized by the profession, their weightings are determined arbitrarily, based on the experience of a group of geotechnicians and the available information pertaining to the sector studied.

Table 2 presents the factors and the partial weightings of these factors that are taken into consideration in evaluating the retrogression potential of an initial rotational landslide. As expressed in equation 4, the product of all of these partial coefficients gives the global weighting coefficient "K_{Fr}":

$$K_{Fr} = K_D \times K_{St} \times K_{Sur} \times K_{WL} \times K_{Ns} \quad [4]$$

where:

- K_D: coefficient representing the constraints on the disposal of debris
- K_{St}: coefficient representing stratigraphic conditions
- K_{Sur}: coefficient representing undrained shear strength
- K_{WL}: coefficient representing the liquid limit
- K_{Ns}: coefficient representing the stability number

Table 2. Example of calculation of K_{Fr}

Factors	Range	Partial weighting coefficient
Removal of debris hindered by obstacles (K_D)	yes	0.8
	no	1
Favorable stratigraphy (K_{St})	yes	0.8
	no	1
Undrained shear strength (K_{Sur})	0.5 to 1	1
	0.2 to 0.5	1.5
	< 0.2	2
Liquid limit (K_{WL})	60 to 80	1
	40 to 60	1.5
	20 to 40	2
Stability Number (K_{Ns})	3 to 4	0.8
	4 to 5	1
	5 to 6	1.5
	6 and +	2
Global weighting coefficient for large retrogressive landslides (K_{Fr})		**Min = 0.51 Max = 8**

* The values associated with each of these factors may vary slightly from one region to another.

In order for the debris from the first rotational landslide and subsequent landslides to be evacuated and not act as a counterweight, which would disrupt the propagation of movement, the spread of the debris must not be hindered by obstacles.

The influence of stratigraphic conditions, such as the position, thickness, and length of the layer of sensitive clay, are taken into account. In the case of this partial coefficient, only unfavourable conditions are taken into account at the present time, because this element is difficult to quantify.

Lebuis *et al.*, 1983, have demonstrated that there is a proportional relationship between the retrogression distance and the undrained shear strength "S_{ur}". The lower the undrained shear strength, the more easily the debris will flow.

According to Lebuis *et al.*, 1983, there is an inverse correlation between the retrogression distance and the liquid limit. Their compilation also reveals that the landslides that exhibit the strongest retrogressions have liquid limit values that varying between 20% and 40%. The use of the liquid limit "w_L" would allow for the required remolding energy to be weighted, because soils with a high liquid limit are more plastic and more difficult to disturb.

The available disturbance energy, which depends on the height of the slope and the undrained shear strength, among other factors, can be estimated using stability number "N_s". Slope with a high "N_s" value have greater potential energy for disturbing sensitive clays. Mitchell and Markell, 1974, suggested using a minimum value of 5, but this can be modulated as a function of site investigations within the sector studied.

The higher the value of "K_{Fr}", the greater the probability of an initial landslide occurring where the main scarp will be cleared of debris, and therefore, prone to the development of secondary failures.

The global coefficients (K_{Rot} and K_{Fr}) have the effect of extending the range of variation of the site probability values "$P_{Site-fr}$" as a function of the probability of the occurrence of large retrogressive landslides within a sector "$P_{Secteur-fr}$". However, these general coefficients most often have the consequence of increasing all of the values of "$P_{Site-fr}$". Therefore, a weighting coefficient "K_P" must be applied in order to centre the average of the probabilities attributed to each of the sites as a function of the probability within the sector (equation 5).

$$K_P = \frac{\overline{P_{Site-fr}}}{P_{Secteur-fr}} \quad [5]$$

$$P_{Site-fr} \times K_P = \left(P_{Site-fr}\right)_p \quad [6]$$

3.2 Consequence Analysis

The potential severity of consequences "C" for a zone at risk can be evaluated for each of the triggering zones by applying equation 7:

$$C = (V)\left[\sum_{1}^{n}\left(P_T \times P_S \times E_{vp}\right)\right] \quad [7]$$

where:

- V: vulnerability
- P_T: temporal probability
- P_S: spatial probability
- E_{Vp}: estimate of the number of people at risk of being affected

Despite the fact that the sparse statistics that are available reveal that not all of the people on a site where a large retrogressive landslide occurs will die, their vulnerability value has been set at 1. This choice is based on the meagre amount of data, the very high degree of disturbance of land caused by such landslides, and the importance of human life.

The temporal probability "P_T" represents the probability that there will be a vulnerable element within the zone of influence of the landslide at the time when the movement occurs. As mentioned by Fell *et al.*, 2005, the temporal probability is different for each occupant of a building. The highest occupancy rate for a given building is considered. In the context of a regional risk analysis, it is assumed that residents are at home 16 hours per day. For local business and farms, it is estimated that people work there 8 hours per day. These probabilities can be adjusted later as a function of the degree of precision of the available information.

The spatial probability "P_S" is based on the principle that the closer a vulnerable element is to the triggering zone, the greater the probability that it will be affected by a retrogressive landslide, regardless of the size of the zone that may potentially be affected. Each threatened zone is divided into four sub-zones parallel to the potential triggering zone. Therefore, the value of "n" in equation 7 is equal to 4. A probability is associated with each of the sub-zones, as determined on the basis of the inventory of scars of flowslides within the mapped sector in relation to the size of the zones at risk. The probability value is multiplied by the number of persons threatened in each of the subdivisions, and the sum of the products obtained gives the global spatial probability value.

An average of four persons per home and two workers per local business or farm is used in the analysis as a preliminary estimate. In cases where the exact number of people is known, a more precise value can be used.

3.3 Risk Estimation and Evaluation

The evaluation of the probability that a large retrogressive landslide will occur, along with the consequences associated with such an event, are shown in the form of logarithmic graph of the probability of the occurrence of large retrogressive landslides as a function of the consequences. According to the Geotechnical Engineering Office, 1998, and as used by Fell *et al.*, 2005, three risk levels can be defined: unacceptable, ALARP (as low as reasonably possible), and acceptable. As a general rule, the goal in ALARP zones is to reduce the risk.

Based on this concept, we have produced a graph using five risk classes, in which the unacceptable risk level corresponds to a very high risk, the acceptable risk level corresponds to a very low risk, and the ALARP risk level is sub-divided into 3 equal sub-classes (high, moderate, and low risk). This graph makes it possible to classify each of the potential zones according to this risk scale (Figure 5).

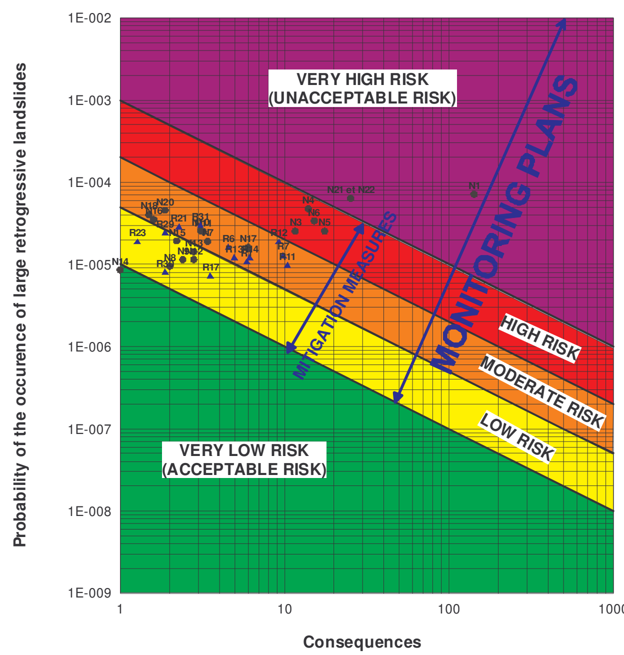

Figure 5: Classification of triggering zones by degree of risk

The results shown in the graph in Figure 5 are then transferred to the risk map (Figure 6). The location and type of property (home, store, farm, storage building, vacant lot) within the zones that are potentially affected by a large retrogressive landslide are also shown on this map.

4 RISK MITIGATION AND CONTROL

The risk maps facilitate the management choices for land-use managers. The risk management plan that accompanies these maps contains three types of actions. The first action consists of holding public meetings in order to inform those people who are affected with respect to the situation, the measures that will be undertaken by authorities, and the role that residents can

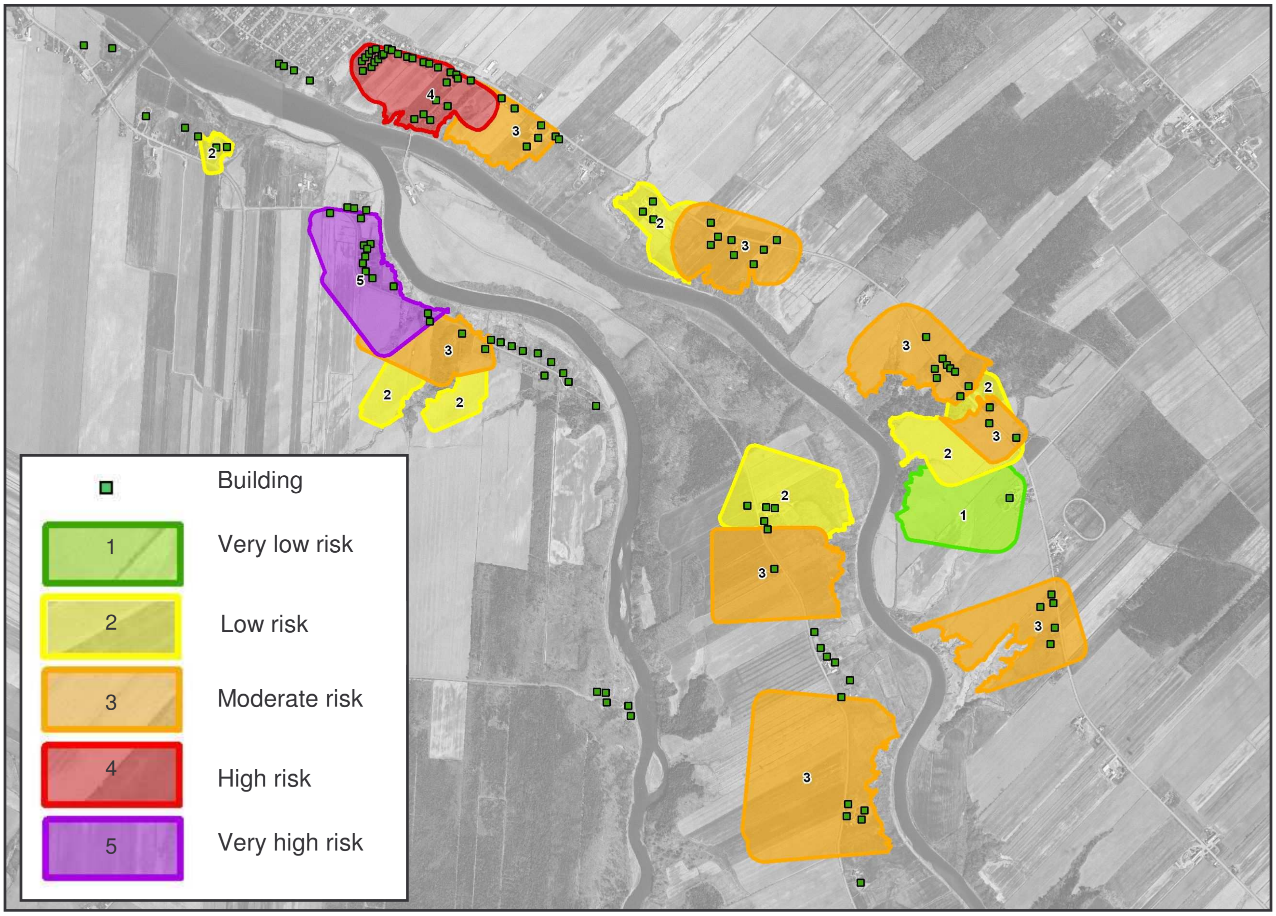

Figure 6: Example of a risk map for the dangers of flowslides

play in reducing risks, particularly by being aware of what activities are inappropriate, but also by being vigilant for the advance signs of instability (cracks, rotational landslides, etc.). The second type of action aimed at managing the risks consists of preparing monitoring plans for zones that are subject to natural landslides. Inspection maps can be prepared in order to facilitate the work of municipal and government workers. Finally, when managing instances where the risk level is too high, and where monitoring measures do not allow for the risk to be reduced to a level that is deemed to be regionally acceptable, it is appropriate to act quickly in order to reduce the risk level.

Figure 7 presents the flow chart for recommended actions for each risk class.

The sectors that are considered to be at very low risk should not receive any special attention, except when mass movements are reported, in which case the situation should be reassessed.

For sites within an ALARP zone, measures aimed at mitigating the risk level should be applied. Where there is a risk of flowslides, it is understood that these occur subsequent to initial deep rotational landslides that leave a steep main scarp. Therefore, for zones at low risk, an on-site inspection and reassessment of the situation should take place only after a reported movement. Sites that are classified as being at moderate risk should undergo an annual inspection of the banks only in cases where the probability of occurrence exceeds a threshold that is predetermined based on the probability for the sector. Zones that are at high risk should be subjected to a monitoring plan, with annual inspections of the triggering zones. Whenever earth movement is reported, the situation should be assessed quickly.

Special attention is paid to very high risk zones. For each of these zones, the imminence of the danger is evaluated by a geotechnical expert. In cases of imminent danger, steps must be taken to evacuate people who are located in the zone, and emergency works must be carried out. If the danger is not seen as imminent, a monitoring program that is adapted to the site is established, and prevention work is considered.

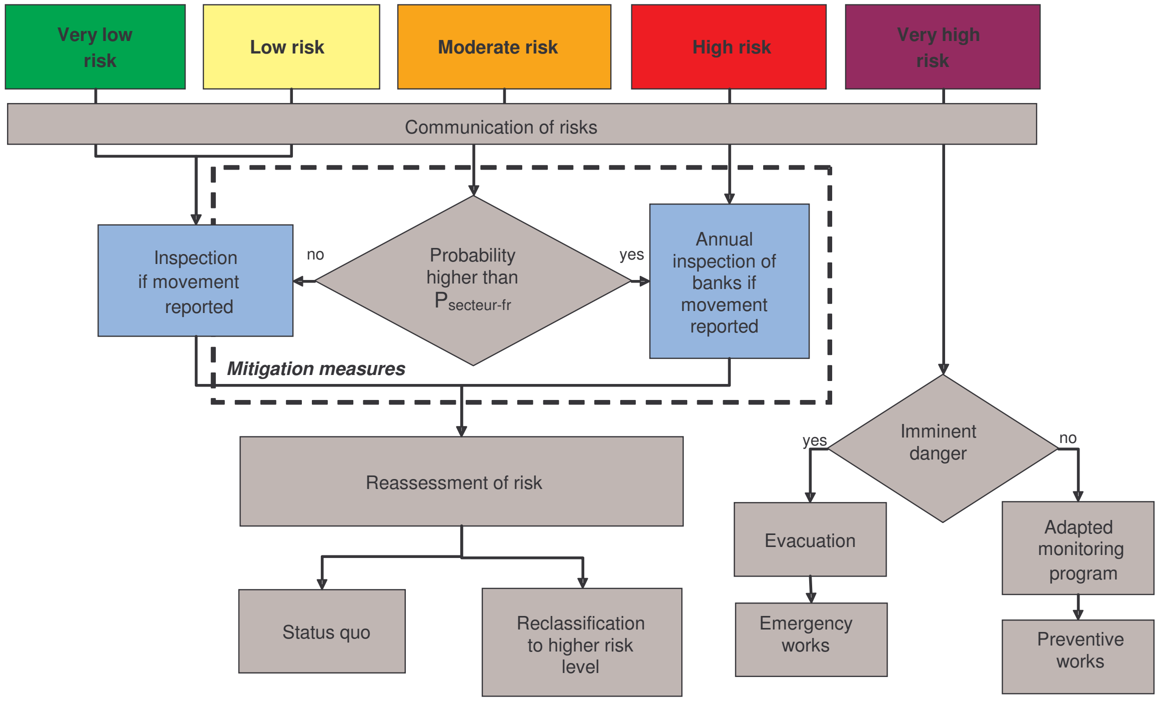

Figure 7: Flow chart showing the proposed approach for managing each of the degrees of risk

5 DISCUSSION

The risk evaluation method is based on elements that are characterized by varying degrees of precision.

Measuring the probability of the event is considered to be the most uncertain aspect, because it is based on very small samples. In fact, the number of historical events is always very limited in time, which results in a very rough estimate of the value of "$P_{Région\text{-}fr}$". Studies are currently underway to determine whether it is possible to use all of the large retrogressive scars within a watershed that have been observed since the regional hydrographic network was established. This approach would allow the use of a greater volume of data.

In addition, the evaluation of the event is based on the judgment of the expert in using the coefficients "K_{Rot}" and "K_{Fr}". The extent of the probability range that is obtained using this method has a very significant influence on the risk evaluation. For example, the variance between the minimum and maximum values of "$P_{Site\text{-}fr}$" can vary from 0.24 to 157.6, which represents a probability modulation of slightly more than two orders of magnitude.

On the other hand, the evaluation of consequences produces much less subjective data. The evaluation of temporal probability, vulnerability, and the number of elements at risk gives very "reproducible" results. With respect to spatial probability, the amount of data within a region is significant enough to make a relatively accurate evaluation.

The monitoring program constitutes the most delicate part of the risk management process. There is no guarantee that an initial deep rotational landslide will be detected in time to allow for preventive action. However, this approach should be considered to be a "security net", with the mesh size being made as small as possible in order to intercept the largest possible number of events. Therefore, this approach can be seen as part of an effort to reduce risks, and not to eliminate them completely.

6 CONCLUSION

The quantitative approach to risk evaluation that is described above is part of the global landslide risk management plan for the clayey soils of Québec. It facilitates the work of land-use managers in dealing with this type of risk by providing them with tools that allow them to compare the level of risk of susceptible sites within their territory, which in turn allows them to adopt measures aimed at minimizing the risks for sites where the risk level is deemed to be unacceptable.

This approach is subject to continuous development in order to respond to the specific needs of the managers who use it. It is currently being implemented in the Nicolet region, which is located in the heart of the clays that were deposited by the postglacial Champlain Sea.

Finally, an adaptation of this approach is being prepared in order to apply it to other types of landslides, especially the superficial landslides that pose a major danger, especially in the Saguenay–Lac-Saint-Jean region. This adaptation will be the subject of a later publication.

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