GIS Susceptibility Maps for Shallow Landslides: A Case Study in Shawinigan, Quebec, Canada

Michael Barbosu and James Gray

Abstract Landslides on various scales represent an important category of morphological processes in Quebec, playing an important role in the evolution of slopes, as well as causing instability problems for infrastructures and occasionally, loss of life. In this paper, we present the potential for shallow landslides, within the La Bissonnière amphitheatre, near Shawinigan, itself created progressively over the last 10,000 years, by a combination of episodic quick clay flows and fluvial downcutting of the St Maurice River and its tributaries. An infinite slope model, using the so-called factor of safety was used to produce GIS shallow landslide susceptibility maps for the area and the validity of the model was confirmed through field observations and comparisons with orthophotos.

Keywords Landslides · GIS susceptibility maps · Factor of safety · Shawinigan

1 Introduction

In the lowland areas of Quebec, covered at the end of the last glacial period by sensitive marine clays, slopes created by the fluvial incision of streams and rivers have created conditions favorable to catastrophic quick clay flows of varying magnitudes [12, 13].

Marine clays have indeed created the main pre-conditions for the larger, more deep-seated landslides, but for shallow, superficial landslides, other factors need also to be taken into account.

This paper evaluates these factors and uses them to design a GIS-based shallow landslide susceptibility map for the large La Bissonnière amphitheater, along the St Maurice River, near Shawinigan, Québec.

M. Barbosu (✉)
Rochester Institute of Technology, Rochester, NY, USA
e-mail: mxbsma@rit.edu

J. Gray
University of Montreal, Montreal, QC, Canada

2 Previous Studies

The deglaciation of the middle and lower St Lawrence Valley and the concomitant invasion of the lowlands by the Champlain Sea have been described in detail in [17].

Many authors have described landslides or quick clay flows in the region, some of catastrophic proportions [3, 5, 8, 12, 13].

The St Lawrence Lowlands descends gently from the Canadian Shield to the present St Lawrence River by a series of terraces, cut during recessive phases of the Champlain Sea invasion. The combination of initial relief between the margins of the Canadian Shield and the Saint Lawrence River, the thick blanket of sensitive marine clays and overlying sands, silts and clays, created ideal pre-conditions for both deep-seated quick clay flows and also for shallow landslides. Most slopes are adjacent to the hydrographic network and this is the source of the differences in altitude, while the process of embankment of the rivers lead to the destabilization of slopes. Several case studies in the area emphasize abundant precipitation or rapid snow-melt as triggering factors for such landslides [3, 7]. Moreover, higher water tables create zones susceptible to shearing [14] and therefore to mass movements.

For the St. Lawrence Valley, mass movements were classified into four major categories [13]:

(a) Rotational landslides, where the fracture plane corresponds to an arc of a circle and the movement of the material occurs in a rotation, having deeper fracture surface and considerable debris volume.
(b) Retrogressive landslides, which essentially have the same mechanisms as rotational landslides, except for the fact that there is a succession of ruptures; this type of landslides can cause the clay to liquefy.
(c) Clay flows, characterized by a very strong retrogression and major liquefaction of the clays.
(d) Shallow landslides, that can be up to 2–4 m deep and are mainly generated by the water saturation of the soil. They develop in marine sediments and they occur in large numbers each year, especially along rivers and steep escarpments, in clayey terrain [9]. These landslides are a consequence of changes in the stress on the slope and many of them represent a preliminary step for a progressive failure, which can develop into a large-scale mass movement.

The current work concerns shallow landslides in the South Shawinigan region of Quebec.

3 The Study Area

The Shawinigan region of Quebec is notorious for the landslides that have taken place here and the several scars from clay flows [5, 12]. The sites of old landslides in marine clay show a high susceptibility to new, superficial ones, along the stream

gullies; they can cause local instability and then spread over larger areas, [15]. The unconsolidated deposits in the region are composed of sand at the surface, clayey silt at depth, and an irregular layer of till at the base, as presented in [8]. These deposits rest on a substratum made up of Precambrian rocks and crossed by the Saint-Cuthbert fault. The region is also characterized by a series of stepped terraces on both sides of the Saint-Maurice River, that are cut across by the amphitheater mentioned above.

Our particular study area, described in detail in [8], is located in the Mauricie area of Quebec, on the site of the La Bissonnière amphitheater, outlined below in Fig. 1a.

For the La Bissonnière amphitheater we also generated the Digital Elevation Model (DEM), presented in Fig. 1b.
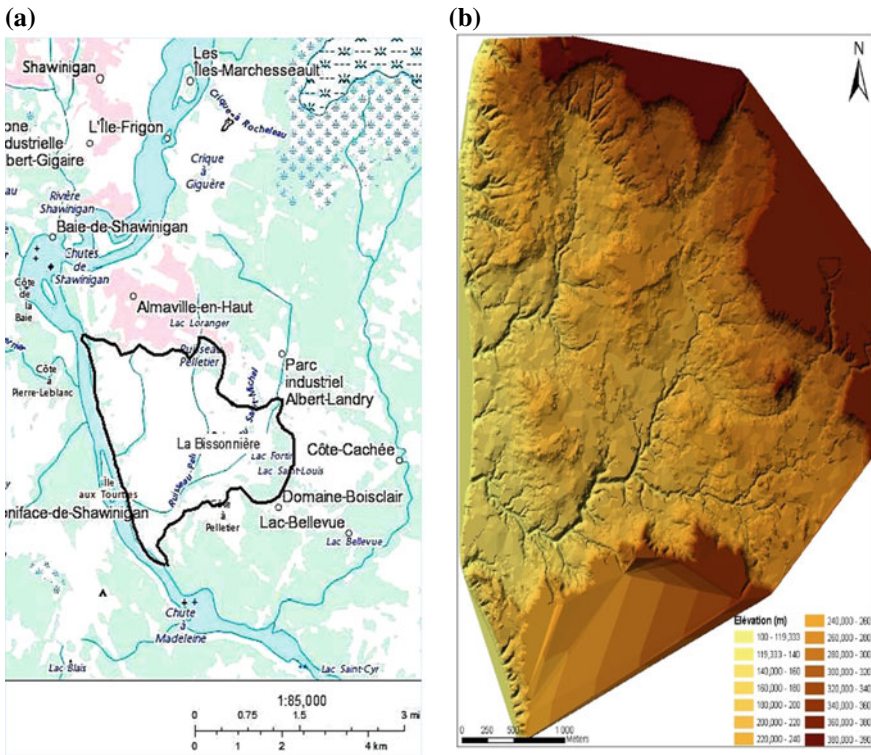

Fig. 1 a Study area with approximate boundary of La Bissonnière Amphitheater © Open Government License—Canada, 2022. **b** DEM generated for the study area, in La Bissonnière Amphitheater

4 Methodology

Our goal is to develop and implement a model used to create GIS-based shallow landslide susceptibility maps for the La Bissonnière amphitheater.

Landslide susceptibility was defined by [4] as the tendency of a landslide to occur in a specific region in the future and there are several indicators used to suggest whether a site is susceptible to mass movements.

The slope angle is one of them, and in the context of a temperate climate, the angle of equilibrium for clays is around 20°, so slopes with an inclination greater than this value are more likely to become unstable [11].

Changes in the position of the water table is another important factor to consider, because it induces a change in pore pressure and can generate shear planes in cracks that exist in clays [10, 11]. In fact, when any variable that influences the slope stability undergoes a strong variation in a very short period of time, it can generate a destabilization of the material and cause a land slip or reactivate a pre-existing one [2, 20].

It may be, for example, an exceptional rainfall event, leading to water saturation and erosion, a seismic shock, or an anthropogenic action—like building new road embankments or trenches at the bottom of the slope, etc.

Shallow landslides—which represent the focus of our study—have the plane of failure oriented parallel to the surface of the slope, are translational, and can have a thickness of up to 2–4 m. To obtain the susceptibility map for an area to shallow landslides we used the infinite slope model [16, 19].

This model comes with the following assumptions, applicable to our study area:

– we assume that the failure occurs as a single layer and the failure plane is infinitely wide, with a shearing surface and a water table parallel to the ground surface;
– we also assume that all parameters involved in the model are continuous functions, allowing us to perform spatial interpolation between the sample points;
– finally, we consider that susceptibility to landslides is a constant over time, which is true for shorter periods of time, as is our case, but over long time periods, there is some temporal variability [6].

In the present study of the Shawinigan region, the information we had and collected on the subsoil, along with the existence of large-scale topographic maps allowed us to opt for an approach of generating landslides susceptibility maps based on this infinite slope model, with a spatial evaluation of the factor of safety, FS.

FS is the ratio between two contradictory forces acting on a slope: the frictional force (resistance) and the inertial force (movement); here we used the formula [16, 18]:

$$FS = \frac{c + hg\cos^2\theta\,(\rho_{mat} - \rho_{water}m)\tan\phi}{\rho_{mat}hg\sin\theta\cos\theta} \tag{1}$$

where:

c = cohesion of the material (kPa)

ρ_{mat} = density of the material (kg/m^3)

ρ_{water} = water density = 1000 (kg/m^3)

θ = slope angle (degrees)

h = thickness of the sliding mass (meters)

Φ = angle of internal friction (degrees)

g = gravitational acceleration = 9.81 m/s^2

$m = d/h$, the ratio between the vertical distance d (from the sliding surface to the phreatic surface) and h (defined above). This way, m varies between $m = 0$ if the water table is at or below the slide surface and $m = 1$ if the water table is at the ground surface.

Note that even if in theory, FS = 1 would be the limit for slope stability/instability, in practice, FS = 1.5 is accepted as a critical threshold state because of the approximate nature of Eq. (1), given the limited number of measurable parameters and the fact that other factors, like the influence of vegetation cover, etc., are ignored. In our current study and in the subsequent maps we took 6 classes of susceptibility:

– very high susceptibility (FS less than 1);
– high susceptibility (FS between 1 and 1.5);
– moderate susceptibility (FS between 1.5 and 2);
– low susceptibility (FS between 2 and 3);
– very low susceptibility (FS between 3 and 4);
– stable areas (FS greater than 4).

This classification indicates areas with different degrees of stability, where landslides may occur. The prediction based on measurable parameters is very complex, [1], because of the uncertainty concerning some initial conditions, like the thickness of the sliding mass, the properties of the materials, and the hydraulic conditions, like the position of the water table, which is highly variable over time.

Given the variety and amount of data that involve landslide processes, the most appropriate approach for generating landslide susceptibility maps is with Geographic Information Systems (GIS). Here we used the ArcGIS software with Spatial Analyst and the Raster Calculator. The algorithm developed to generate the susceptibility maps for shallow landslides involved the following steps:

– topographic maps were digitized and the DEM, shown in Fig. 1b, was obtained; then, the DEM layer in Triangulated Irregular Network (TIN) format was converted to a raster format, each raster cell having 1 m^2;
– samples from 45 points (with a range of depth between 2–4 m) in the La Bissonnière amphitheater were collected and soil geotechnical analyses were performed; these lead to ranges of the angle of internal friction (22°–34°), cohesion of material (10–30 kPa) and density of material (545–1420 kg/m^3). Particular values determined for the 45 points along with interpolated/extrapolated values for all other points in the region were used in the equation of FS.

Finally, FS was fed into the Raster Calculator and susceptibility maps were generated at a scale of 1:5000, showing instability of slopes for each pixel.

Our final result has an interactive character, which allows the modification of certain parameters. In the current paper, this latest feature is exemplified with two scenarios concerning the position of the water table: $m = 0$ (water table at or below the slide surface) and $m = 1$ (water table at the ground surface); these two situations are illustrated in Figs. 2 and 3, respectively.
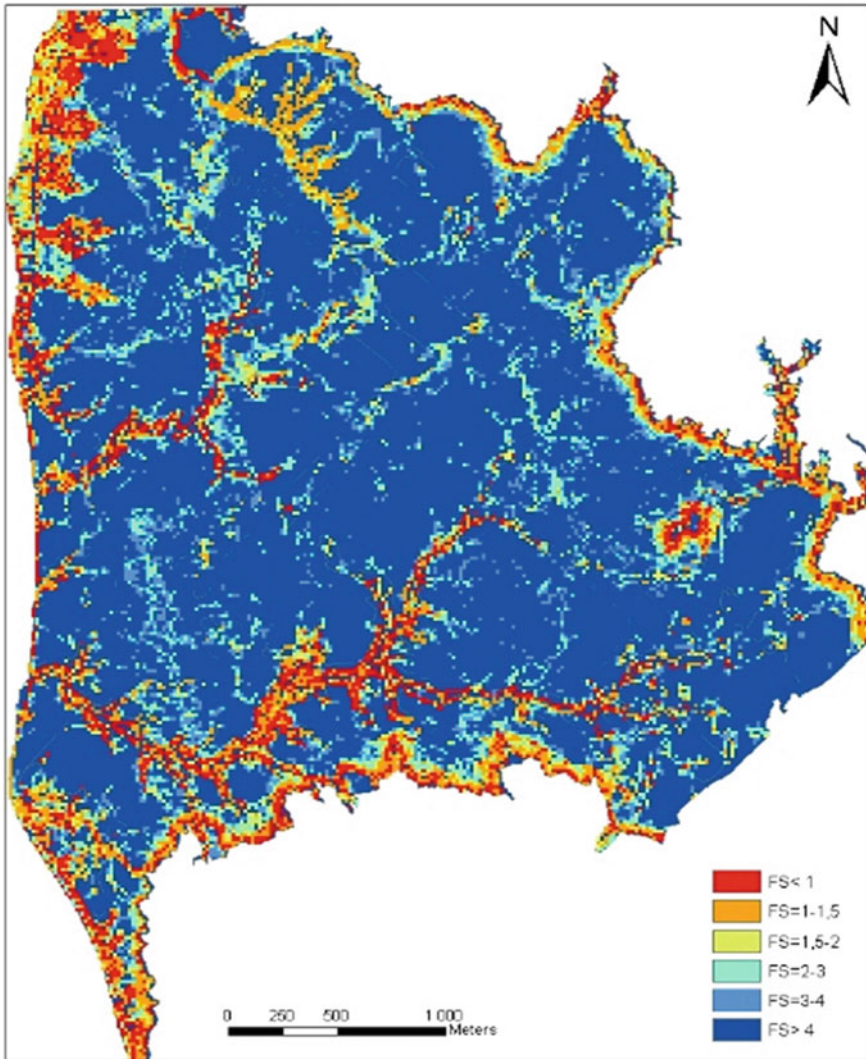

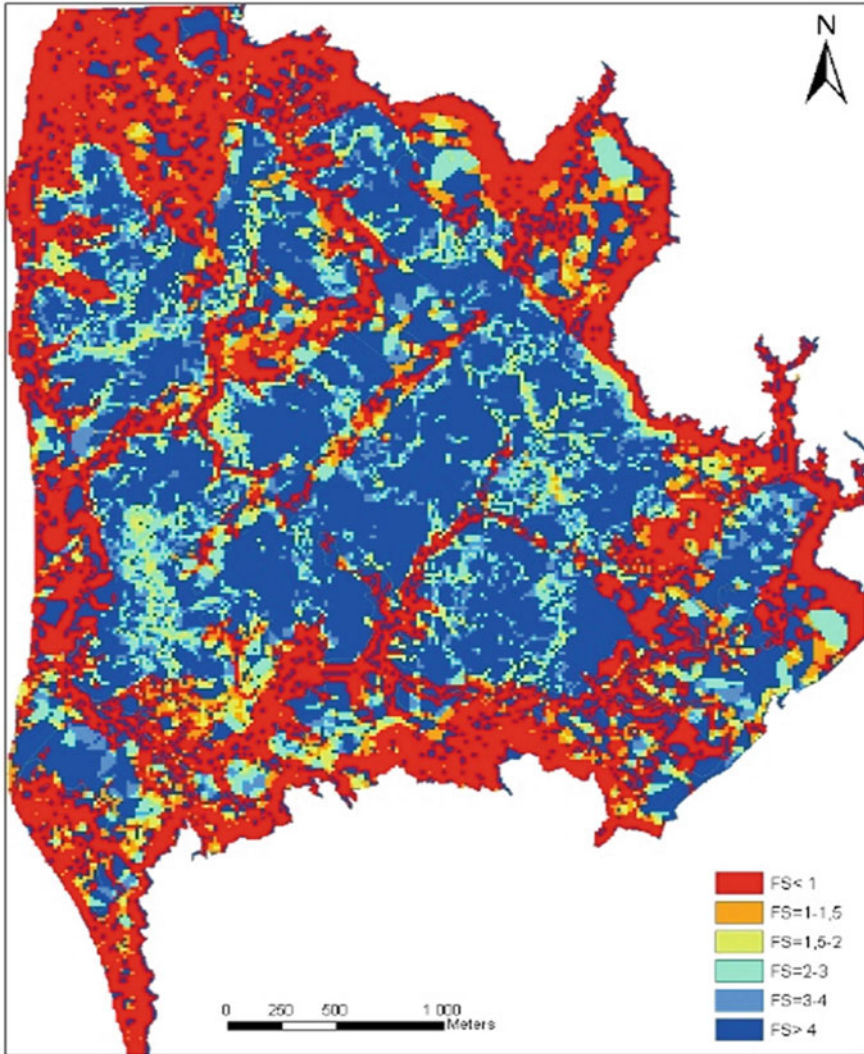**Fig. 2** Landslide susceptibility map for La Bissonnière, when $m = 0$

Fig. 3 Landslide susceptibility map for La Bissonnière, when $m = 1$

5 Results and Conclusions

The current work shows the potential of the GIS spatial analysis technique used along with the infinite slope model to assess susceptibility to shallow landslides. GIS is very efficient for handling and processing a large amount of data in a short time and at a relatively low cost. Changes in input parameters, certain human activities, and

seasonal climate variations can also be incorporated into the model, updating and improving landslide susceptibility maps almost in real-time.

Based on the methodology described in the previous section, in Fig. 2 and Fig. 3 we generated maps of susceptibility to shallow landslides for La Bissonnière; they are the final output of our model and represent, as mentioned above, the two extreme scenarios for the position of the water table, i.e. for $m = 0$ and $m = 1$.

Maps from Figs. 2 and 3 indicate that most regions in the La Bissonnière amphitheater are relatively stable, except for some sections occupied by escarpment and small ravines, which are subject to small superficial landslides. In percentages, zones affected by these shallow landslides vary from 6% when $m = 0$ to 35% when $m = 1$. As expected, most regions of high and very high susceptibility correspond to areas with steep slopes. However, we can identify sectors susceptible to landslides that are not necessarily related to slopes, but to soil properties, under conditions of high humidity. These areas are located in the N and NE part of the amphitheater and are distinguished by the low cohesion of materials and the higher content of clays. We also notice that, while overall this ancient landslide amphitheater has returned to a state of relative equilibrium, with a very low risk of large-scale quick clay flow or landslide, shallow landslides still occur. They are associated with direct or indirect anthropogenic impacts and as indicated in [14], about 80% of landslides that occur each year are the result of the erosion of a watercourse at the base of a slope, while the remaining 20% result from inappropriate human interventions. Therefore, in the current context of climate change, the whole issue of risk assessment and susceptibility to landslides should be monitored and constantly reassessed.

We checked and confirmed the validity of the model through comparisons of our susceptibility maps with orthophotos and recurrent field observations; besides, the latest landslide we visited, occurred in the city of Shawinigan on October 24, 2021, at the north of our study area, leading to the evacuation of 4 houses situated on the Boisclair street.

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