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Landslide hazard mapping within a regulatory framework: which lessons can be learned from a quantitative approach in New-Caledonia?

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ABSTRACT: A project was engaged to create landslide hazard maps for multiple municipalities in New Caledonia within a regulatory framework. A quantitative method was selected, offering the benefits of both qualification and quantification of landslide hazards, including temporal and intensity factors. Although some bold choices were made in the project's implementation, feedback from experience confirms the suitability of the strategy for regulatory purposes.

Keywords: landslide hazard, quantitative method, regulatory framework, mapping

Introduction

Landslide hazard H_L expressed the spatial and temporal probabilities that an event with a particular intensity occurring within an area for a reference period (Corominas et al., 2014):

$$HL = P(SL) \times P(TL) \quad (1)$$

With L represents a specific type of landslide (with a certain magnitude); H_L corresponds to the landslide hazard; P is a probability; $P(S_L)$ denotes the spatial probability for the type of landslide; T represents a given period; and $P(T_L)$ depicts the temporal probability of landslide occurrence within the period. Two groups of methods can be used to assess H_L : qualitative (i.e. expert and multicriteria methods) and quantitative (i.e. statistical and physically based methods) methods. In France and its overseas territories, including New Caledonia, the preference has traditionally been for qualitative, expert-based methods (Thiery et al., 2020). However, the available heuristic landslide hazard maps in New Caledonia lack consistency and standardization, making practical applications for land-use planning challenging. The need for quantifying and mapping landslide hazards became evident after a significant event in Houailou in 2016, resulting in fatalities, injuries, and property damage. This challenge is exacerbated by the increasing number of events linked to climate change impacts (Colas et al., 2022).

In recent years, the multiplication of available spatial data and quantitative mapping tools under GIS, R and Python have simplified the process of assessing H_L . The advantage of this type of approach is that large areas can be assessed and mapped rapidly, and spatio-temporal probabilities can be obtained to better quantify the hazard. Given these requirements and observations, it is evident that this type of quantitative approach should be employed in New Caledonia. Nonetheless, it's essential to maintain a certain simplicity to ensure its applicability and comprehensibility by uninitiated (end-users, practitioners, etc., Thiery et al., 2020). Furthermore, it should enable the tracing of each stage to facilitate an understanding of the various choices made for regulatory implementation.

Thus, the objective of this article is to outline the different steps of quantitative H_L mapping applied in New Caledonia within a regulatory framework. After introducing the area and its characteristics, an explanation of the methodology and its underlying philosophy is described. Then, the outcomes of a calibration and validation step and systematic application to several



municipalities are presented. These results emphasize the challenges faced at different stages of the methodology and the insights gained from conducting quantitative H_L mapping within a regulatory framework. This allows for the evaluation of the complexities and difficulties related to the cartographic context of the study.

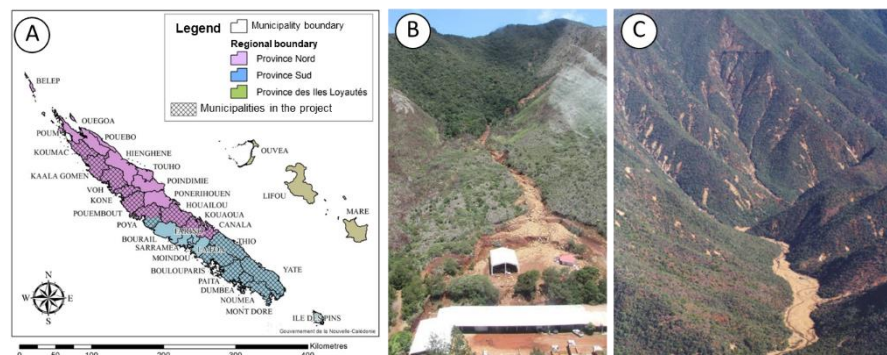
Site

New-Caledonia is located in the southwestern part of the South Pacific Ocean, and comprising five islands (Fig. 1). The main island, known as Grande Terre, stretches 400 km in length and 50 km in width. It is structured by a continuous line of medium-elevation mountains oriented northwest-southeast, incised by deep valleys. This mountainous relief divides the island into two distinct regions: the narrow, steep-sloped east coast and the broader west coast with a well-developed piedmont area extending between the peaks and the coastline (Colas et al., 2022). The island is characterized by three distinct morphological regions:

- (i) The southern massif, primarily composed of peridotites, with mountains reaching approximately 1,600 meters (a.s.l.), deeply incised by valleys, and a metamorphic complex known for its steep slopes and a substantial regolith layer;
- (ii) The central chain, featuring an ancient depressed zone marked by hills and flattening features, with altitudes ranging between 400 and 600 meters (a.s.l.);
- (iii) The western piedmont, a vast system of glacis connecting the coast and alluvial plains to the western edge;

New-Caledonia experiences periodic tropical depressions and cyclones, with a recorded 55 such events in 141 years (source: www.meteo.nc). These events bring rainfall intensities exceeding 350 mm within 24 hours. The island's steep slopes, surficial formations, and heavy rainfall make it prone to numerous landslides and debris-flows.

Figure 1. A. New-Caledonia and municipalities in the project. B. Debris-flow in Houailou (2016). C. Shallow landslide in coarse materials.



Methodology

The methodology relies on essential assumptions to account

for each component of the hazard equation (1). It is designed to be understandable within a regulatory framework, especially for non-scientists. The field and observation component serves as the foundation of this project's logic. The use of numerical models aids in quantifying and tracking the various stages of the process. This rationale involves systematic inventories conducted in each municipality. For each one an associated database includes information on event type, the nature of materials involved, occurrence and reactivation dates, source documents, and morphometric parameters. Spatial probabilities of failure and propagation are computed based on morphometric attributes. A straightforward quantitative method (Weight of Evidence, Thiery et al., 2007) is employed to assess failure susceptibility. It allows for a quick analysis of the influence of each variable class and obtaining failure probabilities based on the density of phenomena per class. The strategy used for assessing susceptibility is based Thiery et al. (2007). Propagation is assessed using an empirical method that relies on the reach angle of the phenomena (Corominas et al., 2014). A cellular automaton computes propagation probabilities for each type of event (Flow-R, Horton et al., 2013). Temporality is determined for the next 100 years through probability calculations by period, assuming stationarity (the same number of phenomena will recur for the same period in the future). Finally, intensity is



based on velocity, translating the potential damage to a residence for each type of event. Before the systematic application of the methodology, a cross-calibration-validation technique (Chung and Fabbri, 2003) is used in the Mont-Dore to define the set of best predictive variables.

Results

The first step was to create an inventory for each municipality with a specific nomenclature based on the materials involved and mode of propagation (Fig. 2). 27372 landslides of different types have been inventoried for 12 municipalities (Fig. 1A & 1B) for a density of 3.25 event per km². From the cross-validation-calibration technique used in Mont-Dore 4 essential variables for each type of landslide emerged (i.e. slope classes, landforms, lithology and surficial formations). Other variables were tested, but without any improvement for the various statistical tests (success rate, prediction rate, relative error, certainty tests). Each susceptibility map was then reclassified into 5 classes according to JTC-1 recommendations with some adjustments (Fig. 2.A). For each failure susceptibility class, propagation envelopes were computed. The rules adopted were defined on the basis of the reach angle distributions for each event and for each susceptibility class (Fig. 2B). Annual probabilities for each class are then applied according to the number of events per year for each susceptibility class. Finally, these probabilities are updated by integrating the intensity (i.e. velocity classes) selected for each type of event. The Fig. 3 shows the final results for the Mont-Dore and Houailou.

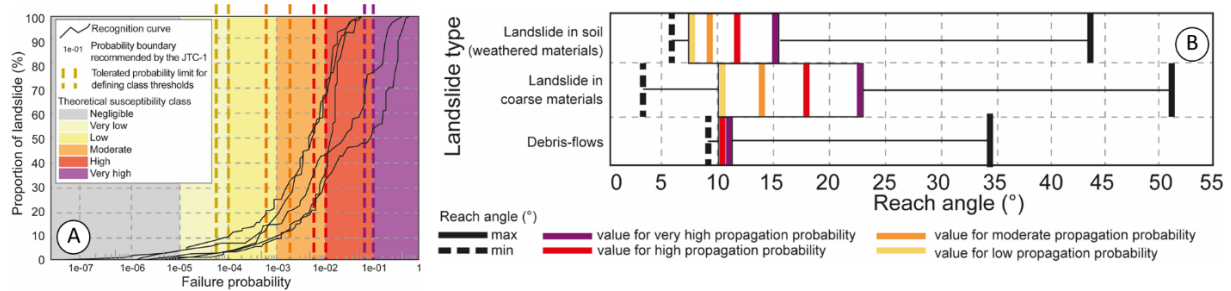


Figure 2. A. Recognition curve for landslide in coarse materials to identify failure susceptibility classes for several municipalities and tolerance admitted to establish the classes. B. Reach angle identified for different type of landslides and minimal values selected for each failure susceptibility classes for 6 municipalities.

Discussion: lessons learned from this operationally-oriented project

While the methodology may appear simple and easy to implement, in practice, several challenges were noticed. They provided valuable lessons that should be considered for the remainder of the project and for other hazard mapping projects applied in a regulatory context.

(i) Lesson 1: in France, typically, H_L maps are generated based on the prediction of the most probable and intense event expected over the next 100 years. However, this approach does not necessitate a breakdown by landslide type. In this study, a comprehensive inventory and a classification system for the observed events was performed. Furthermore, despite the inventory not being exhaustive (as some events may have been overlooked for various reasons), it appears to be representative. The hazard maps obtained have yielded positive feedback.

(ii) Lesson 2: the environment in New Caledonia is distinctive, encompassing formations prone to landslides, both natural and human-induced. To address this uniqueness, a specific map of surficial formations was carried out, considering such as weathering and mining formations prone to landslides and debris flows.

(iii) Lesson 3: despite calibrating and validating the methodology, it became evident that adjustments were required. They involved considering only the relevant areas or adopting a specific strategy that incorporated a simplified lithological map. In a regulatory context, as opposed to a research project, practicality and adhering to reasonable deadlines are essential. Thus, while not deviating from the underlying methodology's philosophy, some pragmatic adjustments were deemed necessary.

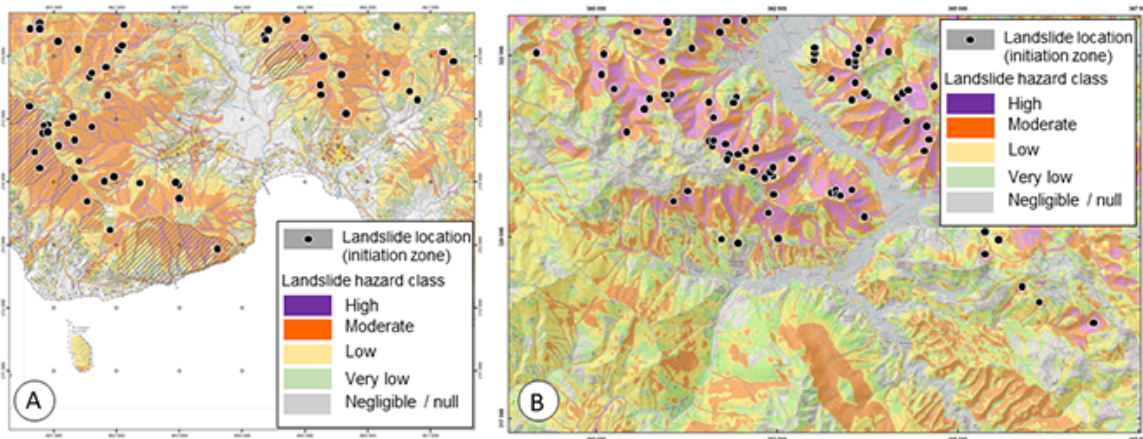


Figure 3. Extract of landslide hazard map (for all landslides). A. For Mont-Dore. B. For Houailou.

(iv) Lesson 4: the calculation of propagation envelopes is based on strong assumptions derived from reach angles and statistical calculations. This solution proved suitable for our mapping. However, two salient points have to be emphasized. The first concerns landslide reach angle classes. The approach is based on quantiles to be used per susceptibility class. While this choice is suitable for our purposes, it raises questions about its applicability elsewhere. The second point concerns the reach angles selected for debris-flows: some expert adjustments were performed with values sometimes quite far from the statistical results (probably due the quality of the DTM and the complexity of phenomena difficult to model with empirical method and cellular automaton). However, values remained within the ranges used generally.

(v) Lesson 5: to establish a framework for H_L assessment, intensity based on velocity has been incorporated. This intensity criterion relies on expert opinion rather than monitoring, which may raise concerns about its singularity. However, recent cyclonic events that triggered landslides in Mont-Dore have demonstrated that the hazard classes determined with this criterion align well with the observed events. This feedback underscores the suitability of the strategy adopted for a regulatory framework.

Conclusion

The H_L mapping project for the 15 municipalities of New Caledonia demonstrates the feasibility of creating quantified hazard maps using a representative inventory. Recent feedback from the commune of Mont-Dore affirms the suitability of the adopted strategy. However, it's important to note that current maps do not consider triggering factors, and despite their regulatory nature, they lack specific thresholds. Addressing these aspects is the next step, which will involve the development of a demonstrator.

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