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Yannick Thiery, Olivier Maquaire, Mathieu Fressard, Mélody Prémaillon,  
Marc Peruzzetto, Séverine Bernardie, Gilles Grandjean

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## **Landslide risk assessment and mapping at national scale for France: toward reflections on the integration into the national prevention strategy**

Y. Thiery<sup>1</sup>; B. Colas<sup>2</sup>, O. Maquaire<sup>3</sup>, M. Fressard<sup>3</sup>, M. Premaillon<sup>2</sup>, M. Peruzzetto<sup>4</sup>, S. Bernardie<sup>4</sup>, G. Grandjean<sup>4</sup>

<sup>1</sup> BRGM, Pessac, France

<sup>2</sup> BRGM, Montpellier, France

<sup>3</sup> IDEES - UMR 6266 CNRS - Université de Caen Normandie, Caen, France

<sup>4</sup> BRGM, Orléans, France

**ABSTRACT:** Indicators and landslide risk maps for France at national scale are computed and presented. Two quantitative approaches are employed, and the results, including the landslide hazard map and landslide risk maps generated from composite indicators for built-up areas and roads, are examined. These documents are intended to be used in the national strategy for landslide risk prevention.

**Keywords:** landslides, hazard and risk, national scale, France, strategy for prevention

### **Introduction**

Landslide risk is the spatial and temporal probability of a phenomenon of a certain intensity occurring over a defined period of time in a specific area, causing damage to people, buildings, infrastructure and services (Thiery et al., 2020). To assess this risk, both the hazard and the vulnerability of exposed elements must be considered. Assessing and anticipating landslide risk are generally conducted at the local, and regional scales, involving the production of cartographic documents using different methods (Thiery et al., 2020). Few countries, such as Cuba, Georgia, India, China, and Italy, have undertaken quantified assessments on a national scale involving different quality datasets and specific mapping strategies (Donini et al., 2022).

While France was a pioneer in the systematic assessment and mapping of landslide risk at the municipal level (PPR, Plan de Prévention des Risques, MATE/MATL, 1999), and some semi-quantitative National Landslide Susceptibility Maps (NLSM) have been produced (Malet et al., 2013), no indicative landslide risk assessments and maps have been undertaken at the national scale. It conveys that the French national strategy lacks a comprehensive and informative documents about the most vulnerable areas regarding landslides.

This work presents a quantified approach to producing a national landslide risk map (NLRM) in France at 1:500 000. The methodology was based on the principles the exposed elements and risk assessment part. These principles are as follows:

- i. Use of a quantitative, data-based calculation method, reducing the subjectivity of weightings used previously (Malet et al., 2013);
- ii. Introduction of new spatial variables to improve the identification of specific areas;
- iii. Introduction of exposed elements (built-up areas, roads) to assess landslide risk.

The approach is designed to be straightforward and practical, minimizing the reliance on overly complex data. The documents generated serve as a preliminary step in identifying landslide risk areas. Furthermore, they can initiate a process of consideration regarding how to incorporate these documents into the national landslide risk assessment strategy, particularly in areas lacking hazard maps for regulatory purposes, which may warrant increased attention.

### **Materials and method**

The spatial variables, principally derived from national databases, can be grouped into 6 groups (landslides, topography, geomorphology, geology, landuse, physio-geographic areas).



Landslides were derived from the BD-Mvt, the national incident database (Thiery et al., 2020). The phenomena are essentially shallow landslides causing damage to infrastructure; debris flows and mudflows are not included in the study. It lists the locations of events, trigger dates, activity, and sometimes the damage caused. Topography was represented by two DEMs selected from IGN databases; one at a 250 m resolution and the other at a 50 m resolution. They were used to generate maps as: slope, aspect, curvature, etc. Geomorphology was automatically derived from DEMs into 8 major classes (Iwahashi and Pike (2007)). Soil parent materials was derived from a simplification of lithological surveys conducted at a one-millionth scale (<https://infoterre.brgm.fr/page/cartes-geologiques>). Two maps were used: one with 11 classes, and one more detailed with 27 classes. Additionally, a map depicting the state of regolith destructuration based on the density of faults, their types, and the different class of seismicity was created. The idea was to add a component on the state of the lithology as a function of tectonics. Landuse was derived from Corine Land Cover (CLC), THEIA database (<https://www.theia-land.fr/product/carte-doccupation-des-sols-de-la-france-metropolitaine/>) and road database from IGN (<https://geoservices.ign.fr/route500>). Physio-geographic units represented macro-geographic units based on climatic areas and relief.

Considering that a comprehensive landslide risk assessment, including the temporal aspect and propagation, is not feasible at this working scale and due to the lack of consistency about this information in the BD-MVT (Thiery et al., 2020), it was decided that the susceptibility map would replace the hazard map. The strategy was divided into four steps:

- i. Selection of the best spatial variables (i.e. landslides, topography, geomorphology, geology, land use, physio-geographic area ...) according to their aptitude to build LSM. The computations were performed with a cell size of 250 m in order to optimize the processing time.
- ii. After defining the optimal set of spatial variables, calculations were conducted using a 50 m cell size and dividing the country into 18 physio-geographic units;
- iii. Each unit was subjected to a statistical validation procedure with four tests before reclassification into 6 classes following the limits given by the JTC-1. The limits are given for guidance purposes. The reclassified maps were merged to obtain a single NLSM.
- iv. Finally, the new NSLM (Fig. 1) was compared to different local landslide databases not implemented in the national landslide database (BD-MVT) and to different national, regional, and local LSM for different areas.

Once validated, the NLSM served to generate indicative NLRM for the built-up areas and the roads for each municipality. Data used were THEIA landuse database and IGN road database (Route500©). Two indicators were computed for each municipality:

- i. The first was the absolute risk index (ARI) representing the total of weighted surfaces for exposed elements to a specific hazard class. It quantitatively reflects the surface areas of exposed buildings or roads, assigning higher weights to areas with higher levels of hazard. The objective is to prioritize efficiency, operating on the premise that: "if we were to select a single municipality for our prevention efforts, with unlimited resources, which one would we select?"
- ii. The second was the relative risk index (RRI). Its computation involved dividing the ARI by the total surface area assessed, whether it's a municipality or the entire stake's surface area. RRI aimed to identify municipalities most significantly impacted by the risk, based on the proportion of the area being considered.

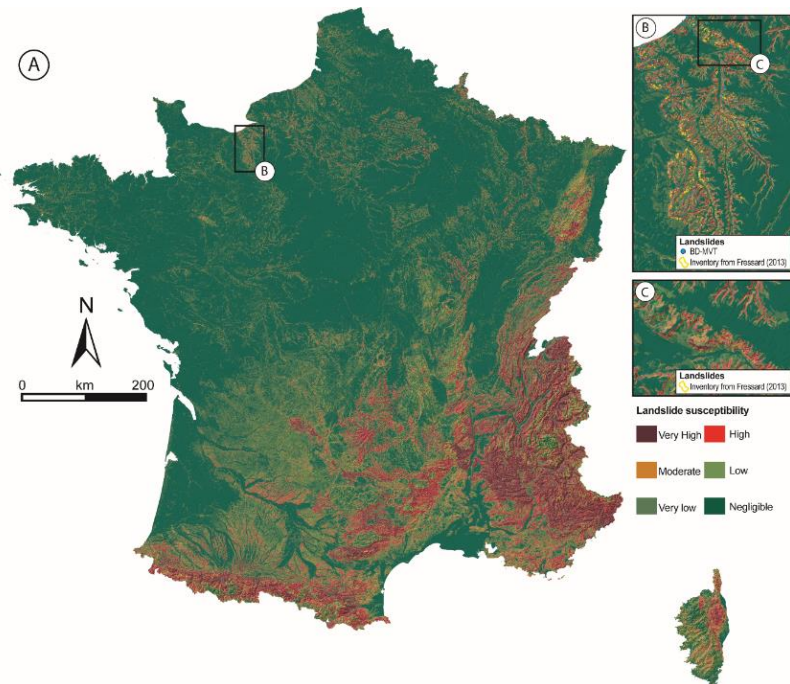
Both indices were standardized and merged to form a composite municipal risk index (CMRI). This ranking system has allowed for the organization of municipalities in order of priority. Consequently, three maps can be presented for each exposed element.

## Results



The results obtained for the NLSM were considered as excellent. (Fig. 1). For the entire territory, the relative error the success rate and the prediction rate were 0.27, 72.8%, and 73.7% respectively. The non-recognition rate was low with 9% (i.e. very few landslide occurrences were classified as negligible). Plateau edges, known to be prone to landslides, were accurately identified with recognition rates exceeding 80% (Fig. 1B & 1C). Recognition tests using landslides from local landslide databases not integrated into the NLSM computation process demonstrated the identification of between 80% and 97% of landslides within the very high, high, and moderate susceptibility classes. These results display strong similarities with LSM obtained at different scales with various techniques. Despite variations in the number of classes, NLSM aligned well with the high and moderate classes with the other maps.

Figure 1. National landslide susceptibility map (NLSM; Thiery et al., 2022). A. LSM for metropolitan territory and Corsica. B Zoom of the NLSM for the Pays de Caux (with BD-Mvt and independent landslide inventory). C. Zoom for the Touques area.



The calculated risk indices for urbanized areas and roads in each municipality help to pinpoint priority municipality. For each index, a classification based on Jenks thresholds was attempted in order to prioritize the risk to built-up areas and roads for the various municipalities (Fig. 2).

For ARI, where prioritization is not constrained by funding limits, 238 municipalities were considered in very high risk or risk 1 (R1). These are highly urbanized municipalities located mainly on the Côte d'Azur and in the Northern Alps. For roads, 400 municipalities are identified as R1. The same areas stand out overall, with the addition of the Pyrenean foothills. This index also expresses the way in which the various municipalities have developed on morphological sectors prone to landslides.

For RRI, which takes into account the surface area of the municipality, 2056 and 1788 municipalities were identified as R1 for risk to buildings and risk to roads respectively. For both indexes, the municipalities located on major communication axes stand out, such as the Seine axis to Normandy, Champagne, the Rhone axis, the Garonne axis, and part of the Côte d'Azur.

Lastly, the CMRI (Fig.2) was used to prioritize the municipalities to be targeted, both in terms of the total surface area potentially impacted by landslides and the relative proportion of the territory affected. For built-up areas, 480 municipalities were classified as R1 (Fig. 2A). The municipalities of the Côte d'Azur, the northern Rhône axis, and Champagne axis stand out. For roads, 1376 municipalities were defined as R1 (Fig. 2B). The same areas been identified as for the built-up risk map, with the addition of the Pyrenean foothills, part of the Massif Central and the Causse hills and plateaus.

## Discussion - conclusion

The results of the National Landslide Susceptibility Map (NLSM) are highly satisfactory, both from a statistical and expert perspective. The methodology, based on selecting the most





relevant variables and computation by physio-geographical units, has significantly improved the map's quality. Comparisons with other maps and inventories demonstrate the effectiveness of the strategy. However, it should be noted that some areas, particularly in the Alps and parts of the Pyrenees, appear to be underestimated due to a problem of transfer information in the BD-MVT (Thiery et al., 2020). Indeed, these areas are supplied with event data by the RTM services and not the BRGM. There remains a problem of interoperability of data which are located in the municipality centroids and not on the slopes. The calculations are thus biased and do not reflect reality. These regions must be cross-referenced with local inventories provided by local services.

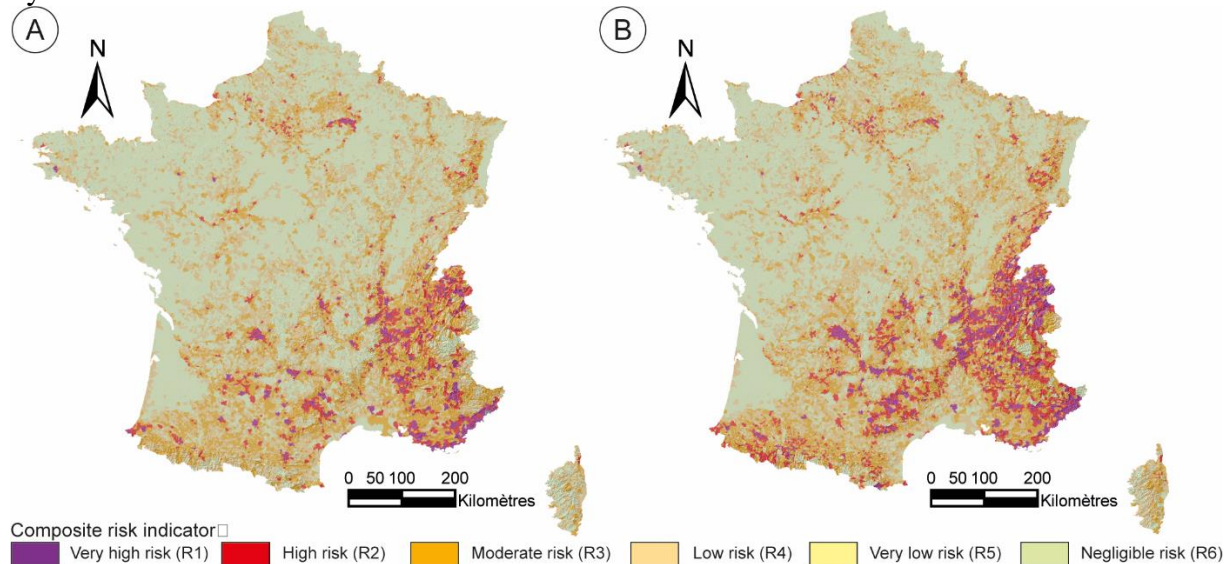


Figure 2. National landslide risk maps based on the CMRI. A. Landslide risk map for built-up areas. B. Landslide risk map for roads.

The results for the indicative risk maps are promising. The utilization of THEIA database has improved upon prior results, as mentioned in Thiery et al. (2022). While there are uncertainties regarding the quality of the BD Route (with missing sections in certain municipalities) and the subjectivity of classifications, these documents offer an overview of municipalities that could be prioritized within the Ministry of the Environment's risk mapping strategy. However, before finalizing these documents, a comparison with the GeoHazards database (<http://www.georisques.gouv.fr/>) and the prefecture policy in term of landslide hazard mapping is necessary. The cross-checking of information on planned, ongoing hazard and risk analyses and PPR approved is considered essential to successfully complete this study.

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