# Improvement of landslide hazard assessments for regulatory zoning in France: STATE–OF–THE-ART perspectives and considerations

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**ABSTRACT –** In France, in the context of regulatory mapping (PPRNs –Prevention Plans of Natural Risk based on French regulatory rules), landslide hazard assessment follows an empirical approach and uses basic available data. Therefore, the results are closely linked to the quality of the expertise and divergent opinions may arise in some specific cases. In recent years, numerical approaches using GIS, the availability of new databases, the development of new acquisition tools in the field and web visualization services have improved the knowledge of phenomena and different landslide-prone areas. Numerical approaches using GIS, that allow the transparency and traceability of results, have various levels of complexity and require different quantities of input data. However, they are often neglected by experts and new data and tools are not currently used to develop regulatory mapping documents. Numerous scientific examples show that these numerical approaches, web services and new tools can be a significant help in improving knowledge and provide a credible alternative to the expert approach, even in a regulatory context such as a PPRN. Thus, through this synthesis carried out as part of the regulatory mapping of landslide hazards and risks in France, a state-of-the-art spatial assessment of current landslide hazards is performed. The new tools and newly available databases to support this type of analysis are then described. Finally, the perspectives and limitations of alternative approaches and new tools and data are discussed, leading to some considerations for the improvement of the current method of producing landslide hazard maps for PPRNs in France.

**Key words** – landslides; hazard; regulatory zoning; France; alternative approaches

# 1.Introduction

Slope movements correspond to the movement of rock, earth or debris down a slope under the influence of gravity and influence of natural (snowmelt, abnormally high rainfall, earthquakes) or anthropogenic stresses (earthworks, vibrations, deforestation, exploitation of materials or aquifers; Varnes, 1978; Cruden, 1991; MATE/MATL, 1999; Hungr et al., 2014). Among these phenomena, landslides are characterized by the displacement of coherent materials along a failure surface (shear surface; Varnes, 1978; Dikau et al., 1996). The failure surface can be rotational, translational along a pre-existing discontinuity (e.g., along a stratification joint) or complex, mixing rotational and translational failures. Failures can be not only punctual, shallow, slow and limited in space and time but also fast with large magnitudes, affecting a whole hillside (Cruden and Varnes, 1996; Guzzetti et al., 2012). Whether landslides are active, latent, inactive or potential, they are characterized by fairly diffuse spatial and temporal distributions and can be located not only in mountainous regions with uneven relief but also in regions with more moderate relief (e.g., cuesta fronts; plateau hillslopes) and favorable predisposing factors (Dikau et al., 1996; Foster et al., 2007; Dewitte et al., 2008; Fressard et al., 2016).

Landslides are ubiquitous phenomena, and they are present all over the world (Froude and Petley, 2018). However, some areas are more frequently affected than others, such as mountain slopes subject to increasing anthropisation (Petley et al., 2007; Safeland, 2011; Jaboyedoff et al., 2016), high seismicity areas (Fan et al., 2016) or regions with intense or long periods of low- to medium-intensity rainfalls (Guzzetti et al., 2007; Fell et al., 2008; Petley, 2012; Segoni et al., 2018). Over the past 100 years, Asia, the American continent and the European countries of the Alpine arc have been the mostaffected areas (Schuster, 1996, Klose et al., 2015). From a general point of view, since the 1980s, approximately \$1,046 of overall losses and \$127 billion of insured losses can be counted worldwide for hydrological events, including landslides (Munich Ré, 2018). Japan and Italy were extremely reached, paying the highest price with more than \$3 billion.$yr^{-1}$ of damage. They are followed by the United States (from 2.1 to 4.3 billion.$yr^{-1}$ of losses) and India (more than 1 billion.$yr^{-1}$ dollars of damages; Catenacci, 1992; Schuster, 1996; Schuster and Highland, 2001; Klose et al., 2015). In addition to material damage, landslides can affect people with injuries and death. For instance, they have caused between 4,000 $yr^{-1}$ and 5,000 $yr^{-1}$ victims for the last 15 years, mainly in Central America, the Caribbean arc, South America, East Africa, Asia and Turkey. Finally, despite the increase in mitigation policies that are often costly, it remains difficult to reliably predict these phenomena (e.g., \$4.4 billion.$yr^{-1}$ for Japan for the period 1973-1992; Moriyama and Horiuchi, 1993; Nishimoto, 1993; Glade 1998). Therefore, there is a strong societal need for the mapping of landslide hazards (through its temporal, spatial and magnitude components) to build an efficient disaster risk-reduction strategy. This needhas steadily increased over time due to several factors: (i) economic and demographic growth, (ii) increased population mobility, and (iii) the loss of risk memory and over-confidence in different protection systems (Charlier and Decrop, 1997; Finlay and Fell, 1997; Alexander 2002; Crozier and Glade, 2005).

In Europe, policies to prevent natural hazards and risks based on specific mapping methods have been in place since the 1970s (e.g., Austria in 1975; SafeLand, 2011). If there is no standardization between European countries, it is possible to distinguish some groups of countries producing informative or legal documents (maps at different scales and reports) that are applicable nationally or regionally. Through a detailed review made by Malet and Maquaire (2007) and SafeLand (2011) deliverables, it is possible to distinguish (i) the countries willing to produce landslide hazard documents to be used for land-use planning (e.g., Andorra, Spain, Austria, Romania, and the UK); and (ii) the countries with a legal framework based on the production of regulatory documents related to binding legislation enforceable against populations and administrations (i.e., Italy, France, Norway, Sweden, and Switzerland; Leroi, 1996; Maquaire et al., 2004; Malet and Maquaire, 2007; Safeland, 2011). In France, landslides have been caused between \$10 and \$11 million.$yr^{-1}$ of damage (Grislain-Letrémey and Peinturier, 2010). While direct consequences can be assessed relatively quickly using the CAT-NAT surveys ("Natural Disasters surveys": a system guaranteeing adequate compensation for French citizens in case of a disaster caused by a natural phenomenon), indirect consequences are more difficult to estimate because: (i) they go beyond the local context and (ii) they can last for a long time. For example, in 2015, the destabilization of the Chambon slope, located in French Alps in the Isère department, required $5.6 million for the development of a runway on the left bank, as well as $13.4 million for geotechnical studies, the installation of lake shuttles and a diversion runway (Sanchez and Doceul, 2016). To these costs, $27.3 million must be added to secure the old tunnel and the construction of a diversion tunnel. However, these direct costs do not include indirect costs, such as economic losses related to local business activities, the financial impact on businesses outside the valley or losses related to tourism activity (Thiery and Terrier, 2018).

France as a pioneer in this field and has been pursuing a policy of natural risk prevention for several decades. This policy is based on the mapping of risk areas and the implementation of regulations on their development. Prevention Plans of Natural Risk (PPRN) define the exposure areas to natural phenomena, both direct and indirect, and they characterize the possible intensity of these phenomena for different hazards; they represent the fundamental tools to take into account hazards and risks in the development, construction and management of a territory (Law No. 82-600, 13th July 1982 and Law No. 95-101, 2nd February 1995). PPRN regulations accompany risk zonation and are applied to exposed areas (transcribed in the regulatory zoning): (i) they define the development conditions for new projects (in urbanized or non-urbanized areas); (ii) they force the vulnerability to remain stable for urbanized areas; and (iii) they propose protection and safeguarding measures for the identified risk areas. The PPRN must allow the possible development of a municipality towards the areas least exposed to natural hazards. In October 2017, 2,062 municipalities (of 12,591 exposed) were covered by an approved PPRN (Fig. 1). The assessment was carried out according to an empirical approach (i.e., an expert's approach) based: (i) on the available data with regard to the current knowledge and (ii) on the expert's knowledge (MATE/MATL, 1999; Antoine et al., 2000). Thus, the expert defines the type(s) of phenomena and the respective roles of the predisposing and triggering factors to establish an estimated hazard boundary for the next 100 years. However, this approach remains difficult to implement and is subject to many limitations, including: (i) the discontinuous nature of the phenomena over time and space and (ii) the quality of the available information (e.g. reliable and complete historical data, incomplete spatial data, etc.), (iii) the difficulties in identifying the causes of the phenomena, and (iv) the errors in application inherent to the person in charge of the case and his or her degree of expertise. Therefore, the relative subjectivity of the approach and the lack of a harmonized hazard qualification can lead to difficulties in producing documents by population group and generate legal issues related to their application.

Over the past fifteen years, the democratization of cartographic approaches using GIS (Geographic Information System), the development of new techniques to acquire topographic, soil and subsoil data, the reduction in the cost to acquire high and very high resolution spatial data, and the availability of spatial databases dedicated to geosciences have tended to reduce the uncertainties associated with these limits. Thus, currently, in France, some considerations have to be carried out on the available tools and methods contributing to improving landslide hazard zoning within a legislative framework such as the PPRN.

This contribution focuses on the analysis and mapping of landslide hazards also within the French regulatory framework. After reviewing the history of hazard and risk zoning in France, a state-of-the-art method relating the different digital mapping approaches to landslide hazard used in different contexts(scientific or not) is established. The concepts of hazards, risks, legal zoning, the different approaches of mapping used at different scale of work, and the quality of data will be discussed, showing some specificities related to this type of studies.. Then, we will focus on tools and techniques with the opportunities they offer to improve landslide hazard mapping within a regulatory framework such as the PPRN. Finally, strategies to revise PPRNs in France are proposed through examples using new data, tools and specific cartographic processing sequences, leading to improvements in landslide hazard zoning in complex physio-geographical contexts.

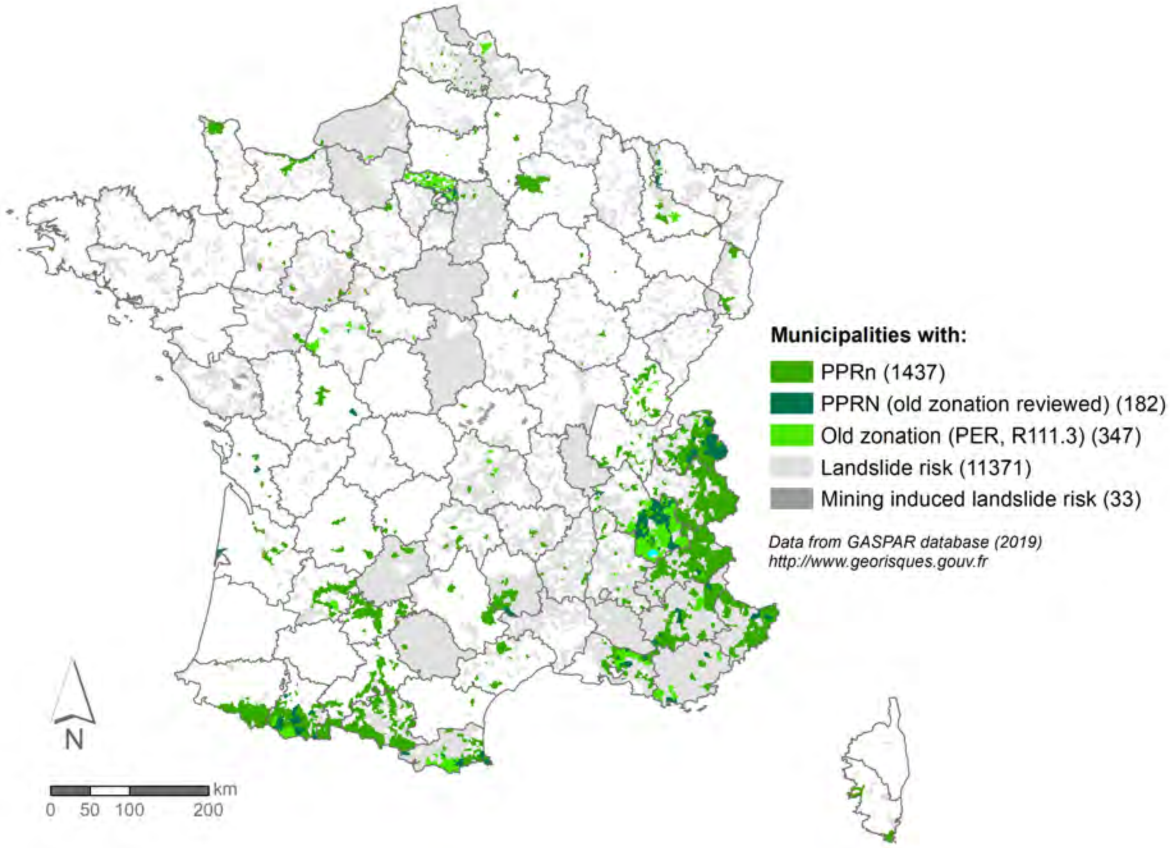


***Fig. 1.*** *Progress status for the landslide PPRN (landslide risk maps based on regulatory procedure) for 2019*[1] *(source: http://www.georisques.gouv.fr)*

## 2. Landslide hazard assessment in France: state-of-the-art approach

In general, landslide hazard assessment aims at answering to four questions: what, where, when, and how does the phenomenon occur? Thus, the hazard may be expressed as the occurrence of a particular type of landslide, including its volume, runout, velocity (varying with the distance from the source area) and intensity for a given time period (i.e., temporal frequency; Antoine et al., 2000; Cruden and Fell, 1997; Fell et al., 2005; Corominas et al., 2014). This approach requires the identification and classification of all phenomena of a territory (i.e., an inventory) and the assumption that landslides will occur under the same geological, geomorphological, hydrological and climatic conditions as known phenomena. Nvertheless, quantifying a hazard level remains a difficult exercise. Indeed, the data necessary for a complete and rigorous analysis (including triggering factors, triggering date, age, and runout) are not always available and/or are insufficiently detailed. Consequently, frequently at the scale of a catchment area, only the susceptibility to a type of phenomenon is obtained. This is referred to as a relative hazard assessment (Wu et al., 1996; Corominas et al., 2014).

### 2.1. *Regulatory zoning in France*

#### 2.1.1 Historical background

ZERMOS maps (Zones Exposed to Risks of Soil and Subsoil Movement; Fig. 2A) were the first attempts of informative or orientation mapping to expose areas at risk of soil and subsoil movement (Humbert, 1977). Initiated in 1971, these 1:25,000 maps were intended to constitute synthesis documents based on the spatiotemporal probability of the landslide occurrence (Humbert, 1977). The implemented qualitative methodology was based on systematic field observations and expert zoning (Antoine et al., 2010). These maps could be used as a basis for POS-ZERMOS to define levels of constraints to natural phenomena on the 1:5,000 land-use plan (Guillopé and Porcher, 1979).

In 1982, the PER (a risk exposure map of foreseeable natural risks; Law n° 82-600; Fig. 2B) was implemented, raising the question of hazard and risk mapping. The PER was a synthetic and technical document intended to be applied for different types of natural phenomena (floods, landslides, earthquakes and avalanches). It was not only informative or consultative but also constituted a regulatory document that can be invoked against third parties imposing constraints on the future development of the municipalities concerned (Fressard, 2013). This approach also adds the notion of predictability, allowing the introduction of phenomenon occurrence where no indication was found before. Three main documents were produced and presented as a report: a risk zoning plan and rules and regulations. In addition, in the appendix, it is possible to deliver a hazard map, a technical report and, ultimately, a vulnerability map. The methodological principle is the same as for the ZERMOS maps, i.e., it is carried out by an expert (Champetier de Ribes, 1987).

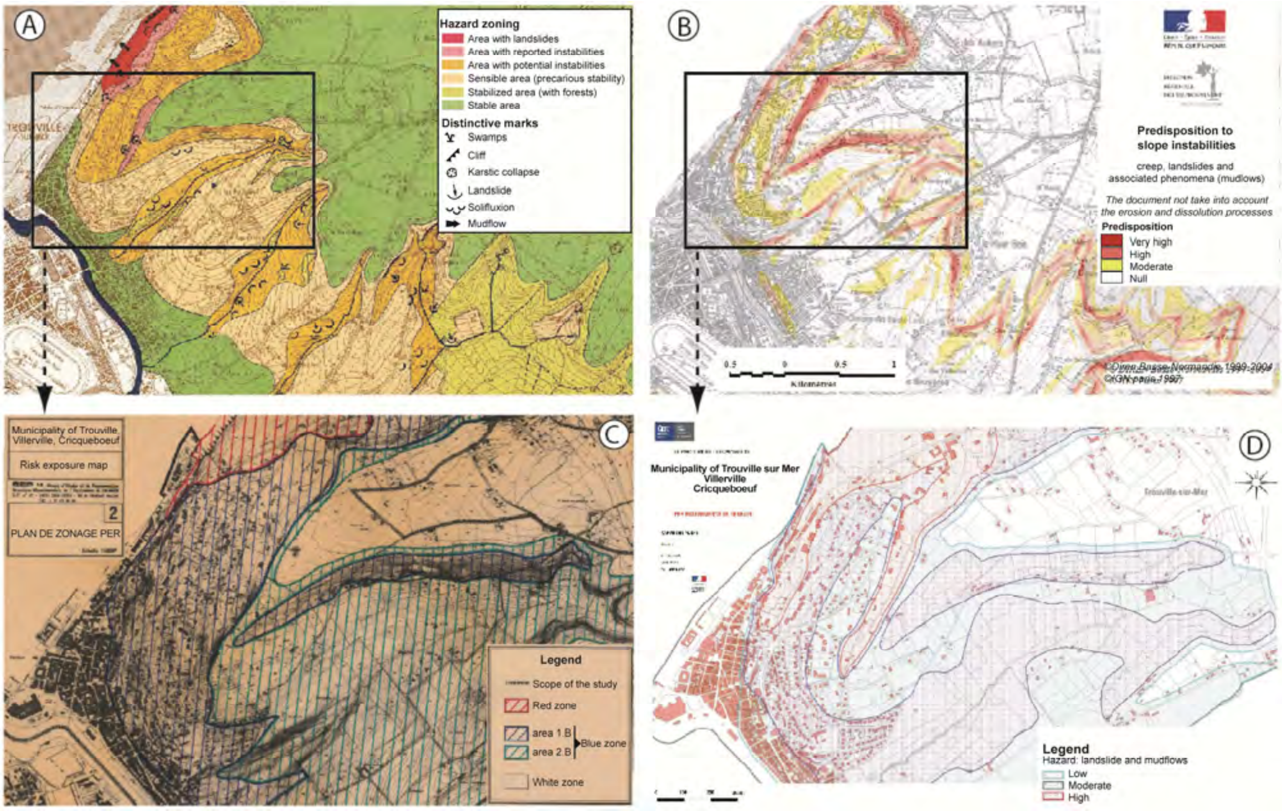


*Fig. 2. Extracts of landslide hazard maps produced for different regulatory zoning. A. Extract of a ZERMOS hazard map for Trouville/Pont l'Evêque at the 1:25,000 scale (BRGM, 1976). B. Extract from the landslide susceptibility map produced by a combination of lithology and slope at the 1:25.000 scale (DREAL, 2004) C. Extract of the risk exposure map (PER) for Trouville/Villerville-Cricqueboeuf at the 1:10.000 scale (LCPC, Rouen, 1986). D. Extract from the hazard map at 1:10,000 of the Trouville/Villerville-Cricqueboeuf based on the PPRN procedure (DDTM, validated on 24 April 2009).*

#### 2.1.2. Prevention Plans for predictable Natural Risk (PPRNs)

In 1995, the PERs were replaced by the Prevention Plans for predictable Natural Risk (PPRNs; Fig. 2C) with the law n° 95-101. Through this tool, there was a desire to simplify and homogenize the regulatory mapping procedures (PER), which proved to be complex, substantial and rigid (Fig. 3; MATE/MATL, 1997; Maquaire, 2002). For the PERs, three documents are produced as a report for presentation: a risk zoning plan, rules and regulations. In addition, it is possible to deliver an informative map of phenomena, a hazard map, and a map of the risks. The PPRNs have the dual vocation to define risk areas according to a reference hazard for the next 100 years and protect infrastructures and people for this centennial period.

From a landslide hazard assessment and mapping perspective, the PPRNs follow the same recommendations as the PERs with a qualitative assessment focusing on the current knowledge and available data ("The expert approach is preferred over specific studies that go beyond the scope of the PPR and the mission assigned to the state and should only be reserved for very specific cases, which are characterized in particular by the existence of major human, socio-economic and public interest issues": MATE/METL, 1999).

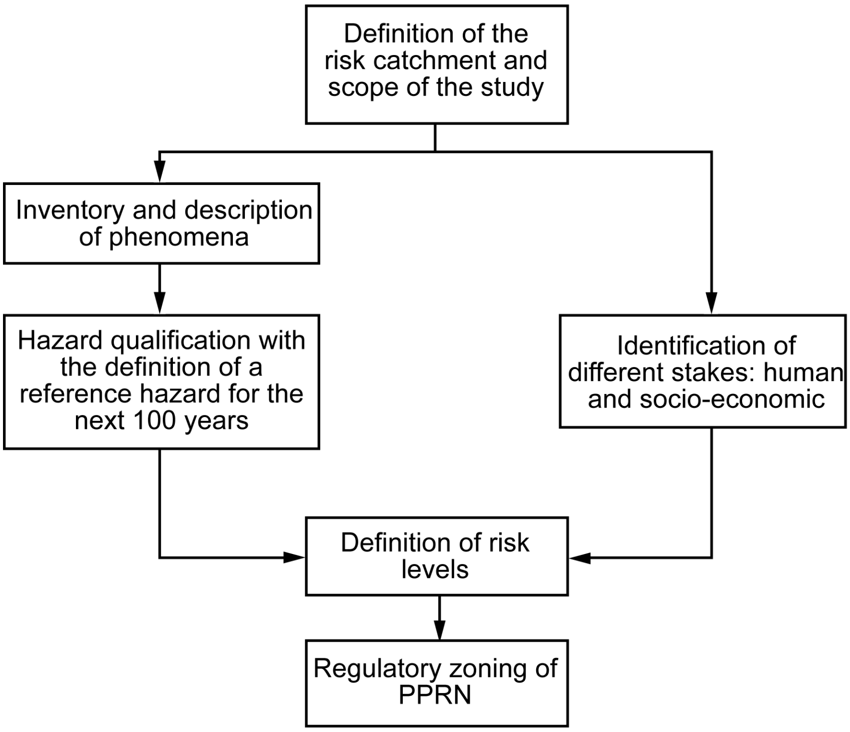


***Fig. 3.*** *Steps of the methodology used to construct a PPRN (from MATE/METL, 1999)*

However, some modifications are still to be noted: (i) the notion of a risk basin will be applied rather than the entire municipal territory; (ii) the working scale will be 1: 10,000 with some flexibility to limit investigations in case of low and/or moderate hazard; (iii) the temporal nature is no longer fixed in time or space allowing modifications (i.e., revisions) if new elements come to light. In addition, the qualification of the hazard intensity depends not only on the typology of the landslides, geological and topographical conditions but also on the intensity of the phenomenon assessed from (i) the estimated magnitude of the phenomena for the next 100 years; (ii) the level of the expected damages in case of occurrence; and (iii) the level of importance of works to implement in order to stabilize the slopes. In this sense, the intensity is assessed according to the importance and the magnitude of the cost of the measures required to protect infrastructures, goods and people. Increasing intensity classes are identified according to whether these measures are the responsibility of an individual owner, a group of owners, or a developer as it extends beyond the parcel and requires collective intervention and investments.

## 2.2. *Landslide hazard assessment with spatialized numerical approaches: methods not yet widely used in regulatory frameworks in France*

While the hazard mapping methodology for PPRs is qualitative, there are other methods to assess landslide hazards involving different disciplines, such as geomorphology, geology, hydrogeology, mathematics, statistics, or geotechnics

(Guzzetti et al., 1999; van Westen et al., 2006; Corominas et al., 2014). While some of these methods have benefited from an increase in computing capacity, all of them are based on the relationships between existing landslides and the environmental factors of the study site. Thus, each method must have a common source of necessary and indispensable information: the inventory of phenomena (Fig. 4). An exhaustive synthesis can be found in Soeters and van Westen (1996) and Corominas et al. (2014).

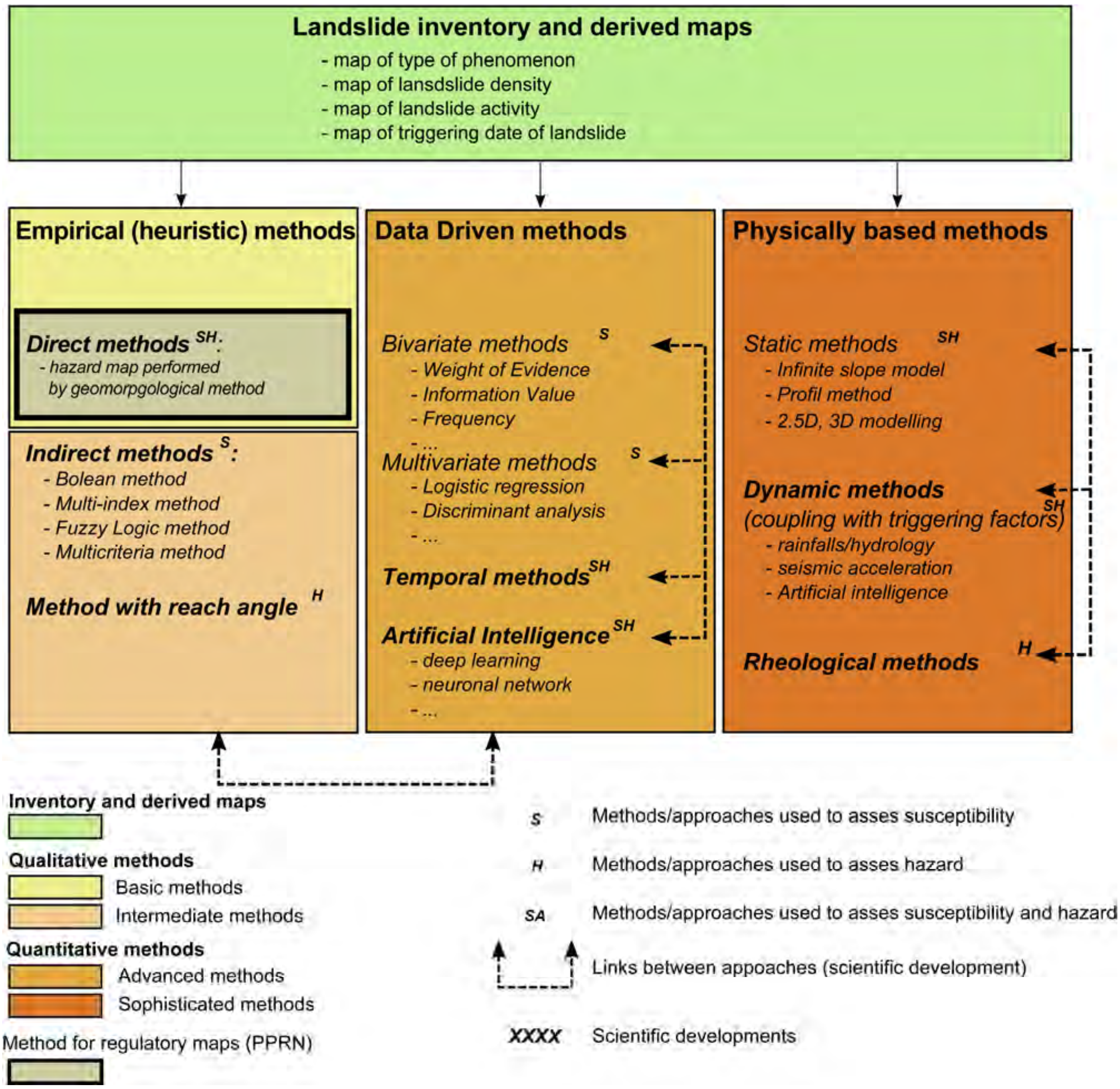


**Fig. 4.** *Methods for landslide susceptibility and hazard assessment (from Soeters and van Westen, 1996; van Westen et al., 2006; Fell et al., 2008; Corominas et al., 2014; Reichenbach et al. 2018).*

### 2.2.1. A common basis: the landslide inventory

The inventory of phenomena in a territory (watershed, municipality, region, etc.) can be obtained (i) either conventionally by field observations, analysis of existing documents, and remote sensing (visual analyses); (ii) or by semi-automatic or automatic remote sensing techniques (Cascini, 2008; Guzzetti et al., 2012). Spatial information can be mapped and then digitized with GIS in the form of points or polygons delimiting the envelopes of phenomena. It is also possible to separate the source area from the runout area. For each type of geometric shape, it is possible to provide a more or less exhaustive set of information. Beyond the debate on the type of geometry to be adopted, the minimum of information required is the type of phenomenon, its activity degree, its age (if possible), its morphometric parameters, the triggering conditions and the reliability of the information. From inventory maps, it is possible to produce indicative maps such as activity or landslide density maps (Fig. 4; Soeters and van Westen, 1996). Nevertheless, without an inventory, it is illusory to produce a reliable hazard map, and strong uncertainties inherent in the lack of information will remain in the final documents (Maquaire, 2002).

In addition to the inventory of phenomena, indicators of instability, which are generally observable in the field, should be considered and mapped as follows: (i) damage to infrastructures such as deformations of roads or cracks in buildings; (ii) morphological features such as scarps and cracks; or (iii) hydrological and hydrogeological information such as permanent or temporary springs, areas of water retention, and hydrophilic vegetation.

Thus, the phenomena inventory and the spatial report of this information (also called an "informative map of phenomena") constitute two prerequisites for any assessment of susceptibility and hazard regardless of the scale of analysis and the approach chosen (Cascini, 2008; Fell et al., 2008; Corominas et al., 2014).

### 2.2.2. Qualitative, heuristic or empirical methods

Qualitative (i.e., empirical or heuristic) methods can be divided into two categories: (i) so-called direct 'geomorphological' methods and (ii) indirect methods (Fig. 4).

The direct method is based on a geological and geomorphological analysis in the field. This type of method has been used for ZERMOS mapping and can be used for regulatory mapping. The assessment and/or zoning is carried out in the field by the expert who, based on his observations and experience, places the boundaries and the estimated degree of hazard for homogeneous areas. Thus, the expert directly synthesizes the information and can integrate a large number of factors. The advantages of the method are its rapid implementation and the integration of the runout of landslides into the different envelopes. The major drawbacks lie in a poorly explained approach with implicit rules that are difficult to reproduce by others (van Westen et al., 2008). GIS cartographic software is used as a digitization tool for the final hazard map (Thiery, 2007).

In indirect methods, in contrast to direct methods, the expert rationalizes and clarifies his reasoning to quantify each contributing factor in a mathematical way. Indirect methods are based on common rationales: (i) selection of phenomena, including intensity, (ii) selection of the contributing factors (in the form of spatial variables), (iii) assignment of a relative weight for all the classes of each contributing factor (with each weight being proportional to the contribution expected by the expert to generate the type of phenomenon selected), and (iv) combination the spatial variables using GIS to obtain, after reclassification, homogeneous classes of landslide prone areas. Several approaches can be used: (i) the Boolean logic function, (ii) the index map combination function, (iii) the fuzzy logic function, and (iv) multi-criteria analyses (e.g., Hierarchical Process Analysis, Saaty, 1977). The latter two are the most complete in terms of variable combination and expert rule formalization. Moreover, they provide a certain flexibility, as the geomorphological approach, by maintaining a certain objectivity offered by the formalist framework that directs their application (Poiraud, 2012). For these indirect methods, only susceptibility for one landslide dynamic is generally assessed. In the case where several susceptibility maps were produced for different landslide types for one area, it is possible to produce a unique map combining the different results. In some cases, for each cell (i.e. point, pixel or unit area), the final class is systematically given to the higher susceptibility class (Thiery et al., 2007).

### 2.2.3. Quantitative methods

Quantitative methods are considered more objective. Theoretically, they are reproducible for similar environments by producing identical results with the same set of variables (Carrara et al., 1995; Rossi and Reichenbach, 2016), and they need a strategy in two steps with to obtain reliable results: (i) a calibration step allowing to check the quality of variables, their usability for the study and local conditions, and an adjustment of the numerical values assigned to the different parameters in order to be close to the observations (Depicker et al., 2019), and (ii) a validation step allowing to verify if results correspond to the reality. In principle, validation of results has to be performed with a set of variables not used for the calibration step. There are several types of calibration/validation strategies. They may be based on a spatial and/or temporal partitioning of the dataset to be modelled (i.e. landslides; Chung and Fabbri, 2003), a partitioning of the study area into two more or less equal area zones (Chung and Fabbri, 2003; 2005) or on a subarea characteristic of the study area (Thiery et al., 2007; Thiery et al., 2017a). The last way allows: (i) to reduce the calculation time, and (ii) to multiply the tests with different datasets, and then to apply the results on the study site.

Two main types of quantitative methods can be differentiated (Fig. 4) with: (i) statistical/probabilistic methods (i.e. data-driven methods, called advanced methods) and (ii) deterministic methods (i.e. physically-based methods, called sophisticated methods). Since the second half of the 1990s, statistical/probabilistic approaches have experienced the greatest growth (Reichenbach et al., 2018). Several methods with bivariate approaches can be distinguished, which are most often based on Bayes' theorem (empirical likelihood ratio, certainty factor, weight of evidence, information value, frequency ratio), multivariate approaches (logistic regression, discriminant analysis), and artificial neural network approaches. All of them are based on same principles with the comparison of the spatial distribution of the phenomena (i.e. landslide inventory) with the different environmental factors (in the form of a spatial variable). Thus, depending on the approach, a relative weight for each factor class is obtained. Therefore, in principle, the weights are defined objectively, without the direct intervention of the expert, and, as for the indirect qualitative methods, a combination using GIS operations is required.

***Table 1.*** *Criteria and examples of tests to assess and validate Quality Level (QL) for landslide susceptibility models and associated terrain zonation (adapted from Chung and Fabbri, 2003; Guzzetti et al., 2006; Thiery, 2007; Reichenbach et al., 2018).*

| Category | Combination of categories | Criteria | Associated tests (indicative) | QL |
|---|---|---|---|---|
| **a** | | No information available or no test performed to determine the quality and prediction performance of the landslide susceptibility/hazard assessment. | - | 0 |
| **b** | | Estimates of degree of model fit available, obtained exploiting the same landslide information used to prepare the susceptibility/hazard model. | Calculation of landslide recognition rate<br>Calculation of relative error<br>Calculation of success rate<br>ROC curve AUC ROC associated | 1 |
| **c** | | Estimates of the error associated with the predicted susceptibility/hazard in each mapping unit available, obtained exploiting the same landslide information used to prepare the susceptibility/hazard model. | Correlation test ($X^2$, Fisher test, Kolmogorov-Smirnov test, Goodman,-Kruskall test, $R^2$, Spearman coefficient)<br>Association test (Cramer V test, Tschumprov T test)<br>Uncertainty test (Student T test, variance) | 2 |
| **d** | [b] & [c] | [b] Estimates of degree of model fit available & [c] error associated with the predicted susceptibility/hazard in each terrain unit available. | Tests used for [b] and c] | 3 |
| **e** | | Estimates of model prediction performance available, obtained exploiting independent landslide information not used to prepare the susceptibility/hazard model. | Calculation of landslide recognition rate<br>Calculation of relative error<br>Calculation of prediction rate<br>ROC curve and AUC ROC associated | 4 |
| **f** | [b] & [e] | [b] Estimates of degree of model fit available & [e] estimates of model prediction performance available. | Tests used for [b] and e] | 5 |
| **g** | [c] & [e] | [c] Estimates of the error associated with the predicted susceptibility/hazard in each terrain unit available & [e] Estimates of model prediction performance available. | Tests used for [c] and e] | 6 |
| **h** | [b] & [c] & [e] | [b] Estimates of degree of model fit available & [c] estimates of the error associated with the predicted susceptibility/hazard in each mapping unit available & [e] estimates of model prediction performance available. | Tests used for [b], [c] and [e] | 7 |
| **i** | | Estimates of model prediction performance available, obtained exploiting independent landslide information and spatial variables not used to prepare the susceptibility/hazard model and located in another area with similar physio- | Calculation of landslide recognition rate<br>Calculation of relative error<br>Calculation of prediction rate<br>ROC curve AUC ROC associated | 8 |

| | | | | |
|---|---|---|---|---|
| | | geographic characteristics. The fact to partitioning the study area in two subareas and used the results of the first area in the second area enters in this category of QL | | |

Once the processing done, the zoning into more or less homogeneous landslide prone areas must be achieved (Guzzetti et al., 1999). This step is a rather complex issue and no consensus exists to delineate the homogeneous areas and to assess their robustness and reliability (Guzzetti et al., 2006). Nevertheless, this step remains crucial and has to be carried out carefully. Thus, some guidelines to assess the quality level of simulated and final maps have been discussed and proposed by Chung and Fabbri (2003; 2005), Brenning (2005), Begueria (2006), Guzzetti et al. (2006), Thiery (2007), Fressard et al. (2014), and Reichenbach et al. (2018). These measures of quality are generally provided by series of tests and cross-validation (i.e. by different standards and complex tests) and have to be carried out at each step of the strategy (i.e. calibration and validation steps). Several Quality Levels (QL) to evaluate results have been proposed and are summarized in the table 1. They have been successfully applied in French catchments located in the Alps by Thiery (2007) and Thiery *et al.* (2007), in Normandy by Fressard (2013) and Fressard et al. (2014), showing the possibility to obtain reliable maps with few uncertainty, increasing the degree of credibility of the results (Guzzetti et al., 2006). Moreover, by this evaluation, it was possible to apply the relative weights computed for one site to another site and create susceptibility maps for certain types of landslides in similar environment (Thiery, 2007). For this reason, a line was added to the table 1 proposed by Guzzetti et al. (2006) and Reichenbach et al. (2018). We believe that the transposition of the weights to other study sites with similar physio-geographic characteristics is an additional level of quality of the susceptibility models and should be envisaged in some cases to validate of results (Thiery et al., 2008).

While the results are robust and can be replicated in other similar sites (provided that the approaches are well calibrated, evaluated and validated), these data-based methods, as with the indirect methods, focus on susceptibility analysis and few incorporate the notion of temporality. When the latter is integrated, it is either in the form of a spatial probability calculation of the return period of phenomena (Crovelli, 2000; Coe et al., 2004) or is acquired by combining statistical analyses of the triggering factors (e.g., rainfalls) and susceptibility (Zêzere et al., 2004). This requires exhaustive inventories with the dates of the landslide occurrences.

Physics-based methods generally use limit equilibrium calculation models (Factor of Safety calculation - FoS). Two types of approaches can be used (Fig. 4): static and dynamic approaches. Calculations are carried out in 2D, 2.5D and sometimes in 3D for a 2D cartographic rendering (Mergili et al., 2014; Dang et al., 2016). Most of calculations are based on infinite slope models, or more rarely, on complex failure models (Thiery et al., 2017a; Thiery et al., 2019a; Vandrome et al., in revision). For the approaches, the triggering factors (rainfalls, ground water level, and seismic acceleration) are integrated. For the dynamic approach, it is possible, after careful calibration and validation, to make predictions by taking into account records and temporal changes in the landscape and/or triggering factors (Bernardie et al., 2017; submitted). Thus, compared to the approaches described previously, these methods require additional quantitative information such as hydrological information (soil saturation, permeability, hydraulic conductivity, etc.) and geotechnical information (material thickness, cohesion, internal friction angle, specific weight, etc.). These methods are considered more accurate and less exploratory than data-driven methods discussed above because physical processes are integrated and quantitative stability values are computed (Corominas et al., 2014). However, given the large amount of information required, they are only applied to small catchment areas or to a particular phenomenon, with the subsequent transposition remaining complex. it appears that a certain generalization of the input data would require approximations leading to inaccuracies in the results (Cervi et al., 2010; Zizioli et al., 2013; Thiery et al., 2019a). Finally, their calibration can be complex for untrained people.

2.2.4. Recent progress in terms of the spatialization of landslide hazard assessment

In recent years, new developments have emerged to improve landslide susceptibility and hazard assessment to reduce uncertainties, to increase the predictive power of models, to adjust zoning and to take into account the runout phenomena. These specific developments are based on:

(i) Different algorithms used in other disciplines (van Den Eeckhaut et al., 2006; Fellícismo et al., 2013);

(ii) Specific strategies adapted to the test sites (van Westen et al., 2003; Chung and Fabbri, 2003; Thiery et al., 2007; Fig. 4);

(iii) The combination of two different methods in an attempt to take into account only the advantages of each approach (Poiraud, 2014; Thiery et al., 2014), which will be referred to as hybrid methods;

(iv) The development of complex models taking into account physical processes (especially triggering processes and the run-out) of one event that have yet to be tested on a risk basin (Corominas et al., 2014).

For the susceptibility assessment, in addition to mathematical modifications of proven approaches (such as the use of logistic regressions for rare events; van den Eeckhaut et al., 2006; Fressard, 2013) to improve the predictive power of models different tests of new methods from data mining and artificial intelligence are intensifying with promising results (Chen et al., 2016; Chen et al., 2017 Pham et al., 2017).

For hazard assessment, beyond the increasing number of physics-based models using limit equilibrium equations and taking into account environmental uncertainties and different types of failure (Baum et al., 2008; Mergili et al., 2014; Thiery et al., 2017a; Vandromme et al., in revision), some developments focus on landslide runout. Thus, two axes are developed:

(i) An axis based on empirical approaches taking into account the maximum runout distance of phenomena and the slope angle energy principles (Horton et al., 2013; Thiery et al., 2017b; Mergili et al., 2019);

(ii) An axis based on numerical approaches modelling the behaviour of moving materials according to different rheological laws following the type of landslide (Pastor et al. 2014). The first axis is used as a mapping tool (Sedan, 2011; Horton et al., 2013); the thicknesses, velocities and geotechnical characteristics of the materials are not integrated. The second axis is more exploratory and still requires further development, particularly for landslides with hydrological control and complex (viscoelastic or visco-elasto-plastic) behaviours and on the way to use them in the framework of landslide hazard assessment for a risk catchment.

***Table 2.*** *Classification for different landslide susceptibility assessment levels according to the methods and data used (adapted from Cascini, 2008). X = mandatory; (X) = optional (depends on the data and their quality)*

| Zoning level considered | Method | Data used | | |
|---|---|---|---|---|
| | | Inventory maps, aerial photographs, topography (DTM), geology, and geomorphology | Soil, surficial formations and thickness of materials | Hydrogeology and geotechnical parameters |
| **Basic** | Qualitative | **X** | | |
| **Intermediate** | Qualitative (indirect) | **X** | **(X)** | |
| **Advanced** | Quantitative: data-driven and hybrid | **X** | **X** | **(X)** |
| **Sophisticated** | Quantitative: physically based models | **X** | **X** | **X** |

## 2.3. *A specific data set and scale of work for each approach*

A state-of-the-art approach would not be complete if the issues of input data (numerical variables), the data resolution and data quality were not discussed. Landslides are controlled by a combination of several factors that must be analysed simultaneously to obtain valid results (Fressard et al., 2014; Reichenbach et al., 2018). The type of the method applied and the envisaged approach are dependent on the number and quality of data and therefore of the problem under consideration (in other words: will we analyse the susceptibility or hazard? Aleotti and Chowdhury, 1999; Glade and Crozier, 2005). Several classifications taking into account these parameters have been proposed (Cascini, 2008; Fell et al., 2008; Corominas et al., 2014), resulting in different levels of analysis and level of zoning. (Tables 2 and 3). Thus, depending on the initial data set, an approach will be chosen. However, it is not always possible to have an optimal, high-quality dataset (because of cost and time issues, unavailability of data and/or the requirement of a long acquisition time, etc.). In these cases, it is preferable to consider a basic zoning approach that can be justified with reliable results and a simple but understandable reasoning rather a complex zoning and high uncertainties and poor traceability (Thiery and Terrier, 2018).

***Table 3.*** *Classification for different levels of landslide hazard assessment adapted from Cascini (2008), the methods described in the text and the data used. X = mandatory; (X) = optional (depends on the data and their quality)*

| **Zoning level considered** | **Method** | **Data** | | |
|---|---|---|---|---|
| | | Inventory maps, aerial photographs, topography (DTM), geology, and geomorphology | Triggering factors | Geotechnical and rheological parameters |
| **Basic** | Qualitative (direct) | **X** | | |
| **Intermediate** | Qualitative (indirect) | **X** | **(X)** | |
| **Advanced** | Quantitative: data-driven and hybrid | **X** | **X** | **(X)** |
| **Sophisticated** | Quantitative: physically-based models | **X** | **X** | **X** |

Finally, it is also necessary to consider the scale of work based on the data acquired and their availability. Thus, it is generally accepted that at small scales, only direct qualitative methods can be used, and at large scales, deterministic methods are recommended. This assumption should be modulated according to the method chosen and the quality of the available data. For example, when the environment is suitable (e.g., a homogeneous environment), it is possible to assess hazards at a 1:25,000 scale for larger areas (Salciarini et al., 2006) or to use quantitative statistical approaches at 1:10,000 scale for smaller areas (Thiery et al., 2007). Table 4 provides a summary overview of the methods, zoning levels and scales that are generally recommended.

***Table 4.*** *Classification of zoning levels, their accuracy and their scope according to work scale (adapted from Cascini, 2008). X = recommended; (X) = applicable with specific precautions or developments; [X] = not recommended.*

| **Scale of work** | | **Zoning level considered** | | | | **Spatial accuracy level** | | | **Type of mapping** | | **Proposed application** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Basic | Intermediate | Advanced | Sophisticated | Low | Moderate | High | Susceptibility | Hazard | |
| **Small (national)** | <1:250,000 | **X** | | | | **X** | | | **X** | | National and regional mapping: informative |
| **Moderate (regional)** | 1:250,000 – 1:25 000 | **X** | **X** | **(X)** | | **X** | **(X)** | | **X** | **(X)** | Regional mapping: consultative |
| **Large (local)** | 1:25,000 – 1:5,000 | **X** | **X** | **X** | **(X)** | **X** | **X** | **(X)** | **X** | **(X)** | Local mapping: informative, consultative prescriptions and recommendations |
| **Detailed (site)** | >1:5,000 | **[X]** | **(X)** | **(X)** | **X** | **[X]** | **(X)** | **X** | **X** | **X** | Specific local mapping: informative, consultative |

# 3. Towards an improvement of the inventory maps and the mapping of different factors

Developing or improving landslide inventory and geospatial environmental data related to landslides is an essential step in analysing and mapping landslide hazards. This step allows the person in charge of the work to understand the slope instabilities well. This step is accompanied by geological, geomorphological and hydrogeological analyses to replicate phenomena in their respective physio-geographical environment and obtain an overview of the favourable conditions leading to instabilities. Spatial information can be derived from prior analysis of aerial photographs followed by field observations (Antoine et al. 2000). This work is very time consuming and can account for a significant part of the expert's working time (Murillo-García et al., 2015). In recent years, the multiplication of new techniques has made it possible to quickly acquire more information to map phenomena and to obtain precise information on topography or on the internal structure of the soil and subsoil, supplementing the available or already acquired data. The greatest developments concern (i) field mapping tools; (ii) remote sensing (aerial photographs, satellite images, Lidar, GPR; InSAR, etc.), (iii) geophysics and (iv) web services.

## *3.1. New field mapping tools*

The use of GPS has revolutionized the methods for mapping landslides, and how geomorphological areas are mapped (i.e. spatial accuracy of object) Their use allows the rapid localization of landscape features and landslides with sometimes greater accuracy than the expert's needs (Malamud et al., 2004). In situ mapping tools, such as tablets with integrated GIS, also facilitate mapping, and it is possible to improve, directly in the field, the first maps produced by remote sensing by adding non-vector information. Recently, tests of maps coupling electronic binoculars ("rangefinder binocular") connected to a tablet and a GPS have made it possible to remotely detect a series of landslides triggered by rainfall in the field (Santangelo et al., 2010). A comparison between two maps, one produced in the field using a GPS and the other produced by simple observation, showed that the results were similar, highlighting the potential of this new technology. Zeb-Revo (a lightweight rotating laser, GeoSLAM®) is widely used for zoning underground cavities (Dewez et al., 2017) and could also become a tool to map landslides and associated features with precision. Some tests are currently underway on simple access sites (Fig. 5), with the idea being to test this technology on more complex sites. Finally, to specify and refine landslide activity maps, the in situ development of high quality imagery capture tools, which measure displacement and surface deformation, by low-cost devices (e.g., tag-RFID: passive radio-frequency identification ranging) are emerging and are currently being tested for various sites (Le Breton et al., 2019).

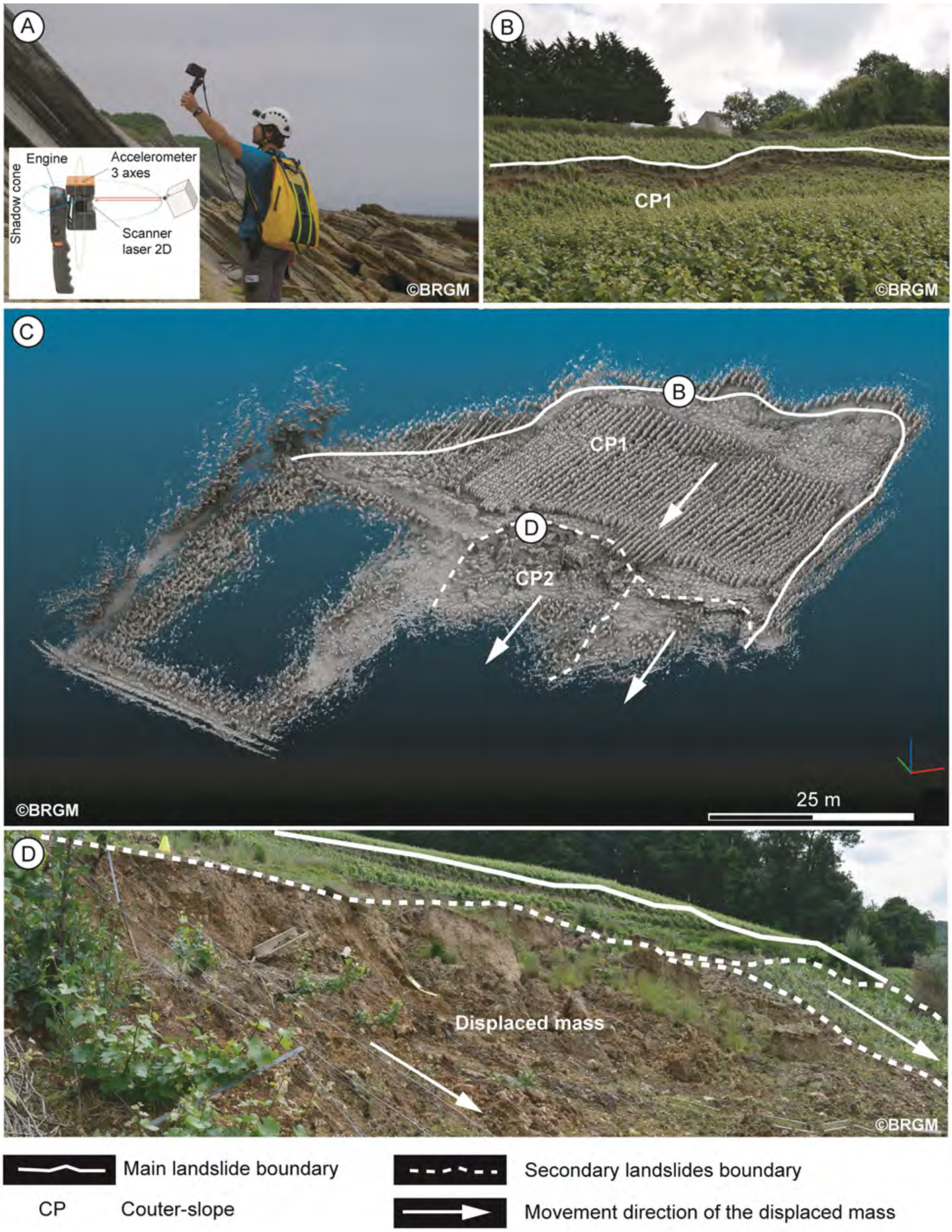


**Fig. 5.** *Example of a point cloud obtained with a ZEB-Revo (a light, rotating 3D terrestrial laser scan) for a rotational landslide in the vineyards of Champagne (Commune of Le Mesnil-le Huttier-2018). A. ZEB-Revo principles (measurements on the Socoa cliffs, Pyrénées Atlantique, France). B. View of a landslide scarp. C. Point cloud and interpretation. D. View of the second landslide scarp.*

## 3.2. Remote sensing techniques and data

The techniques and data from remote sensing have been divided into two groups according to their contribution to the identification of the shapes and/or activity of landslide phenomena: (i) the use of high resolution DTMs obtained by different techniques and (ii) the use of satellite images (panchromatic, multi-spectral or radar).

### 3.2.1. Very high resolution DTMs to detect and identify landforms

Recent developments, the availability and the cost reduction of very high resolution DTMs obtained by airborne and/or ground LiDAR (Light Detection and Ranging), or by drones equipped with very high resolution optical sensors, offer new and unprecedented possibilities to detect landslides and different landforms (van den Eeckhaut et al., 2005; Razak et al., 2011; Guzzetti et al., 2012). These very high resolution DTMs, obtained after point cloud processing (for laser techniques) or photogrammetry by structure from motion analysis (Medjkane et al., 2018), allow precise visual analyses and semi-automatic or automatic spatial processing to recognize some landforms and refine the geomorphological interpretations and knowledge of an area (e.g., calculation of roughness index, identification of specific texture, delineation in slope-units, etc., Sato et al., 2007; Iwahashi and Pike, 2007; Alvioli et al., 2016).

For example, for the la Médaille landslide located in La Martinique, Fig. 6A, 6B and 6C show the difference in terms of landslide visualization between three DTMs obtained in different ways and the contribution of airborne LiDAR in terms of resolution for pattern recognition (Thiery et al., 2016). For the first image (Fig. 6A), it is impossible to delineate some geomorphological features of landslides because the resolution (cell size = 25 m) is not adequate with the scale of the work. In contrast, the two other images (Fig. 6B and 6C) show a significant improvement of the hillshade map due to a higher resolution (cell size = 1 m). However, for Fig. 6B, it is still difficult to clearly distinguish the different compartments of the landslide, while for Fig. 6C, it is possible to better constrain the boundaries. This difference is due to an additional acquisition of points for the DTM presented in Fig. 6C and a specific processing method for the study site.

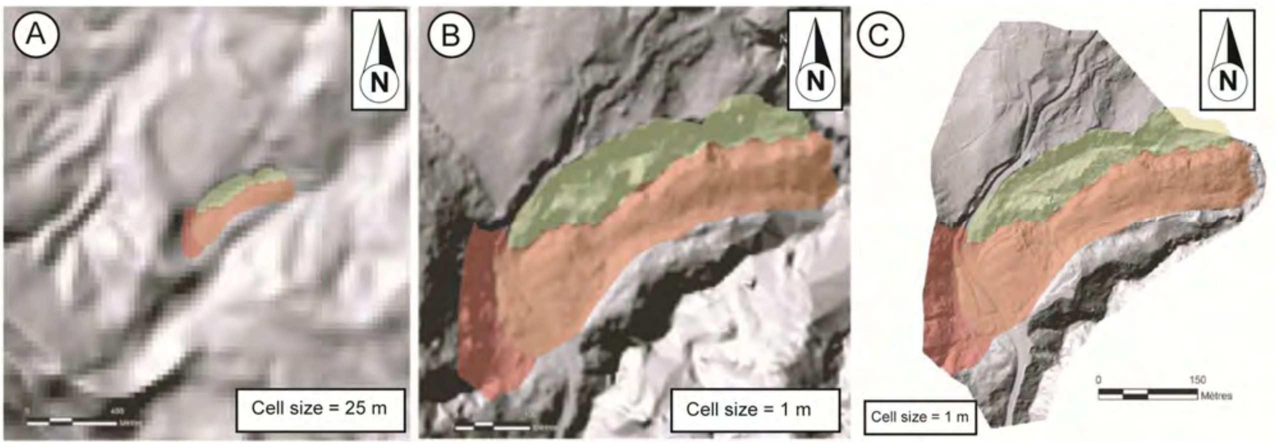


***Fig. 6.*** *Example of hillshade maps of the La Médaille landslide (La Martinique, France; Thiery et al., 2016). The DTMs were obtained at different resolutions and by different technologies. A. Hillshade map derived from BDAlti® with a resolution of 25 m. B. Hillshade map derived from Litto3D® (obtained by LiDAR, elevation resolution of 20 cm / planimetric resolution of 1 m). C. Hillshade map derived from a specific DTM obtained by LiDAR and created specifically for the site (elevation resolution of 10 cm / planimetric resolution of 20 cm – re-sampled to 1 m for the study).*

Fig. 7A, 7B, and 7C illustrate a preliminary analysis of the slopes affected by landslides in a mountainous area in France (Cauterets in the Pyrenees, France) before the field survey. The interpretation was performed by the visual analysis of the hillshade map which was computed from a DTM (cell size = 2 m) obtained by radar and the slope map derived from the DTM. Figure 7D, 7E, and 7F show the same area and the same maps obtained with a DTM obtained by Lidar (cell size = 2 m). The new very high resolution DTM (Fig. 7F) allows the detection of a very large inactive and relict landslide splitting a moraine arc in two. Moreover, the new DTM and derivative map allowed the detection of several new landslides not detected with the DTM obtained by radar and improved the final analysis by visual remote sensing. Because this area is partially covered by forests, it was almost impossible to see the very blurred landforms in the field (Thiery et al., 2019b). The field surveys carried out in 2017 confirmed the interpretation of Fig. 7F. The availability of high-resolution DTMs such as WorldDEM, BDAlti® 5 m, or BDAlti® 1 m should further increase the DTM use and help experts better integrate geomorphology into their hazard zoning process. Finally, multi-temporal acquisitions of high-resolution DTMs make it possible to observe subtle morphological changes, allowing a better recognition of the different activity states of landslides.

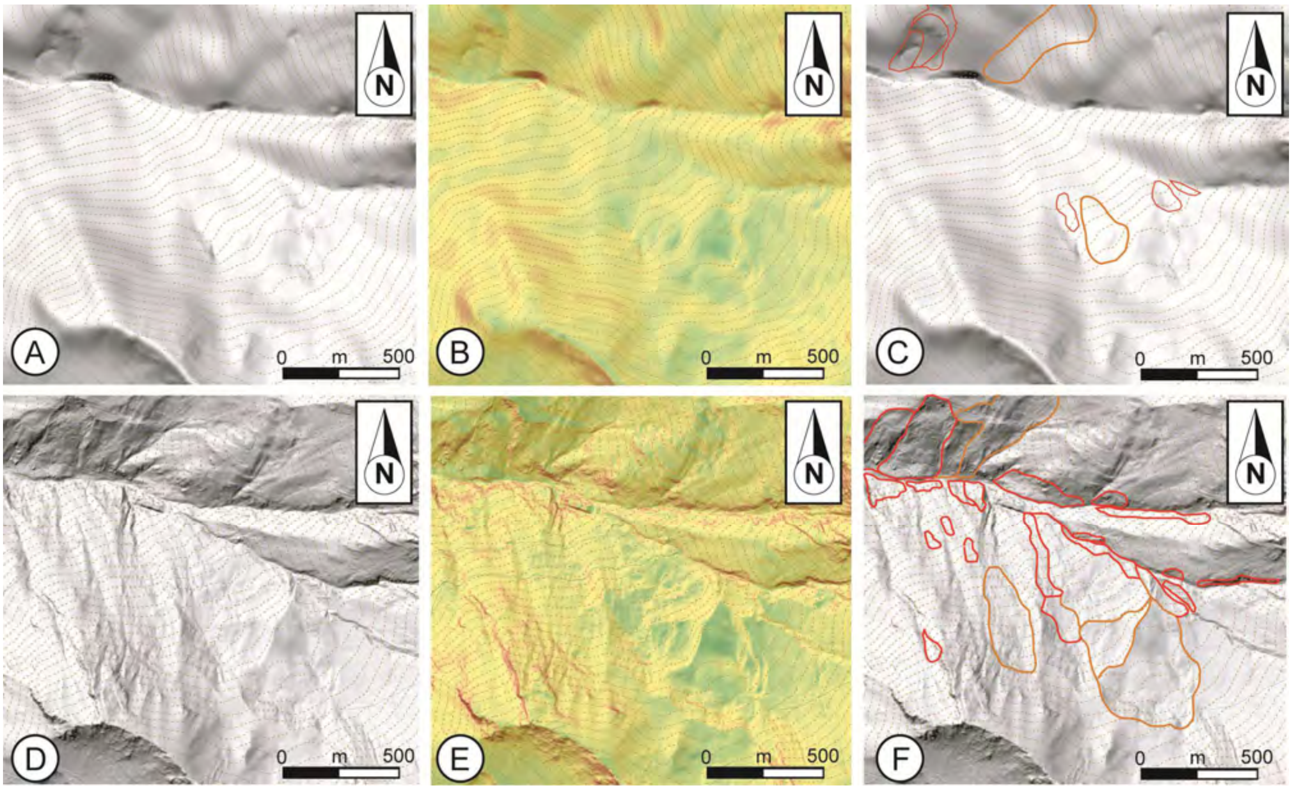


***Fig. 7.*** *Example of hillshade views and geomorphological interpretations for the Cauterets catchment (French Pyrenees, Thiery et al., 2019b). A. Hillshade map derived from the DTM obtained by radar (cell size = 2 m). B. Slope map (cell size = 2 m) computed from the DTM presented in A. C. Landslides inventoried from the analysis of A (red: active landslide; orange: inactive landslide). D. Hillshade map derived from the DTM obtained by Lidar (elevation resolution 20 cm / planimetric resolution 20 cm; the cell size for the figure is 2 m). E Slope map (cell size = 2 m) derived from the DTM presented in D. F. Landslides inventoried (red: active landslide; orange: inactive landslide) from the analysis of D.*

#### 3.2.2. Satellite images to detect landslides and specify ground deformations

In addition to morphological changes, active or newly triggered landslides modify land-use and, consequently, the spectral signature of the soil that can be detected with space-borne sensors. This detection itself is not new (the first analyses date back to the 1970s with Landsat and SPOT images; McDonald and Grubbs, 1975; Sauchyn and Trench, 1978), but the finer resolution and current digital capabilities (i.e., the high capacity of data storage, speed of processing, and new image visualization capabilities) allow the observation of new events that were not previously perceived over inaccessible areas. Guzzetti et al. (2012), after reviewing the extensive scientific literature, conclude that, for landslide detection, high-resolution and very high-resolution images (e.g., Spot, Ikonos, GeoEye, and Sentinel) from optical sensors (panchromatic or multi-spectral) are widely used, while to detect slow deformations, radar images (Synthetic Aperture Radar - SAR) are preferred (e.g., ENVISAT, TerraSAR-X, TanDEM-X, Sentinel, and ALOS/PALSAR; Fig. 8). Murillo-García et al. (2015) add that landslide automatic or semi-automatic detection by high resolution or very high resolution satellite imageries allows the identification of phenomena down to very small sizes (e.g., 20 m X 20 m with GeoEye-1 images and a PLANAR stereomirror). This reinforces the conclusions of Schlögel et al. (2015a) about the usefulness of combining images from different sources to improve the landslide inventory and the associated activity. However, the process is not straightforward and requires several steps, such as pre-processing of the images in several steps (i.e., pansharpening, orthorectification, co-registration, and radiometric correction) and using specific numerical tools that allow 3D processing and stereoscopic viewing. It is then possible to digitize the objects directly on the screen and differentiate the typology, age, and size (Murillo-García et al.; 2015).

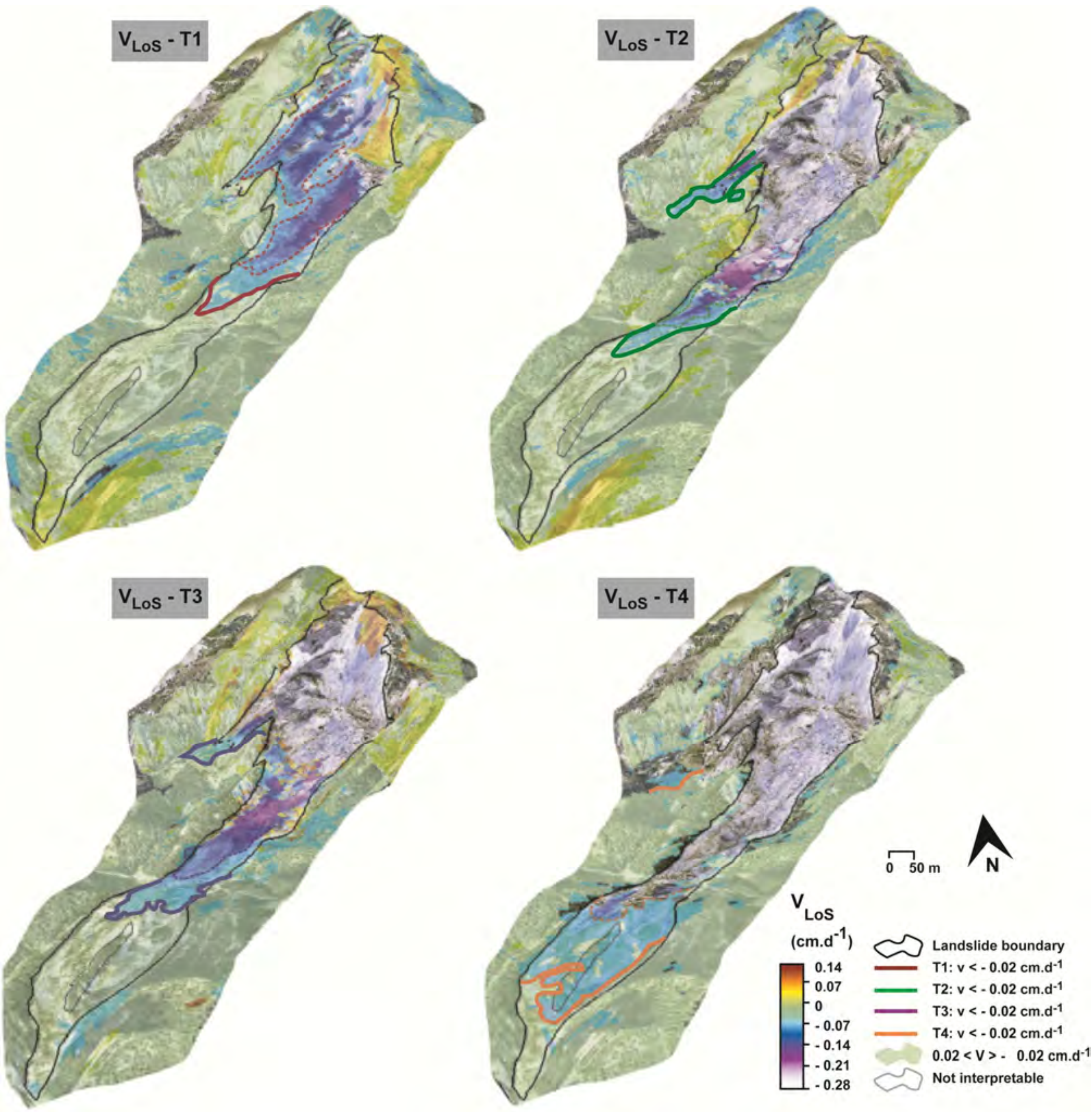


***Fig. 8.*** *Example of computed velocities based on ALOS/PALSAR image analysis for La Valette earthflow located in the Barcelonnette basin, France (from Schlögel et al., 2015b).*

### *3.3. Techniques and data from geophysics*

Geophysical techniques and data to investigate unstable slopes are widely used to recognize the internal structure of landslides, surficial formations or to detect unstable phenomena (Frappa and Lebourg, 2001; Jongmans and Garambois, 2007; Grandjean et al., 2011; Lissak et al., 2014; Pazzi et al., 2019). Three recent techniques currently stand out for their potential: (i) Heliborne ElectroMagnetism survey (HEM); (ii) 3D imaging by seismic or electrical tomography and inter-correlation; and (iii) automatic seismic landslide detection.

#### 3.3.1. Heliborne ElectroMagnetism (HEM; Fig. 9)

The method to obtain data on soil and subsoil formations by HEM  is relatively recent (Reninger, 2012). By combining the advantages of the HFEM (Heliborne Frequency ElectroMagnetism domain system; Dighem®; having good near-surface lateral resolution regardless of topography) and the FTEM (Fixed-wing Temporal ElectroMagnetism system; GEOTEM®, QUESTEM®, SPECTREM®; having a good depth of investigation), this system allows rapid coverage from large areas to sites with very steep topographies and great difficulty of access, with very good accuracy for formation thickness up to 250 m deep (Reninger, 2012). Another advantage is that multiple ground tests can be avoided, thus reducing some costs. Recently, this method has been applied in a particularly complex volcanic domain (with a succession of lava with heterogeneous characteristics) to characterize surficial formations (regolith) or hydrogeological functioning of different formations (Vittecoq et al., 2019). The method has also allowed the characterization of weathered lava formations prone to landslide and to create3D landslide modelsThe new information obtained for shallow and deep landslides provided assistance to landslide hazard assessment projects (Reninger et al., 2014; Thiery et al., 2015, 2016, 2017b).

#### 3.3.2. 3D imagery by seismic or electrical tomography and inter-correlation

Seismic or electrical tomography allows the characterization of the internal structure of a landslide or surficial formation (Samyn et al., 2011; Lajaunie et al., 2019). The majority of the landslide 3D models were created from the interpolation of multiple 2D profiles, and some uncertainties remain (Lajaunie et al., 2019). In recent years, some 3D models based on novel techniques have been developed on either shallow or deep landslides (Friedel et al., 2006; Chambers et al., 2011; Uhlemann et al., 2017).

Seismic tomography allows for the location of contrasts in seismic wave propagation velocities (Gance et al., 2015). The resolution depends on the distribution of sources that are often difficult to implement for active sources. However, it is possible to perform tomography from passive sources, such as seismic background noise, using mathematical processing (cross-correlation or deconvolution; Pilz et al., 2013). Thus, the seismic response is deduced from a station that would have benefited from an active source at another station. This approach has been successfully used in the Barcelonette Basin in the contexts of large deep-seated and complex landslides in clayey areas or in Central Asia to identify formations favourable to landslides (Pilz et al., 2013).

For 3D electrical tomography, the process is based on a network of portable resistivity meters. It measures the spatial variations of electrical potential by current injections between a fixed remote electrode and a mobile electrode grounded successively at different locations (e.g., 30 locations; Lajaunie et al., 2019). The results are impressive with the identification of different types of geological formations (different lithological units and weathered materials) up to 500 m in depth and the discrimination of hydrological structures and different fracturing in the rock (Lajaunie et al., 2013).

For both methods, the results of the identified formations prone to instabilities and their thicknesses were comparable with the results obtained by more conventional methods.

### 3.3.3. Automatic detection of events by seismic network

When a seismic network is deployed, it is possible to detect the location of a geomorphologic phenomenon and its triggering period locally (Bessasson et al., 2007). Recently, with the densification of the broadband seismic network at various scales (global, regional, and local), it is possible to develop automatic seismic detection approaches to build landslide inventories and catalogues (Hibert et al., 2017). For example, Hibert et al. (2017) presented an approach based on the spectral detection of seismic signals and source identification with a "random forest" algorithm. The method, tested for two sites in the Himalayas and Alaska, allows the identification (spatially and temporally) of approximately 80% of the phenomena (large landslides) identified by more classical techniques (e.g. geomorphological analyses).

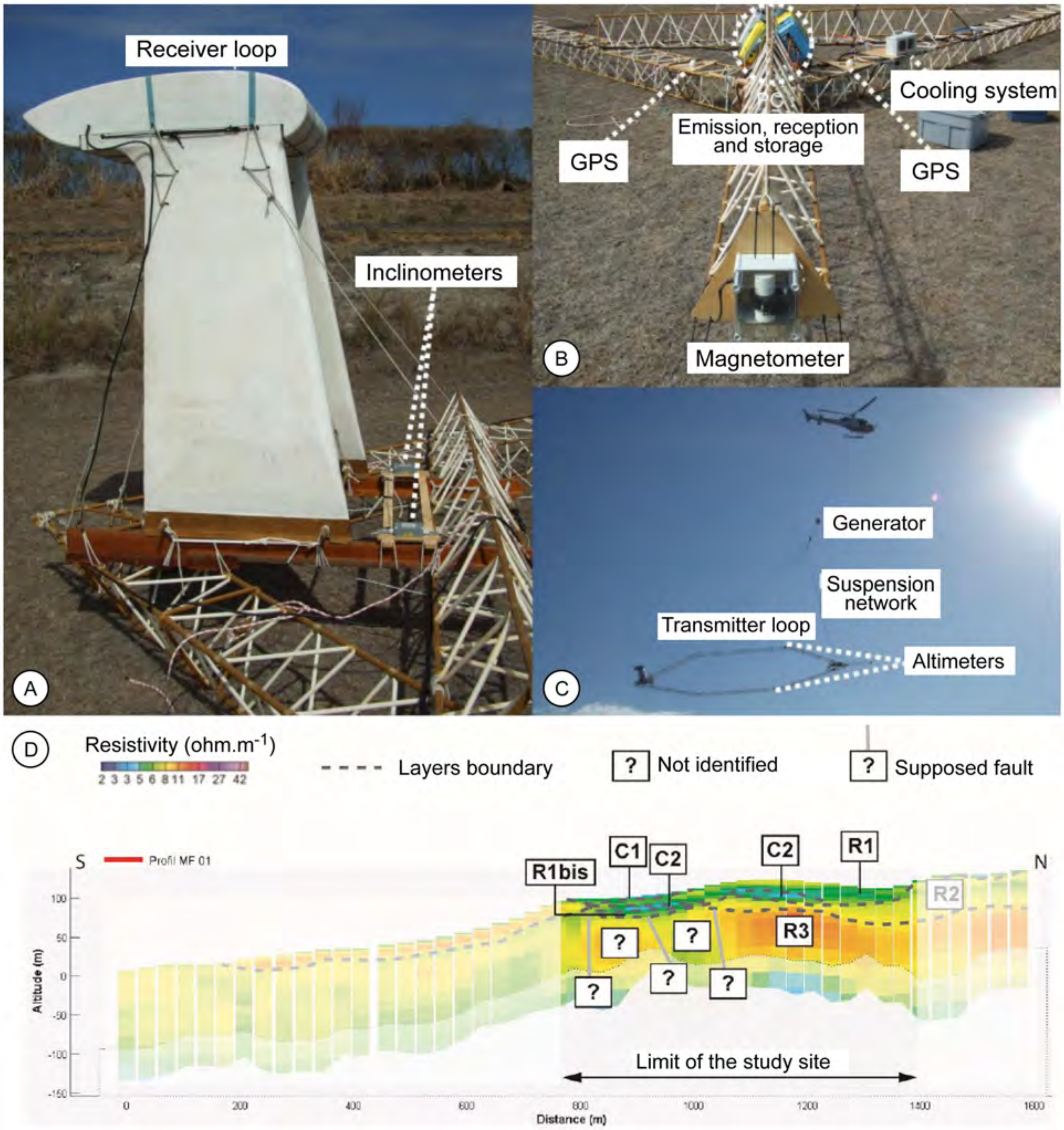


***Fig. 9.*** *Heliborne ElectroMagnetism (HEM) system (SkyTEM®) used for DROMs by the French Geological Survey (Reninger, 2012). A. Back of the system with the transmitter loop. B. Front of the system with the transmitter loop. C. System in flight. D. Example of resistivity cross section and interpretations (adapted from Thiery et al., 2016).*

### *3.4. Web services to improve landslide inventories and environmental information*

Recently, web services connected to spatial databases allow the extraction of spatial information in the office (Table 5). These tools are intended to help prepare fieldwork to better localize and characterize phenomena or to target sensitive areas, reducing the time spent for this step.

#### 3.4.1. Google Earth and Géoportail: web services for visual remote sensing

Classically, a landslide inventory starts with the analysis of aerial photographs (stereoscopy), topographic maps and the detection of the main geomorphological features (scarps, cracks, transverse ridges, flanks, toes of the body, concavities and convexities, etc.) of phenomena (Soeters and van Westen, 1996). In recent years, some web applications, such as Google Earth or Géoportail in France, allow for the mapping of landslides using recent satellite images and recent aerial photographs draping a DTM. Thus, it is possible in the web applications to directly draw the different geomorphological features of slope instabilities and later export them in a GIS environment to complete the inventory. Moreover, the tools include time series satellite images or aerial photographs, allowing the detection of new landslides in time or the improvement of knowledge about the activity of specific landslides. Yamagishi and Moncada (2018) performed an excellent overview of the possibility given by Google Earth. Recent examples in Africa have shown the importance of the tool in improving the landslide inventory in areas with low levels of high-resolution satellite images and aerial photographs (Broeckx et al., 2018; Thiery et al., 2019c).

#### 3.4.2. Infoterre®: a specific geological web service for gathering different environmental databases

In France, the databases mainly used to elaborate PPRNs are available on the "Georisque" website, which is maintained by the Ministry of Ecological and Solidarity Transition (http://www.georisques.gouv.fr/) or on the InfoTerre web service (http://infoterre.brgm.fr/viewer/MainTileForward.do), which is managed by the French Geological Survey (BRGM). Both services bring together large amounts of data and information. However, if the purpose of the "Georisque" web service is to provide information particular to natural risks, the goal of the InfoTerre web service is to provide access to other information relating to (i) the soil and subsoil, (ii) the geology (lithology and surficial formations), (iii) phenomena, (iv) natural and risk maps and (v) hydrogeology. Therefore, this service is more complete for landslide hazard mapping and allows visualizing, downloading and reinterpreting some information, such as (i) boreholes associated with their logs; (ii) geological maps at different scales; and (iii) the location of past landslides (Fig. 10). The main databases integrated in the InfoTerre web service are (i) the national landslide database (i.e., BD-Mvt), (ii) the subsoil database (i.e., BSS), and (iii) the log database (i.e., BD-Log). The BD-Mvt is an incident database of mass movements (landslide, rock-fall, mudflow, subsidence and bank erosion) provided by the French Geological Survey for metropolitan areas and the overseas departments and regions (DROMs). The database lists known landslide locations (x and y coordinates) but with no distinction of landslide type. This is an essential basis for the development of a hazard map established within the framework of PPRN. If available, the database also indicates the date of the occurrence, the destabilized volume and the causes of the instability. The BSS (subsoil database) lists all boreholes deeper than 10 m drilled in a territory (including DROMs). This database is a significant complement of information because descriptions and illustrations of boreholes are often available. The BSS contains technical and geological information acquired during subsoil surveys for road cuttings, quarries, underground works, tunnels or drilling work and are collected from the project owners, drilling companies, etc. By the end of 2012, data from 775,000 information points and 2.3 million scanned documents were available for consultation free of charge. The BSS offers a large amount of precise information to analyse failures (e.g., the types and thicknesses of formations, geotechnical characteristics of materials, and depth of the ground water table). The BD-log includes boreholes from which the geological data have been validated by the French Geological Survey (BRGM). The representations of the drilling sections are standardized from a selection of the most representative workings in the BSS subsoils database. Users have a choice between two levels of information with level 1 consisting of standardized lithological and stratigraphic codes and the names of formations and level 2 consisting of spatially harmonized drilling data. Other databases, such as hydrogeological and geophysical databases, can be accessed; however, the information is limited and unsuitable for landslide hazard assessment and mapping. These databases are regularly updated with new annual information.

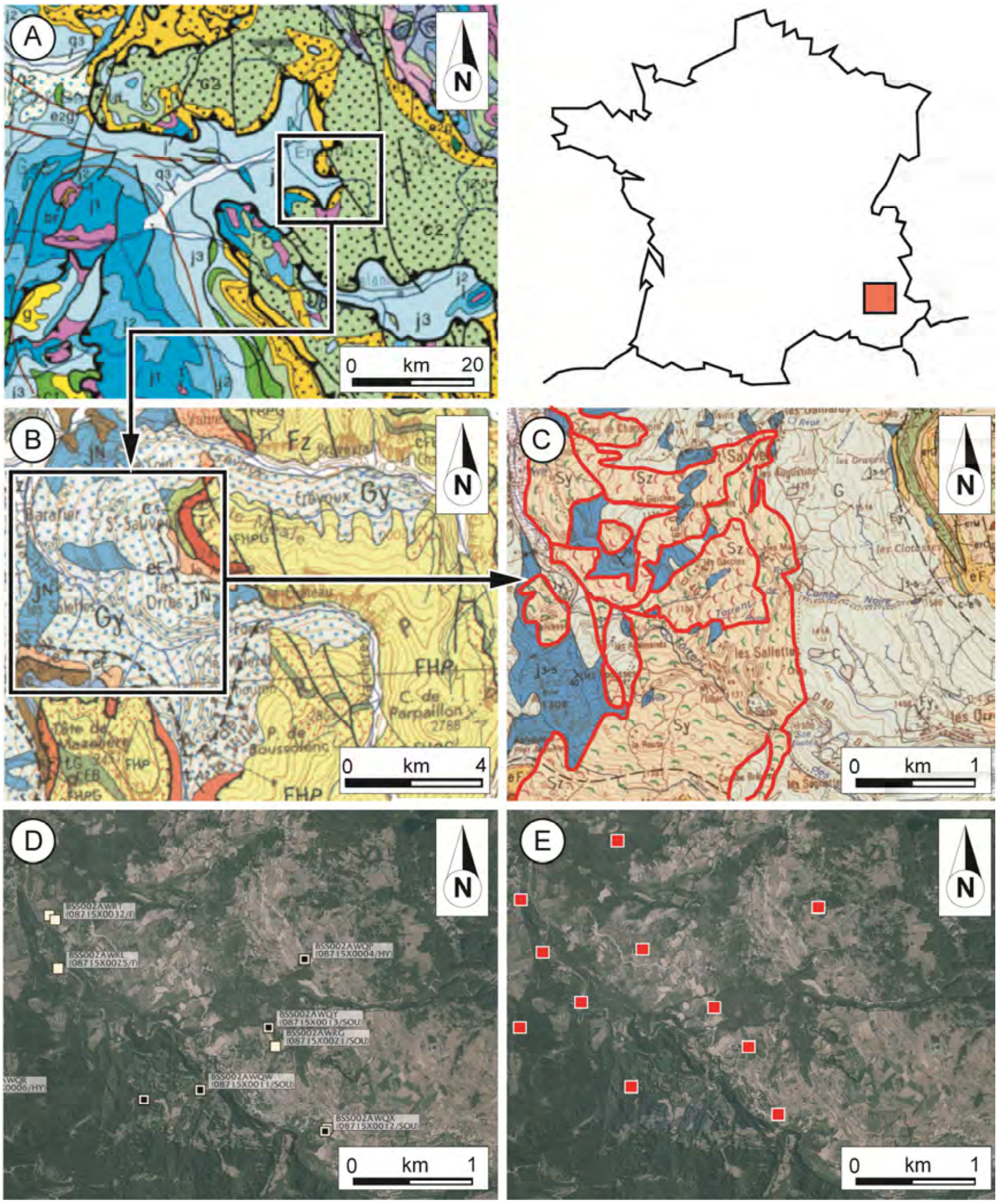


***Fig. 10.*** *Example of available information in the Infoterre webservice. This example is located near Embrun in the French South Alps. A. Geological map at a 1:1,000,000 scale; the map shows the main lithology and structure for the area. B. Geological map at a 1:250,000 scale; the map is more detailed, and it is possible to distinguish some surficial deposits interpreted by the geologist in charge of the map. C. Geological map at a 1:50,000 scale; it is possible to obtain information on geomorphology, especially on the slopes affected by landslides. D. Location of the main boreholes recorded in the BSS database and available in the Infoterre webservice. E. location of the recent landslides recorded in the BD-Mvt database and available in the Infoterre webservice.*

#### 3.4.3. European Ground Motion Service: towards a spatially informative complement for slope instability analysis

The European Ground Motion Service (EGMS) is a European initiative to provide information on natural and/or anthropogenic ground motion phenomena in Europe. Its aim is to give information about landslides, subsidence and infrastructure deformation by analyses of Sentinel 1 data by the persistent scatterers and distributed scatterers radar interferometry approach (EGMS, 2019). Currently, some tests are in progress in 13 European countries such as France. The service is to be available by the end of 2021.. The data that will be measured and validated, according to standards defined during the tests, should provide additional information on landslide activity, particularly large, deep and slow-moving landslides.

***Table 5.*** *Example of web applications and their main characteristics used to visualize landslides, to produce or to improve a landslide inventory and to analyse the physio-geographic environment*

| Tools | Specificities | Multitemporal | Scale of work recommended |
|---|---|---|---|
| **Google Earth** | Worldwide database, 3D visualization, and attention given to the quality of old satellite images | Yes | Applicable up to a 1:5,000 scale of work following the quality of the satellite images |
| **Geoportail (IGN)** | Only available for France, aerial photographs, the possibility to download old aerial photographs in numerical format (not georeferenced), the possibility of the synchronous comparison of aerial photographs for two periods, and the possibility of 3D visualization for recent documents | Yes | Applicable up to a 1:5,000-1:2,500 scale of work |
| **Infoterre (BRGM)** | Web service, a landslide data viewer (BDMvt), geological data (geological map and notice; soil and subsoil log – BSS and BD-Log), geophysical data and hydrogeological data, the possibility to obtain spatial information on geomorphology, old landslides and surficial formations on a geological map (depending of the map) | Yes | Applicable up to 1:25,000 scale of work, depending the quality of documents |
| **Georisques** | Web service, viewer dedicated to natural risk for each municipality, the possibility to obtain spatial information on phenomena (BDMvt), the information on PPRN | Depending on the availability of documents | Applicable at the municipality scale |

# 4. Discussion: what are the perspectives for regulatory hazard zoning or what should be retained for the coming years?

The two previous sections outlined an inventory of landslide hazard assessment and mapping techniques in general and in France, as well as the recent developments allowing an improvement in knowledge regarding the geomorphologic phenomena and their environments. If some of the approaches and techniques have been successfully tested in research projects at different scales, in France for different environment, can they be used for regulatory mapping in France? Thus, this section is based on various works carried out over the last 20 years by the BRGM, or by other institutes, in France and in other countries. We believe that these examples from France and elsewhere provide some materials to support our considerations about PPRNs for future.

## *4.1. Evaluate the available data to improve the inventories*

#### 4.1.1. Can the national landslide database BD-Mvt be sufficient to elaborate a PPRN?

In France, the BD-Mvt presented in section 3.2 provides a first source of landslide information, but it is limited to phenomena causing damage to structures and infrastructures. Therefore, there is a lack of information for natural areas. Moreover, this database is not complete for some departments and municipalities (Fig. 11; Fressard et al., 2014; Hervàs et al., 2019), and it is necessary to complement it for each new PPRN study or revision especially where the local environment is few known (Fressard et al., 2014). Despite the willingness of the PPR guidelines to take into account only available information, this complement is essential and must be mandatory, as the inventory of phenomena is the basis for any hazard study. Recently, this consideration was reinforced by the results obtained by numerical approach by Fressard et al. (2014) to produce a landslide hazard map at 1:10 000 scale (scale used for a PPRN).

Thus, it is advisable to complete and complement the inventory, especially by using polygons in a GIS environment in order to separate the source area and the runout area to increase the level of information on the phenomena (Corominas et al., 2014). This enhancement with complementary information (spatial and/or informative) has to be carried out classically or eventually by the emerging techniques described previously.

However, the latter are used, in most cases, to produce only local data for specific projects (research works, etc.). It is difficult, for the moment, to implement them in the PPRN procedure given the required resources (initial geological and geotechnical knowledge, implementation and measurement time, accuracy, and difficulty of applying them to a risk basin), except in some specific cases where local revision is recommended by the PPRN guideline (MATE/MATL, 1999) and where complementary data acquisitions are requested. Finally, it is still possible to use free data or information or the currently free-of-charge data mentioned as necessary by the PPR guidelines. These data are heterogeneous and require special attention.

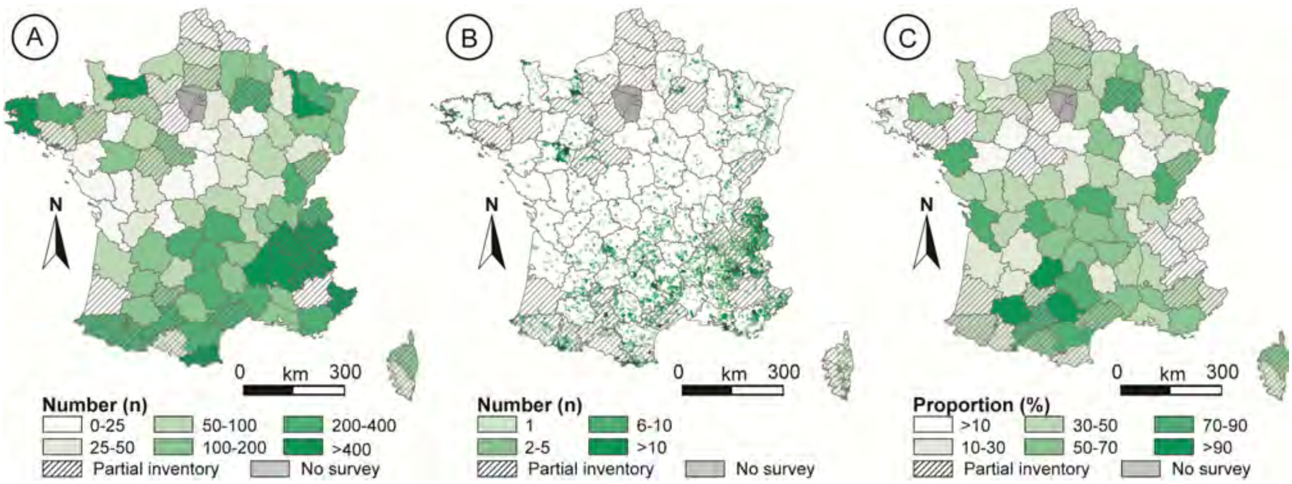


***Fig. 11.*** *BD-MVT and the systematic inventory status in France in 2019 (Source:* http://www.georisques.gouv.fr/*). A. Number of inventoried landslides by department. B. Number of inventoried landslides by municipality. C. Proportion of landslides with information about their size by department.*

#### 4.1.2. Free DEM: towards a particular attention

There are, in France, elevation data with high accuracy free available for public service missions. Table 6 presents different types of national and international elevation data that can contribute to hazard mapping for a risk basin (including the improvement of landslide inventories by visual or automatic procedure or the derivation of geomorphological indices). However, despite the qualitative recommendations mentioned in this table, it is advisable to analyse data before starting a study (by visual analysis or by calculating first and second derivatives such as slope, exposure or curvature; Steger et al., 2020). Indeed, for specific locations, DTMs such as RGAlti® 5 m or RGEAlti® 1 m are available with a planimetric accuracy of 1 m or 5 m and an elevation accuracy of 1 m. However, they can be produced by assembling and resampling heterogeneous data sources produced with different methods producing one data very heterogeneous in term of planimetry and altimetry accuracy (Fig. 12) or including artefacts due to large scale processing algorithms (Fressard et al., 2014). This results in complex DTM outputs that are difficult to read and not always adapted for modelling purposes (Fig. 12; Bouroullec et al., 2019).

***Table 6.*** Overview of data availability (non-exhaustive list) and of their use for landslide hazard mapping and applicability in the framework of a PPR. AU = available for any use; PUM = available for a public utility mission; SRO = available for the state and research institute; P = paying service; OR = on request; AS = available by subscription; NA = Not yet available; +++ = essential; ++ = important; + = moderately important; - = not very important; (X) = precaution (data verification); (XX) = verification of the scale of the application; I = inventory; H = Hazard.

| Topic | Data to be used | | Availability | Data controller | Field of application | Applicability for PPRN zoning | |
|---|---|---|---|---|---|---|---|
| | Type | Product | | | | Usefulness | Precautions |
| **Landslide inventory and geomorphology** | Landslide database | BDMvt | AU | MTES/BRGM | I/H | +++ | (X) |
| | Topographic maps | SCAN25® | | IGN | I/H | +++ | |
| | Orthophotographs | BDOrtho® 5 m | AU | IGN | I/H | +++ | |
| | | BDOrtho® 50 cm | PUM | | | ++ | |
| | | BDOrtho® IRC | PUM | | | + | |
| | | BDOrtho® historique | SRO | | | + | |
| | Satellite images | Pleiades | SRO | IGN | I/H | + | |
| | | Images SPOT | SRO | IGN | | + | |
| | | Ortho HR® | SRO | IGN | | + | |
| | | Sentinel | AU | ESA/Copernicus | | | |
| **Topography and derivatives** | Altimetric database/DTM | BD Alti® 250 m | AU | IGN | I/H | - | (XX) |
| | | BD Alti® 75 m | AU | IGN | | - | (XX) |
| | | BD Alti® 25 m | PUM | IGN | | ++ | (XX) |
| | | RGE Alti® 5 m | PUM | IGN | | +++ | (X) |
| | | RGE Alti® 1 m | PUM | IGN | | +++ | (X) |
| | | ASTER | AU | MTI/ NASA | | + | (XX) |
| | | WorldDEM | P or | DLR/EADSAstrium | | + | (X) |
| **Geology and soil** | Geological maps | Paper | P or AU | BRGM | I/H | +++ | (XX) |
| | | Numerical format (raster/vector) | P or AU | BRGM | I/H | + | (XX) |
| | Maps of the regolith | | NA | BRGM | I/H | ++ | (XX) |
| | Soil maps | | OR | INRA/IRD | H | ++ | (XX) |
| **Hydrology** | Hydrographic network map | BD Carthage® | AU | IGN | H | + | |
| | Depth of groundwater | | OR | State service | H | + | (XX) |
| **Land-cover and land-use** | Land-use maps | CorineLandCover | AU | MTES | | - | |
| | | Regional or local land-use | PUM or AS | Region | | + | |
| **Climate** | Precipitation data | | AS | Météo-France | H | + | (X) |
| **Earthquake/seismic acceleration** | Seismic data and location | | AU | BCSF/RéNaSS | H | + | |
| | | | AU | Sisfrance | | | |
| **Web applications** | Georisques (BDMvt/ geological maps) | Georisque | AU | MTES/BRGM | I/H | ++ | (X) |
| | Infoterre (BDMvt/BSS/BD-Log/geological maps) | Infoterre | AU | BRGM | I/H | +++ | (X) |
| | | Numerical aerial photographs | AU | IGN | I/H | +++ | (X) |
| | Geoportail (“remonter le temps”) Google earth | Google Earth | AU | Google Earth | I/H | ++ | (XX) |

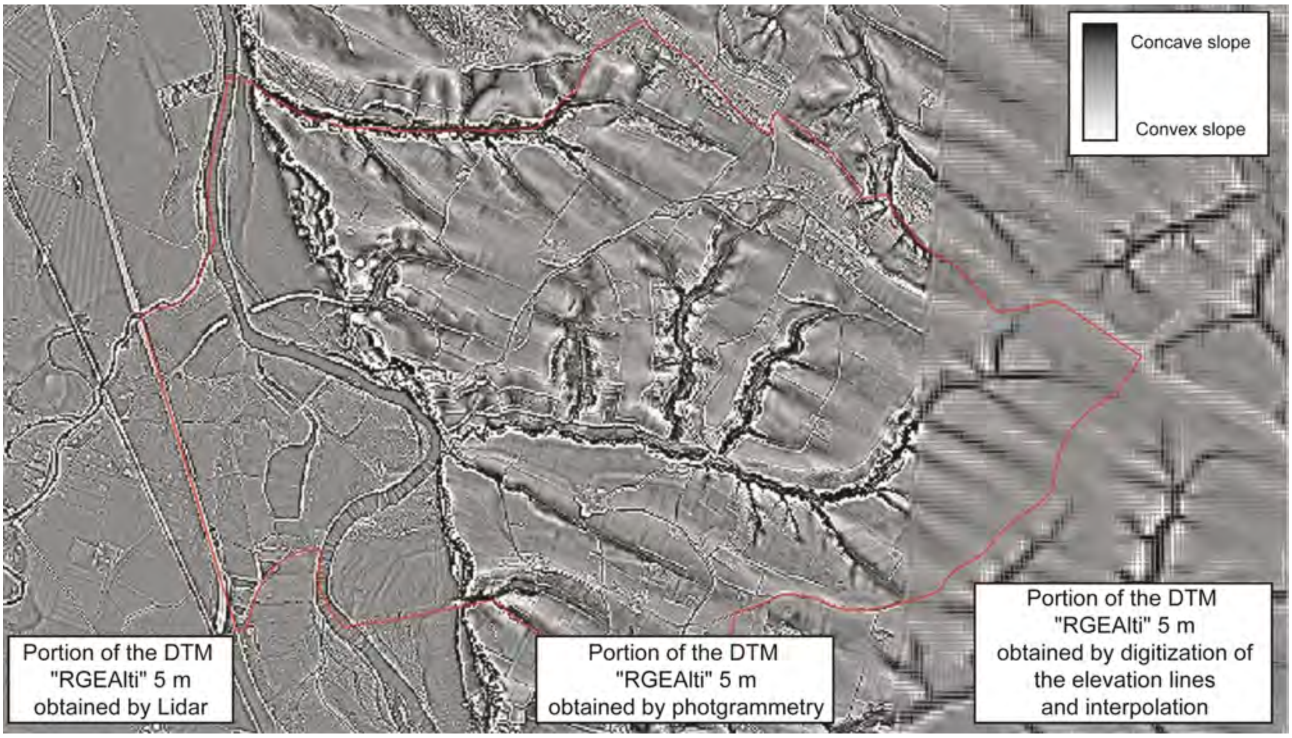


***Fig. 12.*** *Example of the problems related to the use of the DTM RGEAlti® 5 m resulting from a merging of elevation data from several techniques and heterogeneous databases (location in red: municipality of Clermont-le-Fort, France). The map represents a derivative (the curvature is represented by grey shades) from the same DTM obtained by merging different data sources (Bouroullec et al., 2019)*

#### 4.1.3. Visual analysis of remote sensing data: the best compromise for inventories

While satellite images allow rapid mapping in case of crisis (Stumpf et al., 2011), their use seems complex in a regulatory context such as PPRN, particularly radar images requiring long and complex processing times (Table 6). It seems more concrete to use ortho-images from aerial photographs whose resolutions can be metric (Table 6). For instance, the French national geographic institute produces this type of available data free of charge (BD ortho® 5 m). Aerial photographs or satellite images with infra-metric resolution can also be used, for example, the BD ortho® 50 cm, with semi-automatic or automatic landform recognition processing by the classification and analysis of textures and object structure (tools such as eCognition® or ENVI®). However, this type of procedure is complex to implement, and the results are not always satisfactory (Moine et al., 2009). To date, visual analysis is commonly preferred.

#### 4.1.4. Geophysical data: the difficulty of using them beyond the revisions of PPRNs

Geophysical data are acquired locally for specific situations, except for the overseas departments, for which there is full HEM coverage of the islands (Reninger, 2012). In these specific cases, it is possible to use these geophysical data to obtain new information about geology and structures for landslides and soils and subsoils. However, the process is not straightforward and requires new processing, especially for formations up to 30 m deep. The HEM data, for instance, will be used in the second part of 2019 for the revision of the PPRN for each municipality of La Martinique. The project mentions the systematic use of these data after reprocessing and field validation: (i) to improve the soil and subsoil knowledge, and (ii) to locate and map the different landslide prone formations. In parallel, the new information will allow the improvement of the geological map, which suffers from mistakes about the type of lithology and location errors. Therefore, it is very rare to use geophysical data for the development of PPRNs, except in specific cases, such as PPRN revisions where the acquisition of additional data is necessary to improve zoning (MATE/MATL, 1999).

### *4.2. What are the numerical approaches to be used for regulatory hazard zoning?*

#### 4.2.1. General problems of numerical approaches for regulatory hazard zoning

In a general point of view, the landslide hazard maps produced by numerical approaches are few used for regulatory hazard mapping (Reichenbach et al., 2018). France does not deviate from this observation (Maquaire, 2002; Fressard et al., 2014), and numerical spatial approaches for landslide hazard assessment are mostly used for research purposes (Thiery et al., 2014). The reasons are diverse and they can be depicted in few points with:

(i) First, and probably the most important, the majority of numerical landslide hazard maps are not produced in consultation with decision-makers, practitioners and stake-holders. When landslide hazard maps are carried out in an exploratory manner in research projects, they are not intended to be used for development, which is in line with Brabb's (1996) consideration mentioning, "the preparation of hazard maps was not a guarantee that they would be used". Of course, these methods can be complex for uninitiated to understand but the duty of the scientist to explain and to simplify the message of the produced document. Thus, the integration of end-users in the landslide hazard mapping process must become the rule. This is the case for the final approval of PPRNs in France with presentation and approval meetings. However, we believe that it is necessary to go further and from the beginning of the study, the end-users must be integrated in order to help the person in charge of the study to take into account local prerogatives and the sometimes a fine knowledge of the field. This type of test was recently carried out for a Pyrenean valley with the SAMCO project (Adaptation of Society to Mountain risks in the Context of global change; Grandjean et al., 2018). The project shows that the integration of local end-users becomes essential in the reflection process to take into account certain planned changes and subsequently improve the resilience of territories to natural hazards (Houet et al., 2017).

(ii) Second, the choice of numerical method is not easy and become complex when one refers to the scientific literature. Reichenbach et al. (2018) reveal that 6 groups of methods were tested since the 90's. Pourghasemi et al. (2018) go further by mentioning the use of more than 70 different methods between 2005 and 2016. All give good results with reliable outputs. The debate must not focus on the performance of a method over one other. Depending on the method there will be advantages and limitations that need to be taken into account and that will have to be accepted. In order to reduce errors and improve the reliability of results, Chung and Fabbri (2003), Rossi et al. (2010) or Reichenbach et al. (2018) recommend the use of several methods together. This must be the good way, but in the context of producing a PPRNs, it seems difficult since the results have to be produced quickly for a limited financial cost. Thus, in the case of PPRNs, we think that it is better to use simple, proven, and known methods whose advantages and limitations are well identified like intermediate methods or some advanced methods. In addition, in order to be sure of the reliability of results, we recommend the use of a cross-validation procedure or multiplying some tests allowing to show the goodness of fit of the results as mentioned by Chung and Fabbri (2003), Brenning (2005) or Bégueria (2006).

(iii) Third, there are no standards to define the hazard classes. In principle, hazard classes are obtained by discretization of the computed value (i.e. relative weights, factor of safety, failure probabilities) by the expert in charge of the zoning. He/she defines different thresholds in order to rank and portraying landslide susceptibility or hazard. Several approaches can be used, such as natural thresholds, equal-area rank, nested means, quantiles, and the Jenks method. However, there is currently no consensus about the way should be used, which raises a concern for the standardization between maps produced by different experts with different points of view. For landslide susceptibility, one useful approach to use should be the discretization of relative weights by the equal-area rank method (Chung and Fabbri, 2003). This way would provide a generalized and standardized way for relative classification and for comparisons between modelling results (Chung and Fabbri, 2003; Fabbri et al., 2017). Fressard et al. (2014) used this method to compare several results obtained with different set of data in Normandy (France); leading to the selection of the best dataset to produce landslide hazard zoning by a multivariate method (i.e. logistic regression function).

(iv) Fourth, few results are reproducible from one site to another. Nevertheless, some results obtained by quantitative methods (e.g. data-driven methods) can be transposed to another site if the geomorphological context is similar (Thiery, 2007; Thiery et al. 2007; Thiery et al., 2008). This type of transposition is only possible if the input data (i.e. spatial variables) are the same in terms of resolution and classes of variables, which is rarely the case from one catchment to another, or it requires a substantial effort to harmonize the source data.

(v) Fifth, it is necessary to prepare one map per type landslide. Even if it appears obvious, there are too many studies proposing landslide hazard maps without differentiation of phenomenon. However, it is essential to separate them by type because each one has its own predisposing and triggering factors. Once the digital maps have been made for each type of landslide, then it is possible to add them one by one keeping the principle of the strongest class over the weakest class for each terrain unit.

#### 4.2.2. Indirect qualitative, hybrid or data-driven methods: towards the best compromise for new PPRNs

For France, some tests of numerical landslide hazard maps with a legal vocation and presented as an alternative to expert maps for PPRNs have been carried out: (i) in la Martinique (Montpellat, 1994); (ii) in the Barcelonnette Basin (Thiery, 2007; Thiery et al., 2007, 2014; Schlögel et al., 2015a); in the Massif Central (Poiraud, 2012; Poiraud, 2014); in Normandy (Fressard, 2013; Fressard et al., 2014); and in a Pyrenean catchment (Baills et al., 2013; Thiery et al., 2017; Bernardie et al., 2017). The maps obtained by different methods were compared to expert and geomorphological maps with promising results. In the light of these previous works and considerations, two trends are emerging to produce new PPRNs in France with the use of (i) intermediate or (ii) advanced methods (i.e. qualitative indirect methods, hybrid methods or data-driven methods; Table 7). The choice between the two methods will be conditioned by the quality of the landslide inventory, the spatial variables and the willingness to integrate stakeholders into the mapping process. In any case, the person in charge of the study must have a minimum of experience in hazard and risk analyses, this is a non-negotiable prerequisite.

Table 7 provides indications about the methods possible to use in a regulatory framework such as PPRNs. Thus, when the spatial variables are considered to be exhaustive with a sufficient resolution for the working scale (i.e. 1:25,000-1:5,000), and the inventory includes a sufficient number of events, the typology (e.g. shallow, deep, rotational, translational), the activity of phenomena, we recommend using an “advanced method” based on data-driven methods. The advantages of these way is the reliability of the results, the possibility to integrate temporal components especially if a cross-validation is performed. The main disadvantages will be to explain the different steps of mapping and the different computing rules to the stakeholders because the strategy to calibrate and validate the results can be complex (Corominas et al., 2014) and the difficulty to integrate the runout in the mapping process.

If the spatial variables are heterogeneous (i.e. in terms of resolution and classes), and the landslide inventory remains sufficiently accurate (i.e. in terms of the number of events and exhaustivity of information), we recommend using intermediate methods, such as Fuzzy Logic and AHP (Analytical Hierarchy Process; Saaty, 1977), or hybrid methods mixing indirect qualitative methods and statistical/probabilistic methods (Thiery et al., 2014; van Westen et al., 2016). Recent examples (Thiery et al., 2014) have underlined how these methods are appropriate to work with heterogeneous data and can replace efficiently more complex method in a regulatory framework (Thiery et al., 2014).

The advantages of these techniques is that they were developed to analyse complex decisions, allow decision-making by confronting groups of people (experts, decision-makers) about a problem and its understanding. Therefore, they allow (i) the elaboration of scenarios and hypotheses being compared quickly and (ii) the introduction of experts' knowledge and stakeholders' opinion in the mapping process. Moreover, it is possible to integrate local, subtle changes to the data following the field knowledge, which is more difficult with quantitative approaches (Thiery, 2007; Thiery et al., 2014).

If the variables are very heterogeneous and the inventory is almost non-existent, then at minimum it should be necessary to impose to create a new landslide inventory sufficiently accurate spatially and qualitatively. Then, depending on the quality of the variables, the person in charge of the work will use to the previous methods (intermediate or advanced) or to the qualitative methods (i.e. basic; Table 7).

In any case, if it is not possible to obtain new data or improve some data for financial reasons lied to the project; it is possible to use basic methods but with the formalization of mapping rules in clear and explicit documents. Finally, the most important remains the quality of the landslide inventory (Fressard et al., 2014; Depicker et al., 2019) and beyond the method, is the need of transparency and traceability of results that are too often neglected by basic methods. Indeed, these methods regularly generate conflicts because the different rules taking into account are not well explained.

***Table 7***. Summary of the recommended methods following the types, the levels and the complexities of landslide hazard zoning in a regulatory French framework for future studies (informative, new or revisions; adapted from Soeters and van Westen, 1996; Fell *et al*., 2008; Aleotti and Chowdhury, 1999; and Thiery and Terrier, 2018). +++ : Highly recommended; ++ : Recommended if the expert well knows the advantages and the drawbacks of the method; + : Possible with precautious; NR = Not relevant from a cost/benefit ratio perspective; NS : Not suitable.

| **Type of zoning** | | | | **Data** | | |
|---|---|---|---|---|---|---|
| **Zoning** | **Scale of maps** | **Objectives** | **Methods** | **Sufficient data** | **New data indispensable to progress** | **New data and triggering data indispensable to progress** |
| **Regional zoning** | 1: 100,000 – 1: 25,000 | Informative or consultative | Basic | +++ | NR | NR |
| | | | Intermediate | ++ | +++ | NR |
| | | | Advanced | ++ | +++ | NR |
| | | | Sophisticated | NS | NS | NS |
| **Local zoning** | 1: 25,000 | Informative or consultative | Basic | ++ | NR | NR |
| | | | Intermediate | ++ | +++ | NR |
| | | | Advanced | + | ++ | NR |
| | | | Sophisticated | NS | NS | NS |
| | 1-10,000-1,5000 | Regulatory (new project) | Basic | + | ++ | NR |
| | | | Intermediate | ++ | +++ | - |
| | | | Advanced | ++ | +++ | + |
| | | | Sophisticated | NS | NS | NS |
| | | Regulatory (Revision) | Basic | + | ++ | + |
| | | | Intermediate | + | ++ | + |
| | | | Advanced | ++ | +++ | + |
| | | | Sophisticated (static method) | NS | ++ | ++ |
| **Site zoning** | < 1: 5,000 | Regulatory (Revision) | Basic | - | + | ++ |
| | | | Intermediate | - | - | - |
| | | | Advanced | - | - | - |
| | | | Sophisticated (static or dynamic method) | - | ++ | +++ |

### 4.2.3. What are the numerical approaches to be used for the PPRNs revisions?

For PPRN revisions, advanced and sophisticated numerical methods, such as physically based methods, should be considered and recommended. The advanced methods will be reserved for a risk basin revision, while sophisticated numerical approaches will be more appropriate for local revisions.

For the advanced methods, as mentioned in the section 4.2.2 a particular emphasis must be paid to the quality of the landslide inventory and existing data (accuracy, resolution, and number of classes). If these data are not well adapted to the project, then it is necessary to plan the acquisition of new information, as mentioned in the PPRN guidelines (MATE/MATL, 1999). Given the technic chosen, it may be considered, for instance, to improve the landslide inventory, to specify the geological map, or to acquire a digital terrain model.

For sophisticated numerical methods, the acquisition of additional data to improve zoning is recommended by the PPRN guidelines (MATE/MATL, 1999), especially where there are human or socio-economic issues of public interest. This type of work was recently performed in La Martinique following a request of the municipality of La Trinité (Fig. 13A; Thiery et al., 2017b). The project aims to develop an agricultural area considered to have a moderate hazard level but is likely to absorb part of the high population growth of this municipality (Fig. 13B). As the DROMs had full heliborne TDEM coverage (BRGM/SkyTEM® helicopter-borne TDEM project), a multidisciplinary study was proposed. The work combined (i) the integration of data from these surveys to identify the type of weathered material and associated thicknesses, (ii) the creation of a 3D geological model of the area, (iii) the analysis of the slope developments with the elaboration of different scenarios (excavation and integration of new buildings) and modelling landslides with a physical-based model using specific profiles (TALREN®; Terrasol, 2018), and (iv) spatial modelling of shallow and deep landslide failures (ALICE®; Sedan; 2011; Vandromme et al.; in revision) and their associated run-out (BORA®; Sedan et al., 2006), with highly saturated materials reflecting the landslide triggering conditions (Fig. 13C; Thiery et al., 2017b). The simulated map was compared with expert knowledge, and the areas with slope undercutting, which were not taking into account by simulations, were added manually (Fig. 13D). The results of the final map showed that the area considered a moderate hazard level should have been classified at a high landslide hazard level, and it could be difficult to develop this slope despite the integration of slope works (Fig. 13E). This project showed that it was possible to improve the regulatory landslide hazard map and help practitioners in their development process by integrating new data and numerical simulations.

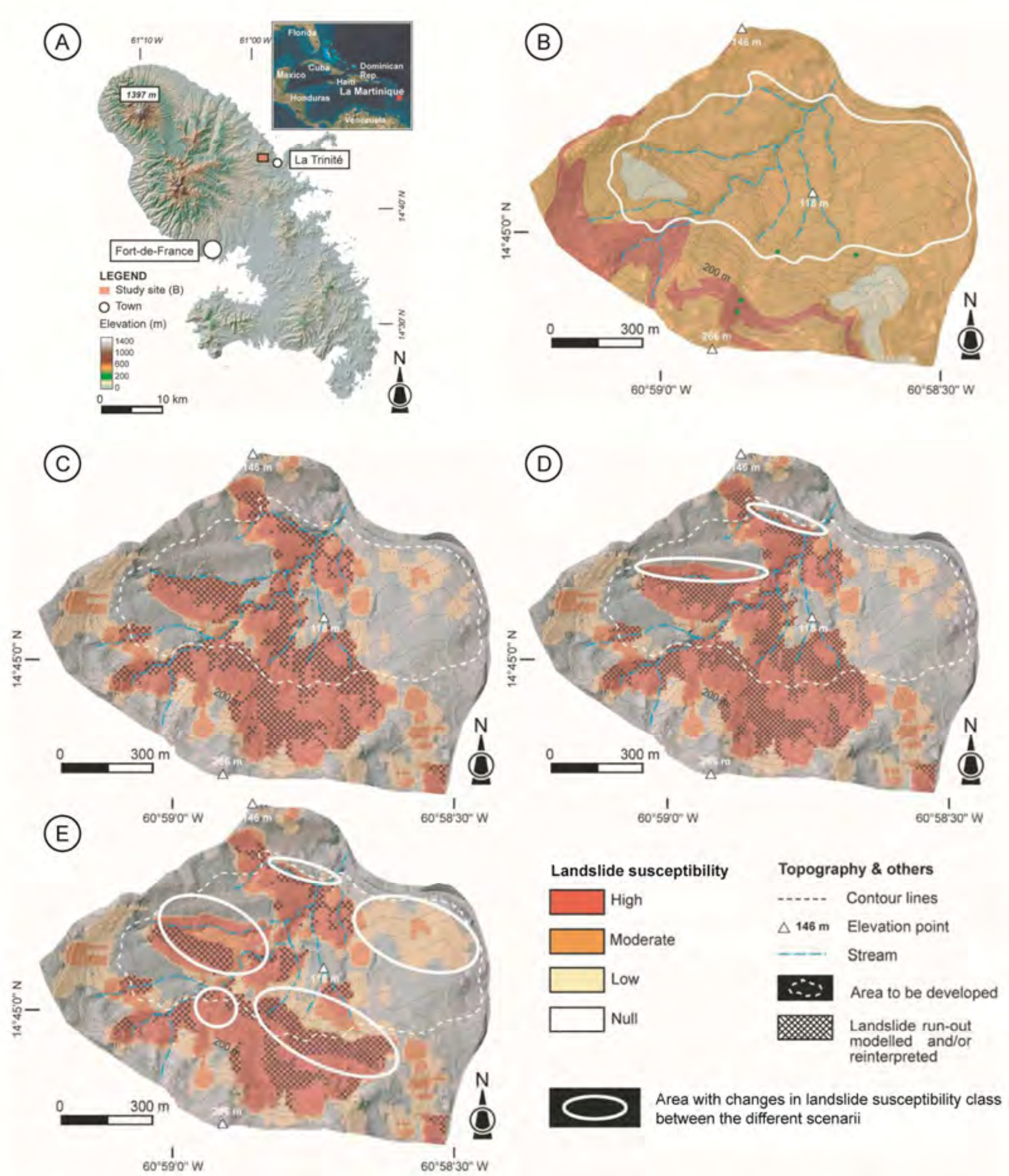


***Fig. 13.*** *Example of an 'advanced' susceptibility map for the community of La Trinité (Martinique, from Thiery et al., 2017b). A. Location of the test site. B. Landslide susceptibility map produced by an empirical approach for the PPRN for the municipality of La Trinité. C Advanced landslide susceptibility map produced by a physically-based model (ALICE®) for failure and a model based on the angle of reach (BORA®) for the run-out of landslides; the map was produced for shallow and deep landslides. D. Advanced landslide susceptibility map integrating expert knowledge on bank erosion and slope undercutting. E. Advanced landslide susceptibility map integrating expert reasoning, bank erosion and slope works (excavations).*

### 4.3. Towards alternative strategies for future regulatory landslide hazard maps

The above examples show that it appears possible to produce and improve landslide hazard maps with numerical approaches within a legal framework if the method is adapted and by taking into account different parameters, especially if some information is well-integrated. Following the previous considerations, it is possible to propose some guidelines for the future elaboration or revision of landslide hazard maps in the framework of regulatory zoning. We assume that in some cases (e.g., a constrained economical context), these guidelines might be difficult to follow; nevertheless, in any circumstances, they have been tested and verified for current use by the various institutes in charge of managing the development of the PPRNs.

### 4.3.1. A strategy using a hierarchical scale approach

Leroi (1996) proposed a three-step landslide hazard analysis and mapping by a hierarchical scale strategy (called by Leroi: “nesting scale approach”) that could be integrated into a regulatory framework (Fig. 14). Such strategy has been attempted in a research context in Cuba (Castellanos Abella and van Westen; 2005; Castellanos Abella; 2008) and in La Martinique in an exploratory context to develop a methodology for revising PPRNs (Nachbaur et al., 2018).

For this oversea department, a landslide susceptibility map has been produced at a 1:100,000 scale using an indirect qualitative method and taking into account 5 variables. Although the results differ from the zoning established on a 1:25,000 scale in 1996 by expert method, it appears that 75% of the surface in the high susceptibility class are common. Thus, it is interesting to note that landslide susceptibility map produced by the qualitative indirect method (after a discussion on the relative weights to be introduced for each variable with local expert) locally improves the zoning. Indeed, some areas not identified in high susceptibility hazard in the expert map but having suffered of recurrent landslides have been identified in high susceptibility by the 1:100,000 scale map. This is probably due to the more precise (i.e. spatial resolution) recent variables allowing to better identify local unstable slopes, in particular the quality of DTMs.

This zoning allowed us to focus on a municipality known for its recurring slope instabilities and identified as high and moderate susceptibility for the majority of its slopes. For this municipality, a new susceptibility map was established at a 1:10,000 scale with the integration of improved geological variables obtained by expert knowledge and the help of a HEM data (i.e. type of lithology, regolith and depth of different formation) . The integration of information about the regolith thicknesses (allochtonous and autochthonous surficial formations) allowed identifying on one hand, the areas prone to shallow landslides, and on the other hand, the areas prone to deep seated landslides. This distinction is essential for this type of zoning at this scale to take into account the potential consequences on vulnerable elements (Nachbaur et al., 2018).

For the third step, it was chosen an area in high landslide susceptibility with recurrent shallow and deep landslides was chosen to develop a hazard map at a 1:5,000 scale. The map took into account failure probability and potential runout according to different scenarios. The failure probability was computed with a spatial physically based model and the maximum runout with a cellular automata (Sedan et al., 2006; Thiery et al., 2017). If the locations in high landslide hazard differ slightly from the map performed at a lower scale, this large scale map allows: (i) to have failure probabilities according to the type of phenomenon and taking into account the saturation of the materials; (ii) to take into account the runout of the phenomena in a numerical and quantified way, which is never achieved for PPRN. Thus, additional qualified and quantified (i.e. probabilities, thickness of failure, volume, velocity of runout) information is given through this map. As with the previous landslide susceptibility map, this information is required as part of the risk analysis (Corominas et al., 2014).

Thus, based on these considerations, the hierarchical method proposed by Leroi in 1996 has been improved and integrates the necessary landslide information to finalize each step and the main objectives for each scale of work. The strategy is not a one-way relationship; each result at each scale of work must be able to provide information or new data to the finer or coarser scale. Using this strategy, it should be possible to establish a database for any homogeneous physio-geographical areas prone to landslides and thus help experts, practitioners, geotechnical offices and institutes obtain general or local information depending on the factors taken into account. This type of database would thus complement the BD-Mvt and the BSS. This hierarchical strategy implies some changes in the way of analysing hazard and landslide risk in France with more exchanges between practitioners, academics, researchers and end-users. The hierarchical strategy should allow to better target areas with high landslide hazards; and local public decision-makers could engage these up- and down-scaled methods, to hierarchize the level of assessment needed for each municipality concerned about risk.

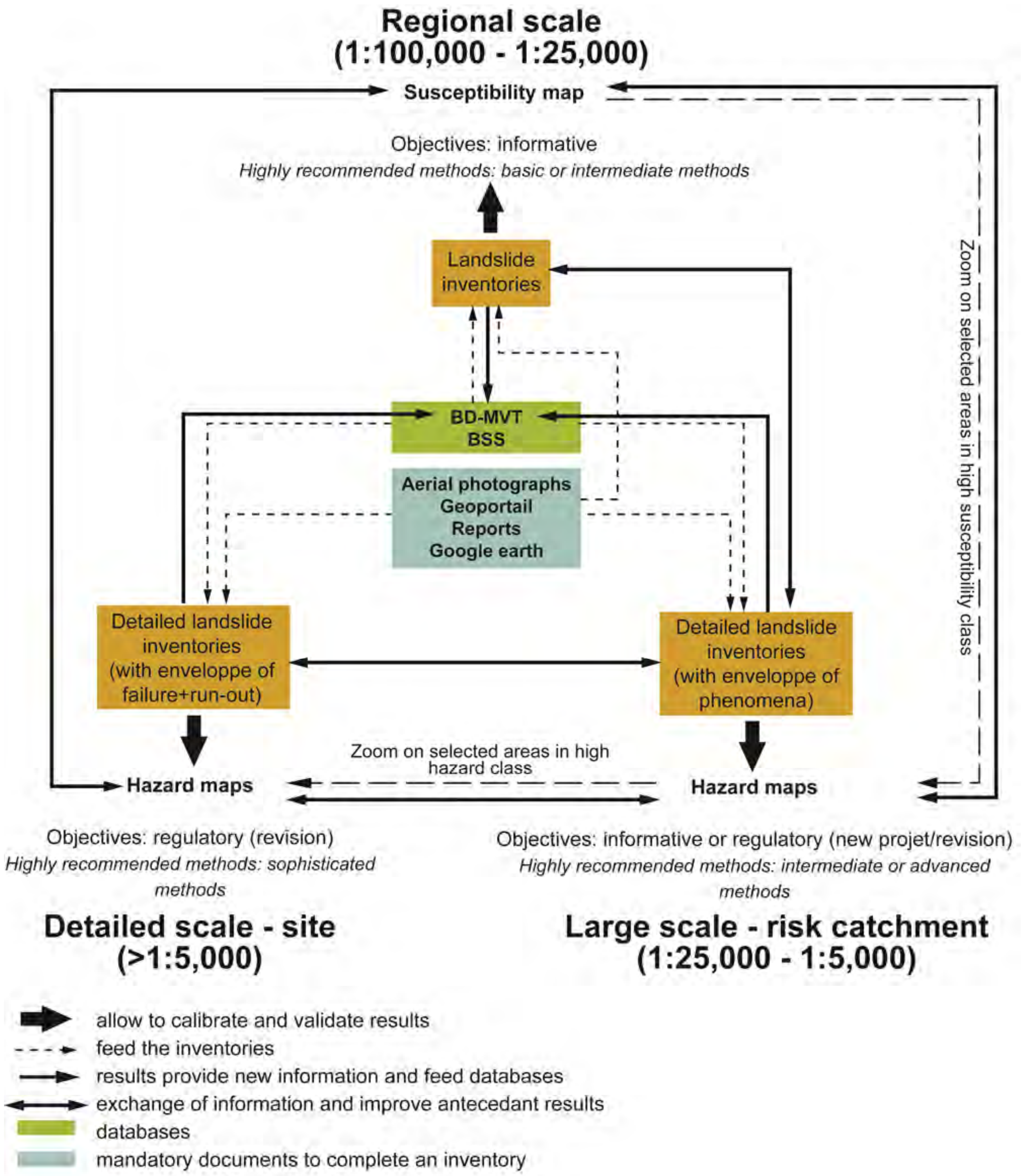


***Fig. 14.*** *Global landslide hazard assessment by a hierarchical strategy (nesting scale approach adapted from Leroi, 1996)*

#### 4.3.2. A strategy based on scenarios, or how to take into account global change?

In addition, to the usual questions (What? Where? When? How?) for landslide hazard zoning, Glade (2001) or Reichenbach et al. (2018) propose to add a change component for each question. In other words, what can happen, where and when, if a parameter (e.g., land-use, climate) is modified? This aspect is mentioned in the PPRN guidelines

(MATE/MATL, 1999). Indeed, landslide hazard maps must be produced for the next 100 years (MATE/MATL, 1999). However, this exercise is complex and only takes into account one major event (the most likely major event as defined by an expert; MATE/MATL, 1999). The majority of studies do not take into account future land-use or climate change. It is therefore necessary to keep in mind several questions relating to the type of phenomena, their temporal dimension, the influence of land-cover and land-use change(s), and the climate change that can influence some triggering factors, such as precipitation.

Thus, it is necessary to take these considerations into account for future landslide hazard mapping and produce a map for each type of landslide, as mentioned by van Westen et al. (2006) and Corominas et al. (2014), but this should be done according to specific spatial and temporal scenarios. These scenarios must be carried out with the help of local end-users who have a certain vision of the territory. This type of test was recently carried out for a French South Alps catchment (Baills et al., 2013) and a Pyrenean valley (Houet et al., 2017; Grandjean et al., 2018; SAMCO project - Adaptation of Society to Mountain risks in the Context of global change). SAMCO project shows that it is possible to improve landslide hazard maps by integrating (i) land-use and (ii) climate change scenarios by using physically based models for the different types of phenomena.

## 5.Conclusion

Landslide hazard assessment and mapping are the first and essential steps in developing regulatory zoning. Without them, it is impossible to carry out the final study, regardless of the method chosen (Asté, 1992). Therefore, beyond the method, whenever landslide hazard zoning must be established, four questions must be asked and answered relating to: (i) its purpose (What is its use?), (ii) the type of information sought, (iii) the level or degree of accuracy needed and (iv) the expected map scale. In France, this zoning, within a regulatory framework, was initially informative (i.e. ZERMOS maps in the 1970s) and gradually became restrictive by applying to development plans (i.e. with the PERs in 1982, then the PPRNs in 1995). Methodologically, this cartography has always been based on a naturalist approach called ‘expert approach’ with existing data, "this type of analysis being preferred over specific studies that go beyond the scope of the PPRN and the State's mission" (MATE/MATL, 1999). Thus, these maps value the state of knowledge at a given moment but remain controversial because of the subjective methodology recommended.

Thus, in this work, we have focused on numerical mapping methods used in an exploratory way and considered as objective. The advantage of these methods is the traceability of the reasoning and data used. These numerical approaches can be implemented within a legislative framework without setting the expert aside, as Bernknopf et al. (1988) and Leroi (1996) already pointed out. Therefore, they can constitute an alternative to the method recommended by the PPRN guide (MATE/MATL, 1999), but only if a well-defined mapping strategy is applied depending on the available data and/or to be specifically acquired. In order to help future people in charge of landslide hazard zoning within this regulatory framework in France, we therefore propose indicative tables on the necessary data, the working scales and the intended purpose of the documents produced (informative, legislative). These tables are to be used as the basis for any new PPRN or revision. The table 6 provides information and characteristics on the quality of data, their usefulness following the objectives (inventory, landslide hazard zoning). By coupling this table with the table 7 it is possible to guide the choice of methods to be implemented according to the context, the available data and the objectives. For instance, if the person in charge of a regulatory landslide hazard map does not have a representative inventory with information on the type, depth and kinematics of landslides, it would be suspicious to propose a sophisticated method. In this case, the person has the duty to propose to check the BD-MVT and propose complements by remote sensing and field survey. Only afterwards, it will it be possible to check the quality of the data and propose a sophisticated approach or not. To complete these considerations, it is necessary to mention that the person in charge of the study must have a minimum of experience to verify that the zoning can be consistent with reality a and finally explain the results clearly to the stakeholders.. Finally, new data should also be used more systematically. Fressard et al (2014) or Thiery et al. (2017) show that it is possible to improve landslide sensitivity and susceptibility and hazard maps with new data without systematically increasing the cost of these maps.

In light of these considerations (newly available data with fine spatial resolution, newly available processing tools, and changes in the natural context), it would be appropriate in some cases to update some PPRNs and, beyond, to consider amending the PPRN guideline to take into account these technical and technological developments. The recent and exploratory examples in La Martinique and the French Pyrenees support these remarks and go even further by proposing or updating new paradigms concerning the regulatory risk zoning in France, such as the hierarchical strategy. This strategy should make it possible to better target areas prone to instabilities and help experts, practitioners, stake-holders to coordinate themselves in function of the stakes. Finally, from our experience two point should allow to conclude this work: (i) the various points raised for this review are valid within a regulatory framework but must also be taken into consideration for the exploratory works in a research context; (ii) it is essential not to neglect the experts whose opinions must remain at the centre of the process and who must make the appropriate choices according to the study area and relevant stakes in the local context.

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