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Multi – criteria methods to enhance the landslide risk management of small-medium Municipalities to plan sustainable mitigation strategies: the analysis of San Colombano Certenoli Municipality

Curriculum coordinator: Prof. Massimiliano Burlando
PhD Supervisors: Prof.ssa Rossella Bovolenta, Prof. Riccardo Berardi, Prof.ssa Teresina Torre

Candidate: ANDREA GIACOBBE

POLYTECHNIC SCHOOL - ENGINEERING
UNIVERSITY OF GENOA – Dipartimento di Ingegneria Chimica, Civile e Ambientale (DICCA)

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INTRODUCTION

General problem and motivation of the research

The protection of human life and property from climate-related events is a high priority for small and medium Municipalities, which must enhance new tools to face on emergency situations and find the right strategies to plan risk prevention measures before the events' occurrence. The present doctoral thesis presents a multidisciplinary investigation into landslide susceptibility assessment as a decision-support tool for public administrations, with a particular focus on small and medium-sized municipalities. The research integrates a technical susceptibility analysis by the Weights of Evidence method (WOE) with a comprehensive review of the administrative and regulatory framework governing landslide risk management in Italy and France, with reference to basin planning instruments and public works procedures. The study concerns on the Entella River basin in the Liguria Region (Italy), including the Municipality of San Colombano Certenoli, located above the city of Chiavari in the Eastern of Liguria Region and North areas of the Maritime Alps Department (France), which have recently experienced severe rainfall-induced landslides.

The Entella River basin, including the Municipality of San Colombano Certenoli, represents a typical Mediterranean mountainous environment characterized by steep slopes, complex lithology, and intense rainfall events. This area is highly representative of small and medium-sized municipalities in the Liguria Region, where hydrogeological instability is widespread and landslide occurrence is frequent. The high density of past landslides and the presence of vulnerable infrastructures make it a suitable case study for testing susceptibility models and evaluate their applicability in real administrative contexts.

The Municipality of San Colombano Certenoli represents a suitable and representative case study for landslide susceptibility assessment due to the fact the area is characterized by complex geomorphological conditions, a high density of rainfall-induced landslides, and significant exposure of infrastructure and settlements. These features are typical of many municipalities in the Liguria Region and, more broadly, in north-western Italy. Furthermore, as a small–medium municipality, it reflects common administrative and technical challenges in local-scale risk management, where limited resources require efficient and reliable decision-support tools. The availability of detailed landslide inventories and thematic cartography also makes the area particularly suitable for testing GIS-based statistical methods and ensuring the transferability of the proposed approach to similar territorial contexts.

The study area in the Maritime Alps (France) provides a complementary context characterized by alpine geomorphology and extreme rainfall-induced processes, as shown by the impacts of a huge storm called Alex in 2020. This area is representative of high-energy mountainous environments where landslides are triggered by intense and localized rainfall events. The inclusion of this case study allows for testing the robustness and transferability of the applied methodology across different climatic, geological, and geomorphological conditions.

The selection of study areas in both Italy and France enables a comparative analysis across different environmental and administrative contexts. While the Ligurian case study reflects recurrent, small-to-medium scale instability affecting densely inhabited territories, the French case highlights large-scale and event-driven processes in alpine environments. This dual approach enhances the generalizability of the results and allows for a broader evaluation of the proposed methodologies under different conditions.

The use of new information and communication technologies (ICT), methods and models constitute a support to all phases of landslide risk management. Knowing the variety of available tools and instruments, is the best way to apply forecasting techniques, data-driven prediction methods as the Weights Of Evidence (WOE) model, and modelling techniques to assess landslide susceptibility. The use of GIS (Geographical Information System) is a way to help the Municipality to elaborate data, designing and creating new maps specifically to the area of interest or in similar ones inside the territory, enlarging the knowledge of factors related to the landslide risk. The GIS is a "container" of not only geographical elements but also of administrative aspects important for the Municipality activity.

The application of geomatics connected to the statistical analysis applied on GIS environment, gives the opportunity to get new landslide susceptibility maps as an intermediate but also precise and suitable tools to be used together with the official cartography. It is a way to be used by technicians and experts to find out the critical aspects close to Municipal roads and exposed assets and help the Municipality to allocate the considerable amount of public funding in the most correct and suitable way for the protection of the area.

This research introduces several innovative aspects in the field of landslide risk management. First, it proposes a geomatics-based susceptibility modelling with an analysis of institutional and regulatory frameworks. This dual perspective is particularly relevant, as it bridges the often-existing gap between scientific modelling and its practical implementation within public decision-making processes. Secondly, it gives an overview of administrative and economic evaluations concerning the landslide risk management in the field of public works. Decision making processes and design strategies are examined to safeguard the San Colombano Certenoli Municipality community. Thirdly, the application of WOE across different territorial and geomorphological contexts in Italy and France, highlights its adaptability and power not only at basin and large scale but also at local scale. Therefore, the emphasis on transdisciplinary with the combination of engineering, geomatics and administrative analysis, is particularly valuable and aligns well with current research trends in landslide risk management.

Goals of the research

The activity within the framework of the PhD cooperation with the Public Administration consists of a supporting role to the San Colombano Certenoli Municipality. The goal of the research project focuses on the interaction with the Municipality to find the most suitable strategies and "best practices," in dealing with landslide risk in the territory and at the same time to study the functionality of the Municipality from an administrative point of view, as regards the procedures adopted for the assignment of public works in the field of landslide risk and the design strategies considered to safeguard the territory. Therefore, not only engineering but also economic-administrative aspects have been considered, in the view of a multidisciplinary and transdisciplinary path.

The goal of the research consists of an advanced landslide susceptibility assessment by developing a multi-scale GIS-based framework focused on the Weights of Evidence method and its application in different European contexts. The comparative analysis between Italy and France, the methodological refinement of WOE, and its operational implementation at the municipal scale means the capacity by the model to be effective in different administrative contexts and with the use of different datasets. The study has the aim to show that statistically based susceptibility models, when properly integrated with planning tools and validated through geomorphological and geomatics - based analysis, can provide effective support to Public Administrations, being a new innovative tool complementary to the common regional cartographies, to evaluate the best design and suitable strategies to face on the landslide risk. In particular, the application to San Colombano Certenoli highlights the potential of this approach to enhance decision-making processes, optimize resource allocation, and improve risk management in other small and medium-sized municipalities with similar features and needs.

Therefore, the research is operational, developing a GIS-based decision-support framework tailored to small and medium-sized municipalities, which often lack advanced ICT resources, integrating the technical support of Municipality experts with the scientific and academic approach, suggesting multiple modelling and mitigation strategies to make the community resilient and capable to manage the landslide risk.

Organization of the dissertation

The PhD thesis dissertation is organized into five main chapters.

Chapter 1 introduces the general problem of landslide risk and outlines the motivation and objectives of the research. It provides the scientific background through a comprehensive review of the state of the art, including landslide classification, inventory mapping, susceptibility analysis methods, and validation approaches. Attention is given to statistical and geomatics-based techniques, with a focus on multivariate regression model and the Weights of Evidence method.

Chapter 2 addresses the institutional and administrative framework of landslide risk management. It analyses the evolution of Italian legislation, the basin planning instruments adopted in the Liguria Region, and the role of Civil Protection authorities. The chapter also discusses stakeholders involved in the risk management cycle and examines project strategies, socio-economic impacts, and mitigation countermeasures for landslide risk reduction.

Chapter 3 presents a detailed case study in the Municipality of San Colombano Certenoli, focusing on the Caruggio di Vignale area, a hamlet of the Public Administration. The chapter describes the characteristics of the landslide body, the current susceptibility conditions, and the proposed mitigation projects for road and hydraulic safety. On field investigations, in-situ damage surveys, and administrative procedures related to the implementation of mitigation works are also discussed.

Chapter 4 is devoted to landslide susceptibility assessment at different spatial scales through statistical approaches. It first analyses the effects of the 2020 Alex Storm in the Maritime Alps and presents susceptibility assessments for selected study areas. The chapter then focuses on the Entella basin and the Municipality of San Colombano Certenoli, applying the Weights of Evidence method using different modelling strategies. The resulting susceptibility maps are validated through quantitative zonal statistics and qualitative on-site analyses and compared with existing PAI cartography.

Finally, Chapter 5 summarizes the main findings of the research, highlights the scientific and operational contributions of the proposed methodologies, and outlines limitations and perspectives for future research in landslide risk management and sustainable mitigation planning.

CHAPTER 1: LANDSLIDE SUSCEPTIBILITY ASSESSMENT METHODS

1.1 State of art

1.1.1 Landslide risk

Intense and protracted precipitations often cause slope movements. In the last ten years, the Liguria Region has faced many experiences for landslide events caused by intense precipitations. The types and kinematics of rainfall triggered landslides depend on climate and geo-mechanical properties of soils in the sites involved.

Climate factors, as rainfall and temperature, affect the hydraulic and mechanical properties of outcropping soils, as well as the water budget of the local hydrographic network, with an impact on subsurface water filtration along slopes. Changes in these conditions in the short-medium term may activate shallow to averagely deep landslides *(Monteleone et al., 2014)*.

Landslides, defined as the movement of a mass of rock, debris or earth down a slope, are one of the major natural hazards and they account each year for enormous property damage in terms of both direct and indirect costs, which have a considerable impact on the Liguria Region. Social and economic losses due to landslides can be reduced by means of effective planning and management.

These approaches include restriction of development in landslide-prone areas, landscaping and construction codes, use of stabilizing measures (drainage, slope-geometry modification, and structures) to prevent or control landslides, and development of warning systems *(Dai et al., 2002)*. When we talk about hydrogeological instability, we cannot fail to consider that the problem falls within the broader context of risk analysis and hazard assessment, concepts for which it is always better to provide an adequate definition.

Risk is defined by the Eq. [1] below (*Canuti et al., 1996*):

$$R_I = H \times V_I \times E \qquad [1]$$

- where H (Hazard) represents the probability of occurrence i.e. the probability that a potentially destructive event, of a certain intensity, will occur in an area for a given period.
- where V is the vulnerability, defined as the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards; it is the degree of loss produced on a certain element or group of elements exposed to the risk resulting from the occurrence of a natural phenomenon of a given intensity (the inverse of the ability of a given area to withstand an event of Intensity I).
- where E is the exposure, as the elements exposed to the risk (buildings, communities, economic sources); it is connected to vulnerability in the hazard prone area.

The research of the susceptibility associated to landslides is aimed at locating areas most prone to instability and therefore at the creation of relative susceptibility maps, with applications either in the field of territorial planning or in the field of Civil Protection. Public Administrations must find the best strategies to face extremes by adopting an efficient landslide risk assessment analysis, as a quantitative analysis, based on numerical values of the probability, vulnerability, and consequences, resulting into a numerical value of the risk.

This approach provides a risk map that depicts the level of risk in terms of fatality or economic loss at different activities in areas at risk. The spatial distribution of landslide risk may be obtained by spatial subdivision of the area under study and multiplication of spatial landslide probability, affected zones, land use or spatial distribution of population or property, and vulnerability *(Brandolini et al., 2012)*.

1.1.2 Landslide classification

Ground movements include a set of movements, brutal, of the ground or subsoil, of natural or anthropogenic origin. The volumes involved can range from a few cubic metres to several million cubic metres *(Thiery, 2007)*. There are many classifications of these phenomena that can be defined in several groups based on the types of displacements, ruptures, and materials. According to Varnes' classification of 1978 (Fig. 1), a distinction is made between falls, topples, slides, spreading, flows and movements of a more complex type. The phenomenon of landslide corresponds to the displacement of a coherent mass on a slope, along a fracture surface and which can propagate beyond it *(Varnes, 1978)*.

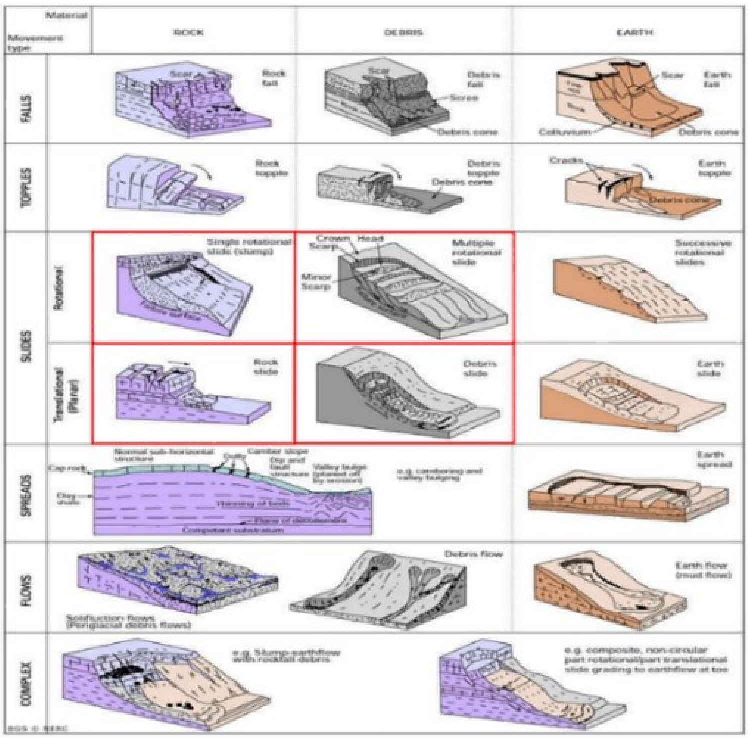


Figure 1 : Varnes classification, (Varnes, 1978)

Falls are landslides that involve the collapse of material from a cliff or steep slope. Falls usually involve a mixture of free fall through the air, bouncing or rolling. A fall-type landslide results in the collection of rock or debris near the base of a slope. Topple failures involve the forward rotation and movement of a mass of rock, earth, or debris out of a slope. This kind of slope failure occurs around an axis (or point) at or near the base of the block of rock. A topple often results in the formation of debris or a debris cone at the base of the slope; this pile is called a talus cone.

A slide-type landslide is a downslope movement of material that occurs along a distinctive rupture or slip surface. The slip surface tends to be deeper than that of other landslide types and not structurally controlled. These landslides are characterised by a prominent main scarp and back-tilted bench or block at the top, with limited internal deformation. Below this, movement is rotational about an axis.

Slides are characterised by a failure of material at depth and then movement by sliding along a rupture or slip surface. There are two types of slide failure, rotational slides (slumps) and translational (planar) slides. If the slip surface is listric (curved or spoon-shaped) the slide is said to be rotational. A translational or planar landslide is a downslope movement of material that occurs along a distinctive planar surface of weakness such as a fault, joint or bedding plane. Some of the largest and most damaging landslides on Earth are translational. These landslides occur at all scales and are not self-stabilising. They can be very rapid where discontinuities are steep.

Finally, flows are landslides that involve the movement of material down a slope in the form of a fluid. Flows often leave behind a distinctive, upside-down funnel shaped deposit where the landslide material has stopped moving. There are several types of flows: mud, debris, and rock (rock avalanches).

1.1.3 Landslide inventory

Landslides, i.e. as the movement of a mass of rock, debris, or earth down a slope, under the influence of gravity *(Cruden et al., 1996)*, can be caused by intense or prolonged rainfalls, earthquakes, rapid snow melting, volcanic activity, and multiple human actions. A landslide inventory map records the location and, where known, the date of occurrence and the types of mass movements that have left discernible traces in an area *(Guzzetti et al., 2000)*. Landslide maps can be prepared using different techniques *(Guzzetti et al., 2006)*. Selection of a specific technique depends on the purpose of the inventory, the extent of the study area, the scale of the base maps, the scale, resolution, and characteristics of the course of landslide mapping. Classes are added, deleted, split, or merged to conform to local geomorphological settings, the type, abundance, and pattern of landslides, the interpreter's experience and preferences, and new findings.

Preparation of a landslide inventory relies on the fact that landslides leave discernible signs, most of which can be recognized, classified, and mapped in the field, through the interpretation of (stereoscopic) aerial photographs, satellite images, or digital representations of the topographic surface *(Rib et al., 1978)*. Most of the signs left by a landslide are morphological and they refer to changes in the form, shape, position, or appearance of the topographic surface. Other signs induced by a landslide may reflect lithological, geological, land use, or other types of surface or sub surface changes. Indeed, the morphological signature of a landslide *(Pike, 1988)* depends on the type and the rate of motion of the mass movement *(Dikau et al., 1996)*.

In general, the same type of mass movement will result in a similar landslide signature. Since morphological convergence is possible, resulting in the same or similar morphological forms from different processes, care must be taken when inferring landslide information from aerial photographs, satellite images, or digital representations of the topographic surface *(Antonini et al., 2002)*. Landslides do not occur randomly or by a chance *(Guzzetti et al., 2002)*. Slope failures are the result of the interplay of physical processes and mechanical laws controlling the stability or failure of a slope. The mechanical laws, which control the size, shape, and spatial and temporal evolution of the landslides, can be determined or inferred empirically, statistically, or in deterministic fashion *(Dietrich et al. 1995)*. Knowledge on landslides can be generalized *(Guzzetti et al., 1999)*, and information on failures gained in an area can be used to detect and map landslides in other areas.

1.1.3.1 IFFI cartography

The Inventory of Landslides in Italy (IFFI) is the national and official database on landslides. It was officially born in 1997, promoted by the Committee of Ministers for the Protection of the Soil (ex-law 183/89) with the aim of creating a complete and standardized cognitive framework of landslides on the Italian territory.

The need to create a National Inventory of landslides in Italy emerged more strongly following the disastrous event of 5 May 1998, which seriously affected the municipalities of Sarno, Siano, Quindici, Bracigliano and S. Felice a Cancello, in the provinces of Salerno, Avellino and Caserta. Since 2005, ISPRA has been publishing the data of the Inventory online to promote the widest dissemination and use of information to local administrations, research bodies, technicians operating in the field of territorial design and planning and citizens.

Since 2016, IFFI inventory is carried out by ISPRA in collaboration with the Regions and Autonomous Provinces due to the institution of SNPA as the National System of Environment Protection *(Legge 28 Giugno 2016, n. 132)*. Archiving information on landslides is a strategic activity for proper territorial planning, considering that most landslides are reactivated over time, even after long periods of quiescence lasting several or several centuries. The IFFI Inventory is an important basic cognitive tool used for the assessment of landslide hazard of Hydrogeological Asset Plans (PAI), the preliminary design of soil protection interventions and infrastructure networks and the drafting of Civil Protection Emergency Plan.

The landslides surveyed in the Inventory of Landslides in Italy are over 625,000 and affect an area of almost 24,000 km^2, equal to 7.9% of the national territory. The data are updated to 2021 for the Autonomous Province of Bolzano; to 2018 for the Umbria Region; to 2016 for the regions of Emilia-Romagna, Friuli-Venezia Giulia, Liguria, Piedmont, Sicily, and Valle d'Aosta; to 2015 for Tuscany; to 2014 for Basilicata and Lombardy. For the remaining regions, the data are updated to 2007. A picture of the distribution of landslides in Italy can be obtained from the landslide index, equal to the ratio between the landslide area and the total area, calculated on a 1 km side mesh. The working methodology adopted for the census of landslides uses the collection of historical and archival data, aerial photointerpretation, and ground surveys.

Photointerpretation is a fundamental tool for carrying out systematic geomorphological investigations on large areas of territory, allowing the identification and perimeter of the main landslide phenomena. The examination of historical data and archival research makes it possible to reconstruct the landslide events of the past, evaluating their evolution, the recurrence time, and the intensity of the phenomenon itself. The in-situ survey makes it possible to verify and integrate the information acquired in the photointerpretation phase and to update the archival data. 44.2% of the landslides in the IFFI Inventory were surveyed using aerial photointerpretation, 30.1% with the collection of historical or archival data, and 7.8% with field surveys.

The integration of multiple methods was used in 17% of cases. The inventory of landslide phenomena is an indispensable tool for carrying out a correct landslide susceptibility analysis that is based on the knowledge of past landslides to predict the potential landslide areas that could emerge in the future.

1.1.4 Landslide susceptibility analysis

Landslide susceptibility is the likelihood of a landslide occurring in an area based on local terrain conditions *(Brabb, 1984)*. Concerning on a mathematical language, landslide susceptibility can be defined as the probability of spatial occurrence of slope failures given a set of geo-environmental conditions *(Guzzetti et al., 2005)*. Indeed, susceptibility measures the degree to which a terrain can be affected by future slope movements. In other words, it is an estimate of where landslides are likely to occur. Studying landslide susceptibility means a qualitative and quantitative assessment of classification, volume or area, and spatial distribution of movements which exist or potentially may occur in the future *(Fell et al., 2008)*.

The landslide susceptibility gives information on the proneness to landsliding, in terms of initiation areas, based on a set of relevant environmental characteristics. In particular, the main data layers required for landslide susceptibility assessment are landslide inventory data, predisposing and triggering factors *(Corominas et al., 2014)*. Among these data layers, the landslide inventory is the most important, as it gives insight into location of past landslide occurrence, as well as their failure mechanisms *(Persichillo et al., 2017)*.

So, it is important to have knowledge of past ground movements to predict what could happen in the future. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding. In some cases, the ground movements are connected to heavy rainstorms with short duration and intense precipitation; typically, some rainfall – induced shallow landslides occur as slope failures with shallow slip surface often triggered by meaningful rainfalls.

The spatial distribution of shallow landslides is influenced by different climatic conditions and environmental settings including topography, morphology, hydrology, lithology, and land use. Among these factors, in slope stability analysis, lithology and geological structure can be considered constant over extended periods whereas morphology, climate, and land use can be affected by major modifications *(Persichillo et al., 2016)*. Although it is expected that landsliding will occur more frequently in the most susceptible areas, but the time frame is not explicitly considered. In the early literature, landslide susceptibility is often referred as landslide hazard. These studies investigate the functional relations between the geographical distribution of landslides and of geo environmental landslide predisposing factors, using different approaches and methods, operating at different geographical scales, and adopting a variety of mapping units *(Reichenbach et al., 2018)*.

1.1.4.1 Methods

Over the past few decades different procedures have been developed to perform analysis on landslide susceptibility at different scales and based on different approaches. The procedures available for the landslide susceptibility assessment can be grouped as based on knowledge-driven, data-driven, or physically based methods. Here there is a brief description of them:

- Heuristic methods or knowledge - driven methods are direct approaches based on the expertise whose knowledge is referred to direct geomorphological and geological indicators which lead to the existent landslide perimeter or susceptibility map realization; experts decide the criteria to be used but the method can be affected by a subjective view.

- Statistical methods or data - driven methods are indirect approaches which correlate information which belong to the landslide past phenomena with a series of factors considered responsible of landslide occurrence and their consequences; this approach usually involves the mapping of the existing landslides, the mapping of a set of factors that are supposed be directly or indirectly linked to the stability of the slopes, and the establishment of the statistical relationships between these factors and the instability process; they are more suitable for large zone application, and they avail of GIS environment for the management and integration of thematic cartographies.

- Deterministic methods or physically apply method, which concern classical slope stability theory and principles such as infinite slope, limit equilibrium methods (e.g. by Bishop, Sarma, etc.) and less commonly finite element and 3-D techniques; these models require standard soil parameter inputs such as soil thickness, soil strength, groundwater pressures, slope geometry etc; the resultant map details the average factor of safety and boundaries while susceptibility classes can be set according to factor of safety ranges.

Recent developments in landslide susceptibility assessment have emphasized the importance of integrating multiple data sources and modelling approaches. Hybrid models combining statistical, heuristic, and machine learning techniques have shown improved predictive performance compared to single-method approaches. Furthermore, ensemble modelling strategies are increasingly adopted to reduce uncertainty and increase robustness in susceptibility mapping. These advancements highlight the need for flexible and scalable methodologies that can be adapted to different territorial and environmental contexts.

1.1.4.2 Susceptibility zoning

Landslide susceptibility zoning involves the classification, area or volume and spatial distribution of existing and potential landslides in the study area. It may also include a description of the travel distance, velocity, and intensity of the existing or potential landsliding.

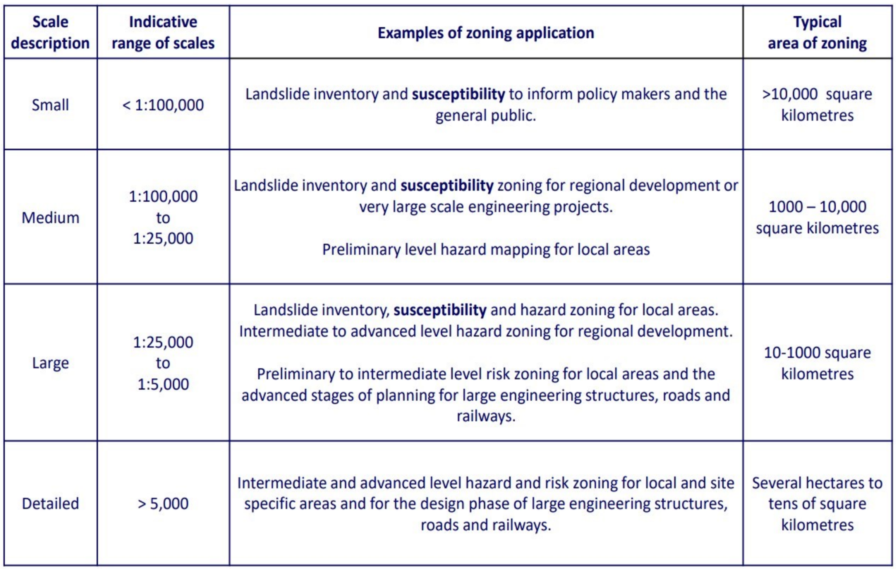
Landslide susceptibility zoning usually involves developing an inventory of landslides which have occurred in the past together with an assessment of the areas with a potential to experience landsliding in the future, but with no assessment of the frequency (annual probability) of the occurrence of landslides. In some situations, susceptibility zoning will need to be extended outside the study area being zoned for susceptibility and risk to cover areas from which landslides may travel on to or regress into the area being zoned.

It will, be necessary to assess independently the propensity of the slopes to fail and areas onto which landslides from the source may travel or regress *(Fell et al., 2008)*. There is no unique procedure capable of estimating the potential of failure of each type of landslide and its expected travel distance. Infact, the conditioning factors as slope angle, lithology, groundwater conditions, are specific for each landslide mechanism.

The preparation of a landslide susceptibility map for zoning purposes is usually based on 2 assumptions:

- The past is a guide to the future so that areas which have experienced landsliding in the past are likely to experience landsliding in the future.
- Areas with similar topography, geology and geomorphology as the areas which have experienced landsliding in the past are also likely to experience landsliding in the future.

These assumptions are often reasonable, but it should be noted that there are exceptions such as when the source of the landslides is exhausted by earlier landsliding. For a correct zoning application, in Figure 2, guidelines to assess landslide susceptibility are highlighted. The choice depends on the type of scale, its range and typical area of zoning.



Scale description	Indicative range of scales	Examples of zoning application	Typical area of zoning
Small	< 1:100,000	Landslide inventory and **susceptibility** to inform policy makers and the general public.	>10,000 square kilometres
Medium	1:100,000 to 1:25,000	Landslide inventory and **susceptibility** zoning for regional development or very large scale engineering projects. Preliminary level hazard mapping for local areas	1000 – 10,000 square kilometres
Large	1:25,000 to 1:5,000	Landslide inventory, **susceptibility** and hazard zoning for local areas. Intermediate to advanced level hazard zoning for regional development. Preliminary to intermediate level risk zoning for local areas and the advanced stages of planning for large engineering structures, roads and railways.	10-1000 square kilometres
Detailed	> 5,000	Intermediate and advanced level hazard and risk zoning for local and site specific areas and for the design phase of large engineering structures, roads and railways.	Several hectares to tens of square kilometres

Figure 2: Landslide susceptibility zoning and its application with respect the range of scales

The aim of susceptibility mapping should be to include the maximum number of landslides in the highest susceptibility classes, trying to achieve the minimum spatial area for these classes *(Barrile et al., 2020)*. It will usually be appropriate to carry out landslide susceptibility zoning as a first stage in the development of landslide hazard or risk zoning for planning purposes *(Fell et al., 2008)*. Concerning on this aspect, it will often be necessary to assess separately susceptibility, hazard, and risk, for the different types of landslides affecting the area for rock falls, shallow landslides, and deep-seated large landslides and to present the results in specific zoning maps as the recommendations or the statutory obligations to mitigate the risk might differ for the different landslide types. These maps may be combined onto one map. In this case, it must be considered that, for instance, the same hazard level may be obtained from different combinations of landslide types, volumes, intensities, and frequencies. It may also be necessary to produce separate maps for landslides from natural slopes and constructed slopes.

1.1.4.3 Geomatics to analyse landslides

In the framework of the activities aimed to acquire knowledge and to monitor landslides, a significant role is played by geomatics. Landslides represent a growing threat among the various morphological processes that cause damage to territories.

To address this problem and prevent the associated risks, it is essential to quickly find adequate methodologies capable of predicting these phenomena in advance. The creation of maps aimed at delineating landslide susceptibility zones represents a significant advancement in geospatial analyses, offering a comprehensive view of terrain vulnerabilities. These maps serve as invaluable tools, providing continuous assessments of slope conditions and enabling proactive measures to mitigate risks associated with landslides *(Marzocchi et al., 2014)*.

Commonly the process of developing such maps involves the integration of various data sources, including satellite imagery, topographic surveys, and field observations, to accurately capture the intrinsic terrain characteristics, as some aspects related to geomatics. The resulting susceptibility maps not only highlight areas prone to landslides but also offer insights into the magnitude of potential hazards posed to communities, infrastructures, and ecosystems. This information plays a crucial role in guiding land-use planning, infrastructure development, and disaster management efforts, thus allowing decision-makers to prioritize resources and implement targeted mitigation measures.

1.1.4.3.1 Geographical information system applications

Digitalization and collaborative approach are the essential aspects driving Open Science, which is the modern way of conducting research. Open Science in its broader denotation can be defined as “a collaborative culture enabled by technology that empowers the open sharing of data, information, and knowledge within the scientific community and the wider public to accelerate scientific research and understanding” *(Ramachandran et al., 2021)*.

The accessibility to the scientific body of knowledge, the improvement of the efficiency of the processes to share research outputs and findings and the evaluation of the science impact considering new metrics are fundamental key points to increase and improve the knowledge on landslides. With means to openly share data, the intent is to accelerate and boost new findings and innovations minimizing data duplications and enabling interdisciplinary and wider collaborative research.

To be effectively used by other researchers, Open Research Data need to be shared following specific principles of Findability, Accessibility, Interoperability, and Reuse (FAIR) *(Wilkinson et al., 2016)* and this led to the creation of several data services that permits to register, store, find and access data following interoperable metadata standards *(Cannata et al., 2023)*.

In the context of Open Research Data, GIS (Geographical Information System) software is an open technological framework for acquiring, managing, analysing, and sharing freely accessible data, allowing the sharing of territorial datasets that allow the creation of digital maps useful for improving the understanding of territorial models and promoting transparency in decision-making processes by a Public Administration.

The use and the application of GIS software is recommended for landslide risk assessment and analysis, thanks to the existence of detailed and updated geographical information directly available in GIS formats as digital elevation models, hillside cartographies, population density maps, exposed assets mapping or derived by GIS elaborations (terrain slopes from map-algebra calculation, roughness coefficient from land-use reclassification, slope aspect). Moreover, the use of GIS allows users to spatially contextualize and relate hazards with vulnerable elements and thus facilitates the evaluation of risk, which is inherently dynamic in space and time.

To decrease landslide susceptibility, GIS helps stakeholders, public and private administrations to improve the landslide risk management. Inside the GIS environment, a series of tools can be implemented to provide useful indications on stabilization and consolidation interventions, to be validated with appropriate design projects, such as those introduced by *(Bovolenta et al., 2017)*. Hence, with limited resources, it could be of great help in the increasingly complex management of the territory.

The procedure correlates the factors influencing the occurrence of landslides with several types of countermeasures, obtaining medium or local scale maps suggesting the most appropriate interventions for the mitigation of landslide risk. The six categories of identified countermeasures are: re-profiling, drainage, retaining structures, reinforcement with inclusions, soil bioengineering, and rock slope protection. The approach provides more information concerning exposure and vulnerability, providing a Decision Support System (DSS) for a more efficient allocation of resources to technical staff of public administrations, designers, insurance companies, operating in landslide risk management *(Glade et al., 2005)*.

1.1.4.4 Statistical approaches for landslide susceptibility assessment

Statistical approaches remain a cornerstone in landslide susceptibility assessment due to their reproducibility and compatibility with GIS environments. However, recent studies have demonstrated that combining statistical approaches with machine learning techniques can significantly improve model performance and predictive capability (*Xia et al., 2023*). Hybrid models integrating frequency ratio, analytical hierarchy process (AHP), and artificial neural networks (ANN) have been successfully applied in different geomorphological contexts, showing higher accuracy compared to traditional methods (*Mersni et al., 2025*).

Assessing landslide hazard and risk with a minimum set of data, a reproducible methodology and GIS techniques, is a challenge for earth-scientists, government authorities, and resource managers. Over the past few decades different procedures have been applied to assess and estimate the probability of occurrence of landslides in a territory within a reference period, deduced from information on landslide susceptibility expressed as the spatial correlation between predisposing terrain factors and the distribution of observed landslides in a territory.

Landslide susceptibility maps can be designed starting from two methods: (i) direct approaches based on the expertise of the target area, and (ii) indirect approaches based on statistical algorithms and computations. The main concept of the indirect approaches is that the controlling factors of future landslides are the same as those observed in the past *(Carrara et al., 1995)*.

Indirect approaches are based on statistical conditional analyses and on the comparisons of landslide inventories and predisposing terrain factors. The methods are applied at the scale of the terrain unit (TU) corresponding to a portion of hillslope possessing a set of predisposing factors. In the scientific community it is commonly highlighted that statistical analyses are more appropriate and reliable for susceptibility zoning at meso-scales (1:50,000 to 1:25,000) because of their potential to minimize expert subjectivity but they depend on the landslide distribution inside the territory, the quality of data and the features of each predisposing factor chosen. To investigate the landslide susceptibility zoning, the research of the best combination of predisposing factors, is fundamental to understand the most suitable landslide susceptibility categories and perform reliable susceptibility maps showing the territory of interest. Concerning the Geographical Information System applications, GIS- based bivariate and multivariate statistical analysis are suitable to analyse large areas, quickly and with limited resources.

Nevertheless, statistical models such as logistic regression and Weights of Evidence are still considered dependable and suitable for large-area applications, especially when the objective is to provide interpretable results for land-use planning and decision-making processes.

1.1.4.5 The multivariate regression model

The susceptibility analysis is based on the assumption that landslides occur in the same geological, geomorphological, hydrogeological, anthropogenic, and climate conditions as in the past. Statistical methods, usually correlate an inventory of past landslides with factors which are supposed to be responsible of slope failure. In that sense they are suitable for wide and different zones and GIS software is used to integrate spatial variables together. The procedure consists of a traditional multivariate statistical analysis in GIS, being landslides triggered by a combination of factors intimately connected. To choose the predisposing factors to landslide, a combination of literature analysis is done. In more details the following key factors are:

- Geo-lithological vector map (1:10.000), for a lithological description of the soils.
- Elevation, slope, and aspect maps obtained by a Digital Terrain Model (DTM), by 20 -30 meters of resolution (higher resolutions are not necessary for a regional susceptibility zoning).
- The water accumulation map calculated by the DTM to consider flow sources, flow direction and soil moisture concentration strongly correlated to density and spatial extent of the landslide.
- Land use cover map and a road map to consider anthropogenic factors which may eventually trigger landslide.
- The rain occurrence and its temporal distribution using the modified “Fournier index”, also named “climatic aggressivity index”. It was defined by Arnoldus (1977), *(Arnoldus, 1977),* in Eq. [2] as:

$$FF_{FAO} = \sum_{i=1}^{12} \frac{pi^2}{P} \qquad [2]$$

where p is the mean monthly precipitation and P the mean annual precipitation.

The logistic multiple regression is a well-working method in which the dependent variable is binary and represents the presence or absence of landslides. It calculates coefficients for each predictive variable represented by the predisposing factors.

These coefficients are weighted in an algorithm which can be used in the GIS environment to produce susceptibility maps. It is a well-working method for dichotomous data, which means that the dependent variable can have only two values (event occurring or not occurring), and predicted values can be interpreted as probabilities since they are constrained to fall in the interval between 0 and 1.

In this study, the dependent variable is binary and represents the presence or absence of landslides. The technique of logistic multiple regression calculates coefficients weighted together for each variable, based on data derived from the study area.

Using the multiple regression model, the relationship between the occurrence and its dependency on several variables can be expressed by the Eq. [3] as:

$$logit(P) = \ln\left(\frac{p}{1-p}\right) = bo + \sum_{j=1}^{n} b_j X_j \qquad [3]$$

Where X_j are the variables, b_j the coefficients and p the landslide occurrence probability obtained by a landslide inventory map. The b_j regression coefficients are calculated with r. regression. multi as a GRASS GIS command. This tool is implemented for the linear regression model; hence the inputs of the model are the maps of independent variables X_j and the logit of the landslide map. The outputs are:

- a map with estimate of logit(p);
- a map with the errors (optional);
- a file with coefficient values, the Akaike Information Criterion (AIC) index and the R^2 correlation coefficient for each explaining variable.

The AIC is a measure of the relative quality of a statistical model for a given set of data while the R^2 correlation coefficient for each variable represents the additional amount of variance observed when the variable is included compared to when it is excluded. This provides a measure of the influence of a single factor in each model *(Bovolenta et al., 2018)*.

Prior to the application of the logistic multiple regression, each variable is analysed singularly through a bivariate statistical approach. In this way, it is possible to understand the real influence of each variable on the landside occurrence and correctly classify the variable map to have a direct or inverse proportionality with landslide occurrence.

Infact, the adoption of a logistic regression model involves the calculation of the value of logit through a linear function of the independent variables X; therefore, a monotonic (increasing or decreasing) behaviour needs to be observed also in the classification of the X variables. The procedure provides accurate landslide susceptibility maps, also useful to guide and suggest the selection of appropriate engineering and landslide mitigation measures helping public authorities to safeguard the territory.

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1.1.4.6 The Weights Of Evidence method

Weights Of Evidence (WOE) is a quantitative ‘data-driven’ method used to combine datasets, following a statistical bivariate approach. The method, first applied in medicine and geology *(Bonham – Carter, 1994)*, uses the log– linear form of the Bayesian probability model to estimate the relative importance of evidence by statistical means.

This method was first applied to the identification of mineral potential *(Bonham – Carter et al., 1990)* and then to landslide susceptibility mapping *(Van Westen et al., 2003)*. It is used to assess the correlation between predisposing factors and the spatial occurrence of landslides *(Malet et al., 2006)* which means the combination of predictive variables (PV), as the predisposing factors, associated to the variables to model (VM) represented by the set of landslides chosen.

Prior probabilities (PriorP) and posterior probabilities (PostP) are the most important concepts in the Bayesian approach. The Prior probability is the probability that a pixel contains the VM from the density of a PV. The Posterior probability is evaluated by the subsequent calculation of the Prior probability and allows to assess a low or high probability of the presence of VM by combining the different PVs.

To perform the WOE, a pre-process data stage must be considered. Two variables are distinguished:

- VM, as variables to model corresponding to the group of landslides chosen; normally the 80% and the 20/% of them are distinguished in training and validation sets: then there is the overall set by considering the entire landslide set.

- PV, as the predictive variables, the predisposing factors which influence the potential occurrence of a landslide.

The next stage is to apply the Weight Of Evidence method on GIS. The goal is to find the best combination of input data (the predisposing factors) given a certain set of landslides to obtain reliable susceptibility maps and validate them with valwoe (statistical validation of susceptibility maps built with WOE) tool. The Weight of Evidence method has three stages:

- Pre-process Data

- Calculate Weights

- Calculate Responses

In the 'Pre-process Data' stage the model computes:

- the training data creation as a binary raster 0-1.

- the evidence raster's clip to the extent of the mask layer.

- the resampling of each evidence raster map to the unit area of each training site (depending on pixel resolution of the map).

The 'Calculate Weights' tool should be implemented individually for each evidence raster. It executes the following calculations:

- estimation of prior odds of occurrence of a landslide per unit cell of the study area (generalized weights raster)

- reclassification of numerical multi-class evidence raster into the 'Favorable' and 'Unfavorable' binary evidence raster (multiband raster maps)

- estimation of the weights of evidence for individual reclassified binary evidence raster or categorical evidence raster using the Bayes' Rule (a csv format of calculated weights).

Finally, the 'Calculate Responses' tool calculates the posterior probability for occurrence of a landslide by combining the prior odds and the 'weights-of-evidence rasters' calculated in the 'Calculate Weights' tool. The final outcomes include**:**

- Posterior Probability Raster**:** the values in this raster, figure out the landslide susceptibility.
- Standard Deviation Raster**:** this raster contains the standard deviations in the posterior probability calculations due to the standard deviation of weights of the evidence rasters.
- Confidence Raster**:** this raster represents the confidence of the model starting from values obtained in the Posterior Probability Raster.

Here there is a schematic way of WOE workflow in Figure 3:

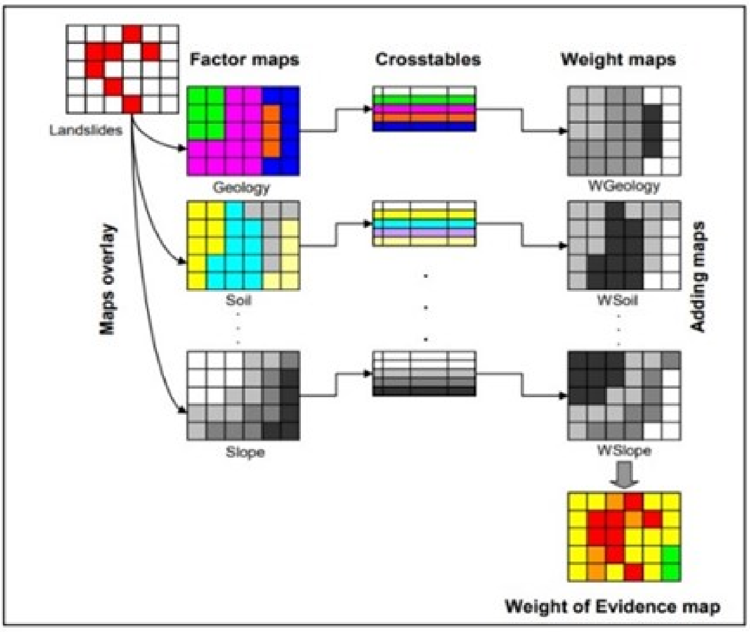


Figure 3: WOE workflow

The model is based on the computation of positive W+ and negative W− weights, whose magnitude depends on the observed association between the VM and the PV following the two Eq. [4,5] by *(Castellanos Abella, 2008)* as described below:

$$W_i^+ = log_e \frac{P(B_i|S)}{P(B_i|\bar{S})} \tag{4}$$

$$W_i^- = log_e \frac{P(\overline{B_i}|S)}{P(\overline{B_i}|\bar{S})} \tag{5}$$

where B_i = presence of a potential predisposing factor to instability; $\overline{B_i}$= absence of a potential predisposing factor to instability; S = presence of landslide; $\bar{S}$= absence of landslides.

Each PV (predictive variable) is shown as a reclassified raster and a positive weight (W+) and a negative weight (W-) per pixel are considered for each class of each PV. The positive weight means the influence of a class contained in a PV. More the positive weight (W+) associated with a class is high, more it will be the influence of a class on the VM (in this case, landslides).

At the same time, the negative weight (W-) highlights the importance of the lack of influence on the VM. In the model, other parameters are calculated, such as the variance, the standard deviation, and the contrast (difference between W- and W+); they make it possible to assess the sensitivity of each class of PVs considered. It is from these weights that each class of PV can be readjusted. Weights are therefore used to calculate the posterior probability by adjusting the prior probability.

The Weights Of Evidence (WOE) method remains widely used in landslide susceptibility assessment due to its simplicity and interpretability. Recent applications have confirmed its effectiveness in different environmental contexts, including Italy, where WOE has been successfully applied using climatic and geomorphological factors derived from national inventories (*Pambianchi et al., 2023*). Moreover, recent studies have demonstrated the benefits of integrating WOE with remote sensing data such as InSAR, improving the identification of unstable areas and enhancing model reliability. Comparative analyses have also shown that WOE performs competitively with more advanced models, especially when combined with geomorphological validation or hybrid approaches.

1.1.5 Landslide statistical validation

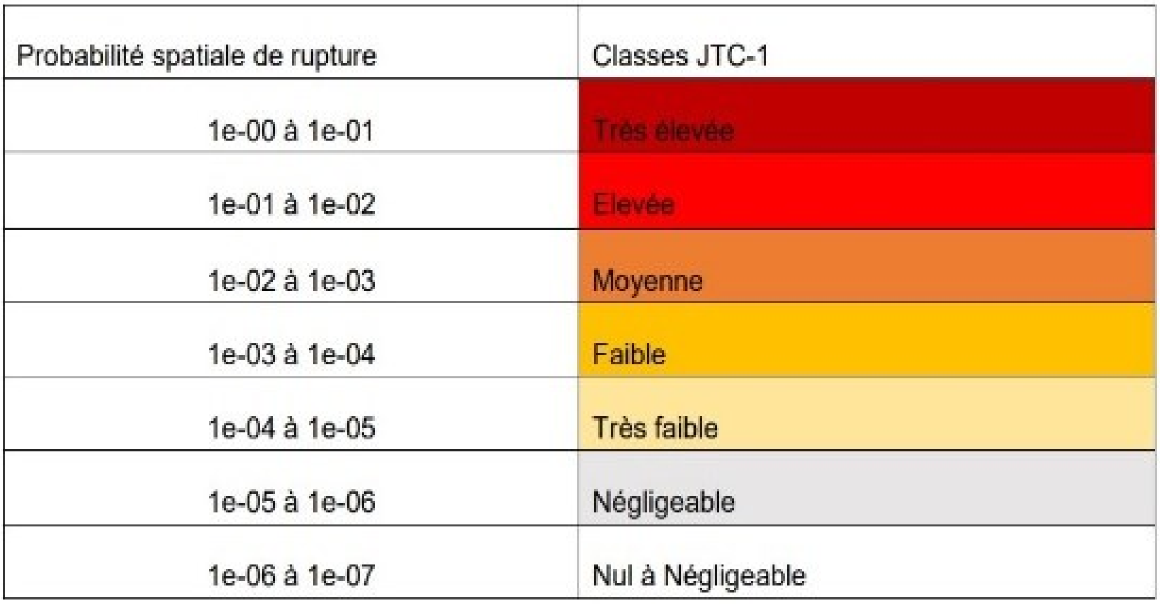
Landslide statistical validation is based on the analysis of historical data, normally detected by movements' inventories, and the construction of predictive models to assess the probability of landslides occurring in specific areas. This validation can be achieved through different methodologies, such as verifying models through field data, evaluating model performance in test areas, and comparing them with other models where necessary.

Statistical validation of landslide movements is crucial to develop reliable models of landslide susceptibility and to predict future events. This practice makes use of different statistical methodologies and validation techniques, to ensure the reliability of the forecasts. In addition, the integration of advanced statistical techniques with physically based models, accompanied by rigorous validation procedures, allows to obtain more precise and useful previsions for the management of hydrogeological and landslide risk.

1.1.5.1 Valwoe tool

The results of WOE (Weights Of Evidence) method must be validated to assess the correlation between predisposing factors and the spatial occurrence of landslides and understand the model reliability. The valwoe (statistical validation of susceptibility maps built with WOE) package *(Premaillon, 2023)*, developed during the project in New Caledonia13 in France, is a tool to understand the reliability of the model and categorize the susceptibility maps levels.

The use of evidence theory will ultimately make it possible to develop a quantitative classification (Fig. 4) according to the JTC-1 thresholds (Join Technical Committee 1). These thresholds have been designed for a need to quantify susceptibility and no longer rely entirely on an expert approach. They were defined by comparing the probability of death of people (from all causes) to the death probability due to landslides *(Fell et al., 2008)*. The JTC-1 thresholds are indicative and may be changed by the expert awareness.



Probabilité spatiale de rupture	Classes JTC-1
1e-00 à 1e-01	Très élevée
1e-01 à 1e-02	Elevée
1e-02 à 1e-03	Moyenne
1e-03 à 1e-04	Faible
1e-04 à 1e-05	Très faible
1e-05 à 1e-06	Négligeable
1e-06 à 1e-07	Nul à Négligeable

Figure 4: Landslide susceptibility classes by JTC-1 Committee, (Fell et al., 2008)

The statistical validation by valwoe concerns on the introduction of input data got from the WOE results on GIS software, which are:

- The post probability map of landslide training set (80%), which means the susceptibility map.
- The confidence map of training set (80%).
- The shape files of training and validation landslide set (80% and 20%).
- The post probability map of the entire landslide set (100%).

- The shape file of the entire landslide set (100%)

The validation tool takes the results of WOE, and the landslide sets chosen to give in output:

- The success and validation curves of training and validation sets (Fig. 5), which give us the AUC (area under the curve) as the percentage of landslides recognizable according to the surface of the PV chosen; these curves compare the percentage of area needed to account for a certain percentage of landslides, using training and test data, respectively; the curve must be greater than 0.5 to make the model reliable.

- The weights charts (W+, W -), in Figure 6, which depict the impact of each predisposing factor on landslide sets; the raster PV maps are divided in different classes; by weighting them, it is possible to understand the influence of a specific category which leads to a landslide occurrence.

- The recognition curve which allows to evaluate the percentage cumulated of landslides recognized (Fig. 7), starting from a classification of spatial probability of failure, as represented by 7 susceptibility classes, following JTC-1 committee classification.

Here an example of valwoe outcomes is shown:

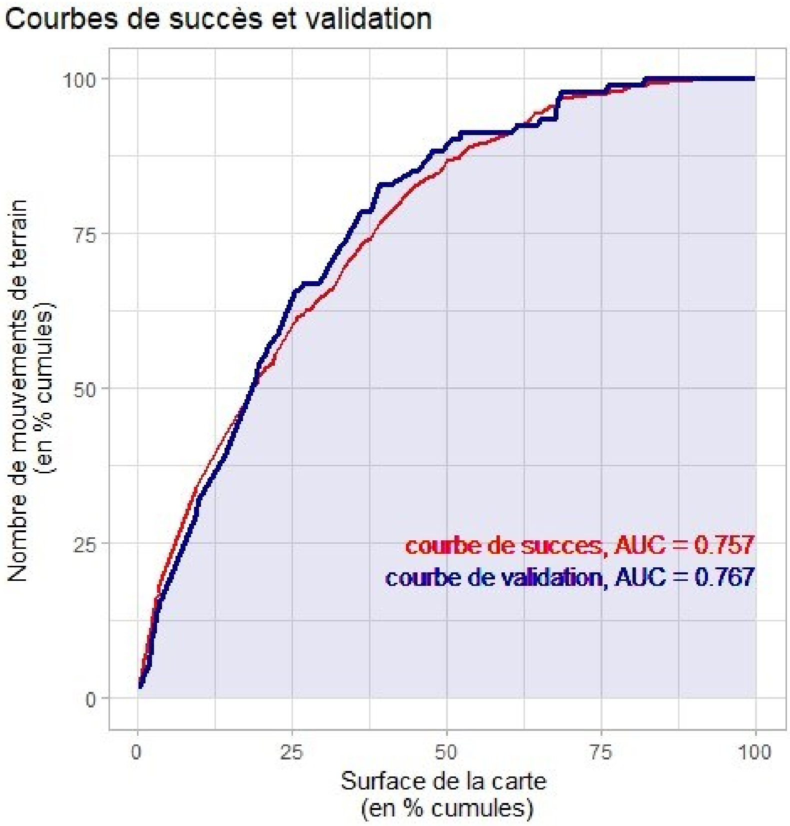


Figure 5: Success (red) and validation (blue) curves for a given landslide set

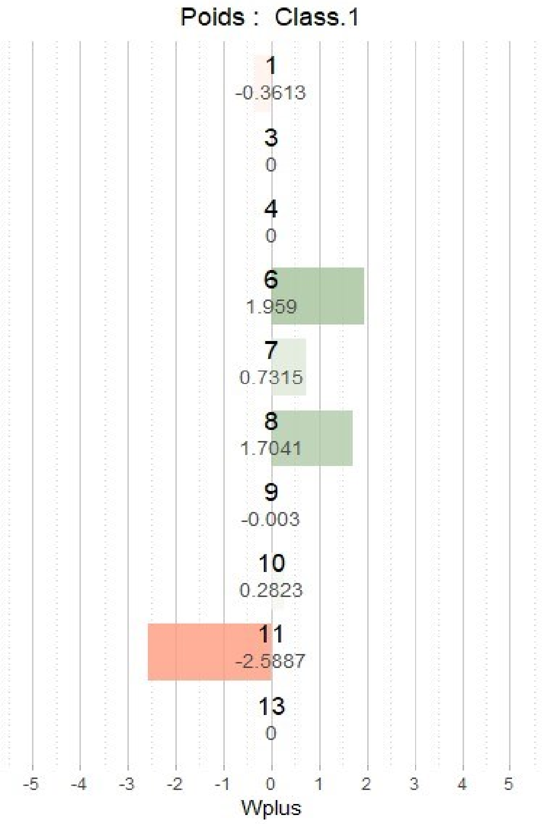
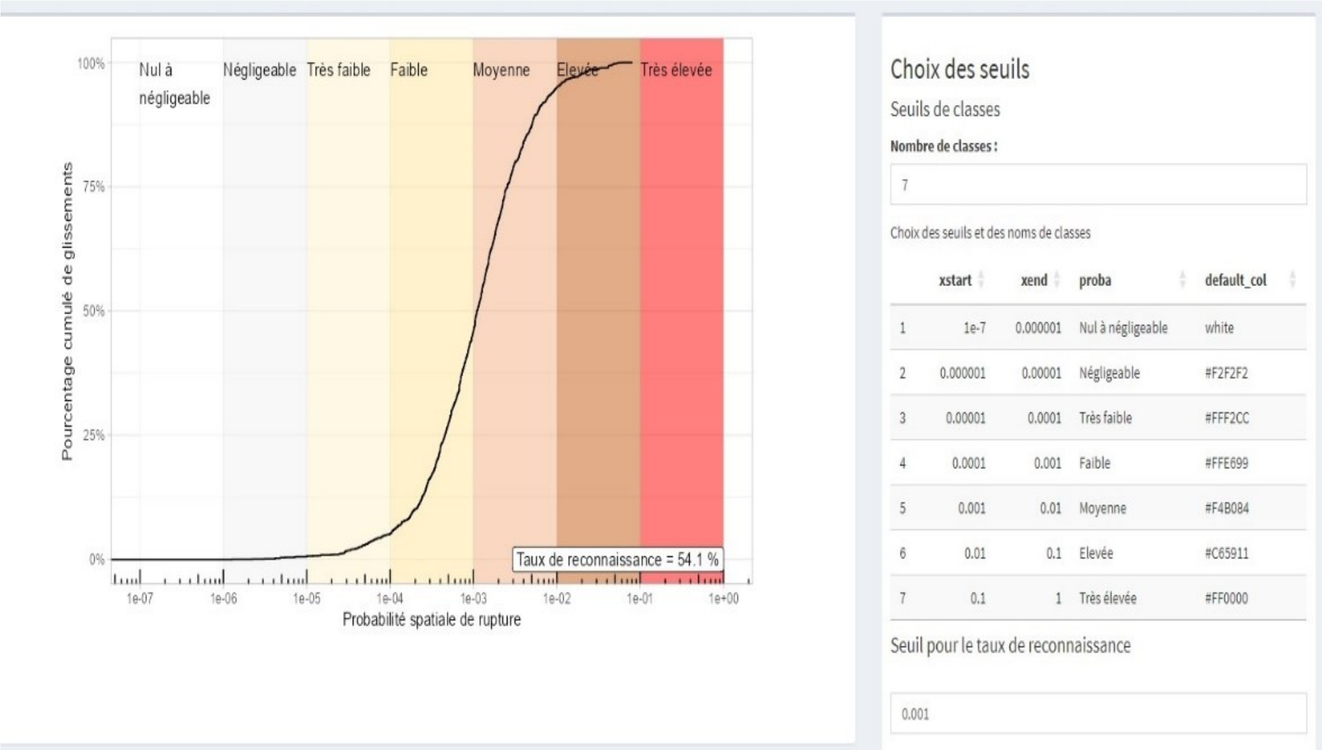


Figure 6: the Weight graph

Analysing the histogram, the classes 6 and 8 have a massive impact on landslide occurrence while the category 11 does not influence the landslide event occurrence.



Choix des seuils

Seuils de classes

Nombre de classes :

7

Choix des seuils et des noms de classes

	xstart	xend	proba	default_col
1	1e-7	0.000001	Nul à négligeable	white
2	0.000001	0.00001	Négligeable	#F2F2F2
3	0.00001	0.0001	Très faible	#FFF2CC
4	0.0001	0.001	Faible	#FFE699
5	0.001	0.01	Moyenne	#F4B084
6	0.01	0.1	Elevée	#C65911
7	0.1	1	Très élevée	#FF0000

Seuil pour le taux de reconnaissance

0.001

Figure 7: The recognition curve with 0.001 recognition rate threshold

As the last result of valwoe tool, with the recognition curve, there is the perception of how many landslides could occur by differentiating the susceptibility classes: in the specific case the 54% of landslide could occur with a mean until extremely high level of susceptibility.

1.1.5.2 Zonal landslide statistics

There is another way to validate results of landslide susceptibility analysis, calculating the percentage of landslides in different susceptibility classes. The method used consists of a zonal statistics.

For example, looking at a susceptibility map in raster format, the number of pixels by susceptibility classes is got by statistics calculation considering either the median or the mean elevation value inside each cell. By the way it is possible to compare a polygon vector layer with a raster map; the polygon layer is represented by sample landslides used for the statistical model. Counting the number of pixels inside each polygon, the belonging susceptibility class is estimated. The results can be depicted in a histogram which figures out the percentage of landslides counted divided by susceptibility classes.

It is a way to understand the model sensitivity and reliability and evaluate the location of high and very high susceptibility zones. Evaluate what are critical areas, gives the opportunity to perform landslide mitigation measures and help the technicians to allocate the economic resources in clever and aware way, by increasing territory resilience.

1.1.5.3 On site validation

The field validation is a more direct way to verify the outcomes derived by a landslide susceptibility map. The typology of landslides depends on the needs of the specific territory. Directly experts carry out the tests of the maps of susceptibility to ground movements. In addition, knowledge of the terrain (e.g. elevation, geology, and anthropic actions) is necessary for the scientific approach and for the discussion of the results obtained a posteriori since the inventory. These field verifications provide useful information to locally understand a site.

The validation and verification steps of the typology associated with a slope movement are essential; they thus make it possible to update the events spotted on orthophotos, adding new landslides. At the same time, the landslide inventory can be greatly consolidated with the contribution (or adjustment) of information on the particle size and the type of surface formation. The superficial formations depend on what is observed once on site in the field: alluvium, colluvium, marbles, and other more altered areas.

The geological site exploration gives the opportunity to have a good representation of the sensitive and non-sensitive areas to landslides and to provide an expert approach (knowledge of the study area) on the continuation of the susceptibility work, consolidating and reinforcing the landslide inventory to provide a more efficient landslide susceptibility assessment.

In Figure 8, an example of rockfall occurred in France in the Maritime Alps Department in May 2024 is shown:

Figure 8: Rockfall along a municipal road in the Maritime Alps Department

Directly examining the case, it is possible to evaluate the impact on the road and an estimation of rock masses which fell. In Figure 9, there is another case happened in Liguria Region; in January 2025, a slope slide broke down a portion of the road, after a heavy storm.

Figure 9: Municipal Road destruction by a terrain sliding effect in San Colombano Certenoli Municipality

CHAPTER 2: LEGISLATION FRAMEWORK INSIDE THE LANDSLIDE RISK MANAGEMENT

2.1 Administrative aspects in landslide risk management

Administrative aspects of landslide risk management concern the frameworks, policies, and procedures to proactively assess and reduce the impact of landslides. This includes creating and implementing hazard maps, developing early warning systems, setting regulations for land use and construction in landslide-prone areas, perform landslide risk mitigation measures to manage emergency response. It means the capacity by a public administration to manage the territory designing public works as structural measures and non-structural strategies, involving the Community.

To manage landslide disaster risk, the participation of a range of stakeholders and taking an integrated disaster risk approach is necessary. This involves a complex process aiming at predicting, reducing, and permanently controlling landslide disaster risk drivers while aiming for sustainable human, economic, and environmental development. Dynamic landslide inventories are fundamental for mapping landslide susceptibility, hazard, and risk. By leveraging this information, stakeholders can better assess and manage the potential impact of landslides on public safety and infrastructure.

Understanding the geological, geomorphological, environmental, and social factors contributing to landslides is essential for developing effective mitigation strategies. Therefore, sustained collaboration between science and policymaking is critical to managing landslide disaster risks. The promptness and implementation of such endeavours will strengthen disaster risk governance and ensure better preparation and prevention measures *(Alcántara-Ayala et al., 2023)*. By implementing these administrative aspects, governments and local authorities can create a more resilient environment and reduce the human and economic impacts of landslides.

2.1.1 The stages of landslide legislation in Italy

Due to its relief, lithological and structural characteristics, Italy is a country in which the landslide risk is particularly high. Of the Italian territory, 6.8% is highly at risk from landslides, which represent a major issue of concern especially with regards to population exposure *(ISPRA, 2008*).

Italy is one of the European countries most affected by hydrogeological instability, due to its complex geological, geomorphological, and climatic conditions. According to the report “Landslides and Floods in Italy: Hazard and Risk Indicators – 2021 Edition” published by ISPRA, landslides are a widespread phenomenon across the national territory, affecting a significant portion of municipalities and exposed elements. Recent data indicate that approximately 94% of Italian municipalities are exposed to landslide and flood risk, with about 1.3 million inhabitants living in areas characterized by high or very high landslide hazard *(Trigila et al., 2021)*.

From a legislative point of view, the first act on the construction of protection works and risk zoning came into effect in 1904. Using factors such as priority of values, focus of policy mechanism, major events, and scientific developments, the development of risk management practices in Italy is characterized by different phases.

The first phase, lasting from 1920 to 1965, focused on building restrictions and risk zoning; it prioritised economic growth and regulating building speculation (uncontrolled building also in risky areas) and aimed at imposing some restrictions to private property to prevent natural disasters. After the end of the Second World War, when Italy experienced strong urbanization and uncontrolled building activity, risk management policies focused on investments in structural defence, with many aimed at soil management and landslide prevention.

When the country was hit by the 1954 Salerno landslide, it provided an impetus for the creation of a national inventory of floods and landslides to help land-use planning in communities.

The second phase was dominated by a concern with creating integrated water and soil risk management and extended from 1966 to 1991. In Italy, the need for establishing an integrated water and soil risk management was driven by one key event, the 1966 Firenze flood. Together with other tragic natural disasters that took place during this phase (the 1963 Vajont landslide, the 1968 Belice, 1976 Friuli and 1980 Irpinia earthquakes), the Firenze flood presented a window of opportunity for consistent changes regarding the landslides system and especially for the promulgation of new laws on integrated risk management and civil protections issues.

Indeed, one of the key drivers of change for the Italian landslide management system is represented by the work of the Inter-ministerial Commission for the study of soil defence and hydraulic works, known as the De Marchi Commission, a group of scientists including experts in hydrology, engineering, geology, and planning. When the De Marchi Commission investigated the 1966 Firenze flood, they uncovered several weaknesses related to water and soil management and local emergency preparedness, arguing for having an integrated management of water and soil resources at the river basin scale.

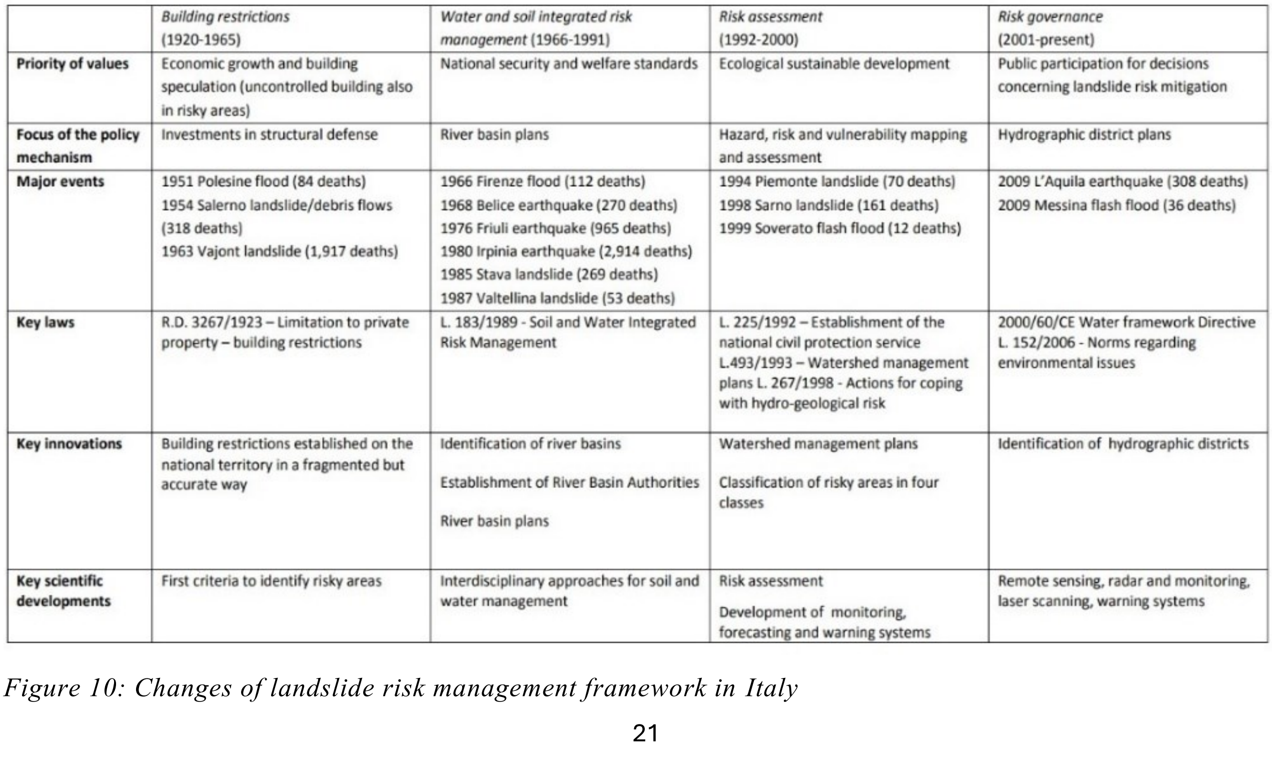
This unitary vision of risk management influenced following legislation, which approached landslides and floods in an integrated way. For example, the act 996/1970 outlined the tasks of rescue services, established the Civil Protection Volunteer Service, and transferred the competence of these problems from the Minister of Public Works to the Minister of the Interior. In this way, the emergencies were no longer seen as simply technical problems but rather as problems of public order *(Pellizzoni, 1992)*.

The 1976 and 1980 earthquake events highlighted the problem of coordination between central and local authorities in emergency situations and led to a more flexible emergency response system that included national, regional, and provincial authorities. In 1984, the National Group for Hydrogeologic Disasters' Defence (GNDCI) was established and went on to become a key factor in the history of landslide science. One of the key innovations catalysed by the 1966 Firenze flood and the work of the De Marchi Commission and the reports of the National water conference in 1972 is represented by the promulgation of the Law 183/1989 which established the River Basin Authorities.

This new organizational structure also marked a change from a system of post-emergency intervention to a system including risk assessment, weather forecasting, and measures for risk prevention. During possibly the most crucial phase in terms of innovation and changes for landslide risk management, from 1992 to 2000, hazard assessment, risk and vulnerability mapping became a leading priority for risk management in Italy.

It was the landslide that hit the municipality of Sarno in Southern Italy in 1998, that highlighted weaknesses in the Italian landslide risk management system. The 267/1998 law on risk zoning put more pressure on identifying areas prone to floods and landslides. It included a first order identification of the landslide risk areas classified in four classes (from R1, low risk, to high risk indicated by R4), a Hydrogeological Setting Plan, a program of urgent measures to mitigate the flood and landslide risk in R4 areas, and the development of a wide range of monitoring, forecasting, and warning systems.

Through the years, in addition to the national River Basin Authorities established by the 1989 law, several interregional, regional, and provincial River Basin Authorities have been appointed to take part in the integrated management of floods and landslides. In Figure 10 this is a representation of how the pattern has changed in terms of landslide risk management.



	Building restrictions (1920-1965)	*Water and soil integrated risk management* (1966-1991)	*Risk assessment* (1992-2000)	*Risk governance* (2001-present)
Priority of values	Economic growth and building speculation (uncontrolled building also in risky areas)	National security and welfare standards	Ecological sustainable development	Public participation for decisions concerning landslide risk mitigation
Focus of the policy mechanism	Investments in structural defense	River basin plans	Hazard, risk and vulnerability mapping and assessment	Hydrographic district plans
Major events	1951 Polesine flood (84 deaths) 1954 Salerno landslide/debris flows (318 deaths) 1963 Vajont landslide (1,917 deaths)	1966 Firenze flood (112 deaths) 1968 Belice earthquake (270 deaths) 1976 Friuli earthquake (965 deaths) 1980 Irpinia earthquake (2,914 deaths) 1985 Stava landslide (269 deaths) 1987 Valtellina landslide (53 deaths)	1994 Piemonte landslide (70 deaths) 1998 Sarno landslide (161 deaths) 1999 Soverato flash flood (12 deaths)	2009 L'Aquila earthquake (308 deaths) 2009 Messina flash flood (36 deaths)
Key laws	R.D. 3267/1923 – Limitation to private property – building restrictions	L. 183/1989 - Soil and Water Integrated Risk Management	L. 225/1992 – Establishment of the national civil protection service L.493/1993 – Watershed management plans L. 267/1998 - Actions for coping with hydro-geological risk	2000/60/CE Water framework Directive L. 152/2006 - Norms regarding environmental issues
Key innovations	Building restrictions established on the national territory in a fragmented but accurate way	Identification of river basins Establishment of River Basin Authorities River basin plans	Watershed management plans Classification of risky areas in four classes	Identification of hydrographic districts
Key scientific developments	First criteria to identify risky areas	Interdisciplinary approaches for soil and water management	Risk assessment Development of monitoring, forecasting and warning systems	Remote sensing, radar and monitoring, laser scanning, warning systems

Figure 10: Changes of landslide risk management framework in Italy

2.2 The basin plan evolution in Liguria Region

The general reference framework for the formation of the basin plan is represented by the rules contained in the framework law of 18 May 1989, n. 183 and more generally by all the regulations that define the institutional order, the attributions of competence and the relative responsibilities of the institutions represented in the Basin Authorities.

Law 183/1989 named "Rules for the organizational and functional reorganization of soil protection" defines the purposes, tools, and methods of action of the public administration in the field of soil protection. Furthermore, pursuant also to Regional Law 36/97, the Basin Plan, as well as its functional excerpts, constrains, in the prescriptive indications, is the principal instrument for the territorial planning at regional, provincial, and municipal level.

For aspects related to the planning of catchment areas of regional importance, the first reference, in chronological order, is constituted by Regional Law no. 9 of 28 January 1993, some articles of which were repealed by Regional Law no. 18 of 21 June 1999. The structure of the Basin Authority of regional importance established by Regional Law 9/93, was modified first by Regional Law 18/99 and then, more recently, by Regional Law no. 58 of 4 December 2009 which effectively abolished the pre-existing technical committees by establishing a single Basin Technical Committee and new paths and timing for the approval of plans and their variants.

These criteria have also been integrated over time and today form a complex mosaic of determinations aimed at homogenizing and improving planning activity in the regional field.

Of this course of laws it is necessary, in this phase of basin planning, to underline the law 4 December 1993, n. 493 and in particular art. 12 which integrates Article 17 of Law No. 183/1989 with paragraph 6 ter which states: "The Hydrographic Basin Plans can also be drawn up and approved for sub-basins or for excerpts relating to functional sectors that in any case must constitute sequential and interrelated phases with respect to the contents referred to in paragraph 3 "(recalls art. 17 of the law of 18 May 1989, No. 183).

Finally, it is necessary to recall Legislative Decree no. 152/2006 which revised the environmental regulations. An impetus to basin planning was provided by Decree-Law no. 180 of 11 June 1998, converted, with amendments, into Law no. 267 of 3 August 1998 "Urgent measures for the prevention of hydrogeological risk and in favour of areas affected by landslides in the Campania region", amended by Legislative Decree 132/99, converted, with amendments, by Law 262/99. The criteria relating to the obligations referred to in paragraph 1 of art. 1 of the D.L. 180/98, have been provided, as required by paragraph 2 of art. 2 of Legislative Decree 180/98, in the "Act of address and coordination for the identification of the criteria relating to the obligations referred to in art. 1, paragraphs 1 and 2", published in the Official Gazette of 5.1.99. The activities envisaged by Legislative Decree 180/98 relating to the identification and perimeter of areas at flood risk and at landslide risk must be divided into the following three phases:

- identification of areas subject to hydrogeological risk.
- assessment of risk levels and definition of safeguard measures.
- risk mitigation planning.

The D.L. 180/98, therefore, intended to give an acceleration to the fulfilments of Law 183/89, especially about the identification and perimeter of areas at hydrogeological risk (understood as flooding and landslide). Since it is a functional excerpt, it does not clearly exhaust all the issues envisaged by the complete basin plan but represents a part of the excerpt plan for the hydrogeological structure of which it will therefore be an integral part, understood as a complete basin plan. It is then approved with the ordinary procedures provided for by Regional Law 15/2015. As part of this excerpt plan for hydrogeological management, the recommendations, criteria, and guidelines issued by the Regional Basin Authority since 2001 have been followed *(Piano di Bacino stralcio del Torrente Lavagna, 2020).*

2.2.1 Hydrographic districts

Law no. 221 of 28 December 2015 on "Environmental provisions to promote green economy measures and to contain the excessive use of natural resources", in force since 2 February 2016, art. 51 has dictated new "Rules on Basin Authorities" by fully replacing articles 63 and 64 of Legislative Decree no. 152/2006 and established the new District Basin Authorities and defined the new River Basin Districts.

The Basin Authorities are responsible for drawing up the District Basin Plan and its excerpts, including the River Basin Management Plan (PGA), provided for by Directive 2000/60/EC and the Flood Risk Management Plan (PGRA), provided for by Directive 2007/60/EC, as well as intervention programmes. The entire national territory, including the smaller islands, is divided into the following river basin districts:

- the Eastern Alps River basin District;
- the Po River basin district, including the Po River basins and some regional/interregional basins in Romagna, Marche, and Tuscany;
- the northern Apennines River basin District;
- the Central Apennines River Basin District;
- the Southern Apennines River Basin District;
- the Sardinia River Basin District;
- the Sicily River Basin District.

Liguria falls into:

- the hydrographic district of the Po River, which is larger than the previous limit of the Basin Authority pursuant to Law 183/89, but for the Ligurian regional territory it has not been modified;
- the hydrographic district of the Northern Apennines which includes the hydrographic basins of the Arno (including a small area falling within the Umbria region), the Serchio, the Magra as well as the regional basins of Liguria and Tuscany.

To ensure joint administrative responsibility for streams, rivers and lakes, there are 40 river basin authorities in Italy:

- 6 nationals;
- 13 interregional;
- 19 regionals;
- 2 provincials.

2.2.2 PAI cartography

Liguria Region belongs to the hydrographic district of the Northern Apennines. In terms of landslides, there is a normative plan titled “Piano di bacino stralcio Assetto Idrogeologico del distretto idrografico dell’Appennino settentrionale per la gestione del rischio da dissesti di natura geomorfologica”, named “PAI dissesti”. It is applied and approved, concerning art. 65, 66, 67 e 68 of legislative decree n. 152/2006, as a functional excerpt of the District Basin Plan.

At the meeting of the Permanent Institutional Conference (CIP) on 28 March 2024, the PAI against the instability of the related safeguard measures was definitively adopted.

The main changes introduced by the safeguard measures compared to the previous PAI are:

- the maps of the PAI instability completely replace the maps of the previous PAI which therefore no longer have formal value. The maps of the current PAI are still available as archival information and are no longer subject to updates and modifications.

- The conditions dictated by the PAI regulations in force are applied to the areas indicated by the PAI instability in coordination with the new discipline, according to the provisions of the safeguard measure until the final approval of the PAI instability by decree of the President of the Council of Ministers.

The “PAI dissesti” provides a constantly updated hazard framework with the general goal of ensuring sustainable levels of risk management from geomorphological instability, favouring the human life protection, environmental, cultural, infrastructural and settlement heritage, to be pursued through prevention, protection, preparation and response and restoration measures such as to face and mitigate active or potentially unstable landslides, considering the competences in the field of civil protection provided for by national and regional laws.

The “PAI dissesti” has the value of a territorial plan for the sector and is the cognitive, regulatory and technical-operational tool through which actions and rules of use aimed at the conservation, defence and enhancement of the soil are planned and programmed according to the management of the risk from geomorphological instability and based on the physical and environmental characteristics of the territory concerned.

Pursuant to the provisions of paragraph 3, the “PAI dissesti”, in compliance with the provisions of Article 67, paragraph 1 of Legislative Decree no. 152/2006, has the following specific objectives:

- the definition of a homogeneous knowledge framework of hazard and risk consistent with the geomorphological instability present in the territory of the river basins concerned, with reference to unstable areas, as well as the definition of the criteria necessary for updating this framework.

- the arrangement, conservation and recovery of the soil in the river basins, with the identification of structural and non-structural measures, interventions and actions, aimed at mitigating the risk to people, cultural and environmental, infrastructural and settlement assets and heritage, as well as to encourage activities that do not compromise the natural evolution of the relief, to preserve the territory from further geomorphological instability, to avoid the occurrence of erosion phenomena and to maintain the solid transport in the hydrographic network in conditions of equilibrium;

- the definition and identification of structural and non-structural prevention and protection measures, consistent with the knowledge framework of hazard and risk defined pursuant to letter a), in coordination with the national strategies for adaptation to climate change and with the directives issued in the field of civil protection and in line with the specific objectives set by the PGRA and the PGA, to be carried out also on the basis of the intervention programmes pursuant to Article 69 of Legislative Decree no. 152/2006.

2.2.2.1 PAI susceptibility classes

For the purposes of achieving the objectives referred to in art. 1, the areas shown in the "Geomorphological instability hazard map" are subject to these Plan Regulations, divided into the following classes, defined based on the criteria of Annex 3, according to the following gradation:

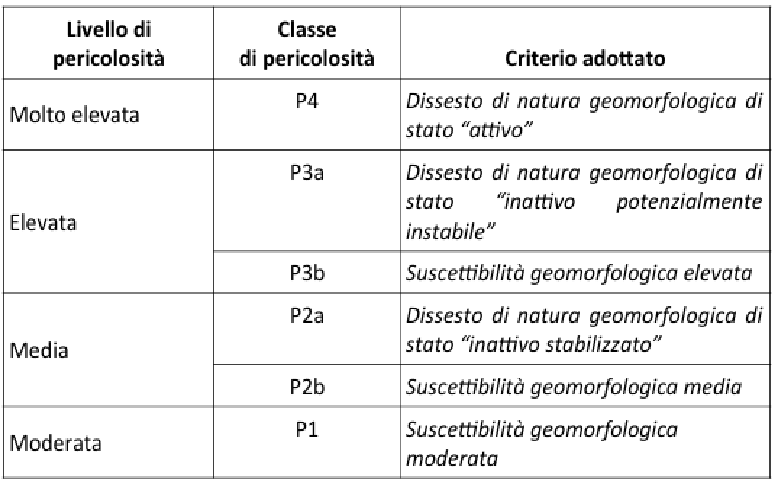
- very high susceptibility (P4) - unstable areas affected by active geomorphological instability.

- high susceptibility (P3) divided into two subclasses: (P3a) as potentially unstable areas affected by geomorphological instability; (P3b) as potentially unstable areas affected by susceptibility to instability of a high geomorphological nature.

- mean susceptibility (P2) divided into two subclasses: (P2a) as stable areas affected by geomorphological instability that are naturally or artificially stabilized; (P2b) as stable areas affected by susceptibility of a medium geomorphological nature.

- low susceptibility (P1) - stable areas with susceptibility to moderate geomorphological instability.

Here there is a representative scheme of different susceptibility levels described in Figure 11:



Livello di pericolosità	Classe di pericolosità	Criterio adottato
Molto elevata	P4	*Dissesto di natura geomorfologica di stato "attivo"*
Elevata	P3a	*Dissesto di natura geomorfologica di stato "inattivo potenzialmente instabile"*
	P3b	*Suscettibilità geomorfologica elevata*
Media	P2a	*Dissesto di natura geomorfologica di stato "inattivo stabilizzato"*
	P2b	*Suscettibilità geomorfologica media*
Moderata	P1	*Suscettibilità geomorfologica moderata*

Figure 11: The susceptibility classes definition by Piano Assetto Idrogeologico (PAI)

2.2.2.2 Guidelines to build in landslide susceptibility zones

The "PAI dissesti" has established rules to build inside the different susceptibility categories, summarized here:

- areas classified as very high landslide hazard (P4).

They are allowed only:

- disruption actions without re- building.
- The interventions strictly necessary to reduce the vulnerability of existing buildings and to improve the protection of public safety.
- The reclamation and arrangement of landslides; ordinary and extraordinary maintenance interventions; the construction of new linear and network infrastructures required by law, declared essential, non-relocatable and without technically and economically sustainable design alternatives.
- Practices for proper agricultural and forestry activities with the exclusion of any intervention that increases the level of risk; interventions aimed at the remediation of contaminated sites.
- The consolidation and conservative restoration of cultural heritage protected under current legislation.

- areas classified as high landslide hazard (P3).

They are generally allowed:

- the interventions described above for areas of high danger;
- the expansion of existing buildings for the hygienic-sanitary adaptation and the construction of new wastewater treatment plants and the expansion of existing ones, subject to a study of the compatibility of the work with the existing state of instability.

- areas classified as medium landslide hazard (P2).

The eligible interventions are:

- subjected to a compatibility study aimed at verifying that the intervention guarantees safety; it does not determine conditions of instability and does not negatively modify the geomorphological processes in the area affected by the work and its appurtenances.

- areas classified as moderate landslide hazard (P1).

They are:

- any type of intervention provided for by territorial and urban planning instruments is allowed.

Any determination relating to any interventions is subjected to the drafting of an adequate geomorphological study aimed at ascertaining the level of danger existing in the area. When drafting urban planning tools, the conditions of instability highlighted, and the relative compatibility of the urban planning forecasts must be assessed *(Trigila et al., 2015)*.

2.3 The Civil Protection role in the landslide risk management

The Civil Protection in recent years has been increasingly organized, under the pressure of the major emergencies that occurred in Italy, and has therefore also required a significant change in the legislation on the subject from 1970 to 1992 with the establishment of the National Civil Protection Service, and from 1992 to today with the transition from the Civil Protection Agency to the Civil Protection Department under the direct responsibility of the Presidency of the Council of Ministers.

Infact, Law no. 225 of 24 February 1992 regulates Civil Protection as a coordinated system of competences to which State administrations, regions, provinces, municipalities and other local authorities, public bodies, the scientific community, volunteers, professional orders and colleges and any other institution, including private ones, contribute.

The first person responsible for Civil Protection in each municipality is the mayor, who organizes municipal resources according to pre-established plans to deal with the specific risks of his territory. When a catastrophic event occurs, the National Civil Protection Service is able, in a very short time, to define the extent of the event and assess whether local resources are sufficient to cope with it. Otherwise, the provincial, regional and, in the most serious situations, the national level are immediately mobilized, integrating the forces available on the ground with the necessary men and means.

The following administrative functions are assigned to the municipalities:

a) the implementation in the municipal area of forecasting activities and interventions on risk prevention established by regional and provincial programmes and plans;

b) the adoption of all measures, including those to deal with the emergency and necessary to ensure first aid in the event of disasters in the Municipality;

c) the adoption, according to regional guidelines and based on the provincial plan, of municipal and / or inter-municipal Civil Protection plans also in the forms of association and cooperation provided for by Law 142/1990 and in mountain areas through mountain communities, as well as taking care of their implementation;

d) the activation of first aid to the population and urgent interventions necessary to deal with the emergency;

e) the supervision of the implementation by the local Civil Protection structures of urgent services;

f) the use of Civil Protection volunteers at municipal and inter-municipal level also through the establishment of municipal and inter-municipal groups *(Groppo, 2006)*.

2.3.1 The Civil Protection Plan

The frequent natural hazards, involving the hydrogeological risk, put in danger the social, economic, and environmental conditions of small- medium Municipalities. The capacity to make a Municipal system resilient is a key point to face on risk with structural and non-structural measures as the Civil Protection Emergency Plan.

The Municipal emergency plan is nothing more than a project that determines the coordination of all civil protection activities useful for dealing with a calamitous event in each area. Therefore, the emergency plan is the tool that defines the Municipality's operational method to deal with emergencies deriving from natural or anthropogenic events, foreseeable or unforeseeable, with its own resources. Planning means preparing during the ordinary period to combat the emergency in a coordinated manner, with all the components of the civil protection system, developing operational intervention procedures to be implemented in the event of a calamitous event being announced and/or occurring to prevent and mitigate its effects on people and property. These events are identified in the plan itself in specific reference scenarios based on information and data on the hazard and vulnerability of the territory.

The Emergency Plan also establishes the goals to be achieved to provide an adequate civil protection response to any emergency, defining the criteria for an organisational model that assigns decision-making responsibilities to the various levels of command and control. It is a document that is constantly updated, which must consider the evolution of territorial planning and changes in the expected scenarios. Each municipality must equip itself with a civil protection structure. The Municipality must approve by council resolution the municipal emergency plan drawn up according to the criteria and procedures contained in the directives indicated by the Civil Protection Department and the guidelines provided by the Regional Council.

2.3.2 The stakeholders inside the landslide risk management cycle

The regulatory system of reference and the well-established operating practices provide for a chronology of actions that can be summarized as follows:

a) emergencies classified among civil protection events must be dealt with, first, by the Municipality with its own means and structures.

b) if the nature and size of the calamitous event require it, the mayor requests the intervention of the Prefect and the Region who cooperate to activate, at local or provincial level, the resources necessary to overcome the emergency (art. 2, c. 1, lett. a), b), L. n.225/1992 and ss.mm).

c) if the calamitous event assumes such significant dimensions or characteristics that they must be dealt with extraordinary means and powers, the Prefect and the Region request the intervention of the State through the National Department of Civil Protection (art. 2, c. 1, letter c), Law no. 225/1992 and ss.mm).

In any case, in the event of an emergency, even at municipal level, the mayor must immediately notify the Region and the Prefecture. Depending on the intensity and extent of the event, as well as the response capacity of the local system, to ensure the coordination of emergency management activities, the operational and coordination centres will be activated in the area at which the Bodies and Operational Structures of the National Civil Protection Service are represented, taking into account the provisions of the PCM Directive of 3 December 2008 "operational guidelines for the management of emergencies" as well as the subsequent guidelines of the Head of Department of 31/03/2015 concerning the "determination of the general criteria for the identification of the Operational Coordination Centres and Emergency Areas".

Concerning different levels to manage a situation of risk, three different areas are highlighted:

- Municipal level.

The mayor as the principal authority must face on the emergency with these duties:

- the first response to the emergency, whatever the nature of the event and the extent of its effects, must be guaranteed by the local structure (the Municipality) through the activation of a Municipal Operations Centre (COC) where the various components operating in the local context are represented.

- The mayor, making use of the COC, assumes the direction and coordination of the rescue for the assistance to the population in the first interventions necessary to deal with the emergency, following the guidelines of Civil Protection Emergency Plan. Then the mayor maintains the community informed about the behaviours to adopt and how the event is evolving.

- Provincial level.

In this case the Rescue Coordination centre (CCS) in which the Prefecture, the Region, the Metropolitan City, the bodies, administrations, and operational structures are represented, is activated to:

- ensure the unitary management of the interventions to be coordinated with those carried out by the Mayors of the Municipalities concerned.

- Assess the needs on the territory to rationally use the resources already available.

- Define the type and extent of regional and national resources necessary to integrate those at provincial level, identifying, where not provided for by emergency planning, the sites intended for relief storage areas.

The Prefect is responsible for the activation and use of state resources present in the provincial territory, for public order and security and issues ordinances exercising, if necessary, the function of subsidiarity towards the mayors.

The President of the Metropolitan City is responsible for the immediate activation and use of his resources, takes care of the road network, infrastructures, and service networks.

In relation to the extension of the area concerned and the population to be assisted and/or the possible need for coordination between the Operational Structures that exceeds territorial competences, to support the activity of the municipal operational centres and to link the interventions implemented at municipal level with those of the province, the Mixed Operational Centres (COM) are activated, located in suitable structures previously identified, to which one or more municipalities belong. The identification, organization and activation of the COMs are the responsibility of the authority responsible for the Rescue Coordination Centre (CCS), i.e. the Prefect.

- Regional level.

The response to emergency is managed by the Regional Operations Room (SOR) which:

- must ensure 24-hour operation in emergencies, guarantees the National Civil Protection Department the updating of information and activities, coordinates at provincial level with the Prefects, identifies the type and extent of national resources that may be necessary to integrate the territorial ones, and makes requests while maintaining the connection with the operational centres activated at provincial and municipal level.

Normally the SOR is structured in three areas:

- the Situation Room which receives, evaluates, and transmits any information relating to the event's evolution; it contributes to coordination with the provincial and municipal levels to organise the rescues, activating the support functions deemed necessary; it ensures that information is constantly updated from local to national level.

- The Communication area which guarantees the link between municipal, provincial, and regional level.

- The Operational Support area which brings together various functions such as the Technical Function (Functional Centre, Computer Scientists, Technicians), the Volunteer and Civil Protection Function, the Operational Structures Function as VVF, the Health Function (Regional Health Services, 118), Logistics Function and Population Assistance Function.

The Region ensures the immediate activation and use of the regional mobile column and voluntary organizations, the management of health emergency interventions, on the basis of its own organization, in line with what has been defined regarding the organization of medical assistance, the dispatch of its own technicians for the verification of the usability of the buildings, the survey of the damage, the assessment of the residual and induced risk, the verification of the potability of the water and the environmental remediation intervention.

2.4 Design strategies in landslide risk management

The primary purpose of a landslide hazard and risk assessment is often to enable the prioritization of sites that will be subject to risk reduction, through management and mitigation in the light of defined budgets.

However, it is important to note that it is only in cases for which the risk is deemed to be greater than that which is tolerable, or greater than the level at which the risk holder is willing to accept the risk *(Winter et al., 2012)*, that risk reduction is required. There are many forms of landslide mitigation.

However, to reduce landslide risk to acceptable levels, either the magnitude of the hazard and/or the potential exposure (or vulnerability) or losses, that are likely to arise because of an event, must be addressed. Thus, it is possible to consider management strategies that involve exposure reduction outcomes and mitigation strategies that involve hazard reduction outcomes.

Further, it is important that those funding such works, including infrastructure owners and local governments, can focus clearly on goals of the outcomes from, and the approaches to such activities rather than the details of individual processes and techniques. Therefore, an approach that promotes a considered decision-making process, must consider of both costs and benefits. It also encourages careful consideration of the right solution for each location and risk profile, potentially making best use of often limited resources.

The challenge with hazard reduction often is to identify locations of sufficiently high risk to warrant spending significant sums of money on engineering works. For example, the costs associated with installing extensive remedial works over very long lengths of roads may be both unaffordable and unjustifiable and even at discrete locations the costs can be significant.

Moreover, the environmental impact of such engineering work should not be underestimated. Such works often have a lasting visual impact and, potentially, impact upon the surrounding environment. It is considered that such works should be limited to locations where their worth can be clearly demonstrated.

2.4.1 Socio – economic damages by a landslide

Landslide events may have significant socio-economic impacts, due to their intensity and velocity. These include the severance (or delay) of access to and from remote communities for services and markets for goods, employment, health and educational opportunities and social activities. The types of economic impacts are summarized here by *(VanDine, 1996)*:

- Direct economic impacts: the direct costs of clean-up and repair/replacement of lost/damaged infrastructure in the broadest sense and the costs of search and rescue. These are easy to estimate for any given event provided that the estimate is made contemporaneously.

- Direct consequential economic impacts: These relate to disruption to infrastructure and are really about loss of utility. The costs of closing a road (or implementing single lane working with traffic control) for a given period with a given diversion, are simple to estimate using well-established models. The costs of fatal/non-fatal injuries may also be included here and may be taken (on a societal basis) directly from published figures.

- Indirect consequential economic impacts: Often landslide events affect access to remote rural areas with economies based upon transport-dependent activities. If a given route is closed for an extended period, then this may lead to concerns regarding the on-going viability of, local businesses. Manufacturing and agriculture (e.g. forestry in western Scotland and coffee production in Jamaica) are a concern as access to markets is constrained, the costs of access are increased, and business profits are affected, and short term to long-term viability may be adversely affected; in addition, tourists may be reluctant to travel to areas to which access is restricted.

2.4.2 Project phases for public works

Legislative Decree 36/2023 (new procurement code) has made an important change concerning the design levels. If previously the design levels were classified as three, now Public Administrations must follow two levels: the technical-economic feasibility project and the executive project.

Recently an integrated form has been applied, as Legislative Decree 209/2024 on 31st December 2024. The measure aims to simplify and rationalize the current regulatory framework, responding to critical issues that emerged during the application of the code and requests for changes by the European Union.

For example, regarding ordinary and extraordinary maintenance interventions, the first level of design can be omitted provided that the executive project includes all the elements provided for by the omitted level. The new code also restores the integrated contract. The integrated contract is a method of awarding public works that provides for a single economic operator to deal with both the executive design and the execution of the works. In practice, the contracting authority entrusts the contractor with both the design and construction phases of the work. Inside the complex field of public works, the new legislative decree aims to ensure:

a) meeting the needs of the community.

b) compliance with environmental, urban planning and protection of cultural and landscape heritage standards, as well as compliance with the provisions of the legislation on the protection of health and safety of buildings.

c) compliance with architectural and technical-functional quality requirements, as well as compliance with the expected times and costs.

d) compliance with all existing constraints, hydrogeological, seismic, archaeological and forestry constraints.

e) energy efficiency and minimisation of the use of non-renewable material resources throughout the life cycle of the works.

f) compliance with the principles of economic, territorial, environmental, and social sustainability of the intervention, also to face land consumption, encouraging the recovery, reuse and enhancement of the existing building stock and urban fabric.
g) the rationalization of design activities and related verifications through the progressive use of methods and tools for digital information management of buildings.

h) accessibility and adaptability in accordance with the provisions in force on architectural barriers.

i) the geological and geomorphological compatibility of the work.

Concerning on the Art. 41 Comma 6 Letter b) and g-bis, the technical – economic feasibility project:

a) identifies, among several practical solutions, the one that expresses the best relationship between costs and benefits for the community in relation to the specific needs to be met and the services to be provided.

b) contain the necessary references to the possible use of methods and tools for the digital information management of constructions referred to in Article 43 (as of 1 January 2025, contracting authorities and concessionaires shall adopt methods and tools for digital information management of constructions for the design and construction of new construction works and for interventions on existing buildings with an estimate of the estimated cost of the works for an amount exceeding 2 million of euros or the threshold of Article 14, paragraph 1, letter a), in the case of interventions on buildings referred to in Article 10, paragraph 1, of the Code of Cultural Heritage, referred to in Legislative Decree No. 42 of 22 January 2004);

c) develop, in accordance with the framework of requirements, all the investigations and studies necessary for the definition of the aspects referred to in the paragraph.

d) identifies the dimensional, typological, functional, and technological characteristics of the works to be carried out, including the choice regarding the possible subdivision into functional lots.

e) allows, where necessary, the initiation of the expropriation procedure.

f) contains all the elements necessary for the issuance of the required authorisations and approvals.

g) contains the preliminary maintenance plan of the work and its parts.

With reference to Art. 41 Paragraph 8 Letter c), the executive project, in line with the technical-economic feasibility project:

a) develops a level of definition of the elements such as to fully identify their function, requirements, quality, and list price.

b) it is accompanied by the maintenance plan of the work for the entire life cycle and determines in detail the works to be carried out, their cost and their implementation times.

c) if methods and tools for the digital management of buildings are used, develop an in-depth analysis of the information content in line with the objectives of the relevant level of design in accordance with what is specified in the information specifications.

d) as a rule, it is drawn up by the same person who prepared the technical-economic feasibility project. If it has been justified the separate assignment, the new designer accepts the design activity carried out previously without reservation.

Finally, there is a new introduction as Comma 8 – bis of Art. 41, which gives more responsibilities to the project manager; in the event of external awarding of one or more design levels, the design contracts entered into by the contracting authorities and concessionaires provide in express clauses the supplementary services 27 to which the designer is required, by way of settlement, to remedy in a specific form errors or omissions in the design that emerged during the executive phase, such as to jeopardise, in whole or in part, the construction of the work or its future use. Any agreement that excludes or limits the designer's liability for errors or omissions in the design that jeopardise, in whole or in part, the construction of the work or its future use is null and void.

2.4.3 Landslide risk mitigation countermeasures

Landslides pose a recurrent hazard to human life and livelihood in most parts of the world, especially in some regions that have experienced rapid population and economic growth. Landslides consist of a big problem to be faced on by Public Administrations, which must find the right tools to prevent them.

Hazards are mitigated mainly through precautionary means, for instance, by restricting or even removing populations from areas with a history of landslides, by restricting certain types of land use where slope stability is in question, and by installing early warning systems based on the monitoring of ground conditions such as strain in rocks and soils, slope displacement, and groundwater levels.

There are also various direct methods of preventing landslides; these include modifying slope geometry, using chemical agents to reinforce slope material, installing structures such as piles, and retaining walls, grouting rock joints and fissures, diverting debris pathways, and rerouting surface and underwater drainage. Such direct methods are constrained by cost, landslide magnitude and frequency, and the size of human settlements at risk *(Meng, 2025)*.

Landslide risk can be prevented or reduced through engineering controls like retaining walls, geogrids, and drainage systems to stabilize slopes and manage water, alongside non-structural measures such as vegetation management, land-use planning to avoid building in hazardous areas and creating evacuation plans. Understanding local risks through hazard maps, monitoring high-risk slopes, and educating communities on how to react to signs of an impending landslide are crucial for safety.

2.4.3.1 Structural consolidation and reinforcement to ensure slope stability

The slope stability has a foremost importance for Public Administrations which are frequently interested by the hydrogeological risk. The design project phases for structural consolidation and slope reinforcement concern the conditions related to the presence of active or dormant landslides on slope analysed, the typology of movements examined (i.e. slides, debris flow, complex landslides), the volume, the extension and the depth of the failure.

If for active landslide it is simple to identify the geometry and the cinematics, solving the problem with a detailed geological site examination, concerning the slopes with incipient instability, there are more uncertainties to identify parameters governing the phenomenon due to the shape and the depth of the potential sliding process.

Evaluating the various possibilities of intervention to reinforce slope, four typologies are underlined:

- Structural interventions.
- Drainage works.
- Surface reprofiling.
- Soil mechanics features improvement.

Normally the structural interventions and the surface reprofiling are more frequently used but, in some cases, they are not enough for a global slope stability analysis. Indeed, they can have a relevant impact to the ecosystem. A challenge that engineers and geologists are facing on, is to find the right compatibility between the environment and the intervention to stabilize the slope.

In the field of geotechnical engineering, structural interventions have the aim to modify the static conditions of the slope. The application of stabilizing external forces on the slope mass follows the principles of Limit Equilibrium Method.

The types of interventions are:

- Retaining walls, revetment gabions and structures with reinforced earth walls; a vertical force is activated on the foot of the slope with the aim to implement a remodelling action of the slope; this structures which are made of concrete or stone have the role to support steep slopes and prevent the movement of soil.

- Anchors which are uniformly applied as punctual elements on the slope; the slope stability is guaranteed by the application of the sum of normal and tangential forces distributed along the sliding slope.

- Micro pile walls, bored pile walls, pile walls which are vertical elements whose interaxis is located orthogonally to the sliding line; in this case the structural elements across the slope in movement and they are joggled in the stable ground under the slope surface; the function of the structural element is to transfer to the ground under the surface, the force necessary to stabilize the slope.

Drainage works are frequently used by engineers since they have the capacity to reduce water interstitial pressures, increase soil shear resistance and improve overall stability. Moving the water away, this type of intervention reduces the weight of the soil and prevents collapse.

In addition, the limited environmental impact makes it possible to find the right compatibility between environmental protection and slope stabilization needs. For example, installing drainage channels, pipes, or culverts, it is possible to effectively redirect water away from the slope, minimizing the risk of landslides.

Drainage works can be distinguished in:

- Surficial drainage.

- Deep slope drainage.

Concerning the first typology it is important to mention surficial drainage trenches with geocomposite. The application of geosynthetics techniques has a highly versatile and cost-effective solution for slope stabilization; these synthetic materials, such as geogrids and geotextiles are laid within the soil layers to provide tensile strength and reinforcement being useful for create stable steeper slopes and reduce the need for traditional, more expensive earthworks.

Looking at the deep slope drainage, experts evaluate the use of:

- Micro drains.

- Deep drainage trenches.

- Drainage wells with medium diameter.

- Drainage galleries with micro drains.

The third typology of landslide risk mitigation measures is represented by surficial reprofiling. This intervention concerns the remodelling of the slope plane, through the movement of volumes of soil with the aim of reducing vertical forces when they take on a destabilizing role and increasing them where the stabilizing role becomes predominant. Normally, the action applied concerns a lightening upstream of the slope and a weighting at the foot of the slope. The upstream interventions concern simple earthmoving operations while the weight on the foot proves to be more complex.

The weighting action on the foot of the slope is based on the construction of common retaining walls until to flexible structures which they are capable to adapt to ground deformation.

An example is represented by cribb walls which are special retaining walls, characterized by a rectangular grid of precast concrete elements or by protected wood elements, whose voids are filled with compact granular material. Sometimes the stability is reached with construction techniques which need reinforced elements to put inside the ground; an example is represented by gabions, geosynthetics structures and wire strips.

The last typology for slope stabilization is the soil mechanics features improvement. This methodology is related to the application of reinforced elements inside the ground with the aim to realise a composite material better than the original source and it concerns the introduction of chemical and physical changing processes of the original ground structure.

One of the methods that has found an important application, is represented by the jet grouting technique.

Jet Grouting (high-pressure cement injection or consolidated columns) is a consolidation technique to mechanically improve a soil; it involves the dissolution and the mixing process between the soil and a stabilizer. This mix takes place by injecting a cementitious binder fluid into the soil at very high pressure (200 - 700 bar) from nozzles located on the drill rods.

The technique allows the consolidation of delimited volumes of soil, to improve its mechanical and hydraulic characteristics. The advantage is the resistance and deformation improvement, and the permeability of the soil.

It involves the drilling and injection phase; drilling is classically carried out with drills subjected to thrust and rotation, while the uphill cement injection phase consists of spraying a high-pressure fluid into the ground, obtaining a disintegration and mixing effect. The injected fluid is composed of water, cement and any other additives or bentonite, depending on the intervention to be carried out. Soil treatment can be done with different injection techniques:

- Mono-fluid, i.e. injection of cement mixture only.
- Bi-fluid system, with air and mixture injection.
- Tri-fluid, with injection of air, water and mixture.

2.4.3.2 Consolidation and drainage of rock slopes

The growing attention to the slope safety concerns also the protection from the instability of rocks elements whose consequences can be identified in the collapse and detachment of blocks.

Normally, the stabilization and safety of rock slopes is carried out by:

- Stabilization on the rock wall with active interventions.
- Boulder deflection with passive interventions.

If active defence interventions are all works that prevent the detachment of stone elements from the slope by increasing the safety factor, passive defence interventions have the purpose of intercepting, diverting or stopping blocks already in motion.

Active defence interventions are identified as:

- Changing of the slope geometry.
- Change in the piezometric conditions of the rock mass.

- Change in the mechanical strength of the rock mass.
- Protection from external agents.

The modification of the geometry of the slope considers the possible presence of debris covers that must be removed or stabilized. Normally the most common technique concerns the actions of scaling and felling large rock volumes.

Removing unstable elements by scaling leads to problems related to:

- Difficulties in the geometric definition of the rock volumes that need to be removed.
- Need to use specialized personnel for rock surveys (operation with abseils on the wall).
- Protection of man-made areas with closure of roads and bridges.

The abatement of large rock volumes normally takes place with the use of explosives. If the advantages of this technique are related to the high execution speed, the low cost and the precision of the action, the disadvantages concern the vibrations induced by the explosion, the need to control the fragments in the air (flying rocks) and the presence of numerous constraints related to the road infrastructures.

Often the discontinuities of the rock mass suffer from water infiltrations that can compromise its stability. The procedure of modifying the piezometric conditions of the rock element is very delicate because the rock masses have irregular fractures, leading to difficulties in the correct quantification of the safety factor.

On the contrary, as regards the control of local instability phenomena that are mostly slips and overturns, the interventions to modify the resistance of the rock mass are:

- Steel bar tie rods;
- Bolting;
- Local and mesh bolts;
- Ligatures;
- Anchors.

Finally, the action of external agents, such as wind, rain and freezing conditions can alter the rock face. Interventions to prevent this from the occurrence, concern the field of bioengineering and they are less expensive measures than structural works leading to slope stabilization using native vegetation and drainage improvements, preventing the situations of erosion.

The works of protection from the alteration of the rock face can therefore be divided into:

- Surface waterproofing by application of membranes.
- Revegetation.
- Construction of drainage systems for the collection and disposal of rainwater.
- Protection of the rock face with natural mantle.

- Protection of the rock face with artificial mantle.
- Hexagonal mesh nets.
- Plant nets.
- Reinforced nets with rope lattices.

Finally, it is important to mention the passive works whose purpose is to intercept the trajectory of falling blocks.

They are:

- the reprofiling of the slope with the creation of intermediate berms to stop the blocks;
- the installation of rockfall protection nets;
- protective walls;
- artificial tunnels;
- trenches;
- gabions;
- cell walls.

2.4.3.3 Monitoring systems for landslide risk prevention

Landslide monitoring plays a crucial role in the management and protection of a territory. By advanced tools and specific methodologies, it is possible to detect early signs of ground instability, preventing damage and saving lives. It is configured as a systematic process of acquisition, transmission, processing and interpretation of data that describe the behaviour of a slope over time.

The monitoring systems, linked to the analysis and strategic management of the instability, include:

- identification and quantification of landslide velocities and type of movement;
- identification of mechanisms, crucial information for the design of targeted mitigation works;
- model validation and calibration; it is possible to provide real and continuous data to validate and calibrate numerical stability and strain models, making them more representative of the real slope behaviour and increasing the reliability of predictions;
- identification of sliding surfaces with geotechnical instrumentation;
- evaluation of the effectiveness of the interventions; monitor the behaviour of a slope after the execution of stabilisation interventions to verify its effectiveness over time, optimising economic resources;
- support for risk zonation; monitoring data help to define more precisely the areas of greatest danger and to support spatial planning and land use, key tools for preventive risk management at the territorial level.

- database for Alert Systems; provide the real-time data necessary for the implementation and management of early warning systems, which are essential for emergency management, civil protection and the protection of human lives.

2.4.3.3.1 The geotechnical sensors

Among the most widely used tools for monitoring landslides, geotechnical sensors are useful for monitoring the subsoil and water pressure.

The main geotechnical sensors are:

- inclinometers, used to detect ground movements in depth along sliding surfaces; installed inside inclinometric tubes, these sensors measure the variations in the inclination of the ground, allowing the evolution of the landslide movement to be tracked over time;

- piezometers, on the other hand, are used to measure the interstitial pressure of water in soils, a fundamental parameter in landslide dynamics, since the increase in pore pressure can reduce the shear resistance of the soil and trigger subsidence;

- tiltmeters used to measure changes in surface inclination of a slope or structures;

- extensometers whose role is to measure the extension or displacement between two points of the slope.

The interpretation of the data collected requires multidisciplinary technical skills. Inclinometric data, for example, must be compared with information from piezometers to identify correlations between water changes and ground movements.

2.4.3.3.2 Remote sensing instruments

In recent years, an important evolution in the field of landslide risk monitoring has been represented by Early Warning Systems (EWS) that integrate real-time sensor networks with analysis software and data management platforms.

These systems allow not only the automated and continuous collection of data, but also the sending of immediate alerts in the event of critical thresholds being exceeded. The adoption of wireless solutions and technologies based on the use of IoT (Internet of things) sensors allows to monitor large areas, reducing installation time and costs.

The landslide sensors acquire parameters such as deformation, inclination, displacement and applied force. The workflow is fully automatic; data are collected by the sensor, sent via radio, received by the gateway and transmitted over GPRS to the cloud platform, which is a web monitoring software.

Among the monitoring systems that allow to acquire data on deformations or other parameters of the landslide phenomenon without direct contact with the unstable area, they are considered:

a) Topographic surveys (total stations, theodolites, GNSS); they measure the surface displacement of the landslide body, automatically and continuously (with the use of GNSS antennas), providing high-precision point measurements, essential for quantifying displacements and controlling the expansion of movement.

b) Lidar (Light Detection and Ranging) measurements; they allow the acquisition of high-resolution digital terrain models (DTMs), evaluating morphological variations and measuring the extent of topographic deformations to characterize landslide activity over time and quantify the volumes involved.

c) Interferometric Measurements from the Ground (GB-InSAR); ground-based radar technique that measures the displacement of a target along the line of sight with accuracy producing multi-temporal and spatially continuous maps of surface deformations in the entire field of view; it operates in any weather and visibility condition and is a valuable tool for detailed monitoring of critical areas and for early warning systems.

d) Satellite Interferometric Measurements (InSAR, PS-InSAR); they measure the movement on the Earth's surface with high precision using satellite radar signals; they are an inexpensive and non-invasive support to identify slow movements over large areas, providing updatable deformation rates and time series of displacements; this technique is particularly effective in urbanized areas or with the presence of stable targets (Permanent Scatterers).

e) Radar Doppler measurements: radar systems developed for real-time monitoring of fast-kinematic instability (rockfall, debris flows); they issue an alarm signal during the occurrence of the event, detecting the speed of the moving material.

f) Cameras; they provide video recordings useful for describing and interpreting the development of phenomena, essential to assess rapid events and for remote evaluation.

g) Aircraft/Drone photogrammetry (Structure from Motion – SfM); it lets the rapid creation of high-resolution digital terrain models is particularly useful in post-event measurements for mapping and determining the volume of deposits and eroded volumes by comparing pre- and post-event models.

The effectiveness of monitoring depends not only on the quality of the tools used, but also on the way the data is installed and managed. The instruments must be placed in strategic points, identified through geological studies and slope modelling, to ensure an accurate representation of the behaviour of the terrain.

It is essential to ensure a correct configuration of the system, verifying the compatibility between sensors, dataloggers and analysis platforms. Regular maintenance and checking of the reliability of the transmitted signals make it possible to ensure the continuity of monitoring and the integrity of the information.

In the most advanced projects, the data is supplemented with meteorological, seismic and hydrogeological information, offering a complete and detailed picture of the situation. Accurate landslide monitoring not only improves emergency management, but it is a crucial tool for responsible and sustainable spatial planning.

CHAPTER 3: THE CARUGGIO DI VIGNALE CASE STUDY

3.1 Introduction

The Val Fontanabuona area located in the Eastern of Liguria Region is historically a territory susceptible to landslides, for climatic, anthropogenic, and geological factors. The area includes the basin of the Lavagna stream, the terminal portion of the T. Sturla basin, as well as the medium-high basin of the T. Cicana (tributary of the Sturla).

Small instabilities of a punctual nature mostly involve the secondary road network of the valley, to which they are closely connected. These instabilities are often accompanied by insufficient or missing drainage and support works for the upstream and downstream parts of the roadway.

These phenomena, identifiable as landslides, rotational or planar slides or small collapses, are in fact very often favoured by the road cut of the slope itself. Other punctual instabilities are caused by bank erosion of major watercourses which, also in this case, can affect the roads of the valley floor or built-up areas located in the immediate vicinity of the edges of river terraces.

A striking example and which constitutes the most critical case, also for the potential development of the process, is given by the erosive phenomenon taking place on the banks of the current bed of the Lavagna stream, in the Scaruglia locality, where, in connection with a bend in the stream, repeated undermining of the bank is removing portions of cultivated land. Other instability phenomena in progress have been detected within the bodies of some paleo landslides.

In the area of the basin there are many detrital areas referable to paleo landslide bodies (the total surface area of these areas, 88 in total, is just over 3% of the surface of the entire basin). These accumulations can be considered now completely stabilized and only in particular conditions, the entire landslide body, or a portion of it, can be considered susceptible to potential reactivation.

Another critical element of the territory linked to the phenomenon of landslides is given by the processes of slow movement of the debris blankets of the slopes or creep. The following are the cases where movements of this type have caused considerable damage to buildings, roads, or artifacts in general. In the locality of Serra, a large sector of the cemetery is uneven with severe damage to the pavement and tomb structures. The instability is caused by the slow movement (creep) of the surface debris blanket and the altered upper portion of the rocky substrate on which the cemetery is located.

Also, in the locality of Serra, before reaching the town coming from Ferrada, another phenomenon was detected attributable to the slow movement of the surface debris cover. Along the road to Favale di Malvaro, along the slopes, in the higher sectors near the watersheds, the erosive phenomena sometimes take on characteristics of marked intensity, causing an intense action of removal of the soil and the surface debris cover. This aspect can become critical when the construction of artefacts and road works is envisaged, which will therefore require adequate slope protection works.

In a scenario characterized by the increasing frequency of landslides, small and medium-sized Ligurian administrations need better support tools to ensure the safety and functionality of infrastructures and safeguard the community. Currently, economic efforts are aimed at emergency management, involving the secondary road network, rather than investing in landslide prevention and monitoring actions. In 2019 and 2020, the Ligurian Levante was affected by intense rainfall phenomena that generated several landslide phenomena, involving several municipalities. More specifically, in November 2019, the Municipality of San Colombano Certenoli located in the territory of Val Fontanabuona, had to face an emergency in the hamlet of Caruggio di Vignale. This is the representation of the Municipality and administrative boundaries in Figure 12:

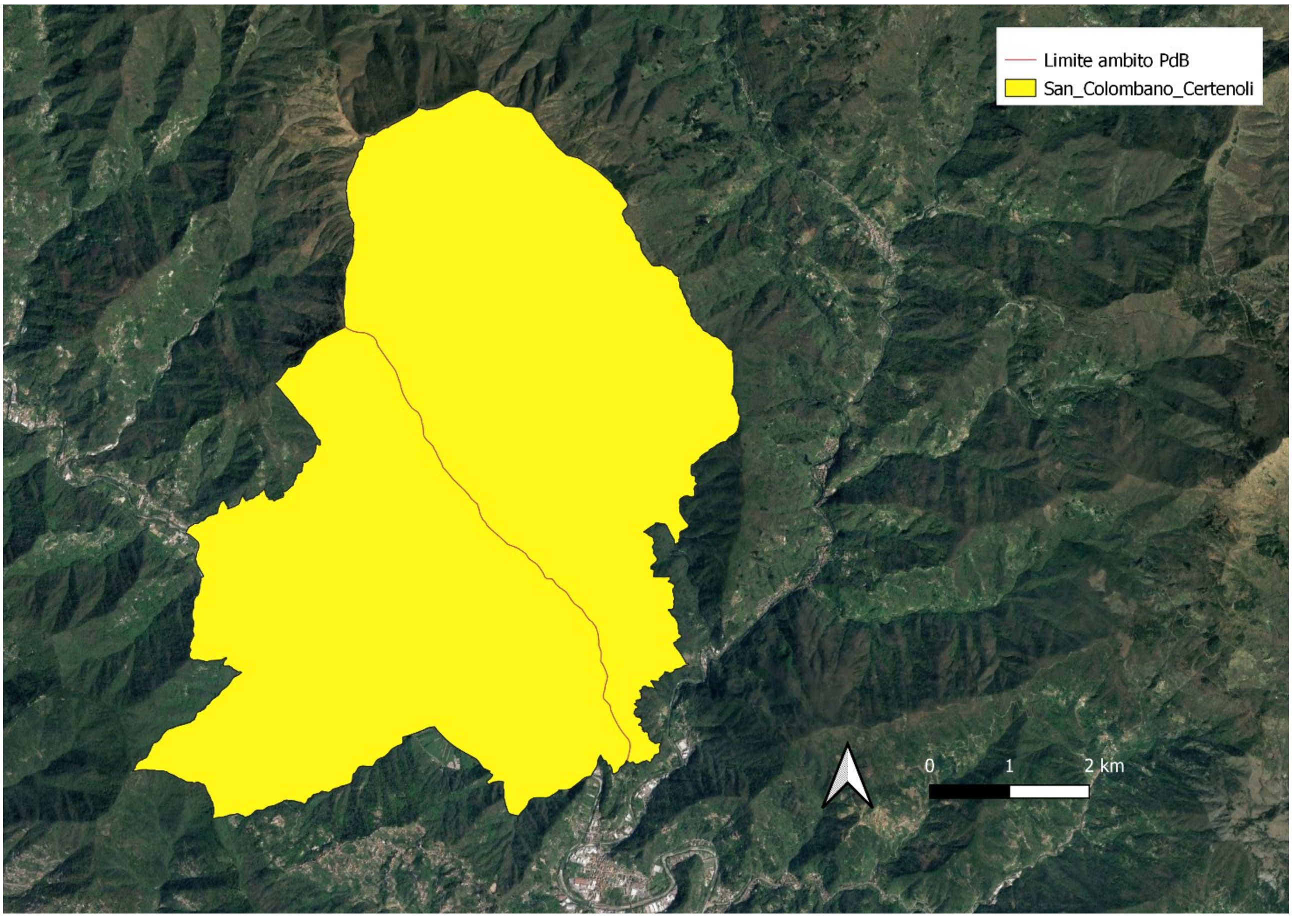


Figure 12: San Colombano Certenoli Municipality and its administrative limit by Basin Plan

The following chapter illustrates the case study of the hamlet of Vignale, with particular attention to the identification of landslide events, the geological characteristics of the area and the management that the Municipality has decided to undertake from a technical-administrative point of view to monitor the area.

3.2 The study area

Between October 2019 and February 2020 with criticality in November 2019, intense rain phenomena involved some municipal areas such as the hamlet of Caruggio di Vignale in San Colombano Certenoli Municipality. In this case, it was a large movement that affected the driveway that connects the main road of Val Fontanabuona with the hamlets of Vignale-San Martino and the exposed above. Indeed, the municipal road called Via A. Norero is the only artery connecting the hamlet with respect to the valley floor of San Colombano Certenoli and the highest part, titled Pian Soprano.

The fraction of Vignale which is located on the orographic left of the Lavagna stream consists of 3 settlements:

a) Caruggio of Vignale.

b) Vignale.

c) Pian Soprano

The Figure 13 shows the study area georeferenced on GIS:

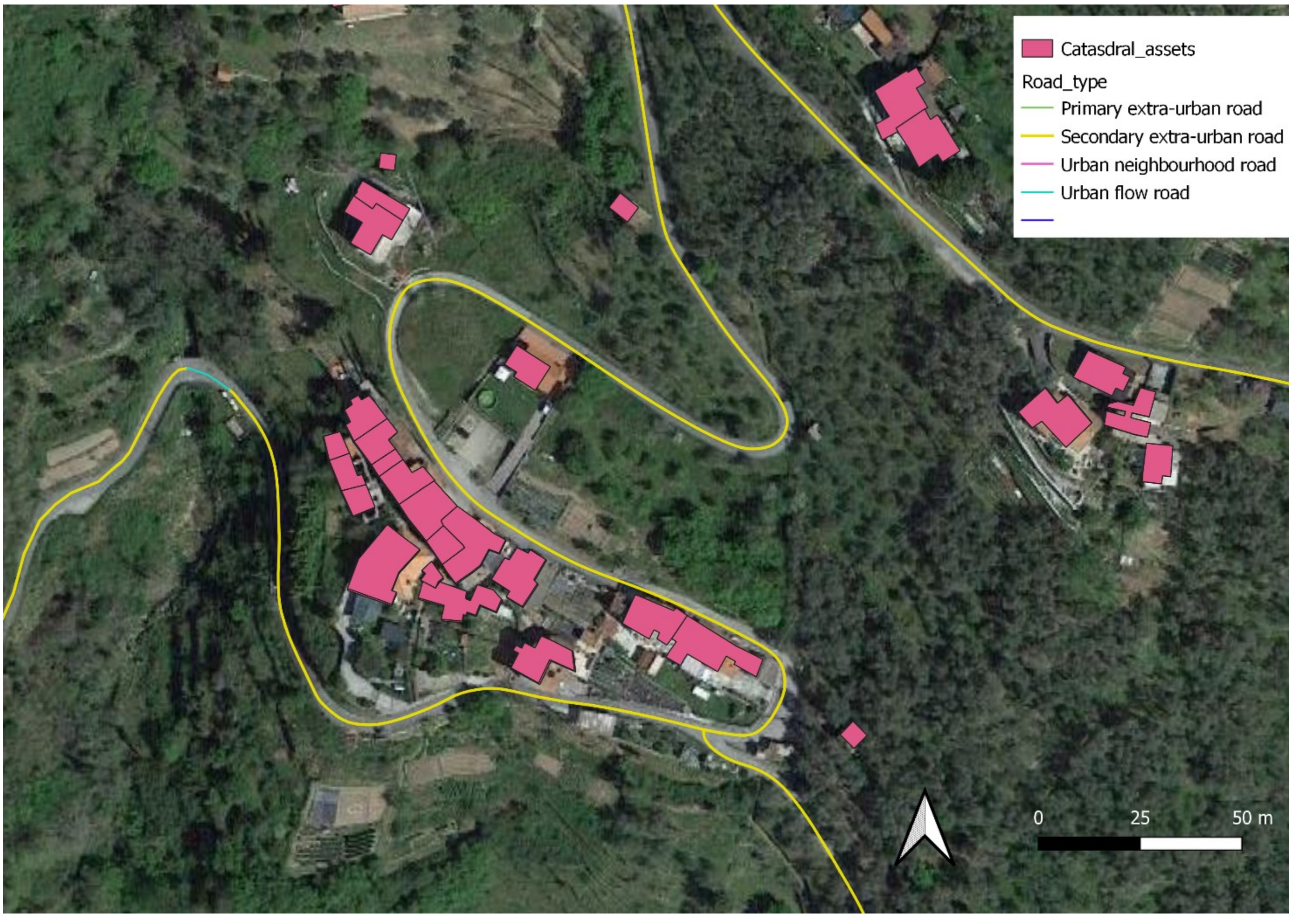


Figure 13: Caruggio di Vignale cadastral exposed assets (pink) and Municipality Road path (yellow)

From a geological point of view, the area of interest is characterized by:

- Clayoscysts, typical of Lavagna valley in the central part of the escarpment.
- Sandstones, lifted clastic sedimentary rock consisting of sand granules with a prevalent non-carbonate composition from Gottero mountain, outcropping both at lower and higher altitudes above Caruggio.
- Argilloscysts, a series of mudstones typical of Salvai mountain.

Indeed, the harsh weather conditions led to a subsidence of the valley edge along the road itself. The consequences were the movement of the roadway and that of the overlying ditch and its nail wall at the foot of the earthy boulder of upstream, increasing the danger. The consequences have been:

- the impairment of the roadway.
- the interruption of the sewer pipe, promptly restored.
- the significant instability of the escarpment upstream of the road network (slips of earthy and stone material).

3.2.1 The landslide body

From a landslide point of view, the picture is extremely complex, as a single and consistent body of ancient and relict landslide whose state of activity is closely connected to the pluviometry regime of the area and above all, to the action of bank erosion by the Rio Vignale, a watercourse that passes under the driveway and continues to the valley. The landslide body is characterized by:

- A complex landslide in a state of activity in the stretch of the municipal road at lower altitudes than the hamlet, with development up to the watercourse called Rio Vignale.

- A dormant landslide, as a slide in the portion of the slope upstream of Caruggio di Vignale with local phenomena of active instability of a punctual nature.

- A complex dormant landslide further upstream, in loc. Pian Soprano.

Here there is a view of the landslide body as mentioned in Fig 14:

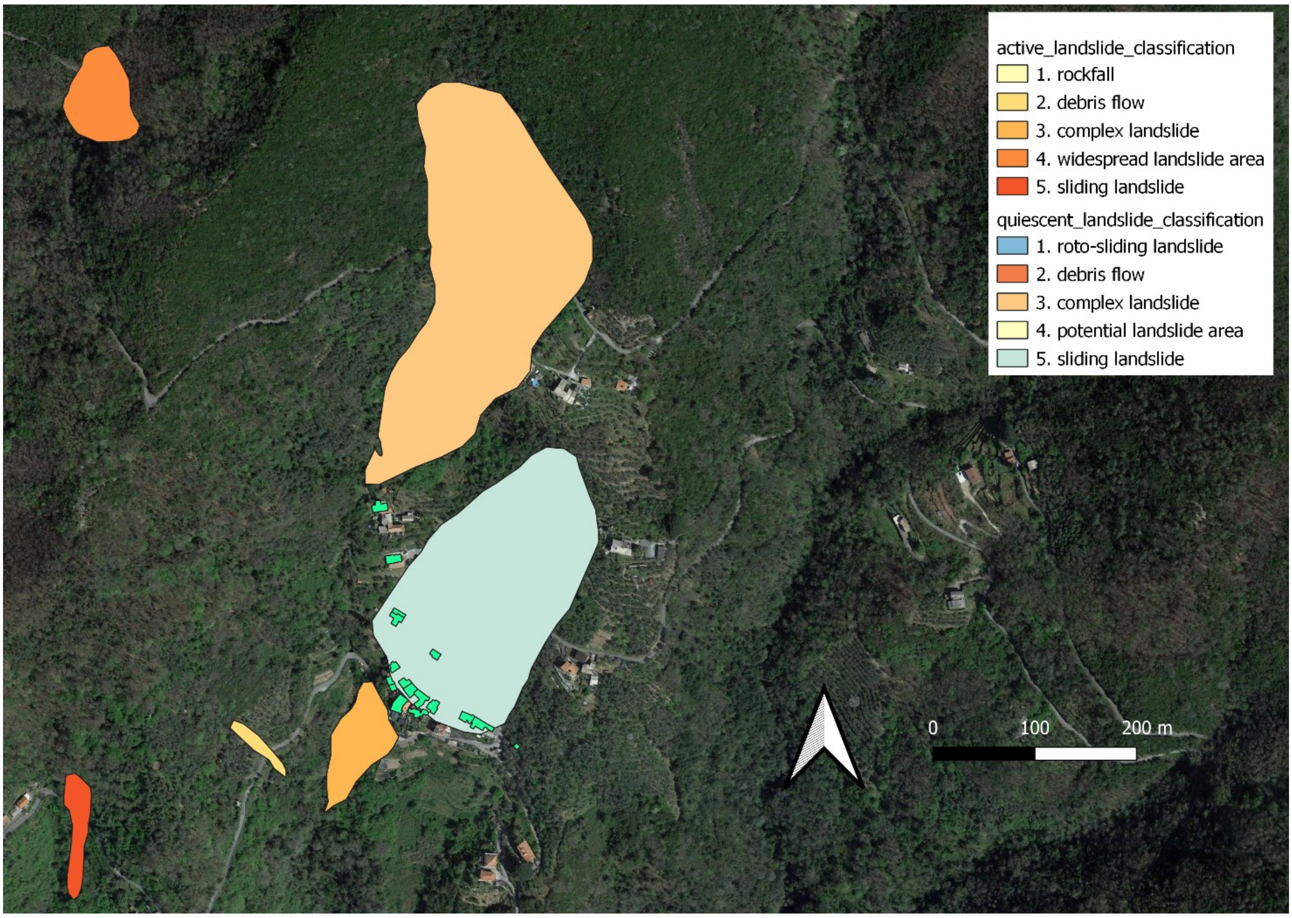


Figure 14: The landslide complexity, as an active complex landslide below the road, a dormant slide above the exposed assets (green) and complex dormant slide in Pian Soprano area.

At the upstream portion of the slope, almost 20 buildings of the settlement of Caruggio di Vignale are located. The main landslide involving the road escarpment currently develops a few meters away from the exposed assets.

3.2.2 The actual landslide susceptibility

In the Caruggio di Vignale case study, the potential danger of the landslide phenomenon is given by the map of susceptibility to hydrogeological instability extrapolated from the Basin Plan. For reasons of classification and clarity of analysis, the zones have been divided into low susceptibility (P1), medium susceptibility (P2), high susceptibility (P3a, P3b,) and very high susceptibility (P4). The landslide involving the driveway, the exposures of the hamlet of Carruggio di Vignale and the slope upstream are characterized by four areas of susceptibility:

- Area concerning the section of the driveway at lower altitudes than the fraction, characterized by susceptibility to very high instability since the landslide is active, classified as P4, also including the Rio Vignale portion.

- The exposed assets above the landslide with susceptibility to medium-low instability (P2 and P1).

- The upstream exposed assets that are in an area of dormant landslide classified as P3a, as high susceptibility for potential reactivation of landslides, including the Vignale area.

- The exhibits in Pian Soprano located in an area with high susceptibility for dormant landslides, classified as P3a.

In addition, the area is also characterized by a portion of susceptibility to high instability of type P3b on the slope downstream the driveway. In this picture (Fig. 15) there is the actual susceptibility of the site of interest:

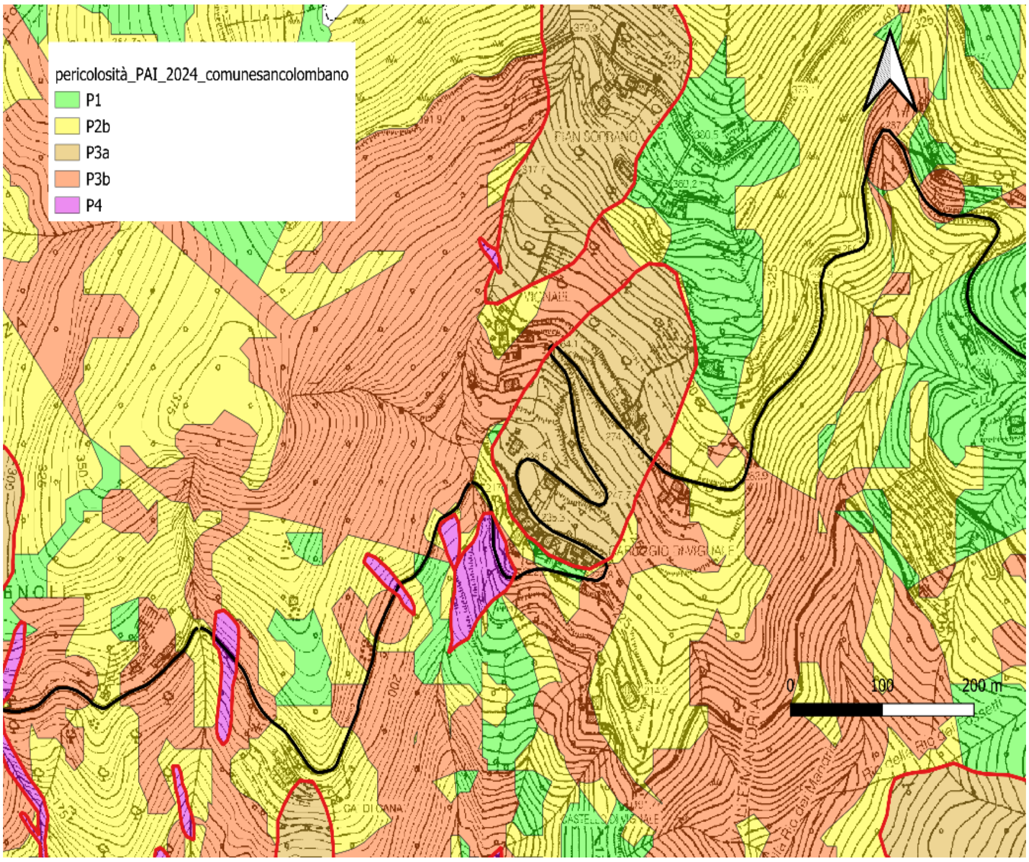


Figure 15: The actual landslide susceptibility in Caruggio di Vignale area by PAI configuration

3.3 Slope consolidation following the landslide movement

In 2014, due to a landslide that affected the Rio Vignale, an extremely urgent intervention was carried out by the Municipality of San Colombano Certenoli. The intervention withstood the stresses of landslides but there was a downward sliding of the soil soaked in water.

Due to the occurrence of intense weather events which happened in November 2019, whose effects caused extreme damage to the road system, in the hamlet of Caruggio di Vignale, the Municipality was forced to request an intervention (Fig. 16).

In December 2019, by the help of a private partnership, a traditional structural intervention, as a reinforced concrete retaining wall supported by micropyles and anchors has been realised. The safety work has been done to maintain the viability on the road and make it temporally safe. Concerning the extreme weather events of November 2019, the effects of them leaded to the partial reactivation of the landslide body involving also the Rio Vignale stream.

Figure 16: The Rio Vignale River erosion and the retaining wall (2019)

Consequently, the river was subjected to an erosion in the left side. The complete absence of rock and bank defence allowed the removal of clay and sandy soil that was transported downstream. In summer 2020, in the San Colombano Certenoli Municipality, after important land reclamation works close to the Rio Vignale area, a cliff was built with the laying of first and second category boulders, coming from loan quarries, arranged to form the new protective mantle of the left bank of the Rio Vignale. In the next picture (Fig. 17) there is the representation of the cliff:

Figure 17: The cliff building (2020)

3.4 The geological site exploration and in – situ damage surveys

The next paragraphs outline the in-situ analysis related to the geomorphology and the geophysical characteristics of the area of interest. To increase details about the analysis, an accurate evaluation of exposed assets is done, to understand the potential damages to Caruggio di Vignale buildings in case of a slope sliding.

3.4.1 First outcomes

In March 2020, the Municipality needed the help of two geologists to understand better the geomorphology and the geology of the area of interest. The experts asked a loan request to start a campaign of site investigations close to the landslide area, involving the municipal road.

The proposal concerned:

- In situ survey, consisting of 3 continuous core drilling with inclinometric tube of 25 m.l. length, the use of many holes to destroy the core set up with piezometric tube of 15 m.l. length, within which to install as many electric piezometric probes able to continuously record the groundwater levels in the subsoil.

- Geophysical analysis (seismic or refraction) to integrate the punctual data of the survey.

The processing and subsequent integrated interpretation of the data would allow to obtain indispensable information on the geological and stratigraphic structure of the landslide.

Indeed, a series of potential interventions for the hydrogeological risk mitigation have been proposed:

- surface water regulation works.
- Deep drainage and hydraulic-forestry arrangements as bank defences, and bridles along the water course.
- Reprofiling of the road escarpment with naturalistic engineering works.

3.4.2 The updated survey

In September 2021, the geological investigations were carried out according to the Ministerial Decree on Infrastructure and Transport 17.01.2018 "Update of technical standards for construction" and the related explanatory circular C.S.LL.PP. n. 7 of 21.01.2019, as well as the legislation on public works (Legislative Decree 50/2016). The intervention site fell within the areas subject to hydrogeological constraints, pursuant to Royal Decree no. 3267/1923 and Regional Law no. 4/1999.

A geological site exploration campaign was designed and carried out with the installation of monitoring instrumentation, consisting of n. 2 continuous core drilling surveys, one vertical and one inclined by 20 °, and n. 2 core destruction probes, one vertical and one inclined by 15°.

The investigations carried out in correspondence of the road downstream of the hamlet, have made it possible to identify a powerful level of loose soils, and variable thickness in correspondence of the road surface. Indeed, the roof of the superficial horizon tends to increase proceeding upstream, reaching a depth of at least 20-25 m.

Concerning the seismic action, according to the N.T.C. 2018, the geologists have evaluated the expected horizontal acceleration ag (in free field conditions on a rigid reference site with horizontal topographic surface), to consider the elastic response spectrum in acceleration corresponding to it.

For the purposes of the legislation, spectral shapes are defined by the following parameters:

- ag = maximum horizontal acceleration of the terrain.
- F0 = maximum value of the accelerating horizontal spectrum amplification factor.
- T*c = period of start of the section at constant speed of the horizontal accelerating spectrum.

To evaluate the influence of the stratigraphic profile on the local seismic response, reference can be made to a simplified approach that is based on the classification of the subsurface according to the stratigraphic conditions and the values of the equivalent speed of propagation of shear waves, Vs, eq (in m/s), defined by the expression in Eq. [6]:

$$Vs,eq = \frac{H}{\sum_{i=1}^{N}\frac{h_i}{Vs,i}} \qquad [6]$$

with:

- h_i = thickness of the i-th layer.

- Vs, i = speed of the shear waves in the i-th layer.

- N = number of layers.

- H = depth of the substrate, defined as that formation consisting of rock or very rigid soil, characterized by Vs not less than 800 m / s.

From the surveys, a category of type B subsoil has been defined which includes "Soft rocks and deposits of very thick-grained soils or very substantial fine-grained soils, characterized by an improvement of mechanical properties with depth and equivalent speed values between 360 m / s and 800 m / s". The morphology of the site can be associated with the T2 category (slopes with average inclination > 15°) of the N.T.C. 2018.

In November 2022, new investigations have been done and from inclinometric activities two levels of incipient deformation have been observed, respectively at 10-11 m e 20 m from the ground level. On the other hand, the piezometric survey indicates a permanent aquifer oscillating between 4 m and 6 m from the ground level in close correlation with the rainfall regimes.

3.4.3 The in-situ damage classification

To understand the status of the exposed assets inside the study area, the road surface state, and the characteristics of landslide body, an on-site survey has been performed. A series of pictures has been got and delocalized on Geographical Information System as visualized in the following figure (Fig. 18):

Figure 18: The on-site investigation in Caruggio di Vignale area

Then to understand the potential impact of landslides in the study area, 19 different exposed assets have been examined. With the instruments given by the Municipality, the cadastral parcels of the assets have been loaded on GIS as seen in Figure 19.

Then with the support of Municipality technicians, a list of information and details have been written on a damage classification sheet divided by different exposed assets.

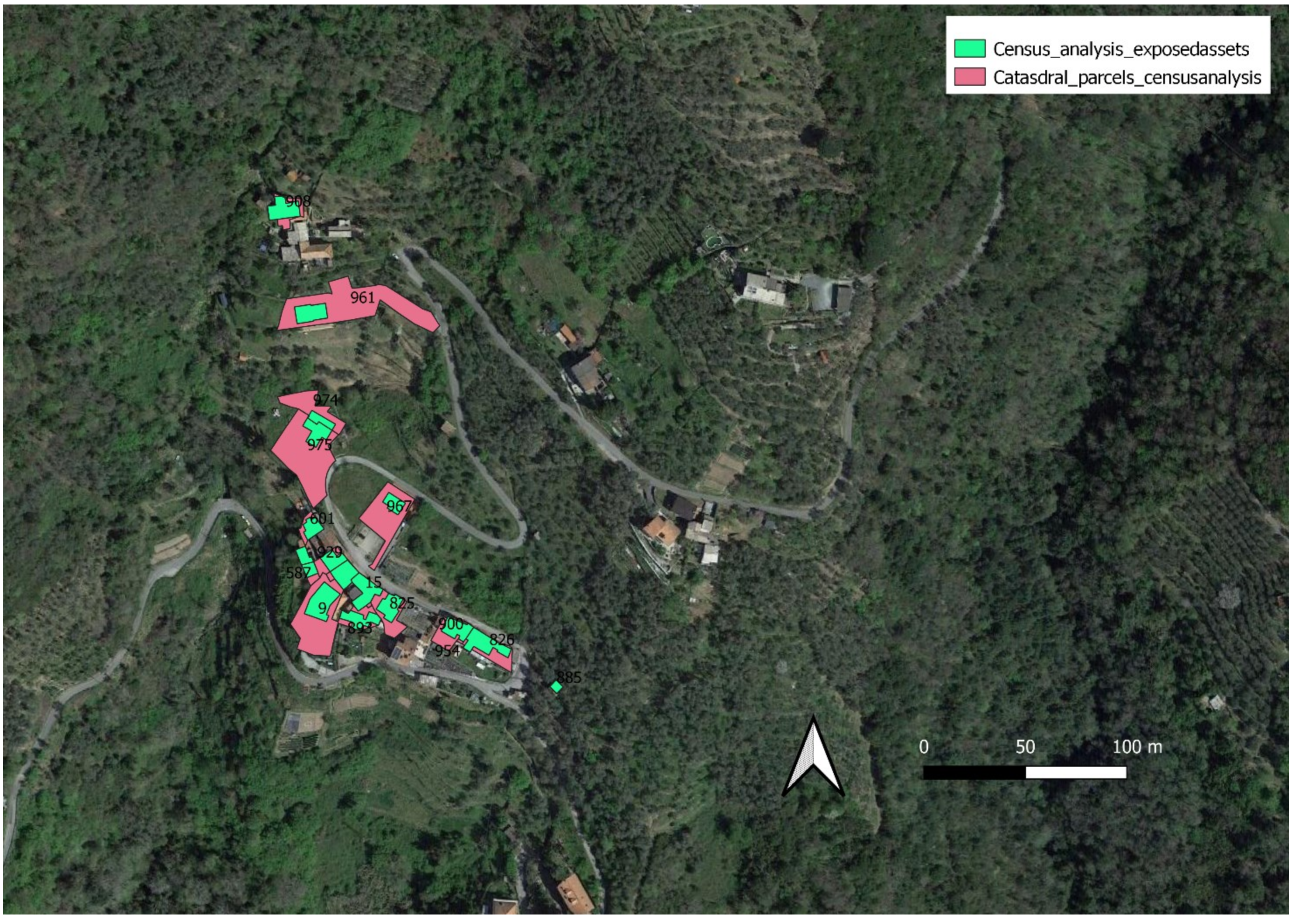
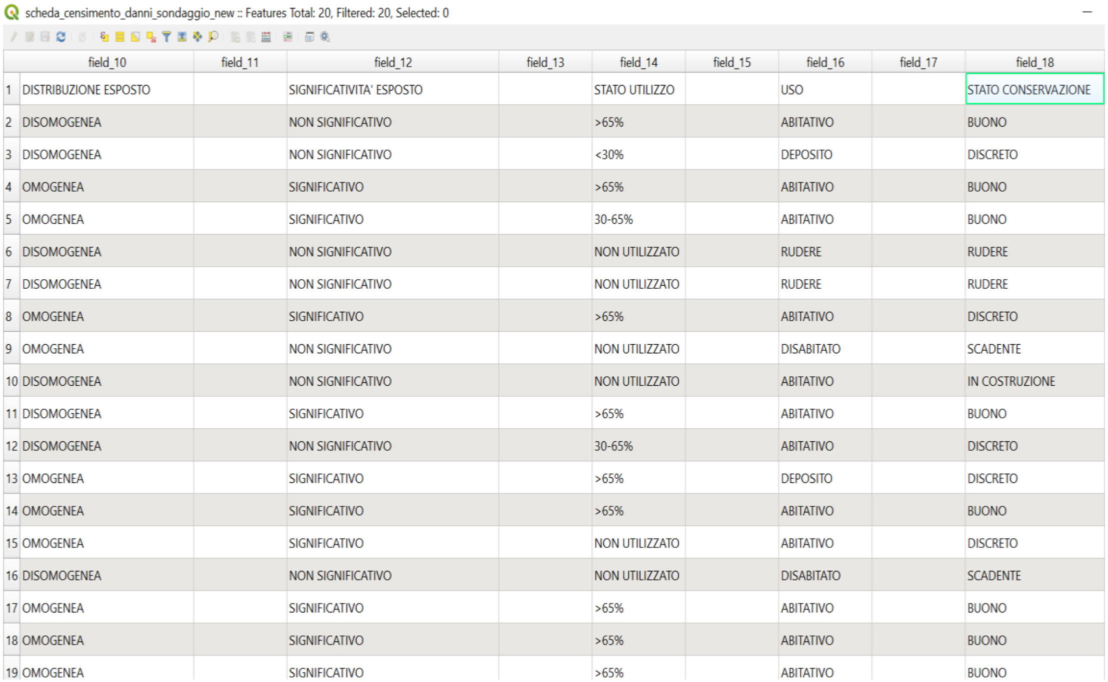


Figure 19: Cadastral exposed assets and parcels of Caruggio di Vignale hamlet

To perform a clear and immediate visualization, the information has been uploading on a spread sheet on GIS (Fig 20). The analysis so far has been increased with a series of photographs that highlight the state of the exposed assets, their distribution inside the landslide area, the age, and the structural issues. In this case, the interest was aimed at understanding the critical aspects of the case study and what solutions could be adopted by the Municipality to address the problem in terms of territorial monitoring.



scheda_censimento_danni_sondaggio_new :: Features Total: 20, Filtered: 20, Selected: 0

	field_10	field_11	field_12	field_13	field_14	field_15	field_16	field_17	field_18
1	DISTRIBUZIONE ESPOSTO		SIGNIFICATIVITA' ESPOSTO		STATO UTILIZZO		USO		STATO CONSERVAZIONE
2	DISOMOGENEA		NON SIGNIFICATIVO		>65%		ABITATIVO		BUONO
3	DISOMOGENEA		NON SIGNIFICATIVO		<30%		DEPOSITO		DISCRETO
4	OMOGENEA		SIGNIFICATIVO		>65%		ABITATIVO		BUONO
5	OMOGENEA		SIGNIFICATIVO		30-65%		ABITATIVO		BUONO
6	DISOMOGENEA		NON SIGNIFICATIVO		NON UTILIZZATO		RUDERE		RUDERE
7	DISOMOGENEA		NON SIGNIFICATIVO		NON UTILIZZATO		RUDERE		RUDERE
8	OMOGENEA		SIGNIFICATIVO		>65%		ABITATIVO		DISCRETO
9	OMOGENEA		NON SIGNIFICATIVO		NON UTILIZZATO		DISABITATO		SCADENTE
10	DISOMOGENEA		NON SIGNIFICATIVO		NON UTILIZZATO		ABITATIVO		IN COSTRUZIONE
11	DISOMOGENEA		SIGNIFICATIVO		>65%		ABITATIVO		BUONO
12	DISOMOGENEA		NON SIGNIFICATIVO		30-65%		ABITATIVO		DISCRETO
13	OMOGENEA		SIGNIFICATIVO		>65%		DEPOSITO		DISCRETO
14	OMOGENEA		SIGNIFICATIVO		>65%		ABITATIVO		BUONO
15	OMOGENEA		SIGNIFICATIVO		NON UTILIZZATO		ABITATIVO		DISCRETO
16	DISOMOGENEA		NON SIGNIFICATIVO		NON UTILIZZATO		DISABITATO		SCADENTE
17	OMOGENEA		SIGNIFICATIVO		>65%		ABITATIVO		BUONO
18	OMOGENEA		SIGNIFICATIVO		>65%		ABITATIVO		BUONO
19	OMOGENEA		SIGNIFICATIVO		>65%		ABITATIVO		BUONO

Figure 20: The in-situ damage classification sheet

3.5 Landslide mitigation works in the Caruggio di Vignale area

After the extreme rainfall events occurred in 2019 and 2020, the Public Administration of San Colombano Certenoli has designed a series of temporary interventions to safeguard the Municipal Road and face on the bank erosion in the left side of Rio Vignale River, as described before. In September 2022 the Liguria Region has proposed an important financial funding to concretely apply consistent landslide mitigation measures to safeguard the road conditions, the status of exposed assets and interrupt the bank erosion of the stream, to make resilient the Community. The next paragraphs describe the stages adopted by the Municipality to guarantee this important work of landslide risk prevention inside the Caruggio di Vignale area.

3.5.1 The Regional financial funding from the Civil Protection department

In September 2022, the Department of Environment and Civil Protection of Liguria Region has allocated fundings whose recipient was the San Colombano Certenoli Municipality.

The loan for the safety works was about € 1.504.670,00, a considerable sum of money, and it is currently connected to "Second plan excerpt of the most urgent interventions referred to in point (d) pursuant to art. Article 25(2) of Legislative Decree n. 1 of 2 January 2018 by the Liguria Region".

It is part of an amount of 94 interventions for a series of Municipalities in Genoa Metropolitan area, with a considerable sum of money of € 32.320.708, 10.

Concerning the situation described by the Liguria Region, the Municipality has requested to divide the loan in this way:

- LOT1: completion of the geological survey carried out previously (€ 150.000).
- LOT2: the works of riverbed arrangement and protection to be defined in agreement with the competent offices of the Liguria Region to regularize the outflow of river water and to definitively inhibit any erosive form of the Rio Vignale (€ 620.000).
- LOT3: safety works of the area upstream of the road including the protection of the residential nucleus (€ 736.670).

3.5.2 The request of the Liguria Region

Due to problems inside the Municipality and the attention by the Region to projects involving other Municipalities, only in May 2023 the two parts kept in touch. The Municipality of San Colombano Certenoli had a remote meeting with the Liguria Region (Environment and Civil Protection Department Office), to review the schedule of the financing plan regarding the safety of the hamlet of Caruggio di Vignale.

It has been established that the goals to reach were:

- Continuation of the geological site exploration and cleaning of the area.
- Interruption of Rio Vignale bank erosion.
- Road consolidation and safety of the residential nucleus.

During the meeting, the Region has exposed its doubts, requesting the Municipality to review the subdivision in lots. The Region has emphasized that Lot 1 initially categorized as an intervention activity, was a monitoring action, included in the technical expenses.

The 2nd lot concerned the category of accommodation works; therefore, it was considered an intervention of extreme urgency but lacked a design definition. Lot 3 because of Lot 2 was currently not financially recognizable because a project was missing, was not considered valid. The suggestion from the Region concerned the construction of a functional lot, meaning a design definition also based on surveys carried out by geologists in recent months. The proposal would have been an overall assessment by merging Lot 2 and 3, indicating a state of executive design already in Lot 2.

After the Region reminder, in June 2023 the Municipality met the technicians to discuss the design project and understand how to focus on the Rio Vignale safety or on the municipal road safety. The Municipality of San Colombano Certenoli has considered as the main priority, the safety works for inhibition of erosion of Rio Vignale and secondly the evaluation of road safety, as the consequence of the first intervention.
After the request of the Region regarding the start-up of a design definition for the safety of the landslide area, it was decided to consider a hydraulic design project that had been proposed previously.

The initial idea was to prepare a general feasibility project to access adequate funding, aimed at carrying out hydraulic works of regimentation of the Rio Vignale, of the reinforced concrete type, consisting of a U-shaped artifact of adequate size. The idea consisted in the construction of a reinforced concrete slab.

This proposal has been rejected by the Region because the Regional Office has not considered the realization of the reinforced concrete sliding plan, suitable for soil permeability. Then the Municipality joined a meeting with the Soil Defense Offices of the Liguria Region in which possible methods of intervention in accordance with current hydraulic regulations had to be based on the consolidation of the landslide foot with the restoration of the stream.

3.5.3 The last landslide risk prevention measure

After the meeting, the Liguria Region asked the Municipality to send again a new timetable for the security of Caruggio di Vignale area. The Regional offices suggested the Public Administration conclude all administrative operations before the end of October 2023. San Colombano Certenoli, worried to lose the important loan, has advanced its answer.

By considering the difficulties inside the Municipality, due to retirement of pivotal figures and tasks related to the implementation of some interventions financed by the PNRR, San Colombano Certenoli has requested an extension of the deadline for the definition of a legally binding obligation to the end of December 2023.

Finally, the lots have been divided into two parts:

- the first functional section related to the arrangement of the stretch of watercourse at the foot of the watercourse (€ 750.000,00).

- the lot related to making the exposed assets safe and putting in security the municipal roadway (€ 754.670,00).

The design project strategy consists of a substitution of the idea of a reinforced concrete slab on the bed river, with a gabion system characterized by six reins to let the correct water flow and inhibit erosion. The development of works is seen in Figure 21 and 22:

Figure 21: The gabion revetment system with six check weirs, front view (a)

Figure 22: The gabion revetment system with six check weirs, lateral view (b)

3.6 Conclusion

The analysis of the Caruggio di Vignale case study within the Municipality of San Colombano Certenoli provided a detailed understanding of the local dynamics of landslide phenomena and their implications on infrastructure and territorial management. The study highlighted how the area is characterized by significant geomorphological fragility, with slope instability processes affecting both natural terrain and anthropogenic elements, particularly the municipal road network.

The investigation of the landslide body, combined with geological surveys and in-situ damage assessments, allowed for a comprehensive reconstruction of the event and its evolution over time. The results emphasized the importance of field observations in identifying critical issues, validating existing data, and updating the knowledge of local conditions. The classification of damages and the updated surveys contributed to a clearer interpretation of the interactions between landslide processes and exposed assets.

The analysis of mitigation works implemented in the area demonstrated the relevance of structural and non-structural measures in reducing landslide risk. Interventions such as slope consolidation, drainage systems, and stabilization works proved essential to ensure road safety and maintain accessibility. At the same time, the study underlined the complexity of administrative procedures related to the design and implementation of such works, including funding mechanisms, coordination between different institutional levels, and compliance with regional requirements.

An important outcome of the chapter is the recognition of the need for an integrated approach that combines technical assessments with administrative and planning aspects. The case study showed how local authorities play a crucial role in managing landslide risk, from the identification of critical areas to the prioritization and execution of mitigation measures. The interaction between field data, technical analysis, and institutional processes emerged as a key factor for effective risk management.

In conclusion, the Caruggio di Vignale case study represents a practical example of how landslide phenomena can be analysed and managed at local scale. It highlights the importance of detailed site investigations, continuous monitoring, and coordinated administrative actions in addressing hydrogeological instability. The findings contribute to a better understanding of the challenges faced by small–medium municipalities and provide useful insights for improving both technical and operational strategies in landslide risk management.

CHAPTER 4: THE WEIGHTS OF EVIDENCE APPLICATION IN FRANCE AND ITALY

4.1 Introduction

Landslides, defined as the movement of a mass of rock, debris, or earth along a slope *(Cruden, 1991)*, are one of the main natural hazards and produce extensive material damage every year. During the autumn 2019 and 2020, Italian and French medium-small municipalities of the eastern part of Liguria region in Italy and the north part of Maritime Alps Department in France, have been crucially influenced by heavy rains and storms which have affected roadways and bridges, isolating completely some local inhabitants.

These realities need improved support tools to ensure the safety and functionality of surficial infrastructures in case of landslides, planning a series of sustainable measures, examining deeply the landslide susceptibility, increasing the analysis with new and efficient details.

The territories of the Ligurian Apennines in Italy and the Maritime Alps in France are examined, and the research study concerns on the susceptibility zoning of landslides at medium-large scale through the WOE statistical method application inside the GIS environment. The Alpine zone in the department of Maritime Alps in France and the Entella basin in Italy are evaluated, concerning on the choice of the calibration area, the identification of landslide events, the choice of predisposing factors to instability and the susceptibility map validation.

The research goal is to create new landslide susceptibility maps, through statistical analysis, outlined as an operational tool that can be used by geotechnical engineers and geologists of Public Administrations for the identification of areas susceptible to instability, concerning linear infrastructures, bridges, and exposed assets, being a useful support for landslide risk mitigation measures planification. The new cartography is finally validated on San Colombano Certenoli Municipality to understand the various levels of susceptibility, examining the problem at local scale and help Public Administration to find out the most efficient design prevention measures in case of landslide event.

4.2 Alex Storm in 2020

During the first days of October 2020 a heavy storm called Alex has impacted on the territories of the North part of Maritime Alps department, getting some damages inside the area. Alex has been an extratropical storm produced by an explosive cyclogenesis process from a low-pressure system southwest of Greenland.

The storm crossed the English Channel, moving southwards with a baric minimum that reached 970 hPa on the ground in a brief time, and bringing with it winds with gusts of over 140 km/h. The flow from the south associated with the storm transported humid and warm air from the Mediterranean towards the Maritime Alps, generating very intense rainfall (up to 600 mm in 24 hours).

The flow was so marked that even the areas of Piedmont that usually remain in rainfall shade, while most of the water is discharged beyond the Alps, were subject to heavy rainfall, especially in the valleys of lower Piedmont in Italy. The fury of the elements was unleashed in the valleys of the Roya, the Tinée and the Vésubie. Streams that normally flow placidly in their banks, were transformed into vehicles of death and destruction.

4.3 The effects on Maritime Alps Department

The storm Alex has given a massive impact on the alpine zone of Maritime Alps. Eighteen people lost their lives, 420 houses were destroyed or damaged, 1490 people were rescued by aerial rescue vehicles such as helicopters, due to the difficulties brought by the storm.

In addition, 70 km of roads were destroyed, isolating some Communities. Consequently, new landslides were born with the need to review the inventory of past landslides. Storm Alex has been called an unprecedented event in mainland France due to the extent of the damage with rainfall exceeding 500 mm in 24 hours, causing the flooding of rivers and landslides.

The department of the Alpes-Maritimes is characterized by an Alpine area to the North and the seacoast to the South with more than 60 km of coastline. The areas of this territory where many landslides have been recorded are:

- the valleys of the Tinée, Roya and Vésubie, heavily affected by storm Alex (2 October 2020), with the appearance of numerous landslides.

- the area near the Var, north of Nice, whose elevation increases rapidly towards the mainland, forming steep slopes.

- the municipality of Menton, with a strong urbanization along the slopes.

In Figure 23, the subdivision between the North and South sections is defined:

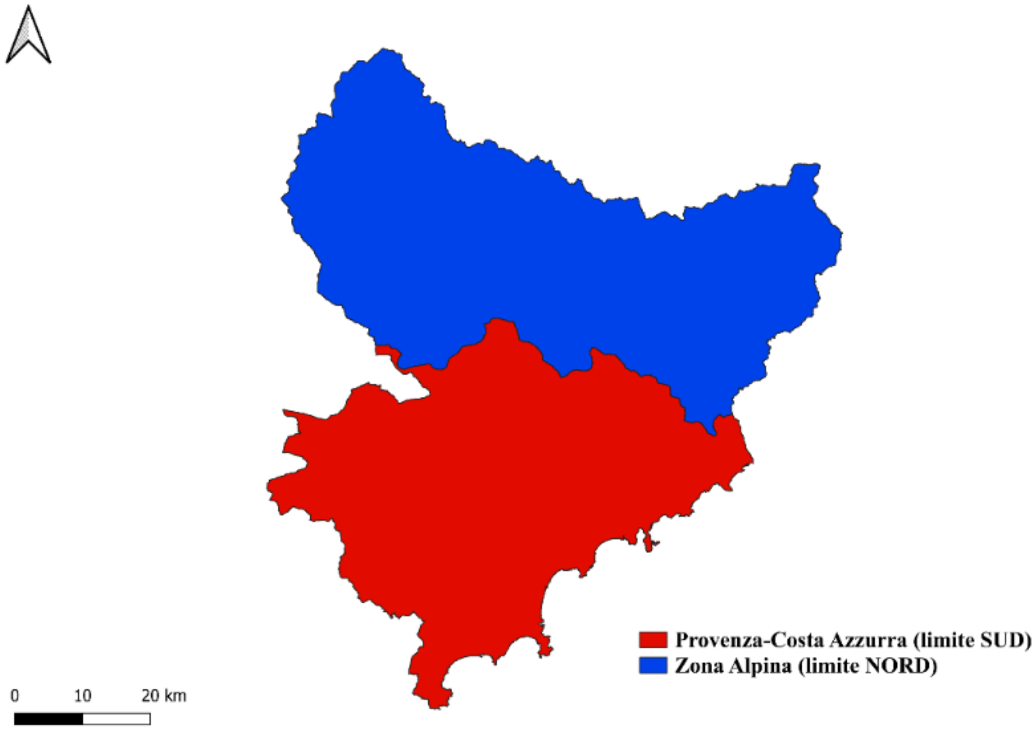


Figure 23: The Maritime Alps Department with North (blue) and South (red) administrative limits

The risk research and scientific community in France is composed of several different actors, including universities and academics, public bodies and agencies, research groups, centres or associations, and private sector companies.

Some hazards are further addressed by specific agencies - in the case of landslides, for instance, the French geological survey (BRGM), as the main public agency dealing with landslide risk, provides information and maps for hazard monitoring and risk management policies. The position of the BRGM is different from research laboratories. It is more focused on applied research. The BRGM assesses the results of fundamental research, defines the practical applications that can be derived from it (e.g. risk mapping or mitigation) and gives advice to ministries and State services as an organization taking part in reflection on the legislative framework.

After the storm, several landslide inventory maps have been realised considering different zones of this huge territory. The first database, the BDMvT (Database of Land Movements) is managed and developed by BRGM, CEREMA and RTM since 1994. It contains all the information present in the France metropolitan area in a point shapefile analysed on GIS (Geographic Information System). We find the location of the phenomena, the dates of occurrence, the details (date, year, etc.) and other information sometimes present concerning the surface, the volume, and the depth of rupture. This is a database that has been improved by the work carried out as part of the AD-VITAM8 project *(Lacroix et al., 2018)*.

A second database, now integrated into the Mvts database, concerns landslide events that occurred during storm Alex. This work is the result of a collection of information carried out in the field immediately after the storm by CEREMA and the RTMs, which were then structured by the BRGM to be integrated into the BDMVT. Thus, 488 events are present.

A third inventory was carried out by BRGM in addition to the previous one as part of the RGF Alpes project, located on the landslides triggered during the post-Alex storm. This inventory is presented in the format of a polygon shapefile and is based on the Ortho-Express-Tempête Alex.

It is concentrated on the valleys of the Tinée, the Roya and the Vésubie. Thus, for 1880 landslide phenomena we have information on the type of landslide, the particle size (fine, coarse) and the surface formations (alluvium, colluvium, alterations, etc.). After the events of 2020, there are 2544 landslides and flow slides, while the terrain movements caused by Alex storm, affecting the Roya, Tinee and Vesubie valleys are counted as 1788. In Figure 24 there is the new representation of landslide inventory after the storm:

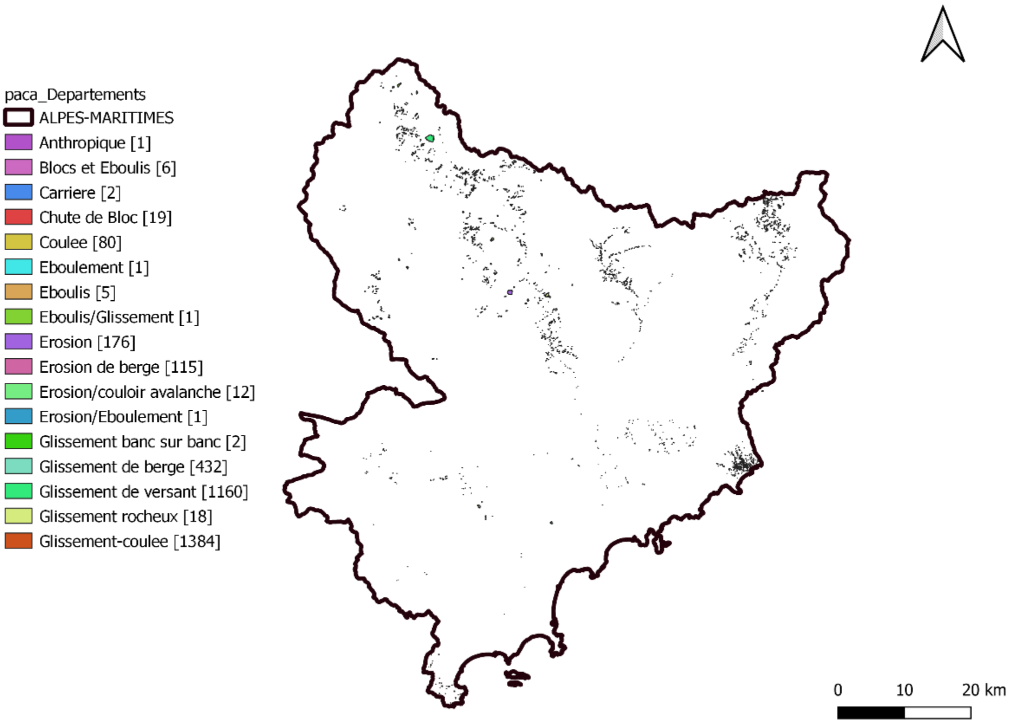


Figure 24: The landslide inventory provided by BRGM after the Alex storm occurred in 2020

4.3.1 The consequences on the Community of Saint Martin de Vesubie

Inside the wide area titled the Alpine Zone there is the small canton of Saint Martin de Vésubie, highlighted in the Figure 25:

Figure 25: The Saint Martin de Vésubie territory in the Alpine Zone of Maritime Alps

In 2020, the Community of Saint Martin de Vésubie was severely damaged by the force of the Alex storm, whose effects are still visible today. The Figure 26 and 27, show the serious situation in which the small Municipality finds itself and the need to increase the resilience of the territory through an efficient reconstruction of the road connecting it to the other surrounding areas and the bridge over the Vésubie river.

Figure 26: Municipality Road collapse due to a flow slide occurred during Alex storm

Figure 27: Roadway bridge detriment due to the water speed and intensity of Vésubie river

4.4 The landslide susceptibility assessment of Alpine Zone

The research activity means a deep study of landslide susceptibility inside the Maritime Alps department to develop landslide and debris flow forecasting system for safety authorities in mountain areas. It has been initially decided to study the North and the South departmental limits separately to understand the changes from a lithological and geomorphological point of view, performing a detailed exam of Alpine Zone, in which the effects of Alex storm have been more in evidence.

Looking at the new inventory represented before (Fig. 25), as a combination of different databases developed by BRGM, BDMvT (Database of Land Movements), Cerema (Centre for Studies on Risks, the Environment, Mobility and Urban Planning), there are 2544 landslides and flow slides, while the terrain movements caused by Alex storm, affecting the Roya, Tinée and Vésubie valleys are counted as 1788.

The BRGM as the main research agency of landslides' studies in France, in cooperation with the University of Genoa, has decided to understand how the territory of Maritime Alps Department has changed in terms of its conformation, performing a shallow landslide susceptibility assessment by statistical analysis. The statistical method used for the landslide susceptibility assessment is the Weights of Evidence model, a data-driven approach to assess the correlation between predisposing factors and the spatial occurrence of landslides, to underline a level of susceptibility closer to a real scenario.

It means the combination of predictive variables (PV), as the predisposing factors, associated to the variables to model (VM) represented by the set of landslides chosen. Each PV (predictive variable) is shown as a reclassified raster and a positive weight (W+) and a negative weight (W-) per pixel are considered for each class of PV. The positive weight means the influence of a class contained in a PV. More the positive weight (W+) associated with a class is high, more it will be the influence of a class on the VM. At the same time, the negative weight (W-) highlights the importance of the lack of influence on the VM. Therefore, the outcomes of the model are:

- The Prior probability as the probability that a pixel contains the VM from the density of a PV.

- The Posterior probability which allows to assess a low or high probability of the presence of VM by combining the different PVs.

4.4.1 The landslides 'choice

To perform a landslide susceptibility analysis of the North department, a map clip has been done on GIS. Only the landslides (glissement de versant) and the flow slides (glissement coulee) have been chosen due to their huge distribution inside the North department, respectively, 752 for landslides and 1110 for flow slides as represented in Figure 28.

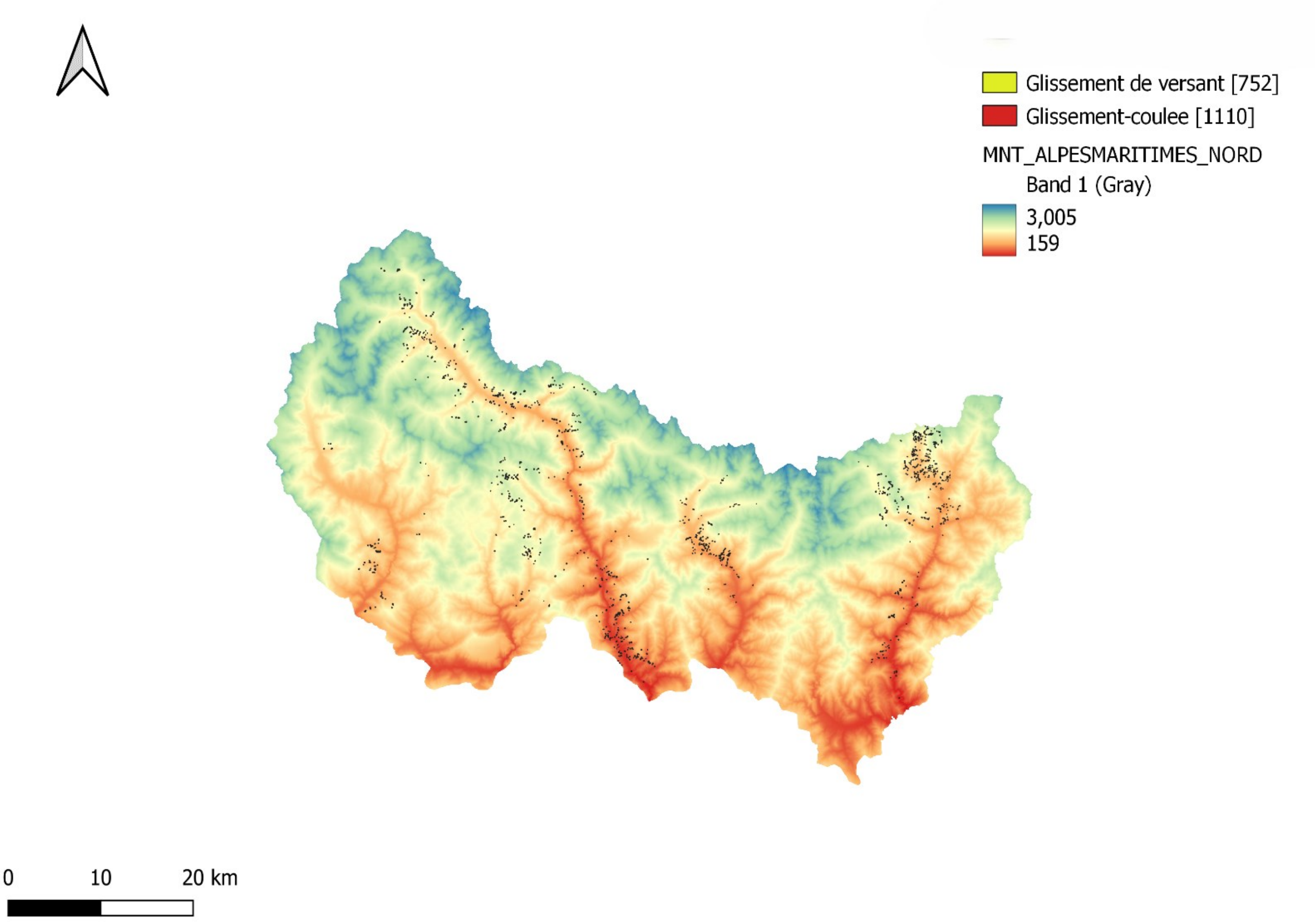


Figure 28: The landslide choice in the Alpine Zone of Maritime Alps department respectively slope slides (glissement de versant) and flow slides (glissement de coulee)

Then four different landslide sets have been considered as:

- Slope slides > 400 m^2
- Slope slides < 400 m^2
- Flow slides > 400 m^2
- Flow slides < 400 m^2

Once decided the type of landslides to treat, it has been calculated the initiation area of each landslide set. To make the study reliable and efficient, the depletion area has been calculated only for movements of big dimensions (> 400 m^2). Here there is a representation of the qualitative method developed on GIS in Figure 29, thanks to the use of curve levels to highlight the altimetry of the terrain. The highest quote means the area in which the rock or the slope starts to have a failure.

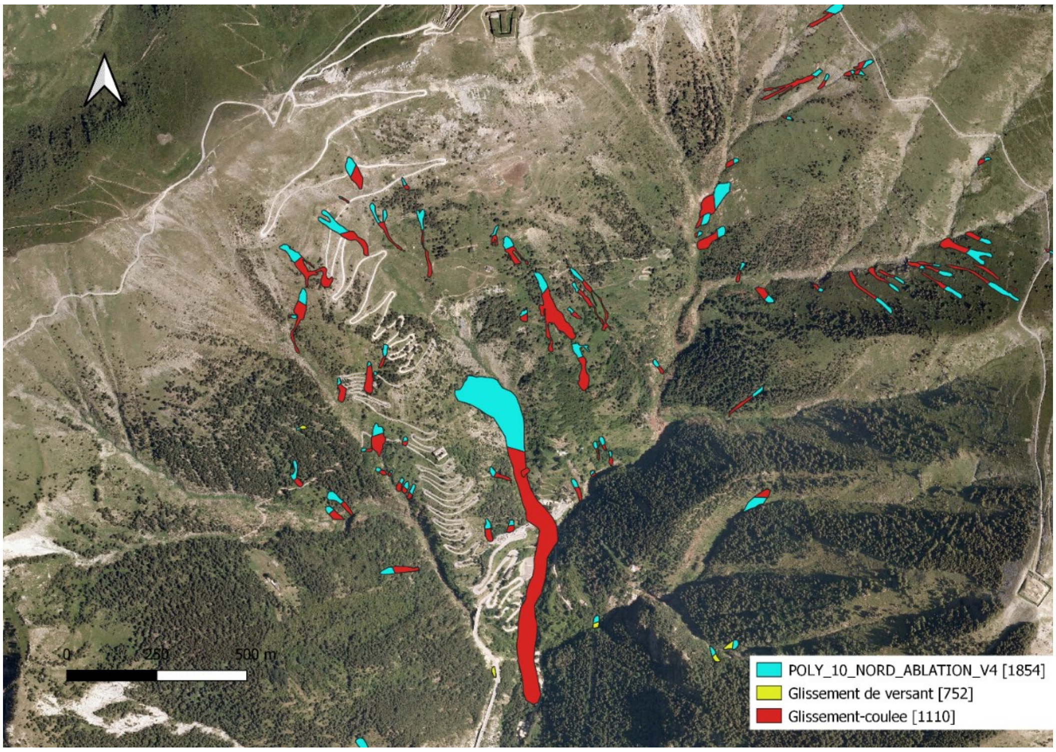


Figure 29: Depletion zone (light blue) and accumulation zone (red) of slope slides and flow slides inside la Roya Valley

After this study, the VM to model have been got, by transforming the landslide polygons in points, providing a random selection to obtain the 80% of them for training section and 20% of them to validate the model as in Figure 30.

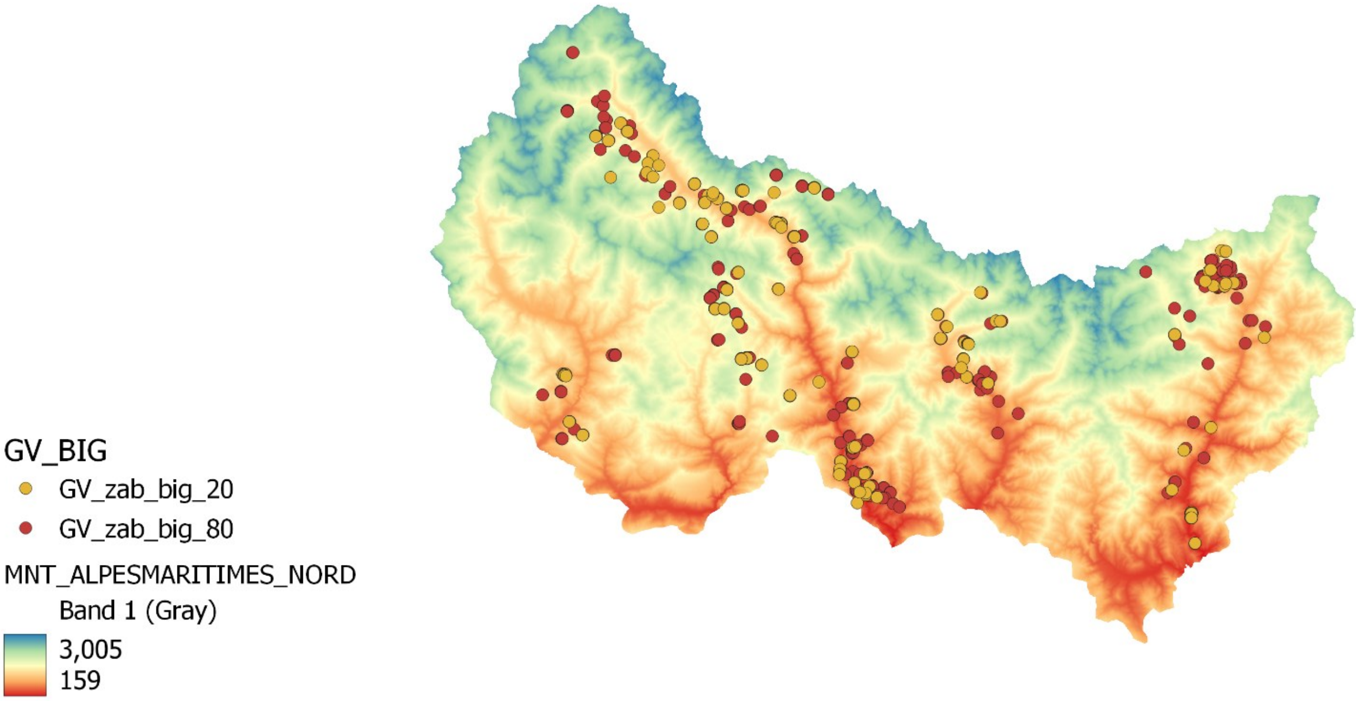


Figure 30: The training (80%) and validation (20%) set for slope slides greater than 400 m^2

4.4.2 The predisposing factors

To apply the WOE approach, it is necessary to collect the predisposing factors (PV) of interest setting a series of raster maps (25x25 m) summarized here:

- the lithology divided in 25 different classes considering the similar lithological features independently by the origin period; they have been harmonized starting from a selection of 110 different descriptions.

- The slope, classified in 10 classes by an interval between 0-5° and more than 45°.

- The aspect, divided in 3 classes with the first from north to east, the second from southeast to southwest, and the third from west to northwest.

- The general curvature divided in 3 classes considering concave, straight and convex slopes.

- The land use, classified in 10 classes considering the level 2 of Corine Land Cover classification.

- The landform map of Weiss, subdivided in 10 different classes following the author's rules *(Weiss, 2001)*.

- The landform map of Iwahashi and Pike, classified in 8 categories following method principles *(Iwahashi et al., 2007)*.

For example, the Figure 31,32,33 show respectively the lithology, the slope and the Iwahashi and Pike landform raster maps.

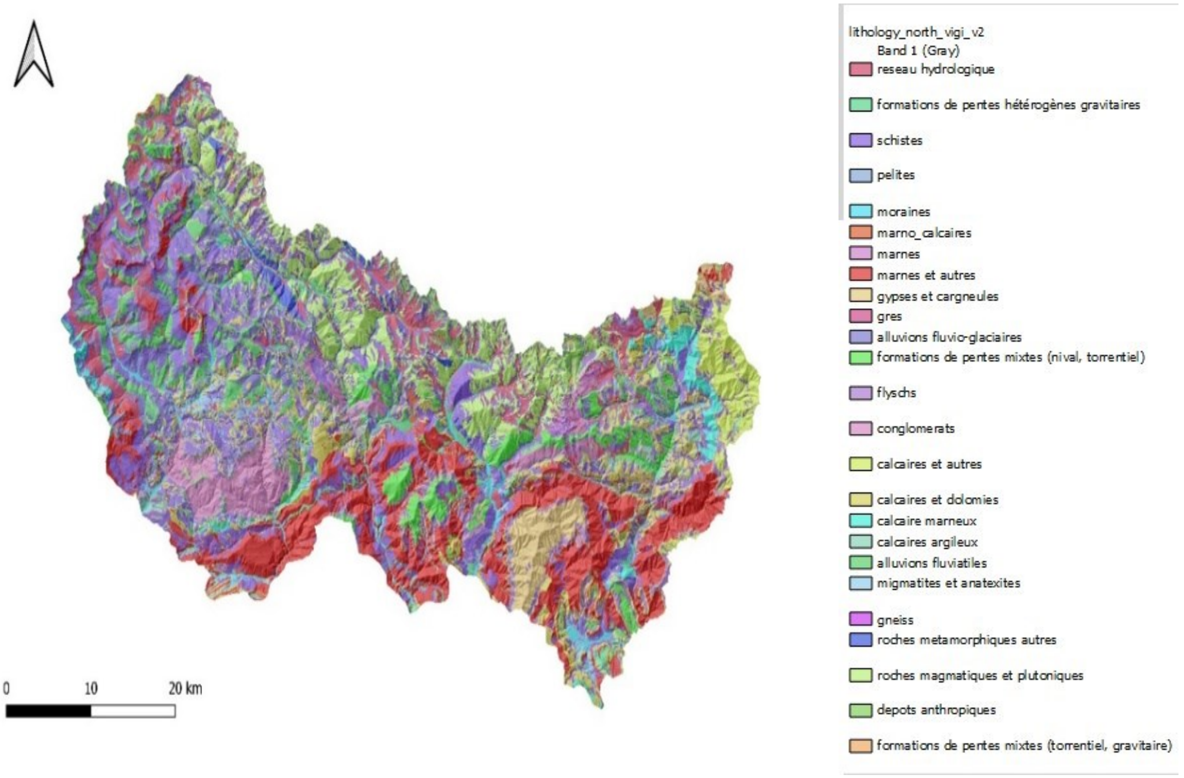


Figure 31: The lithology raster map (25 classes)

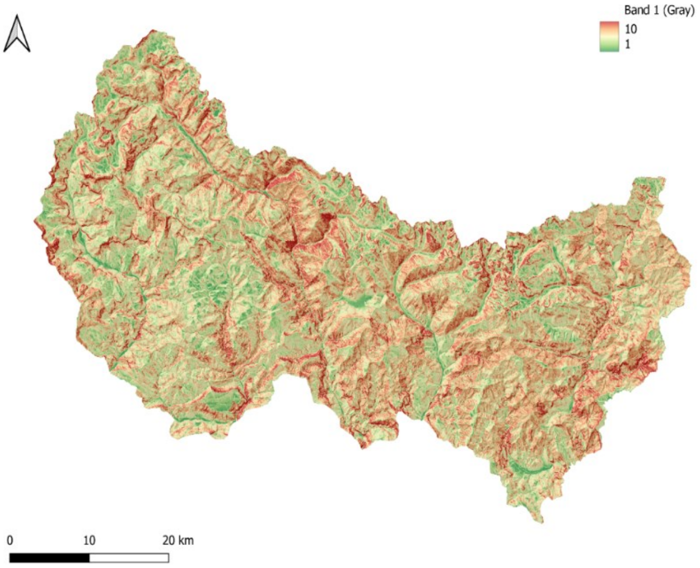


Figure 32: Slope raster map (10 classes)

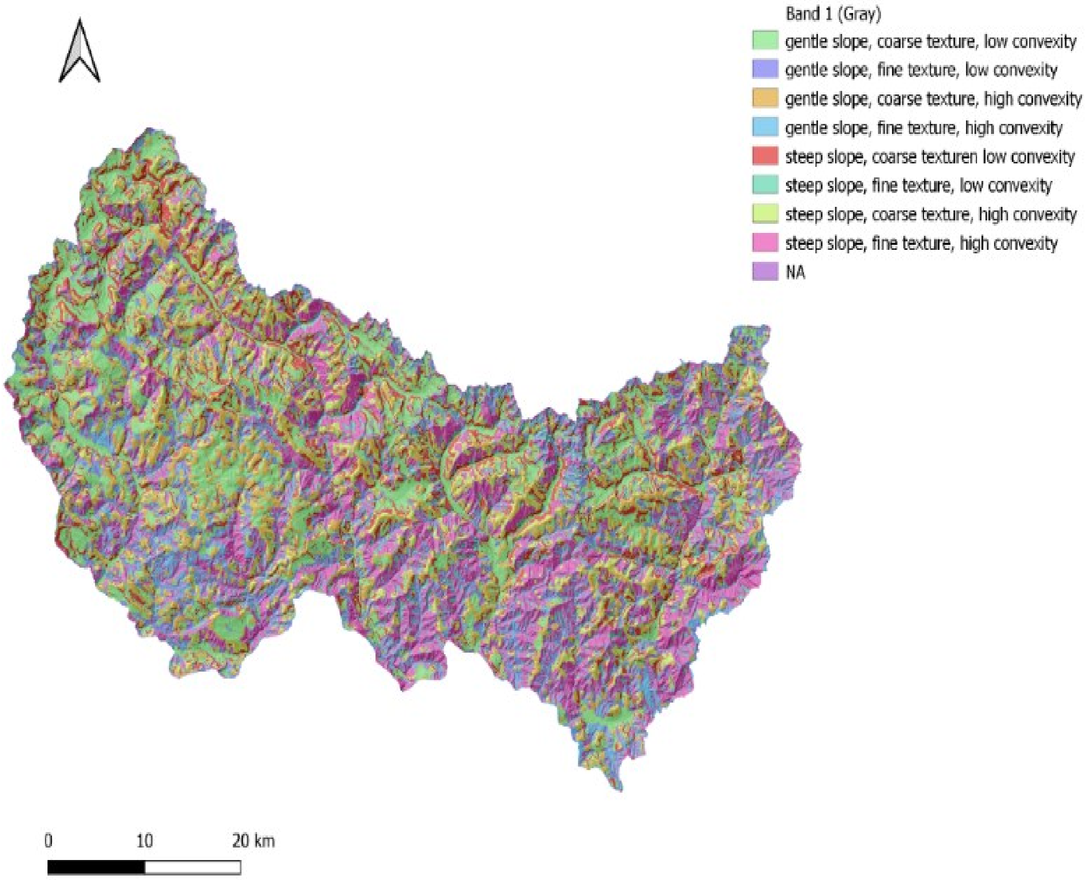


Figure 33: Landforms raster map (Iwahashi et al., 2007), 8 classes

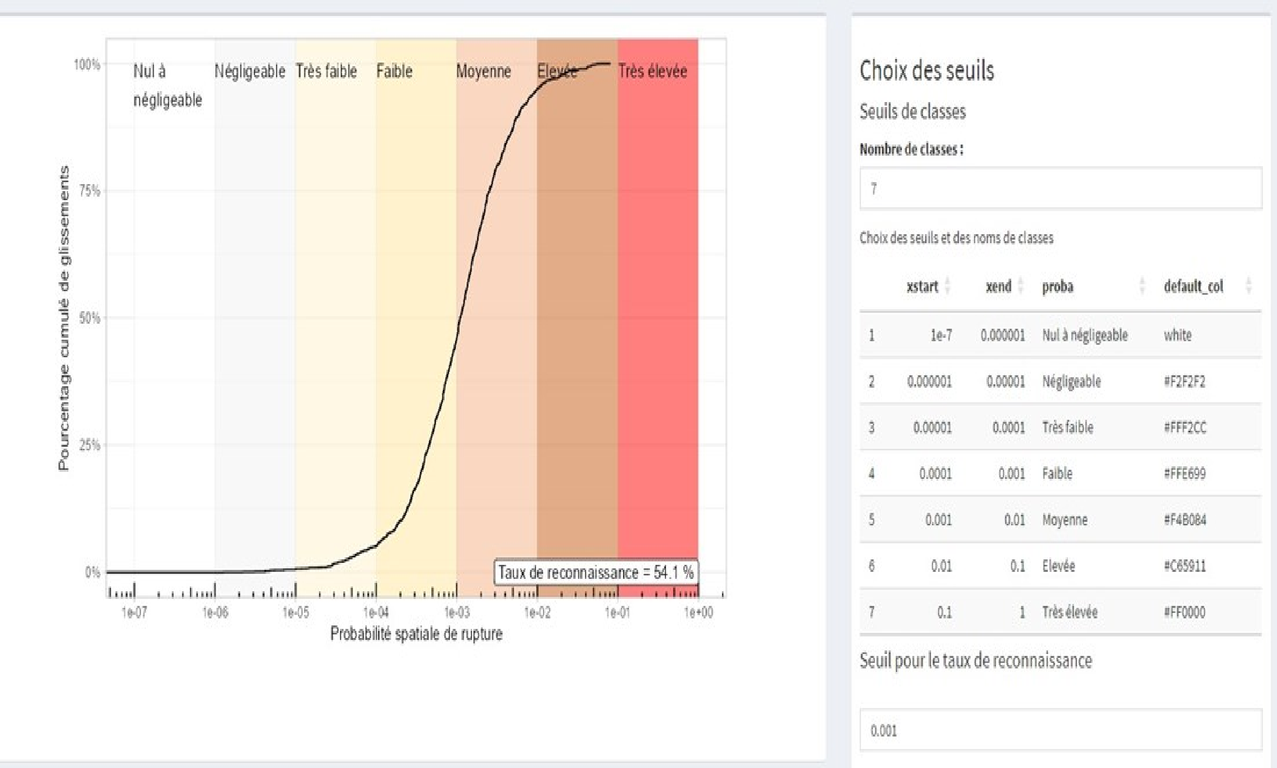
4.5 The landslide susceptibility validation

Once got the landslide set of reference and the predisposing factors, the WOE model has been applied on GIS, following an iteration process by summing different predisposing factors together to find out the best susceptibility map. The results of the statistical method have been validated on valwoe (statistical validation of susceptibility maps built with WOE) an R studio support developed in France during a project in the New Caledonia. The use of evidence theory makes it possible to develop a quantitative classification according to the JTC-1 thresholds (Join Technical Committee 1).

The validation tool takes the results of WOE, and the landslide sets chosen to give in output:

- the success and validation curves of training and validation sets, which give us the AUC (area under the curve) as the percentage of landslides recognizable according to the surface of the PV chosen.
- The weights charts (W+, W -) which depict the impact of each predisposing factor on landslide sets.
- The recognition curve, which allows to evaluate the percentage cumulated of landslides recognized, starting from a classification of spatial probability of failure, as represented by 7 susceptibility classes.

Focusing on movements greater than 400 m^2, it has been analysed that the best combination of predisposing factors is represented by the slope, the lithology, the landforms of Iwahashi and Pike, the land use in CLC2 classification, the aspect, and the curvature. Paying attention on big flow slides which have been the most impacted during Alex Storm, the study focuses on the number of depletion movements expected to fail. Here there is the comparison between the recognition curve in JTC-1 classification and the other with a change of threshold by an expert manner, as shown in Figure 34 and 35:



Choix des seuils

Seuils de classes

Nombre de classes :

7

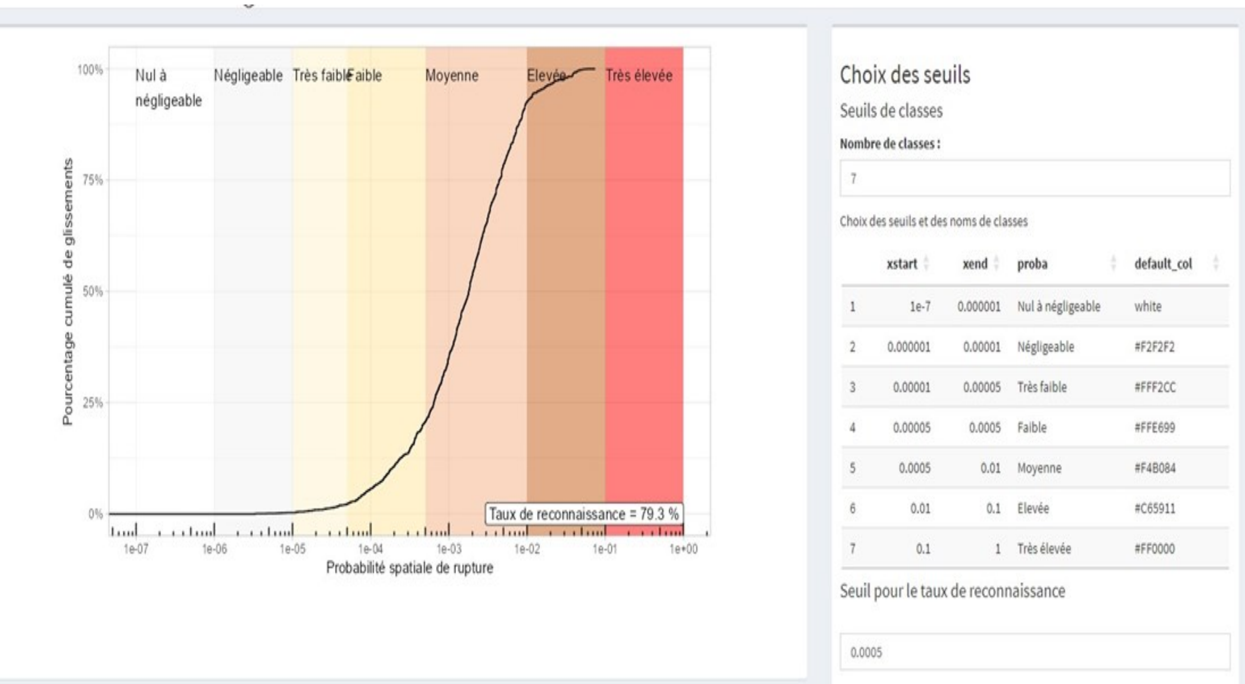
Choix des seuils et des noms de classes

	xstart	xend	proba	default_col
1	1e-7	0.000001	Nul à négligeable	white
2	0.000001	0.00001	Négligeable	#F2F2F2
3	0.00001	0.0001	Très faible	#FFF2CC
4	0.0001	0.001	Faible	#FFE699
5	0.001	0.01	Moyenne	#F4B084
6	0.01	0.1	Elevée	#C65911
7	0.1	1	Très élevée	#FF0000

Seuil pour le taux de reconnaissance

0.001

Figure 34: The recognition curve of big flow slides with JTC-1 threshold (slope+lithology+landforms Iwahashi and Pike+land use +aspect+curvature) with 0.001 recognition rate threshold



Choix des seuils

Seuils de classes

Nombre de classes :

7

Choix des seuils et des noms de classes

	xstart	xend	proba	default_col
1	1e-7	0.000001	Nul à négligeable	white
2	0.000001	0.00001	Négligeable	#F2F2F2
3	0.00001	0.00005	Très faible	#FFF2CC
4	0.00005	0.0005	Faible	#FFE699
5	0.0005	0.01	Moyenne	#F4B084
6	0.01	0.1	Elevée	#C65911
7	0.1	1	Très élevée	#FF0000

Seuil pour le taux de reconnaissance

0.0005

Figure 35: The recognition curve of big flow slides with JTC-1 threshold adjusted (slope+lithology+landforms Iwahashi and Pike+land use +aspect+curvature) with 0.0005 recognition rate threshold

Examining the results, we have a great improvement of almost 25% of flow slides susceptibility, with a recognition rate of 79.3%. The number justifies that the best classification of landslide susceptibility is related to the adjustment of JTC-1 classification, after choosing the best predisposing factors. Practically, by an expert manner, the medium threshold of susceptibility has been modified, improving the recognition rate.

4.6 The outcomes of the analysis

The valwoe validation has pointed out the best classification to perform the final susceptibility map formed by big flow slides. Following the partition of susceptibility classes of the last recognition rate (0.0005), the new susceptibility map of the North limit after the Alex storm, is got in Figure 36.

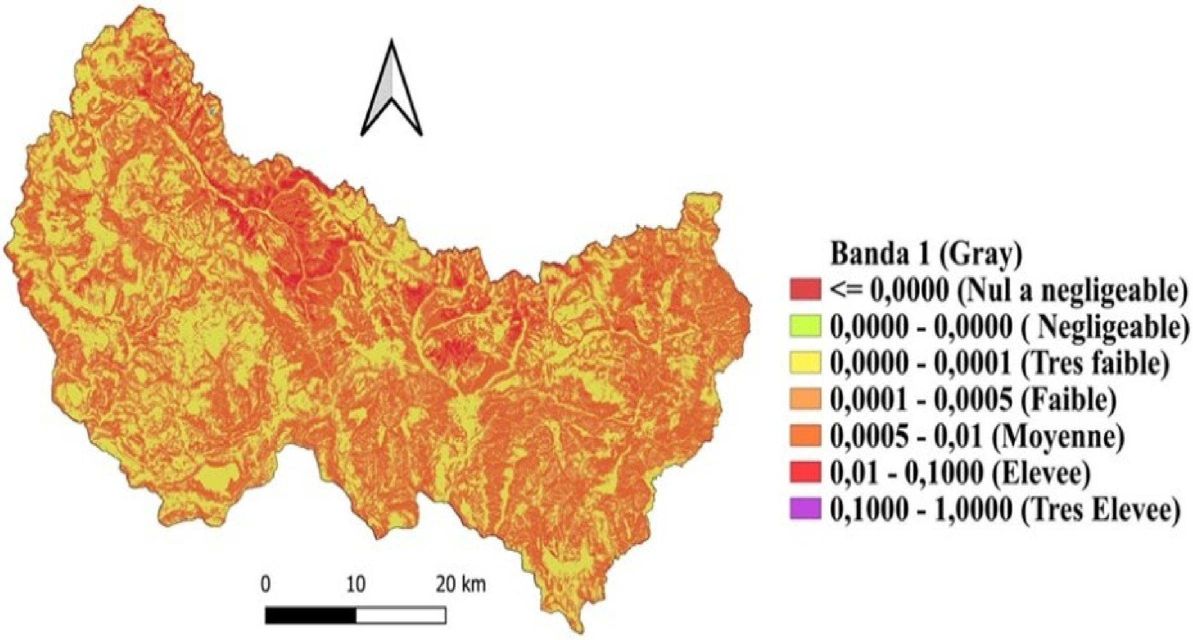


Figure 36: Alpine Zone susceptibility map with JTC-1 threshold adjusted for flow slides greater than 400 m^2

To understand better the different susceptibility classes, a detail inside the map is shown, depicting the level of susceptibility in la Roya valley as in Figure 37:

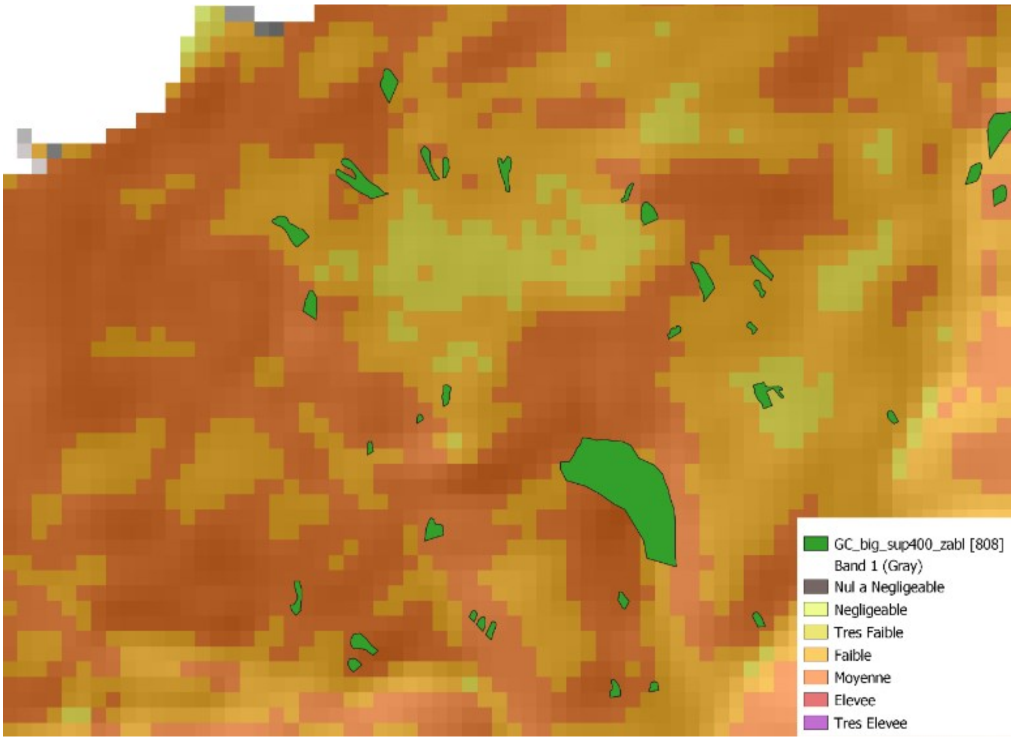


Figure 37: La Roya valley section with susceptibility levels with JTC-1 threshold adjusted for flow slides greater than 400 m^2

In the end to appreciate better the case study, in terms of percentage of recognized landslides, a zonal statistics analysis has been performed to understand the effective number of pixels by different susceptibility levels comparing the big flow slides with the big slope slides in the North department. The results are shown in Figure 38 and 39.

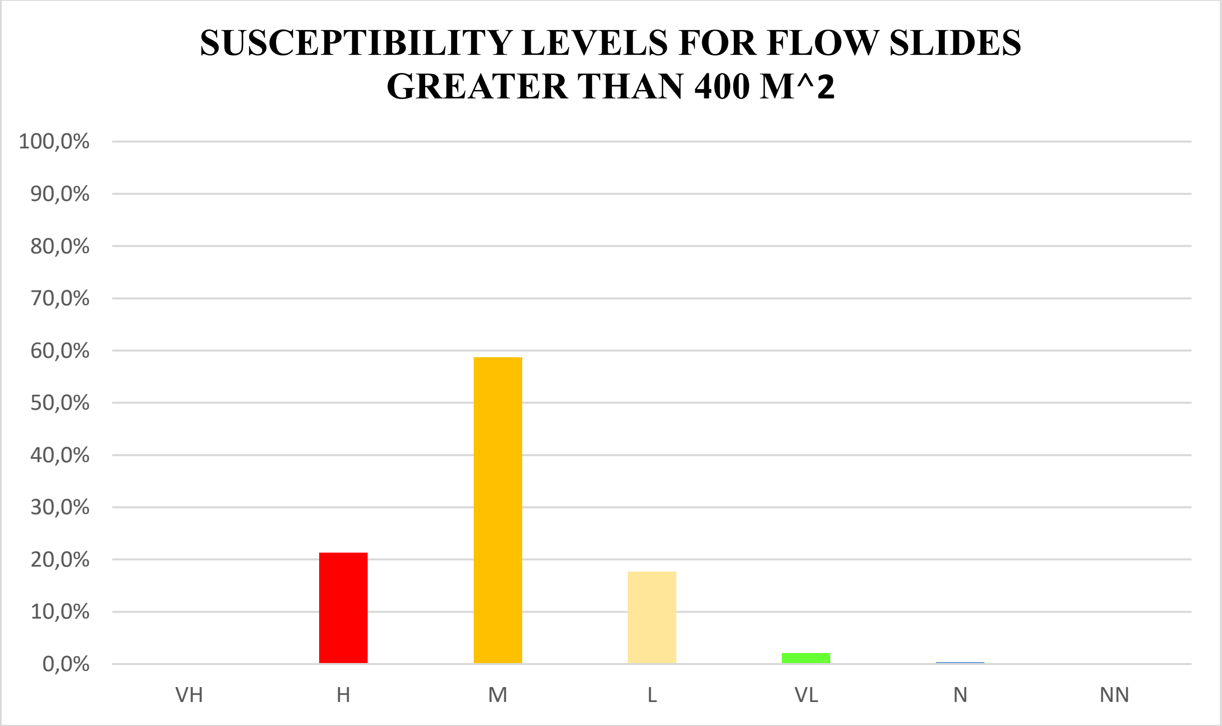


Figure 38: Percentage of flow slides greater than 400 m^2 *by different susceptibility levels depicted in the WOE map*

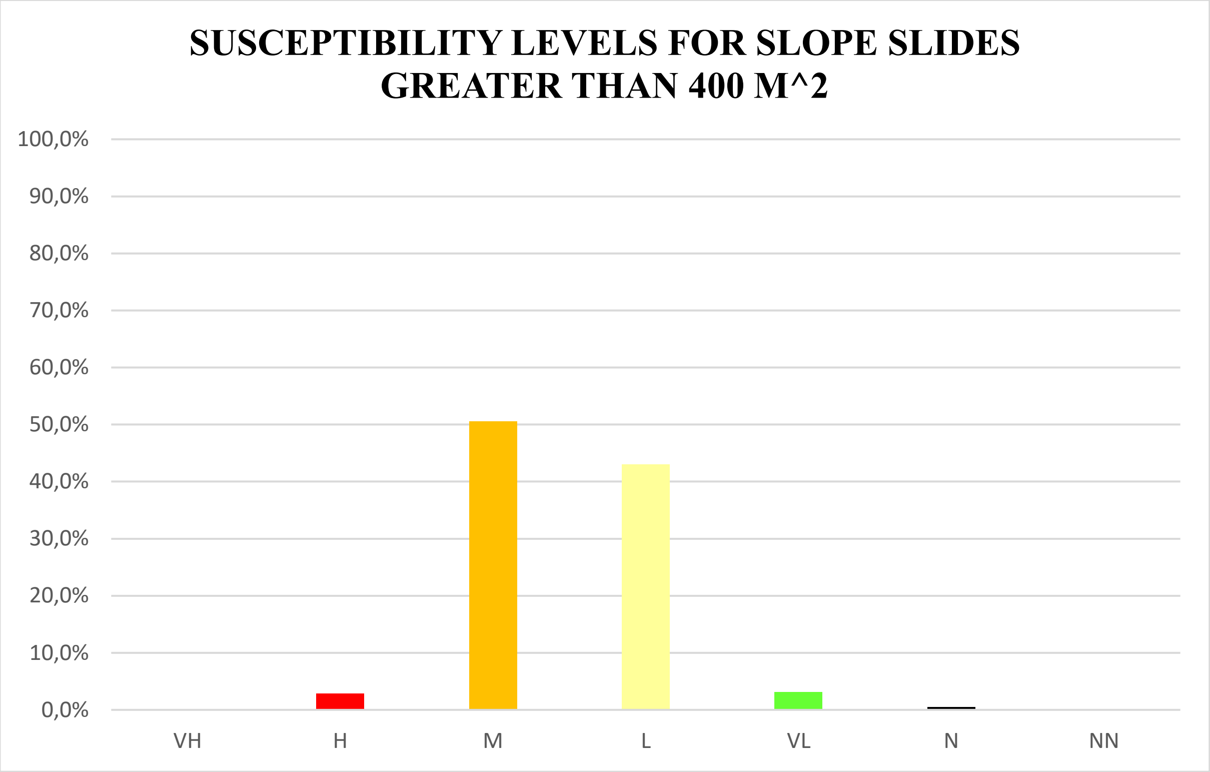


Figure 39: Percentage of slope slides greater than 400 m^2 by different susceptibility levels depicted in the WOE map

Concerning flow slides greater than 400 m^2, the percentage of terrain movements in the highest susceptibility levels reaches the 20%, while some of them are localised in a mean susceptibility value (close to 60%). Concerning slope slides, the half of them is concentrated inside mean susceptibility areas, while the critical levels are lower than previous movements (< 10 %). These are results based only on spatial categories, independently by movement speed and temporality. These thresholds can be improved by providing run out models and rainfall threshold analysis.

4.7 Landslide susceptibility assessment: the Entella basin in ValFontanabuona

Val FontanaBuona area is one of Ligurian Apennines' valley more conditioned by the presence of landslides for geological, climatological and anthropogenic reasons.

It is a narrow and recessed valley, with several steep slopes ; the area is characterized by the T. Lavagna extension which meets the Entella river which crosses the city of Chiavari. Every year the territory is subjected to intense rainfall events which are cause of several landslides. Particolarly the movements which are more frequent are :

- Shallow landslides (0.5 – 2 m) whose sources are normally the presence of colluvium, debris and clay soils ; they are roto - translational slides which involve roads and isolated buildings.

- Debris and earth flows which are common in clay slopes and they can represent a danger for bottom valley areas.

- Rockfalls, localised in areas with highly fractured shales.

- Complex landslides, which are complicated to assess and detect because they are a mixture between different movements.

In this scenario characterized by the increasing frequency of landslides, small and medium-sized Ligurian administrations need better support tools to ensure the safety and functionality of infrastructures, bridges and exposed assets to safeguard the community and increase the resilience of the territory.

In connection with the analysis of Alpine Zone of Maritime Alps Department, the following chapters are related to the development of landslide susceptibility assessment inside the Entella Basin as the calibration area and San Colombano Certenoli as the validation area.

It consists of the application of WOE method to detect a new susceptibility map and compare it with the official Regional cartography represented by the Hydrogeological Basin Plan (PAI). The map has the goal to be a useful and intermediate instrument as support for decision – making choices, evaluating what interventions adopt to prevent landslide risk, with respect the different susceptibility levels. The analyses of the landslide set and predisposing factors are crucial to find results and validate them on the Municipality of San Colombano Certenoli.

4.7.1 The study area

The catchment area of the Entella River and the Sturla Stream is located on the Tyrrhenian side of the Ligurian Apennines. The area of the study basin, equal to about 370 km^2, falls entirely within the Province of Genoa, involving several medium-small municipalities. The area has been chosen because it has geomorphological characteristics very similar to those present in the territories of the Maritime Alps. The following map represents the administrative boundaries of the basin as shown in Figure 40:

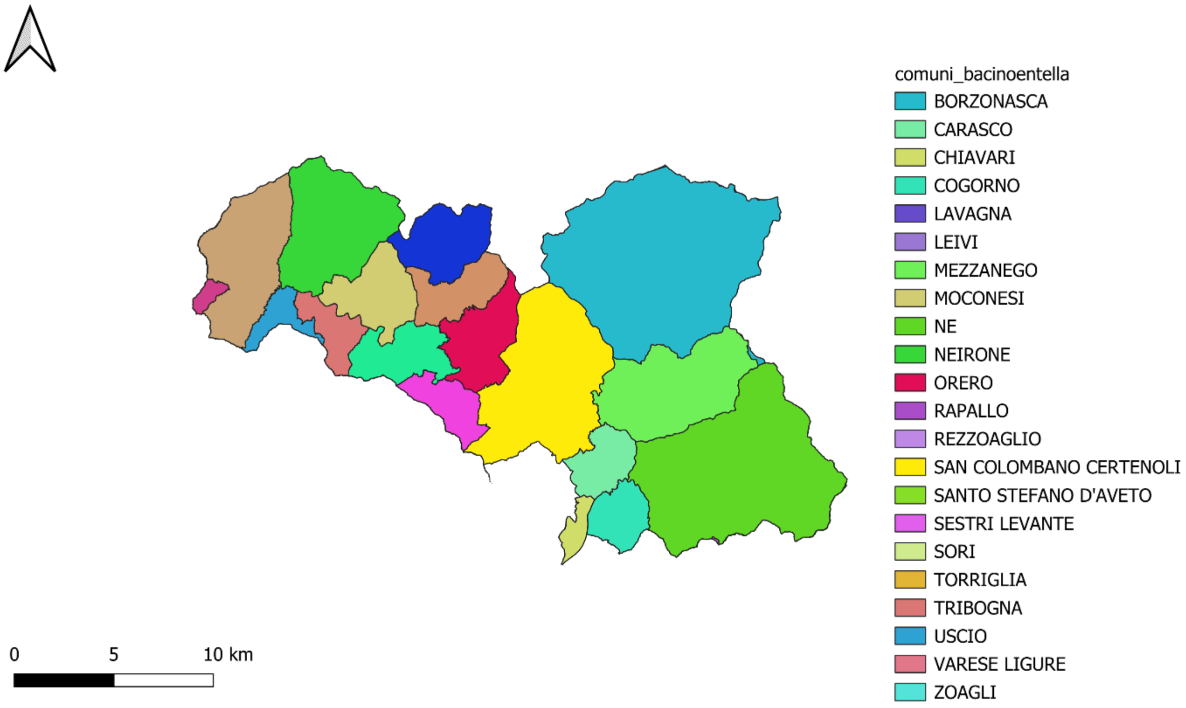


Figure 40: Municipalities within the Entella basin with administrative limits of San Colombano Certenoli (yellow)

4.7.2 The landslide inventory

A crucial step for an efficient landslide susceptibility analysis is the decision – making process in landslide choice with respect the goal to overcome, figuring out past landslides inside the Entella Basin. The Figure 41 points out the current IFFI landslide inventory of Entella Basin.

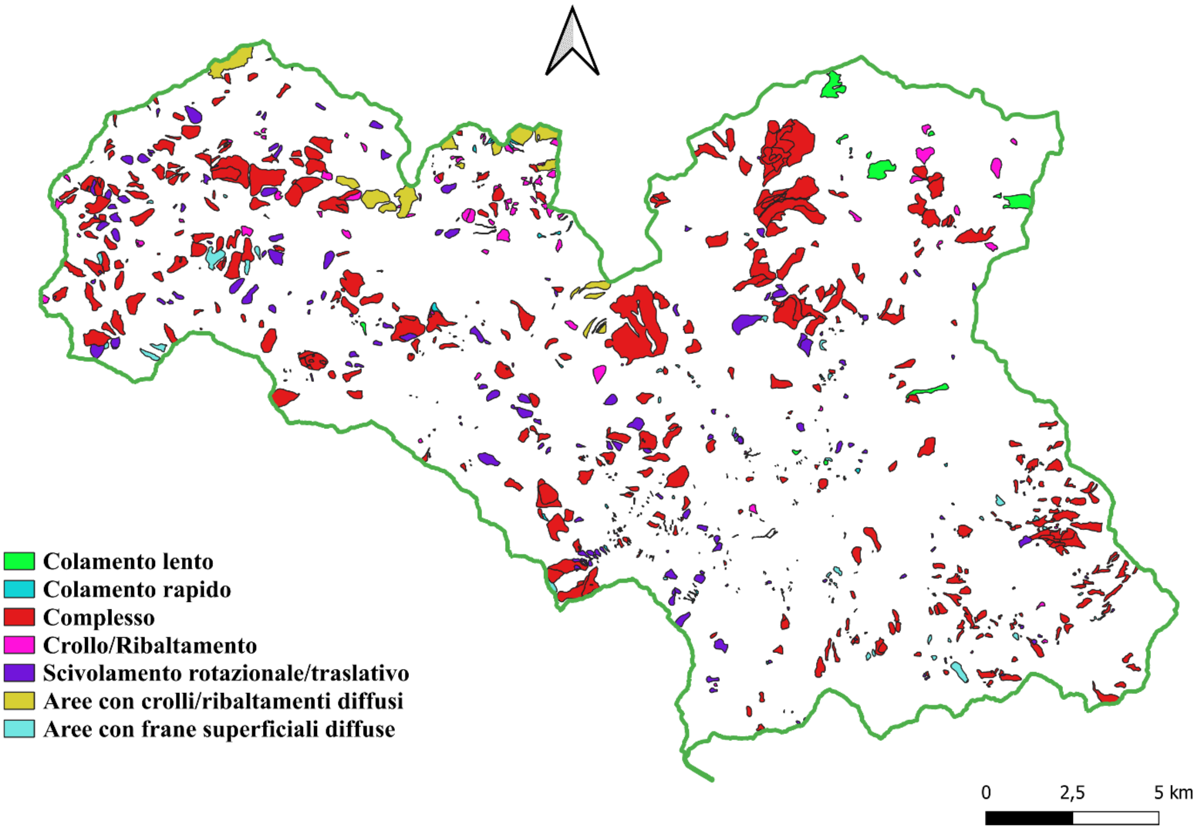


Figure 41: The IFFI landslide inventory of Entella Basin

To guarantee an efficient landslide susceptibility assessment, it has been important to understand the distribution of movements inside the susceptibility validation area, represented by San Colombano Certenoli Municipality. Examining the IFFI inventory, it has been detected that the territory of the Municipality of San Colombano Certenoli is made up of 52% of rotational/translational landslides, 34% of complex landslides, 5% of areas with surface landslides and the remaining 9% of rapid flows.

4.7.2.1 The choice of landslides in the basin

Then two groups of landslides on Entella Basin have been identified: a set formed by rapid and slow flows, rotational/translational slides, and areas with shallow landslides with a total of 432 polygons (set 1), and the second group characterized only by complex landslides, respectively 434 polygons (set 2), as shown in Figure 42:

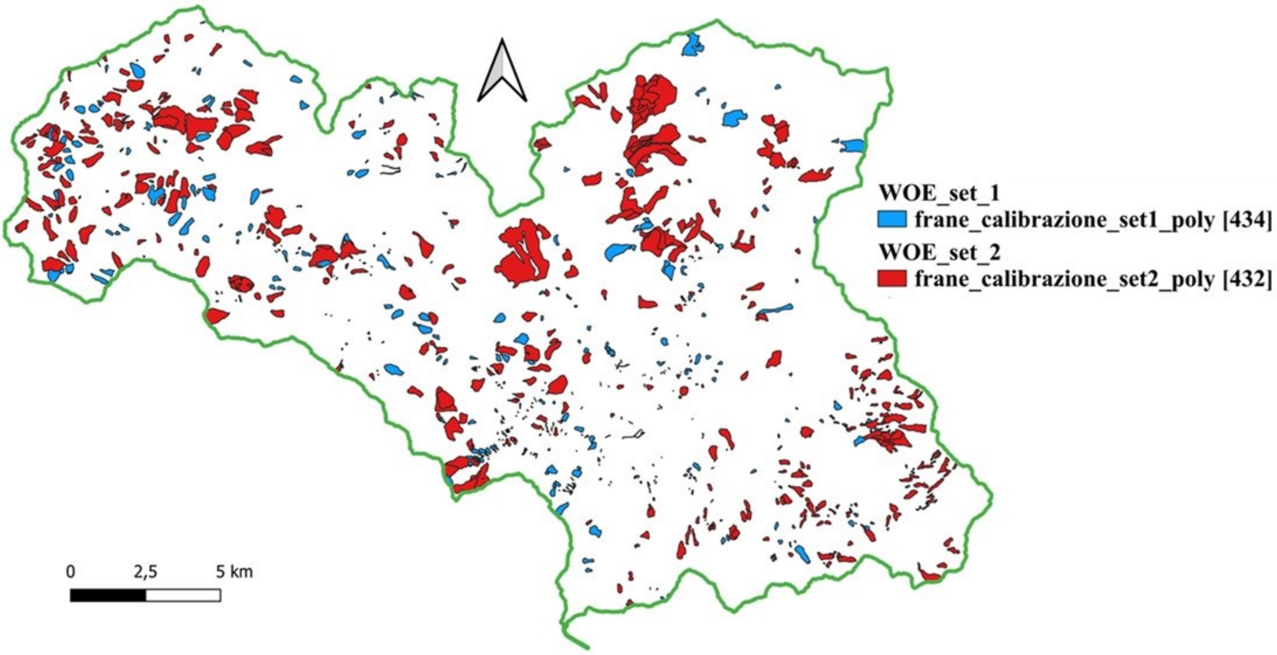


Figure 42: The landslide sets for landslide susceptibility analysis; roto-translational slides, rapid and slow flow slides (blue) and complex landslides (red)

4.7.2.2 The predisposing factors

After the choice of movements to be used to study the susceptibility, to apply the WOE method, a series of predisposing factors which witness the potential landslides' occurrence has been detected. Eight different raster maps have been created with basin-scale of 5 meters resolution, listed in this section:

- the slope map, extracted from the Geoportal of the Liguria Region and classified into 9 categories, evaluating the slope inclination every 5°.
- The map of the digital terrain model (DTM) with an assigned numerical value for every 100 meters of altitude reached (18 classes).
- The slope exposure, the map that has been divided into 4 classes following the cardinal points.
- Land use categorized into 10 classes by analysing level 2 of the CLC classification, with particular attention to anthropogenic aspects, the presence of vegetation and hydrographic elements.
- The lithological map, divided into 13 classes, according to classification provided by Liguria Geoportal.
- The distance from the roads, such that a buffer zone with a radius of 20 meters has been identified to maintain the same geometries of the road elements at the same distance (10 classes).
- The accumulation, indicating the accumulation of the surface water flow in the basin of interest, divided into 6 classes based on the number of drained cells.
- The geomorphic map, as a product of the GRASS GIS software, divided into 10 classes that considers the geomorphs with which the different angles and shapes of the slopes are identified.

For example, in Figure 43, 44 and 45, there is the representation of lithology, the geomorphic map and the distance from roads

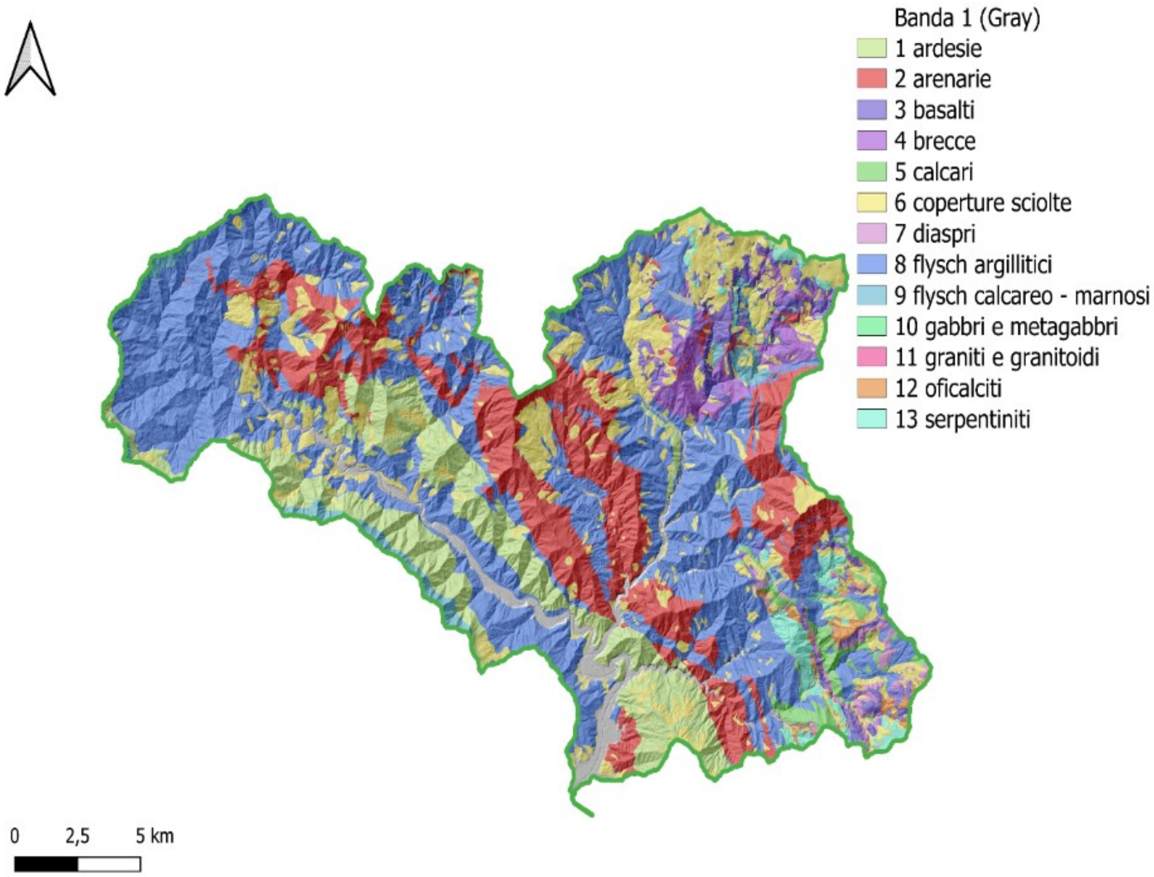


Figure 43: Lithology raster map of Entella Basin by 13 classes (5x5 m) from Liguria lithological sheets

Figure 44: Geomorphic raster map of Entella Basin by 10 classes (5x5 m)

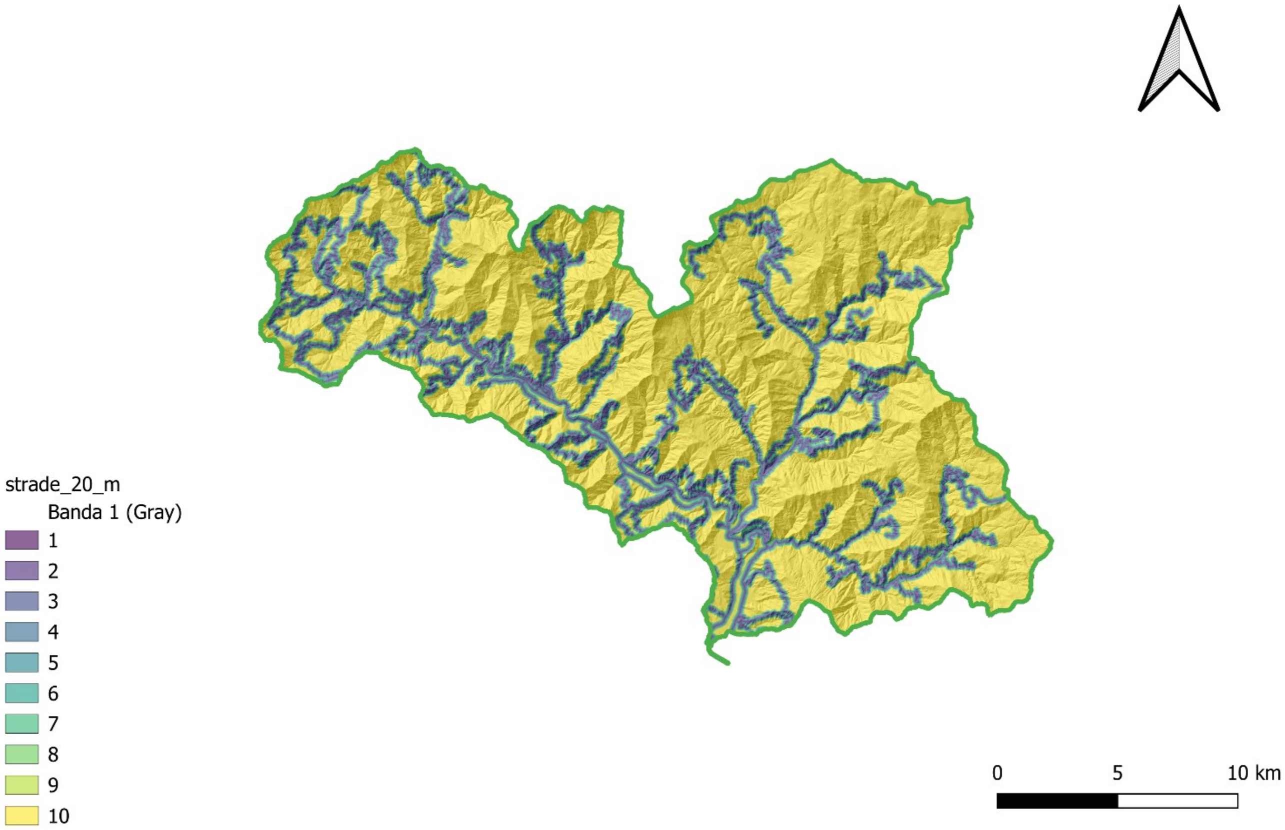


Figure 45: Distance from roads raster map of Entella Basin by 10 classes (5x5 m)

4.7.3 The Weights Of Evidence method: the centroids analysis

In this section, a landslide susceptibility assessment has been performed by the WOE model on the Entella Basin to find a way to predict past landslides. It has been decided to consider as variables to model all landslides of the Entella Basin IFFI Inventory, not involving rockfalls or similarities. The landslide body means the structure of a landslide and its shape along the slope or terrain. The following chapters describe the results in terms of susceptibility, focusing only on the centroids of each landslide, to understand the different levels of susceptibility, examining the core of the landslide body. Indeed, the predisposing factors described previously have been used to find the best combination in terms of WOE map.

4.7.3.1 The centroids computation on GIS

As first step, with a GIS tool, for each landslide polygon, a points shape layer defined as centroids has been extracted. The Figure 46 shows the landslide body and its centroids; the points are the calibration values to perform the statistical model.

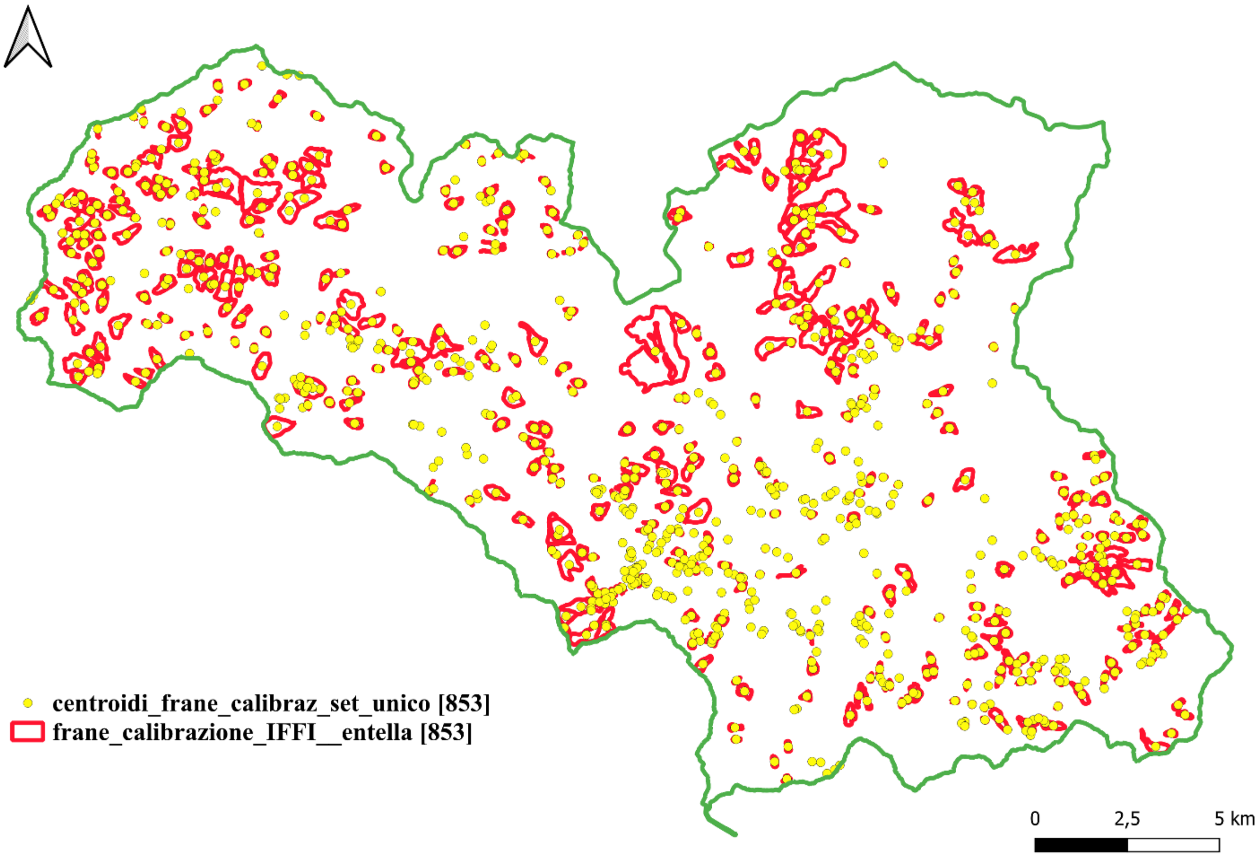


Figure 46: The IFFI calibration set (red) and the centroids for each landslide (yellow)

Then considering only the yellow points, the Figure 47 concerns on the 80% of centroids chosen for the model calibration and the 20% for its validation. This step is crucial for the correct application of the statistical model and to understand the sensitivity of the procedure.

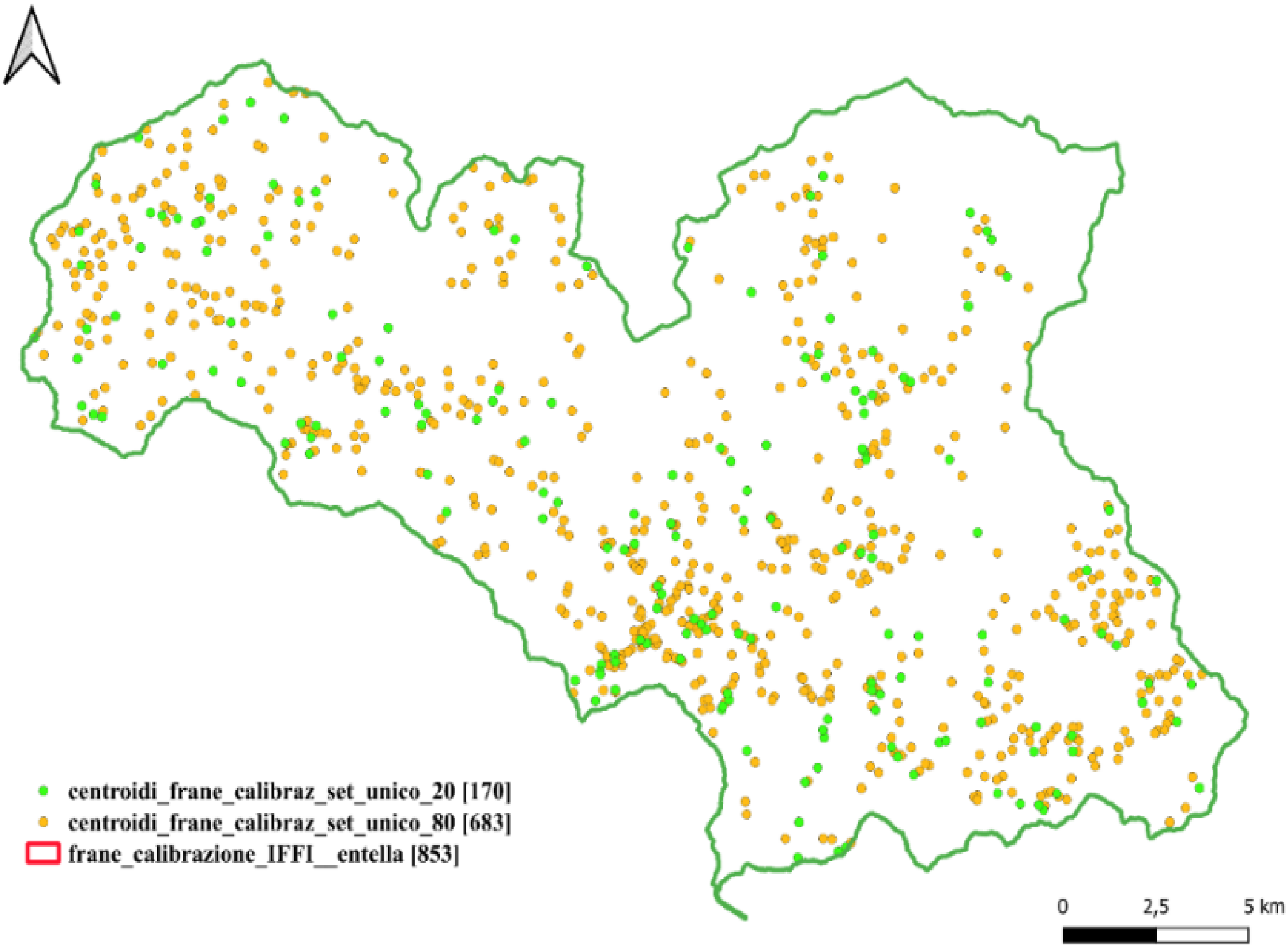


Figure 47: The calibration points as 80% (orange) and the validation points as 20% (green) for landslide centroids

4.7.3.2 The landslide susceptibility map with centroids

After the identification of landslide calibration and validation set, the WOE method has been performed. The points have been transformed in pixels of 5 m x 5m resolution inside the Entella Basin Digital Terrain Model (DTM) map with Boolean values (1 presence of centroid, 0 area out of calibration set) and they have been combined with 8 predisposing factors. The result has been the WOE map implementation, represented in Figure 48:

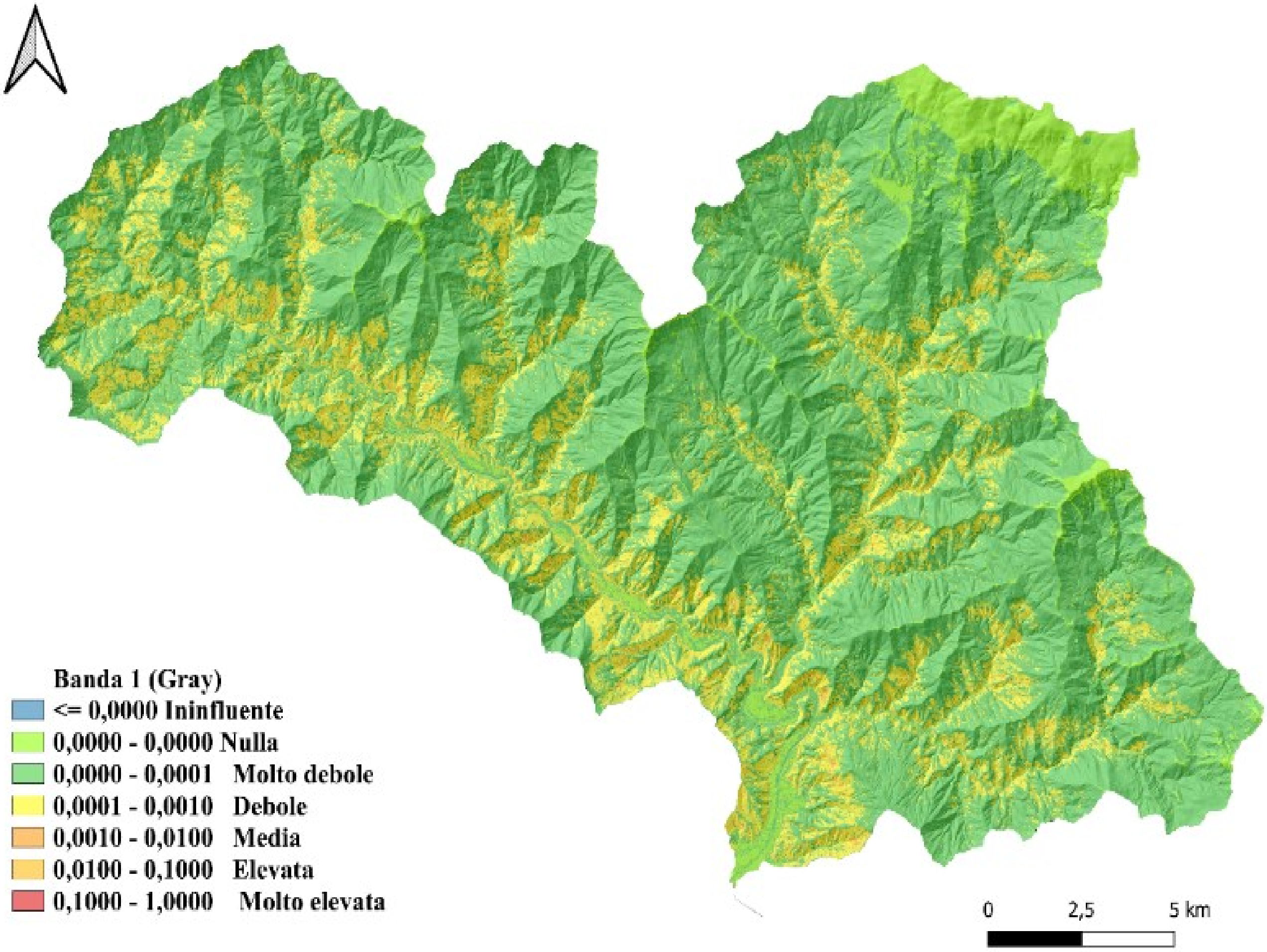


Figure 48: Landslide susceptibility map of Entella Basin by JTC-1 committee classification (negligible, null, very low, low, medium, high, very high)

Observing the cartography, the yellow areas correspond to low susceptibility, while the oranges are zones with mean susceptibility. To understand the probability to have a landslide occurrence, it is necessary to validate the map.

4.7.3.3 The landslide susceptibility validation of the map on the basin

The validation of the map has been done with valwoe, the method used to study the susceptibility inside the North of Maritime Alps Department. To understand the reliability of the model, the percentage of landslide in calibration area and the movements in validation stage are compared inside the success and validation curves as witnessed in Figure 49:

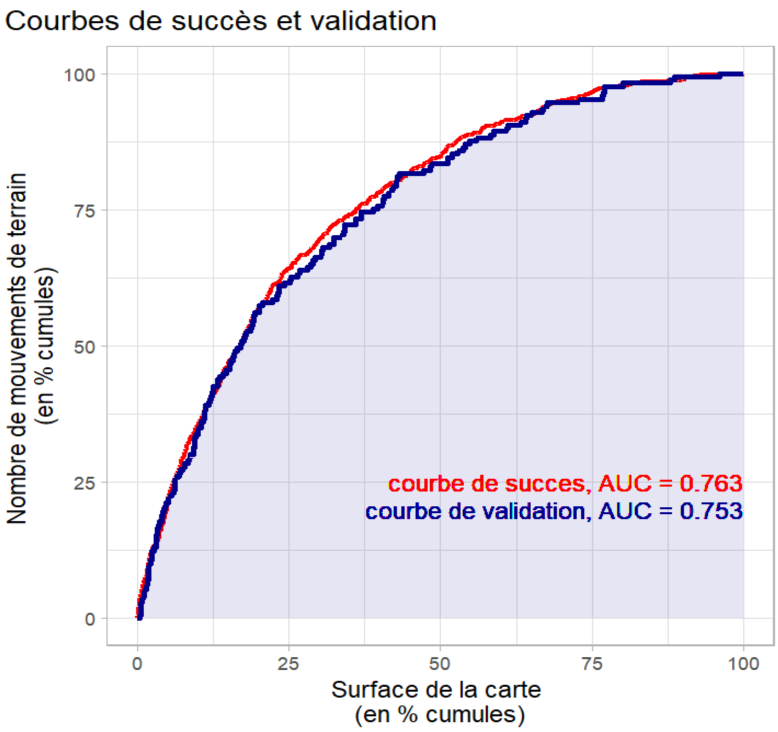


Figure 49: Success curve (red) and the validation curve (blue) of landslide centroids

In the picture the calibration and the validation performance are similar. Statistically, the model has a reliability of almost 76 % for calibration points and 75% for validation points. The two curves are close together and it means that the model seems efficient. The 100% shows a perfect classification which does not exist in nature. Then after the weights' calculation for each predisposing factors' classes, the recognition curve is realised as in Figure 50:

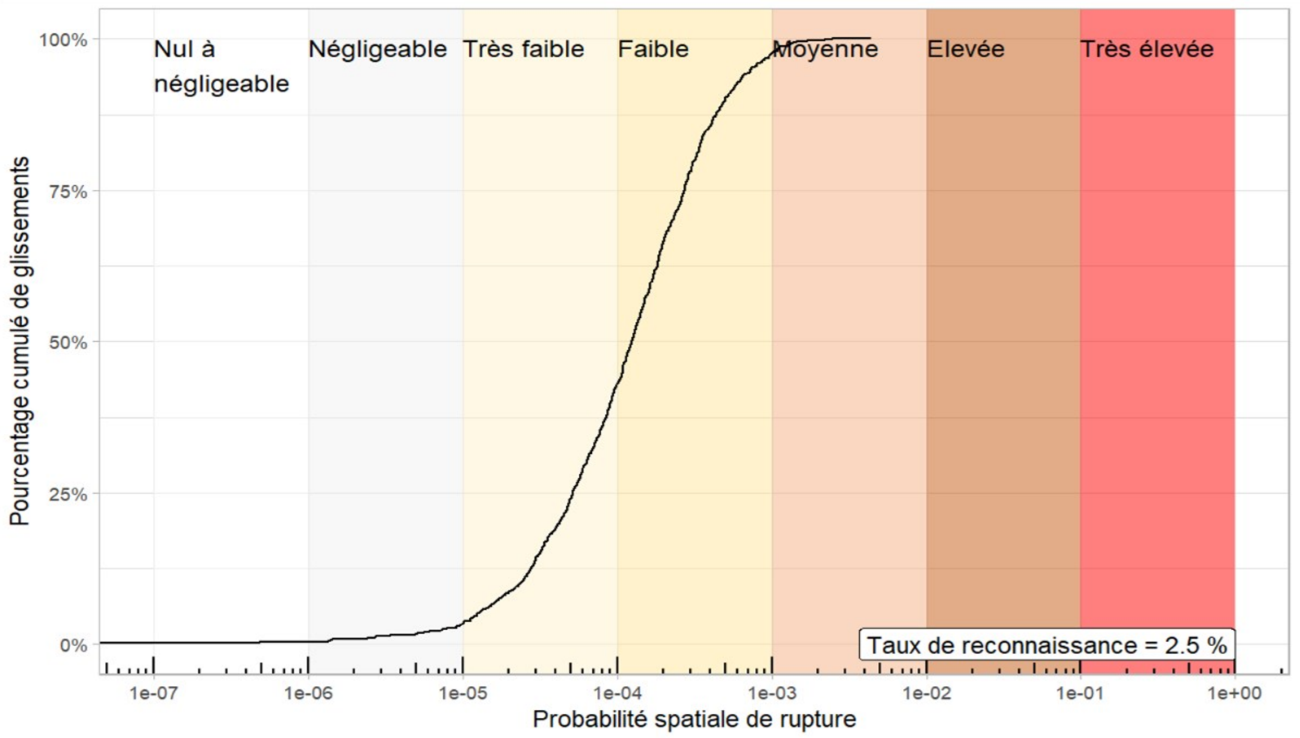


Figure 50: The recognition curve by JTC-1 committee classification for centroids inside the Entella Basin (slope+lithology+land use+aspect+accumulation+geomorphic map+elevation+distance from roads)

The chart figures out the number of landslides possible to occur inside the area examined. The curve witnesses that a large amount of territory is characterized by a low probability to have a failure. Indeed, the percentage of landslides which have a mean probability to occur, is very low (2.5 %) and there is no evidence at high levels of susceptibility, making the study unsatisfiable. The evaluation of not sizeable portions of landslide body, makes the calculation of weights by predisposing factors' effect not efficient, because only the single point inside the landslide is counted. By enlarging the landslide area, covering more points, could be the key point to increase the percentage of landslides recognized at mean – high values.

4.7.4 The Weights of Evidence method: the landslide depletion zones

To improve the landslide susceptibility analysis, the following chapter is dedicated to a statistical analysis looking at some landslides inside the Entella basin, examining roto-translational slides, debris flow at low and high velocity and areas containing shallow landslides. In this section complex landslides are excluded. The calibration and the validation set are examined with the depletion zones' calculation. The statistical method used is again the WOE model to increase and improve the previous results, to find the best combination between the variables to model and the predictive variables represented by predisposing factors to landslide occurrence. The expected goal is to have an efficient landslide susceptibility validation of the WOE map.

4.7.4.1 The landslide set

Looking at the IFFI inventory, a several numbers of 434 landslides are examined inside the Basin. They are roto-translational slides, debris flow at low and high velocity and shallow landslides' zones identified as set 1. The picture 51 shows the landslide set chosen, as the vectorial shape layer with IFFI landslide contours:

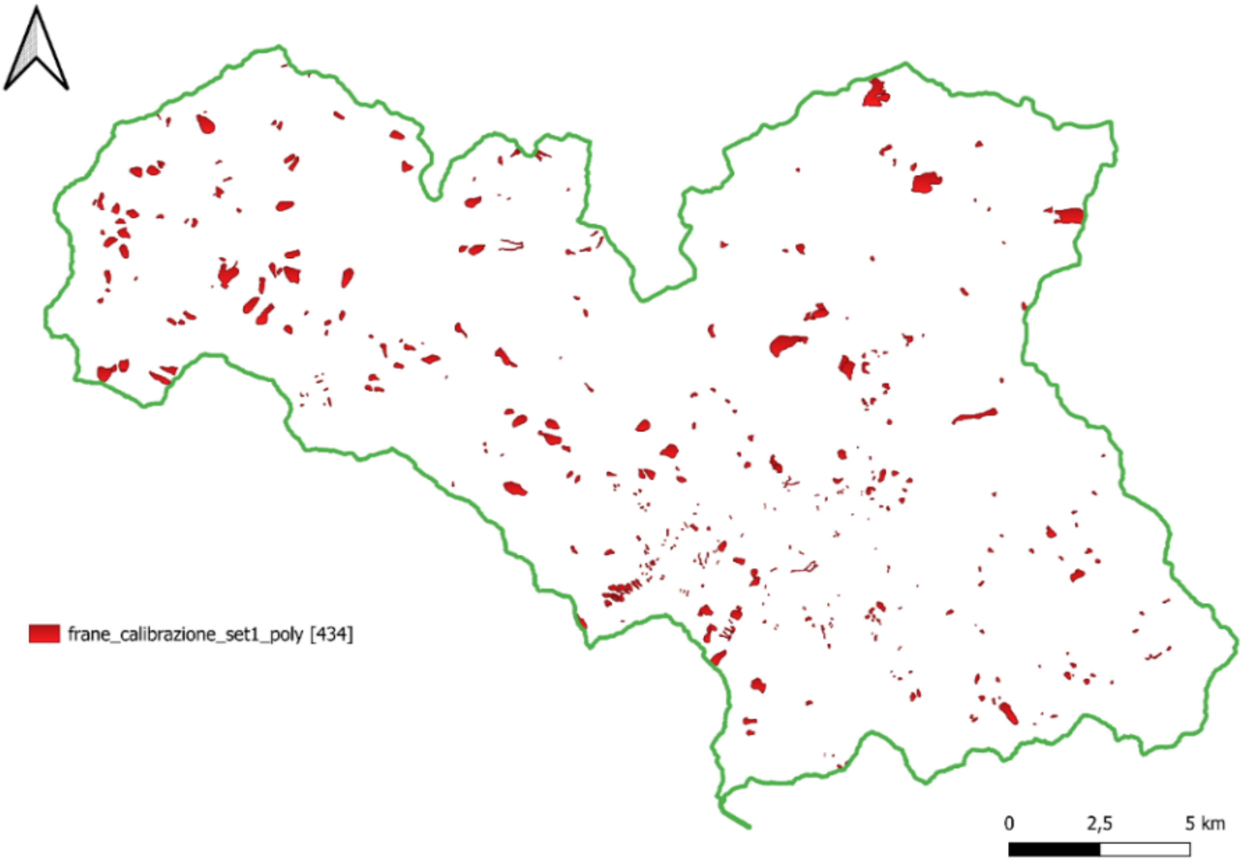


Figure 51: The landslide group defined by roto-translational landslides and rapid and slow debris flows (set 1) inside the Entella Basin

The map shows that the distribution of landslides is homogeneous and the dimension of landslide body concerns on movements lower than 400 m² and greater than 400 m².

4.7.4.2 The depletion zone calculation on GIS

The next step of the analysis concerns on the depletion zone calculation, which is the upper part of a landslide where the material has failed and moved downslope, resulting in a void or "depletion" of the original ground surface. This area includes the main scarp, which is the steep face at the top of the landslide, and the displaced mass that has moved from that original position. It is a crucial phase of the analysis because consists of several procedures to be done on Geographical Information System (GIS). To comprehend the area of interest Figure 52 shows the scheme to evaluate the area of depletion.

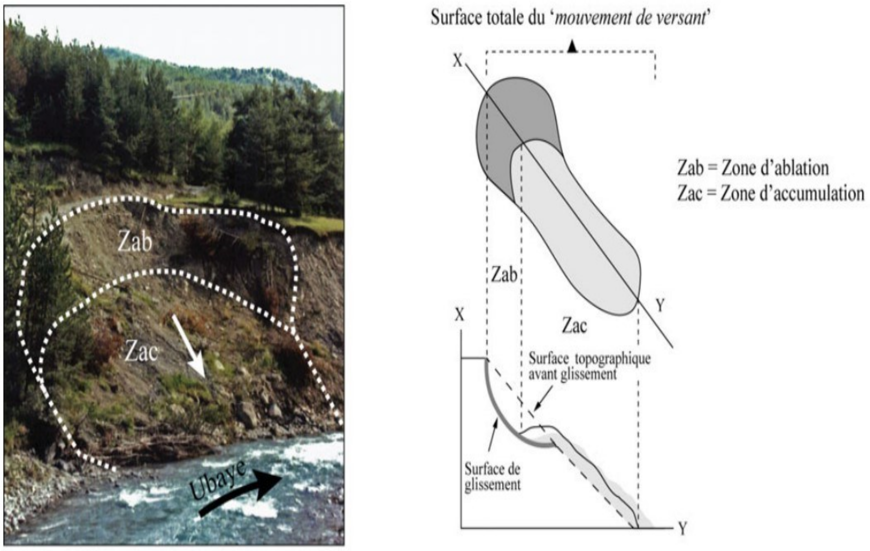


Figure 52: The landslide body, the depletion and the accumulation zone, (Thiery, 2007)

The calculation has followed these steps:

- landslide polygons transformed in landslide raster map, cut on DTM (Digital Terrain Model of 5 meters resolution);
- landslide vector points calculation inside the raster map;
- extraction of the mean altimetry value of vector points for each landslide;
- sample value calculation by GIS statistics tool;
- depletion calculation with Field calculator rule on GIS, to detect the correct area to calibrate inside the WOE model; particularly if the sample value is greater than the mean value, the point is in depletion zone, while if the sample value is lower than the mean value, the point is in the accumulation zone.

As an example, the steps are figured out considering four different IFFI roto – translational landslides in Borzonasca Municipality. The Figure 53 shows the IFFI landslides' bodies:

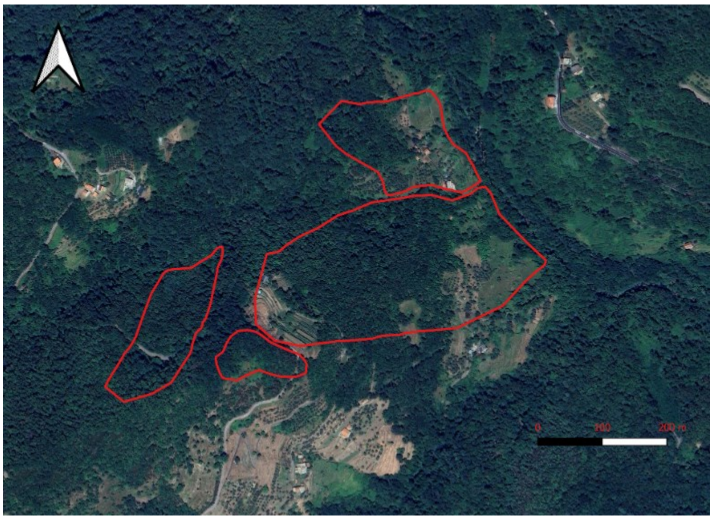


Figure 52: A section of IFFI inventory showing four roto-translational slides

By GIS tools, the next step consists of the landslide cut on Digital Terrain Model as in Figure 54.

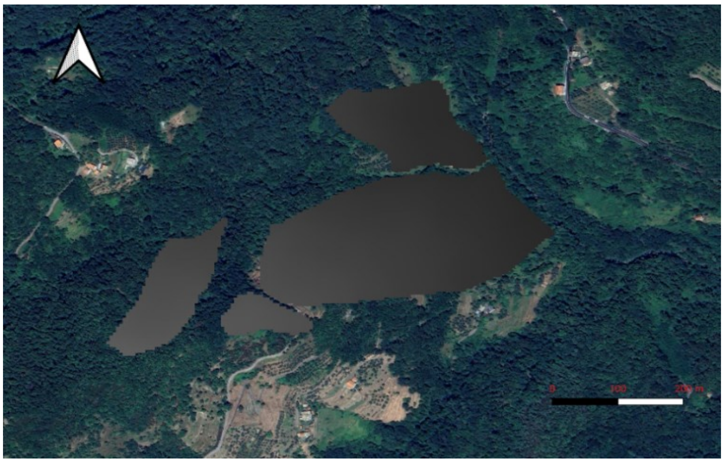


Figure 53: The landslides cut on the Digital Terrain Model (DTM) with 5 meters resolution

Then the landslide raster map is transformed in a vector layer of points represented in Figure 55:

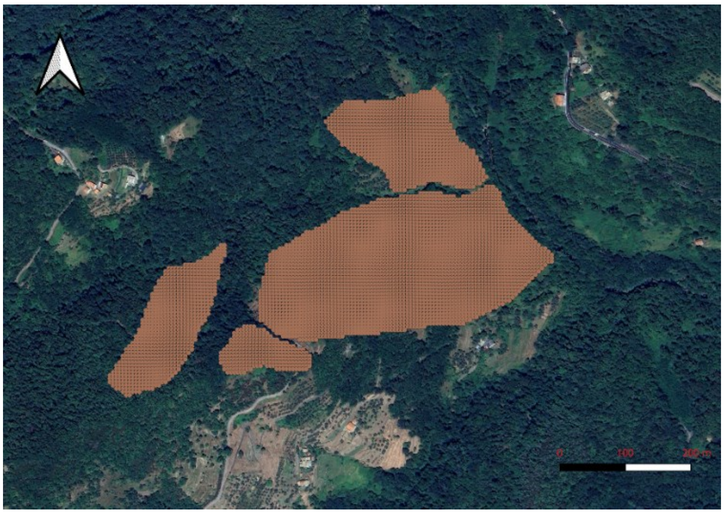


Figure 54: The points layer of landslides chosen

The other phase is the calculation of mean altimetry value for the 4 groups of landslides and consequently the calculation of the sample value to be compared with the mean altimetry parameter and understand the depletion zone. The Figure 56 shows the outcome of the analysis, as a vector points layer inside which the depletion and the accumulation zones are distinguished.

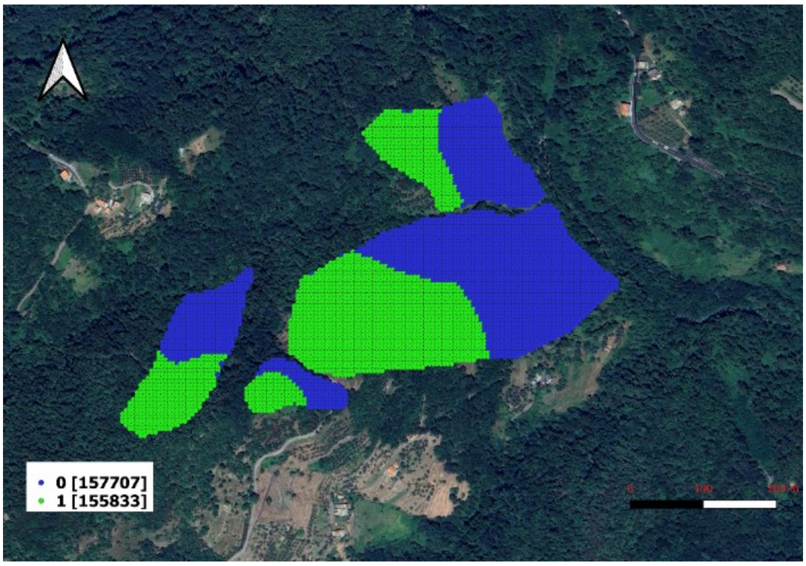
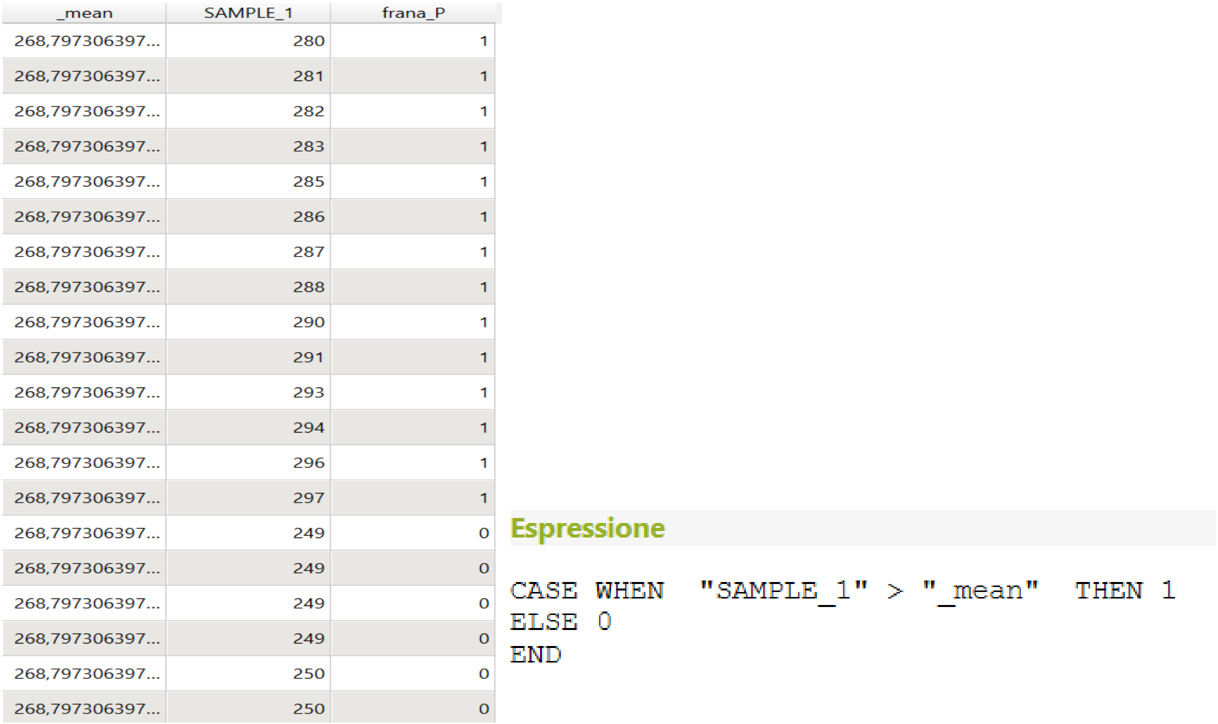


Figure 55: The depletion (1) and the accumulation (0) zones for the four roto - translational slides in Borzonasca Municipality

The depletion and the accumulation areas have been evaluated by a rule established on GIS with Field Calculator, a tool by which it is possible to make a series of mathematical actions and operation; the values to consider are the mean altimetry value for every landslide and a sample value, calculated statistically. These numbers are inserted inside the Attribute Table which shows the features and the attributes; in Figure 57, the rule is explained:



_mean	SAMPLE_1	frana_P
268,797306397...	280	1
268,797306397...	281	1
268,797306397...	282	1
268,797306397...	283	1
268,797306397...	285	1
268,797306397...	286	1
268,797306397...	287	1
268,797306397...	288	1
268,797306397...	290	1
268,797306397...	291	1
268,797306397...	293	1
268,797306397...	294	1
268,797306397...	296	1
268,797306397...	297	1
268,797306397...	249	0
268,797306397...	249	0
268,797306397...	249	0
268,797306397...	249	0
268,797306397...	250	0
268,797306397...	250	0

Espressione

```
CASE WHEN  "SAMPLE_1" > "_mean"  THEN 1
ELSE 0
END
```

Figure 56: The attribute table with mean and sample values and the Field calculator rule

In this case the Boolean value 1 shows the depletion points useful for this type of analysis, while 0 values concern on the accumulation area involving the foot of landslides. Finally in Figure 58, the depletion zone of the four movements is defined.

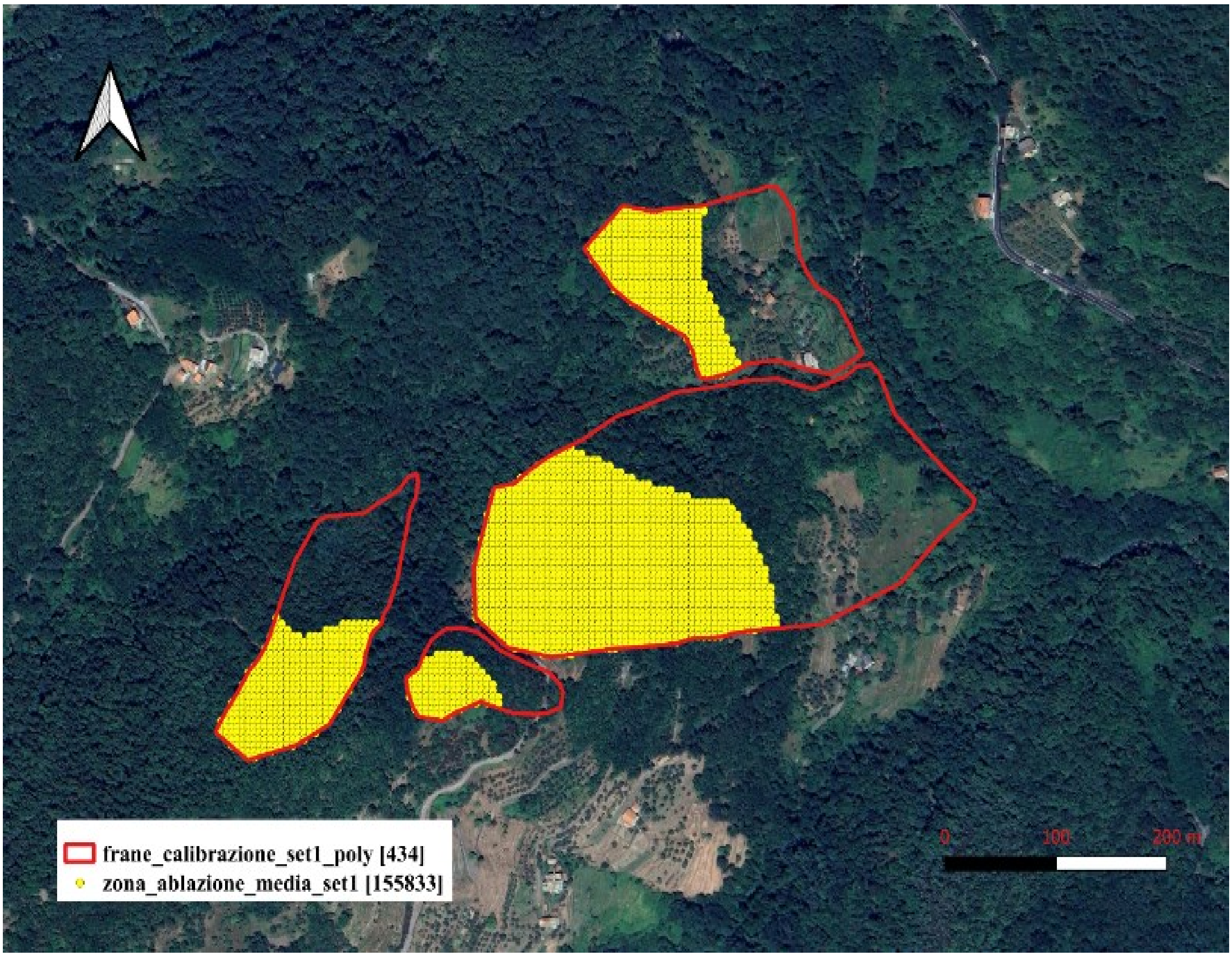


Figure 57: The depletion zone (yellow) and the IFFI limits (red)

4.7.4.3 The calibration variables

The points in yellow show the depletion zone. To apply the model, for each landslide belonging to the set 1, a certain number of points is identified as calibration variables (80%), while the other 20% represents validation variables. The distinction is crucial for the model validation. This is a representation of the points in Figure 59.

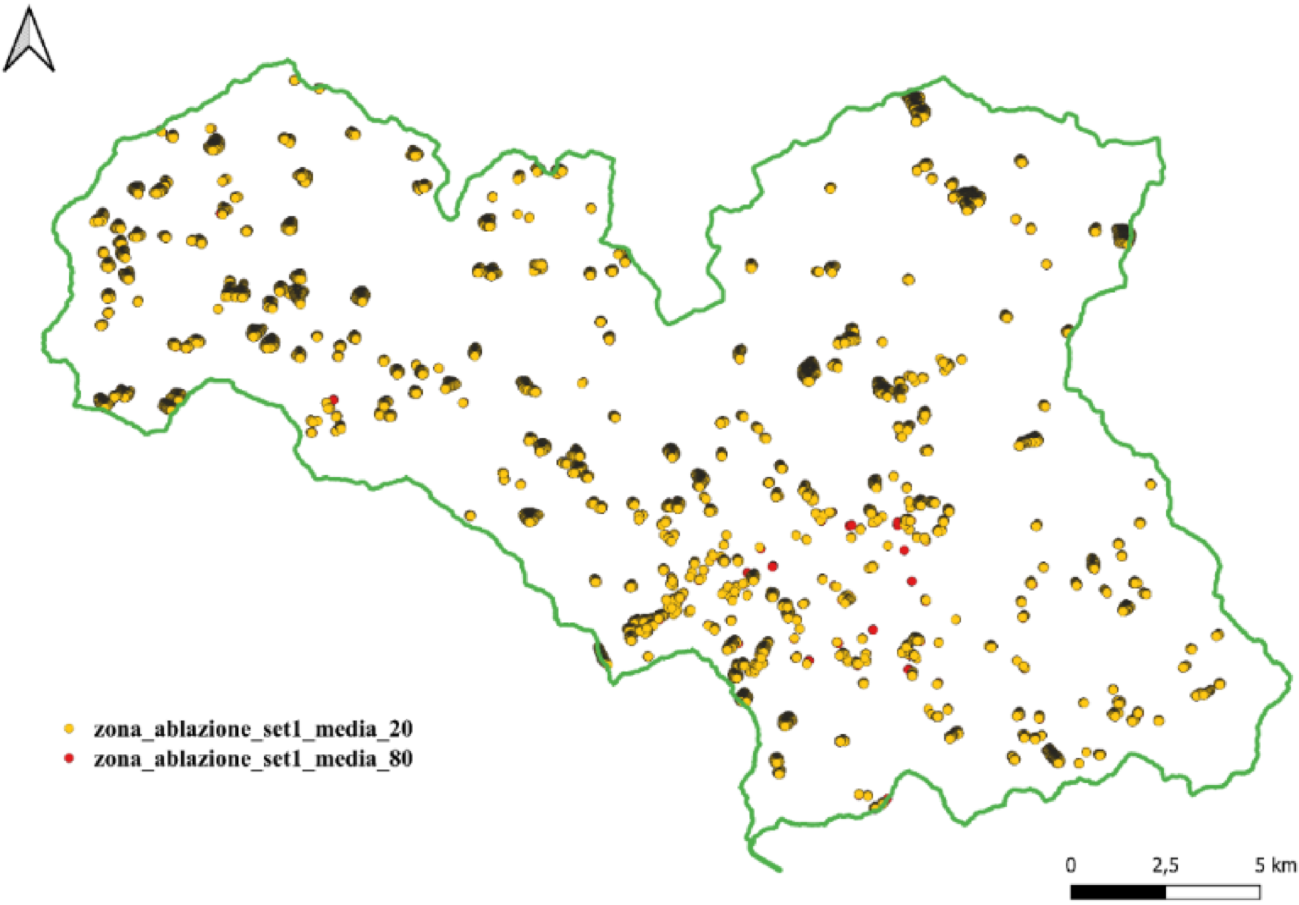


Figure 58: The calibration set of 80% (red) and the validation set of 20% (yellow) for movements selected inside the Entella Basin

4.7.4.4 The landslide susceptibility map in the depletion area

After the identification of calibration variables, the points have been transformed in raster points of Boolean value (1), following the WOE modelling. Each point has been compared with raster maps of predisposing factors. The sum of weights has given as output the landslide susceptibility map of depletion zones by JTC-1 committee classification. The output is shown in Figure 60.

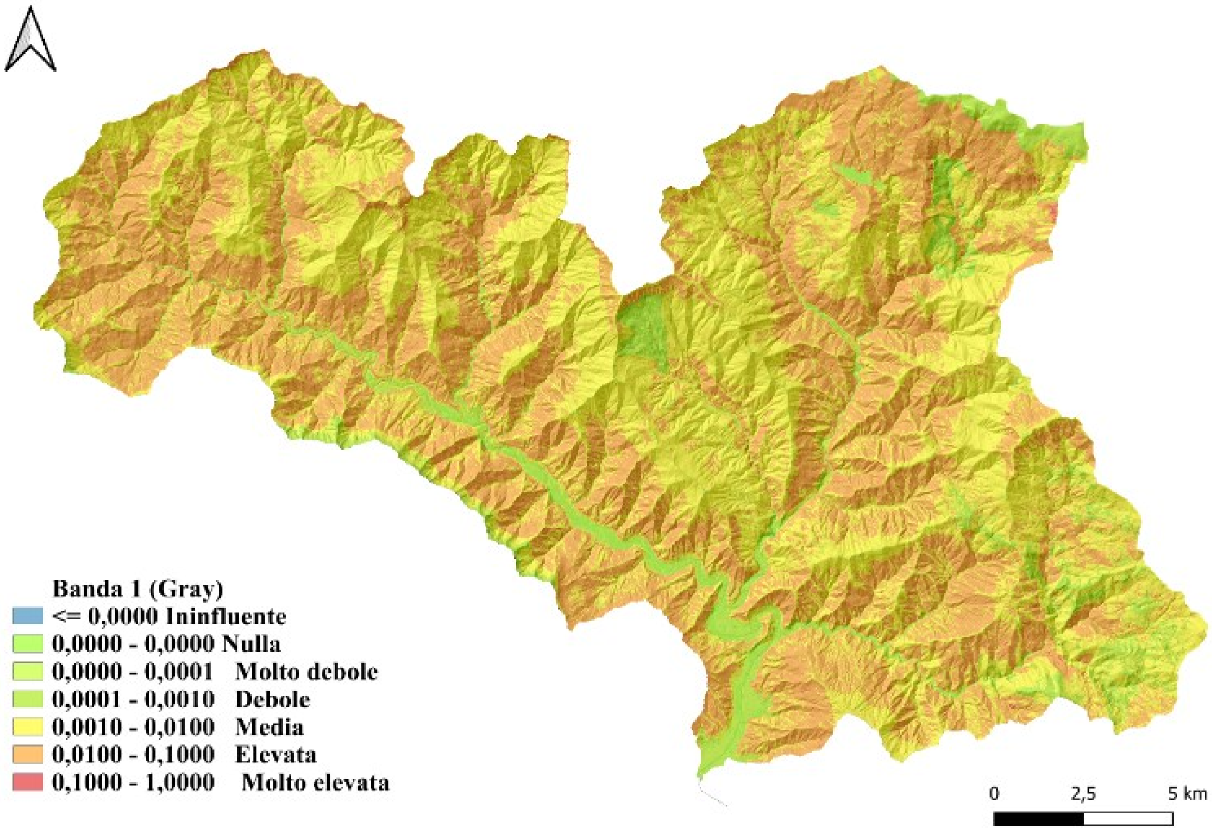


Figure 59: The landslide susceptibility map of set 1 by JTC-1 committee classification of Entella Basin (negligible, null, very low, low, medium, high, very high)

By analysing the map, some areas show a high susceptibility level (orange), increasing the potential risk to have a landslide; the distribution is important in the centre and in the South of the Basin. The yellow zones show the mean probability to have a landslide, and they are concentrated in the North-West of the Basin. The green areas mean a low susceptibility.

4.7.4.5 The landslide susceptibility validation in the depletion zones

Once got the landslide susceptibility map of depletion zones to have an effective result, the next stage is the validation of the map. The method used is valwoe model. To understand the reliability of the model, the success and the validation curves show the quality of the method comparing the percentage of depletion points in calibration area and the other in validation zone. The Figure 61 shows the performance of method:

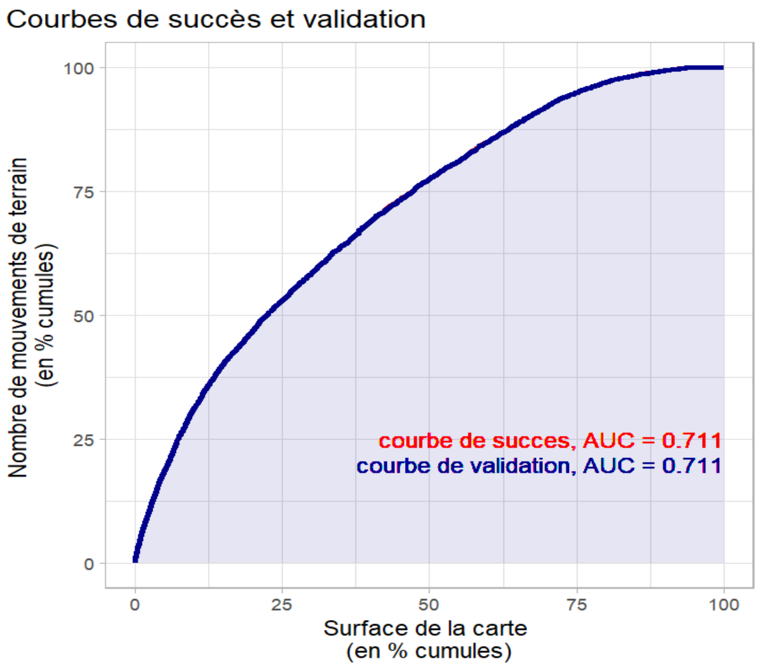


Figure 60: Success curve (red) and validation curve (blue) of depletion areas

In the picture the calibration and the validation performance are equal. Statistically, the model has a reliability of almost 71 %, witnessed by AUC (Area Under the Curve) for calibration points and validation points. Then after the weights' calculation for each predisposing factors' classes, the model gives out the recognition curve (Figure 62):

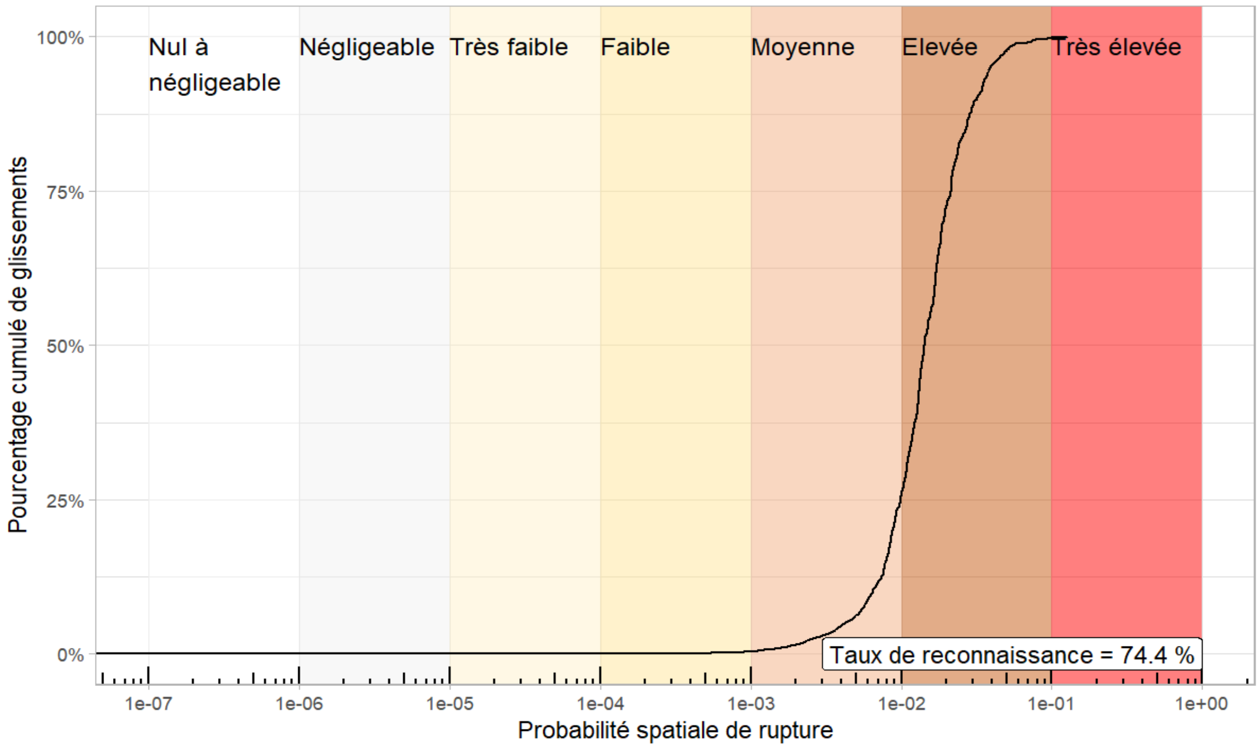


Figure 61: The recognition curve by JTC -1 committee classification for depletion areas of set 1 inside the Entella Basin (slope+lithology+landuse+aspect+accumulation+geomorphic map+elevation+distance from roads)

The chart shows the level of susceptibility, taking a recognition rate threshold equal to 0.001, which is the stage to evaluate the susceptibility inside the landslide map starting from the mean value of probability to have a harmful event. With respect the case related to centroids, the possibility to recognise a probability of landslide occurrence between a band of mean and high susceptibility is 74.4%. It is a great improvement with respect the previous analysis, probably because the portion of landslides' points analysed is greater than the only barycentre. The results of validation witness the influence of some predisposing factors, with the possibility to cover larger landslide depletion areas inside the map, making the susceptibility analysis more efficient. The next step consists of adding to the set 1, the category of complex landslides which are numerous inside the Entella Basin and make an overall analysis to understand if there is an improvement or not.

4.7.5 The Weights Of Evidence method: the landslide susceptibility of complex landslides

Since the landslide inventory of the Entella basin is defined by the 44% of complex landslides, the research study concerns a landslide susceptibility assessment by WOE statistical modelling considering the set 1 and the added group of complex landslides (set 2), to get an overall susceptibility map and validate it on San Colombano Certenoli Municipality. It is an analysis on depletion areas combined with the predisposing factors used in the previous stages. The aim is to improve the study, adding the complex movements and increasing the number of potential landslides recognised on the territory.

4.7.5.1 The group of landslides

Examining the IFFI inventory, it has been decided to evaluate the 434 landslides as roto-translational slides, debris flow at low and high velocity and shallow landslides' zones and the 432 complex landslides which cover the Entella basin. The picture 63 highlights the last landslide set chosen, as the vectorial shape layer with IFFI contours:

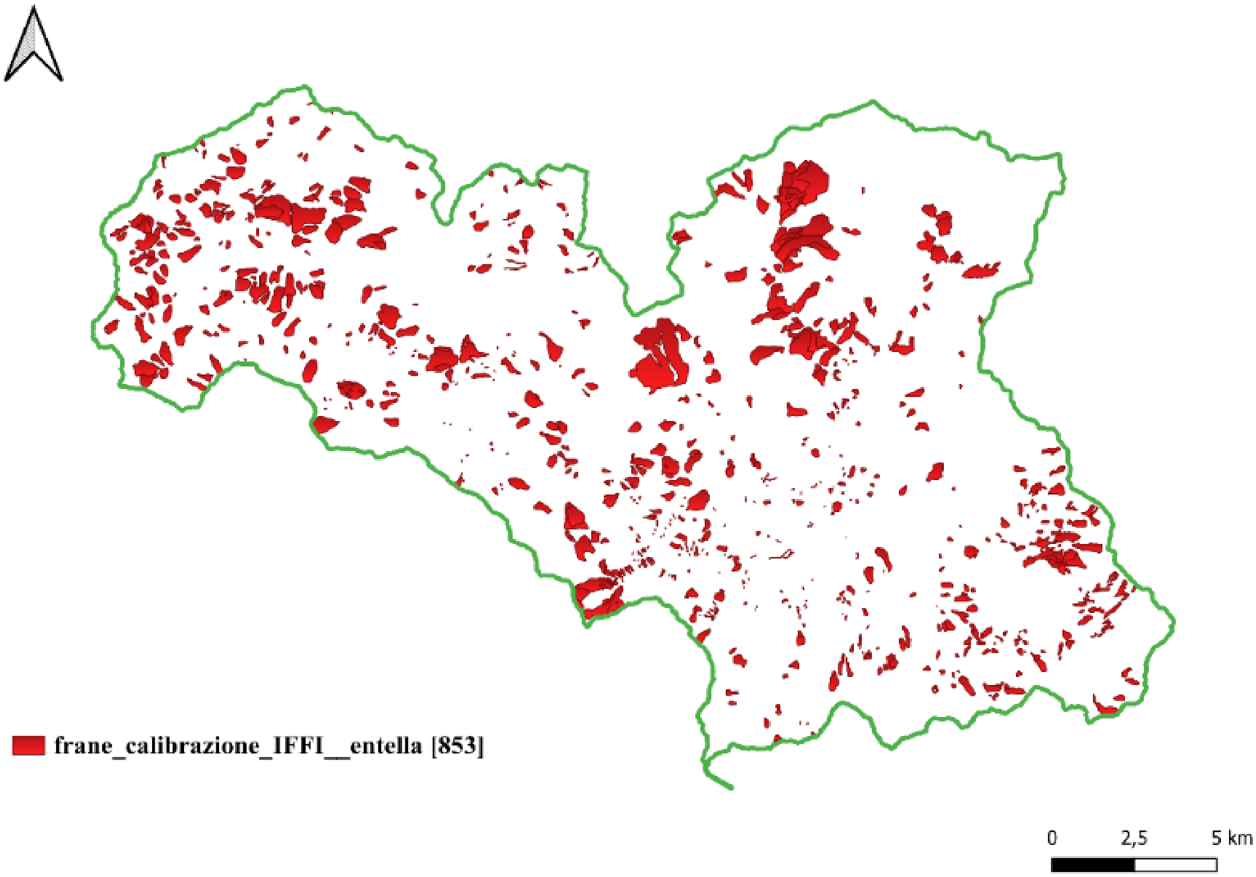


Figure 62: The final group of landslides chosen on Entella basin

The map figures out 853 different movements inside the area of interest. Big landslides are present in the centre and in the Northwest of the territory, while the Southeast is characterised by small surficial landslides.

Examining the data, the next important stage is to identify the variables to calibrate and validate the model, implementing a method to calculate the depletion areas of each landslide.

4.7.5.2 The depletion area calculation on GIS

The next step of the analysis concerns on the depletion zone calculation of complex landslides. It is a crucial phase of the analysis because it concerns on a series of steps with different GIS tools to underline a landslide depletion surface, potentially close to the real life. The altimetry is the point of reference to comprehend the highest and the lowest quote at which the landslide body is located. More the resolution of the Digital Terrain Model is good; more the outcome will be satisfying. In this section two complex landslides in San Colombano Certenoli Municipality are examined. The Figure 64 shows the landslide bodies directly got by IFFI inventory.

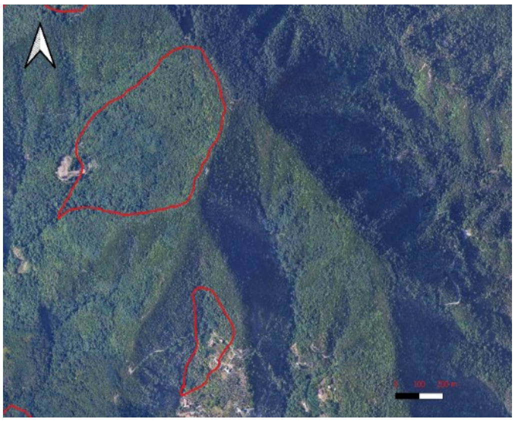


Figure 63: Two complex landslides inside San Colombano Certenoli Municipality

The next step is referred to the landslides' DTM cut on each landslide body considered. To evaluate the area at which there is the failure, it is important to consider which are the highest points with respect the map altimetry. Figure 65 shows the Digital Terrain Model cut on the two complex landslides.

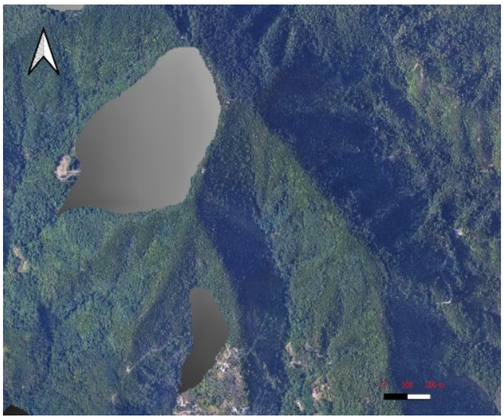


Figure 64: The two complex landslides cut on Digital Terrain Model (DTM) with 5 meters resolution

Then the next stage is to transform the landslides in raster format, into a layer of vector points and calculate the mean altimetry value. The Figure 66 shows the points modelling the two complex landslides inside the territory of San Colombano Certenoli Municipality.

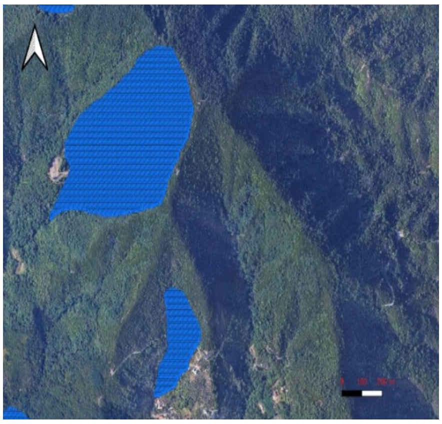


Figure 65: The layer of vector points of two complex landslides

Then by statistical GIS tool, a sample value is calculated and compared with the mean altimetry value. The depletion zone is calculated as in the previous case, by the field calculator rule on GIS, to detect the calibration variables to introduce inside the WOE model; particularly if the sample value is greater than the mean altimetry value, the point is in depletion zone, while if the sample value is lower than the mean altimetry value, the point stays inside the accumulation zone. The result is outlined in the picture (Fig. 67).

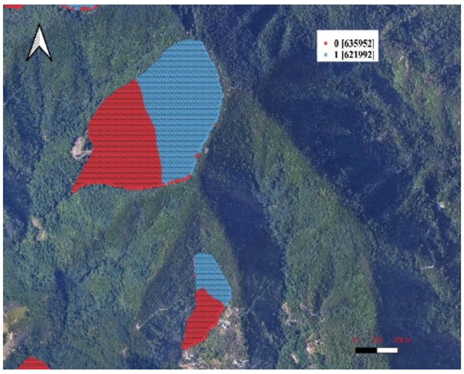


Figure 66: The depletion (1) and the accumulation (0) zones of the two complex landslides inside San Colombano Certenoli Municipality

The depletion area is identified by Boolean value 1 (blue) and it represents the calibration variables of the WOE model, while points in red concern on the accumulation area involving the foot of the two complex landslides. The yellow points figure out the elements of depletion to consider in the examination of the WOE model as defined in Figure 68.

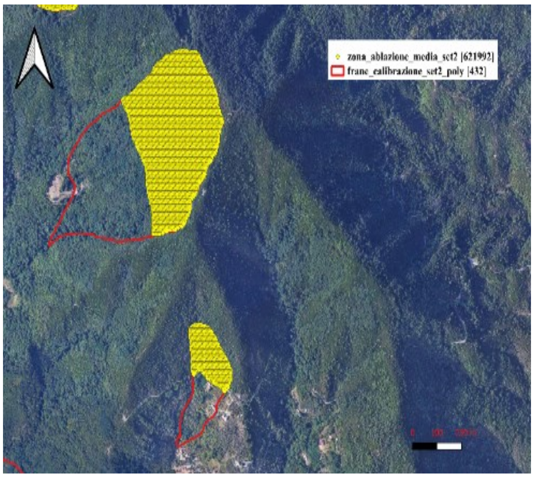


Figure 67: The depletion zone (yellow) and the IFFI limits (red) of the two complex landslides

4.7.5.3 The calibration stage

As a pre-process stage to apply the model, for each landslide, a certain number of points is identified as calibration variables (80%), while the other 20% represents validation variables. The Figure 69 highlights the calibrated and validated depletion zones inside the Entella basin

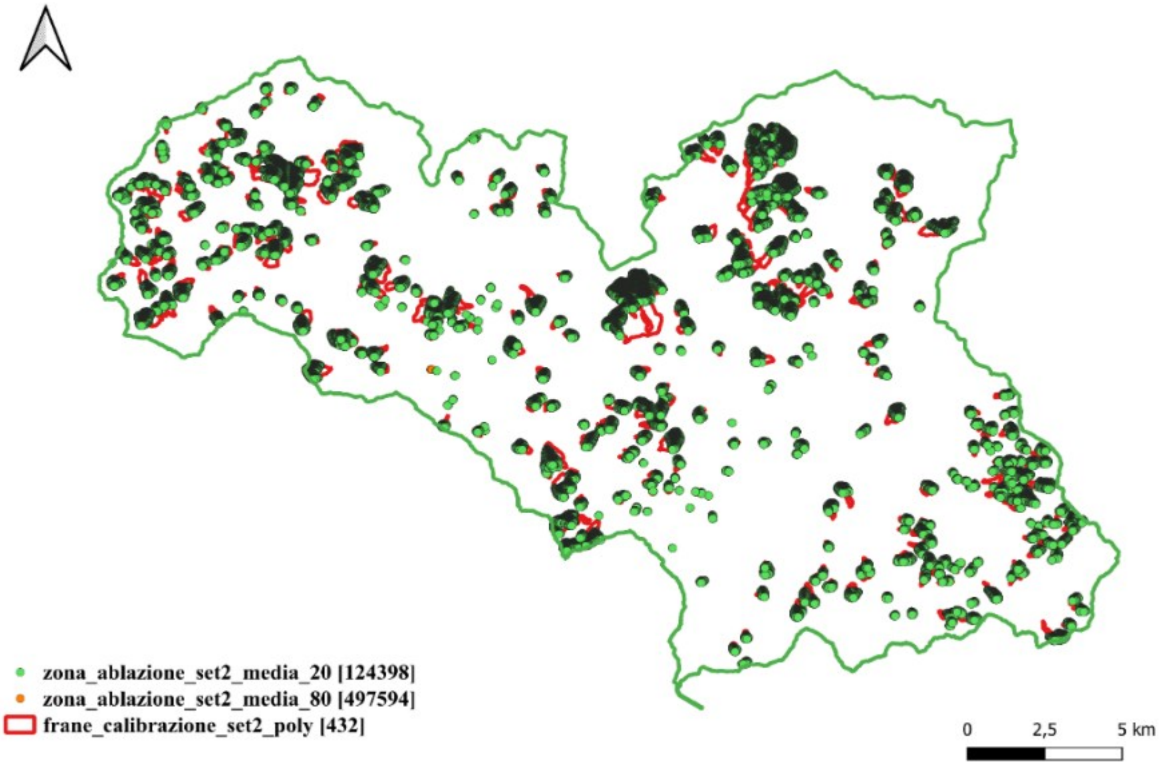


Figure 68: The validation (20% in green) and the calibration (80% in orange) points for the WOE model

4.7.5.4 The susceptibility map with complex landslides

After the identification of calibration variables, the WOE model has been implemented by transforming the points in depletion area in raster points of Boolean value (1). The classes of predisposing factors have been evaluated by the Bayesian Rule to understand their influence in landslide occurrence, calculating the weights of each category (W). The sum of weights, as the combination between landslides and predisposing factors has given as result the landslide susceptibility map of depletion zones by JTC-1 committee classification for roto-translational landslides, debris flow, zones with shallow landslides and complex landslides as shown in Figure 70.

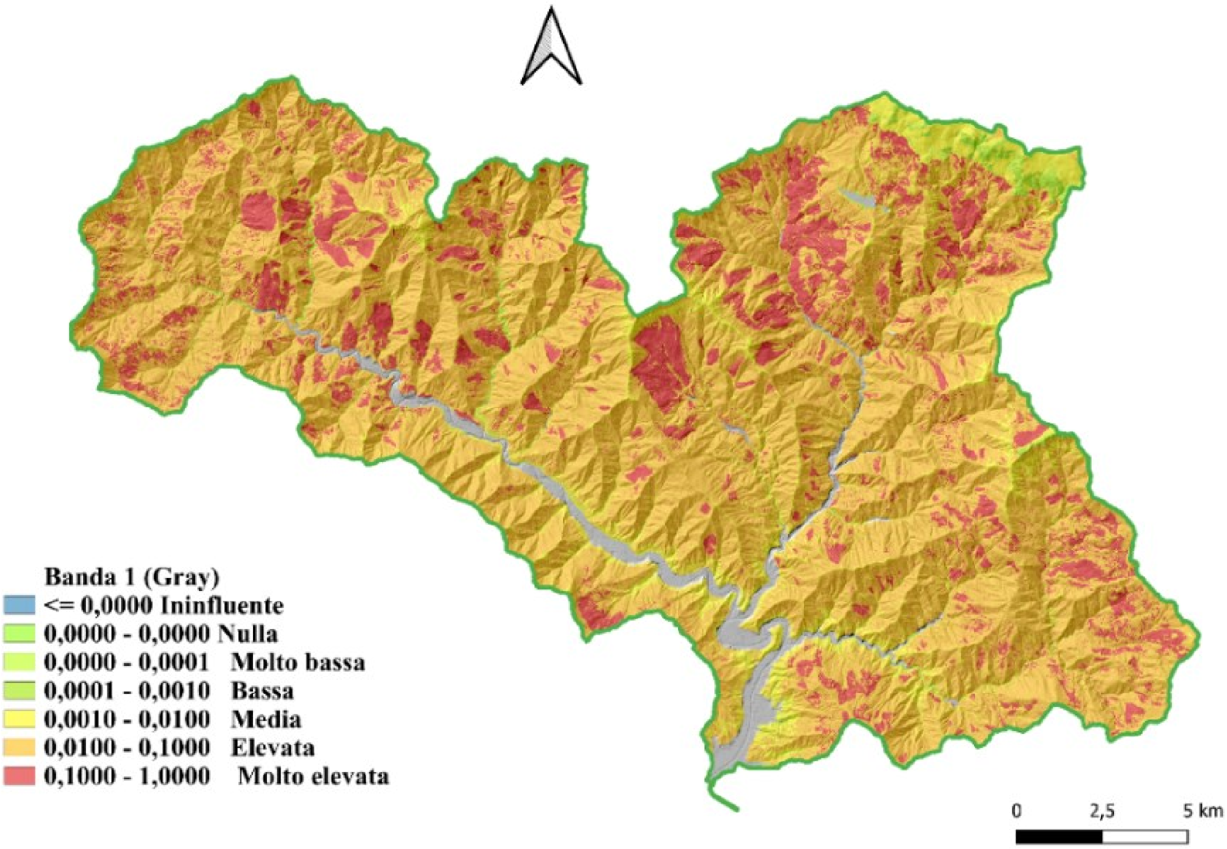


Figure 69: The final landslide susceptibility map by JTC-1 committee classification of Entella Basin (negligible, null, very low, low, medium, high, very high)

Analysing the cartography, there is a great improvement with respect the previous two analysis. By analysing the map, some areas of the map are covered by very high susceptibility levels (red). This portion of the territory must be considered due to the fact landslides could occur as soon as possible, putting in danger roads and buildings; a great amount of Entella basin is characterized by orange zone, highlighting high levels of probability of landslide occurrence while low levels of susceptibility are rare. To have a clearer distribution of landslides inside the area, the next step is to validate the map with valwoe tool and understand if there is an improvement or not concerning the complex landslides' addition.

4.7.5.5 The landslide susceptibility validation

The section is dedicated to the statistical validation of the map using R- Studio tool as valwoe. The goal is to identify the influence of complex landslides on the territory of Entella basin by examining the zone by which the landslide starts to fail down. To understand the reliability of the model, the success and the validation curves show the reliability of the model comparing the percentage of depletion points in calibration area and the other in validation zone. The Figure 71 shows the two lines of calibration and validation.

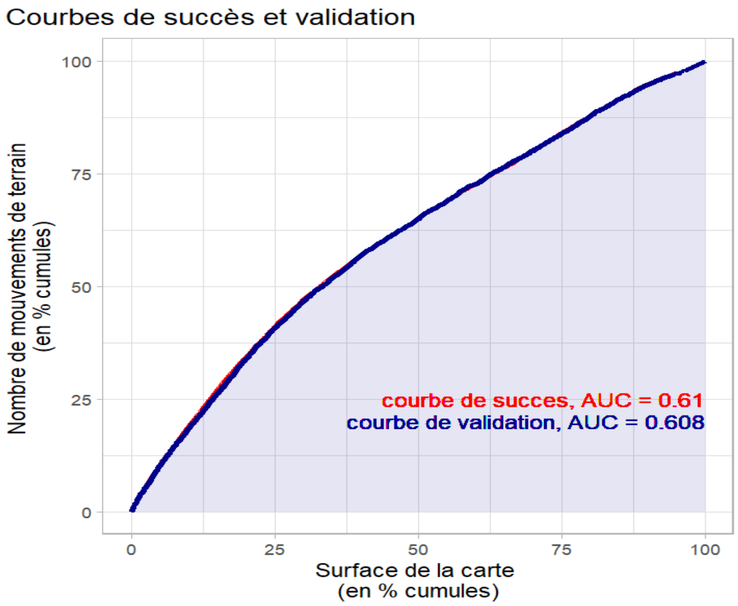


Figure 70: The success (red) and the validation (blue) curves of complex landslides' depletion areas

The chart shows that the 61% of points chosen as calibration areas can be recognized as landslides probable to occur inside the map. The validation points are the remaining variables. The curves are close together, so it means that there is a good reliability of the model. The most important key factor is represented by the recognition curve, to evaluate the potential percentage of landslides susceptible to occur. More the recognition rate is high; more the validation becomes effective and interesting. In Figure 72, the recognition curve of landslides inside the map is represented, following the classification given by JTC-1 committee:

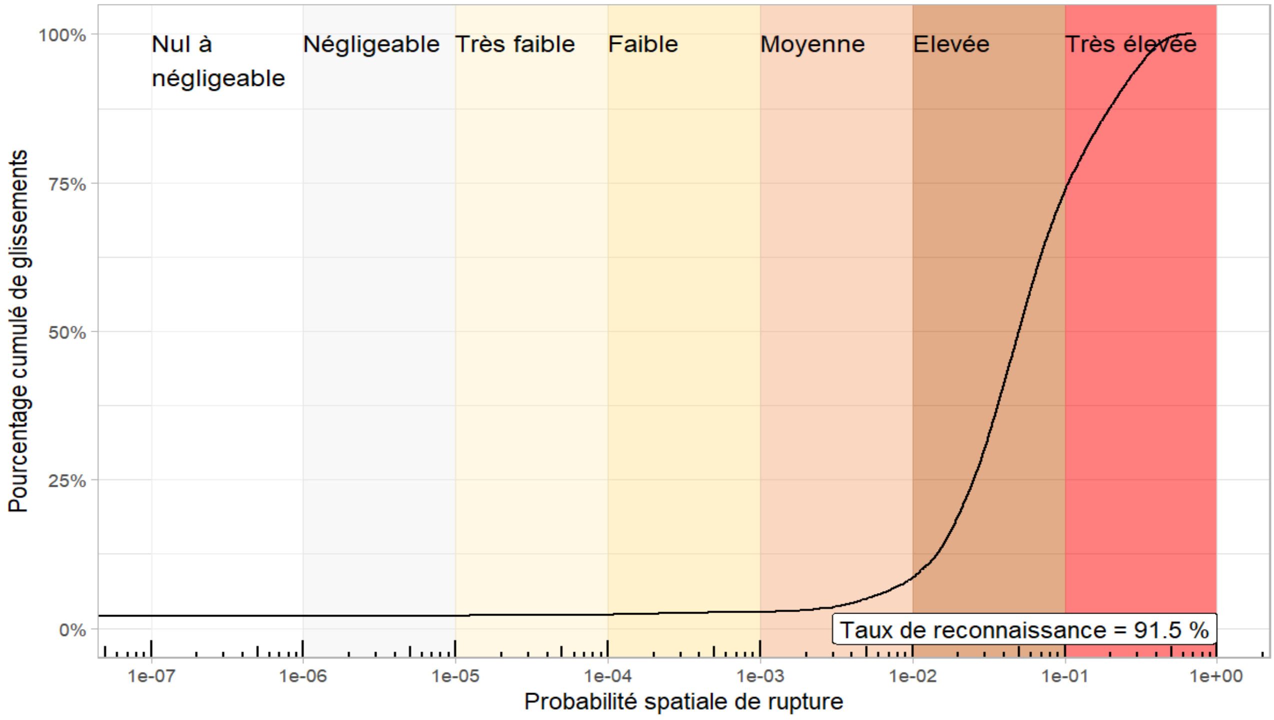


Figure 71: The recognition curve by JTC-1 committee classification for depletion areas inside the Entella Basin (slope+lithology+landuse+aspect+accumulation+geomorphic map+elevation+distance from roads)

The performance of the curve gives out the best result of the entire WOE analysis; the chart witnesses the reliability of the WOE, showing that the percentage of landslides susceptible to have a failure overcomes the

90%. The result signs out that the territory of Entella basin is fragile and vulnerable; the brown and the red sections inside the recognition curve are the most critical levels. There is an improvement of 20% more than the recognition rate of set 1, since landslide bodies of complex landslides are bigger than the only roto-translational slides and debris flow; so, the depletion area covers more points and the influence of predisposing factors classes in weights' calculation is statistically more evident and efficient.

4.8 The landslide susceptibility analysis on San Colombano Certenoli Municipality

In the end the last landslide susceptibility map of Entella Basin divided in 7 classes as defined by JTC-1 Committee is cut on the San Colombano Certenoli Municipality (Fig. 73) to compare the WOE map with the PAI Official cartography. The validation of results on the Municipality could let experts to outline what are the most critical areas, examining the new map as a support tool to be used as a complementary instrument with PAI.

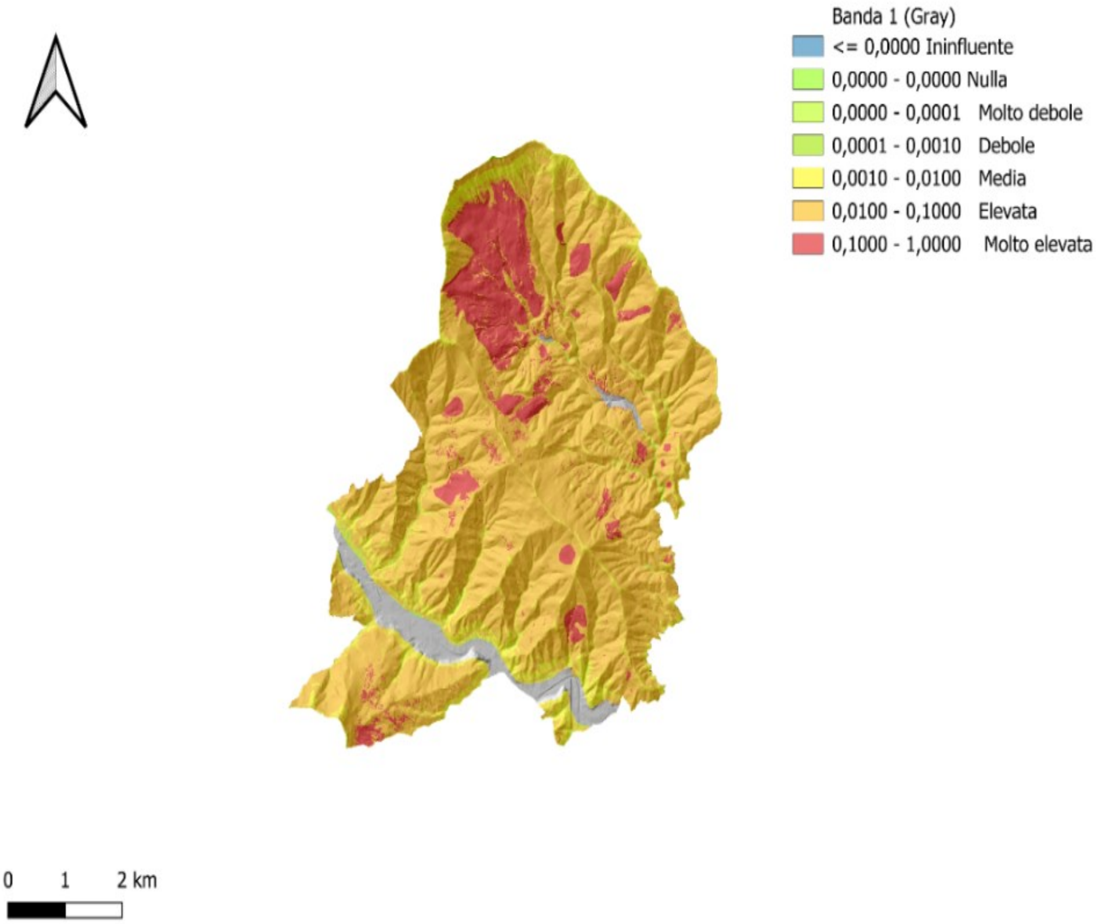


Figure 72: The WOE landslide susceptibility map of San Colombano Certenoli Municipality by JTC-1 Committee classification (negligible, null, very low, low, medium, high, very high)

The raster map by 5 meters resolution, shows the susceptibility zoning inside the San Colombano Certenoli Municipality; the red areas are zones of very high susceptibility, and they are in the North, in the South -East and in the extreme West. Large portions of the map are characterized by areas in which we have a high probability to get a failure. To understand the potentiality of the map, it is important to validate it locally, either by a zonal statistic or an on – site evaluation. To do it, it is important to understand the number and the typology of movements chosen for the WOE model application inside the Municipality.

4.8.1 The number of past landslides as calibration variables in the Public Administration

The knowledge of the number of landslides recognized as calibration variables of the WOE model is one of the most important aspects to validate the map. Examining the IFFI inventory, a histogram has been created defining the percentage of landslides divided by type as shown in Figure 74.

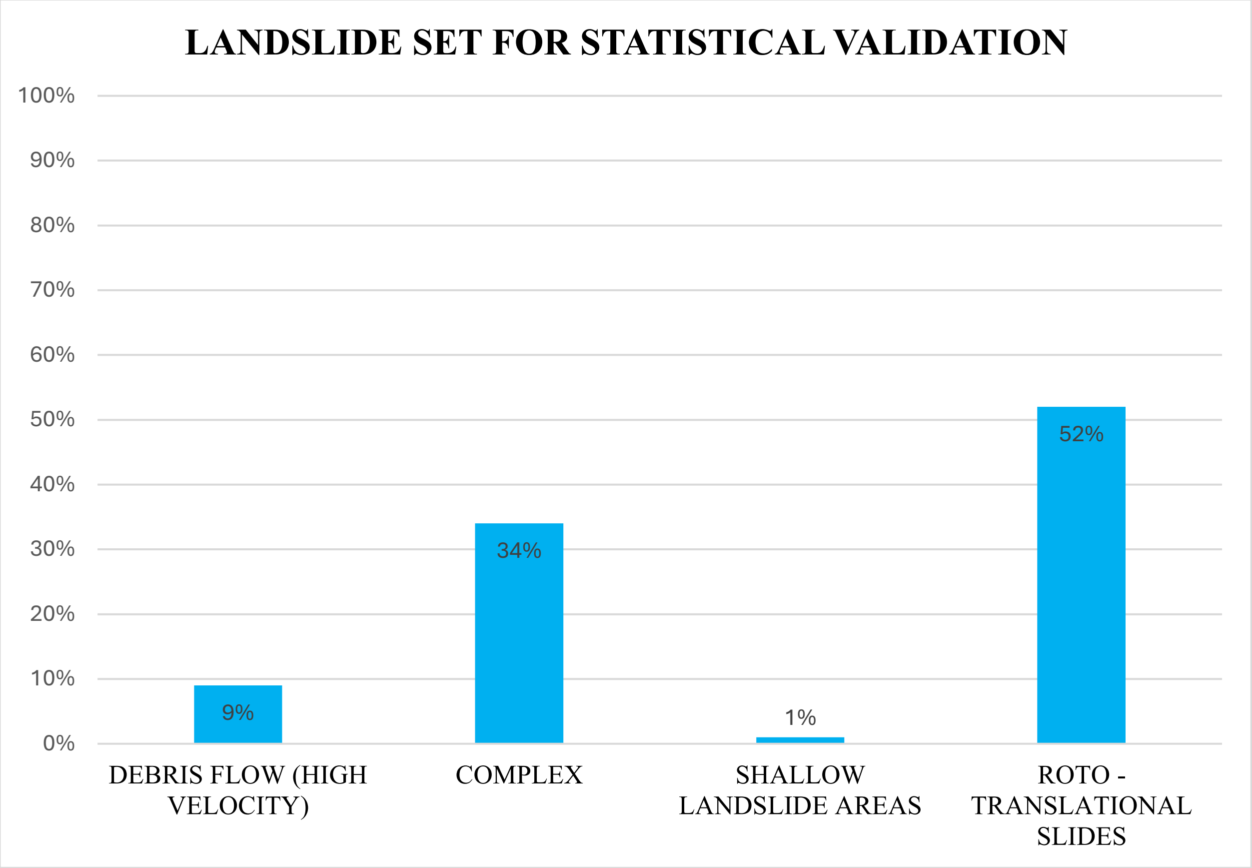


Figure 73: The percentage of landslides as model calibration variables in the territory of San Colombano Certenoli

The graph shows that the most frequent type of landslide movement within the Municipality of San Colombano Certenoli is represented by roto-translational slides (52%) while complex landslides cover 34% of the territory; rapid debris flow, on the other hand, does not exceed 10%.

4.8.2 The total number of pixels by categories in the landslide susceptibility map

To effectively understand the distribution of susceptibility levels within the weight of evidence map, it is necessary to calculate the total number of pixels per category, through the GIS tool, applying a statistical zonation on the entire susceptibility map; the result of the statistical zonation is configured as a histogram that represents the different levels of susceptibility by counting pixels inside the map, as can be seen from Figure 75.

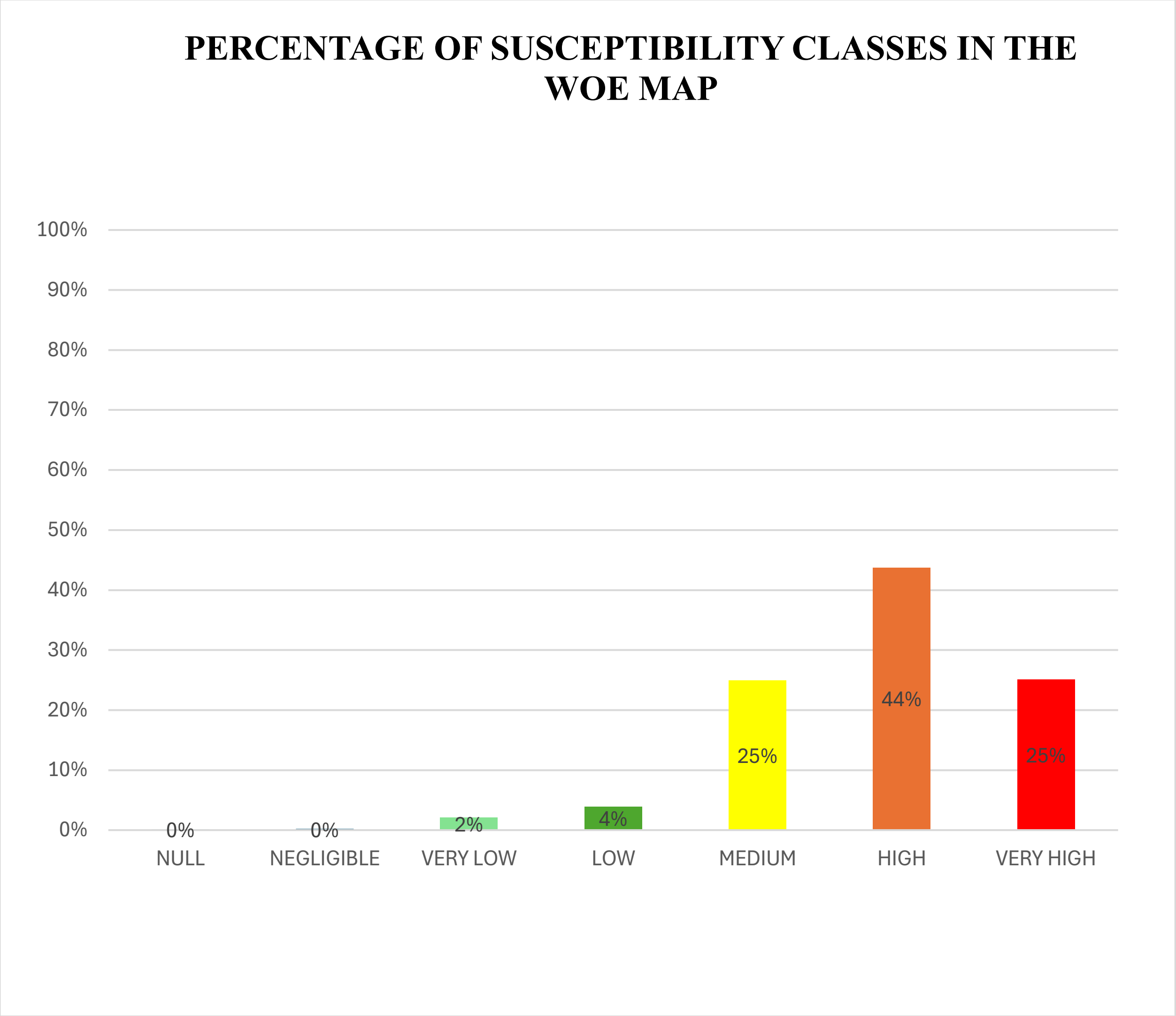


Figure 74: The percentage of WOE landslide susceptibility classes (7 levels) in San Colombano Certenoli Municipality

The graph shows that areas with high susceptibility to instability exceed 40%, while the levels of medium and very high probability of the occurrence of a landslide movement are both at 25%; The histogram however provides a reliable picture and highlights the vulnerability of the territory which, due to its characteristics, is frequently subjected to landslides. The histogram depicts a critical view of landslide susceptibility, showing the vulnerability of the territory of San Colombano Certenoli.

4.8.3 The total number of pixels divided by categories of PAI map

The susceptibility outcomes got by the WOE map must be compared with the actual susceptibility; the situation in terms of landslide probability is furnished by the PAI map, which must be the first reference to evaluate the potential occurrence of the landslide. To exam in terms of pixel the susceptibility, the vector map of San Colombano Certenoli (Fig. 76) has been transformed in the PAI raster map of 5 meters resolution, to extract the histogram figuring out the pixels corresponding to the different susceptibility levels.

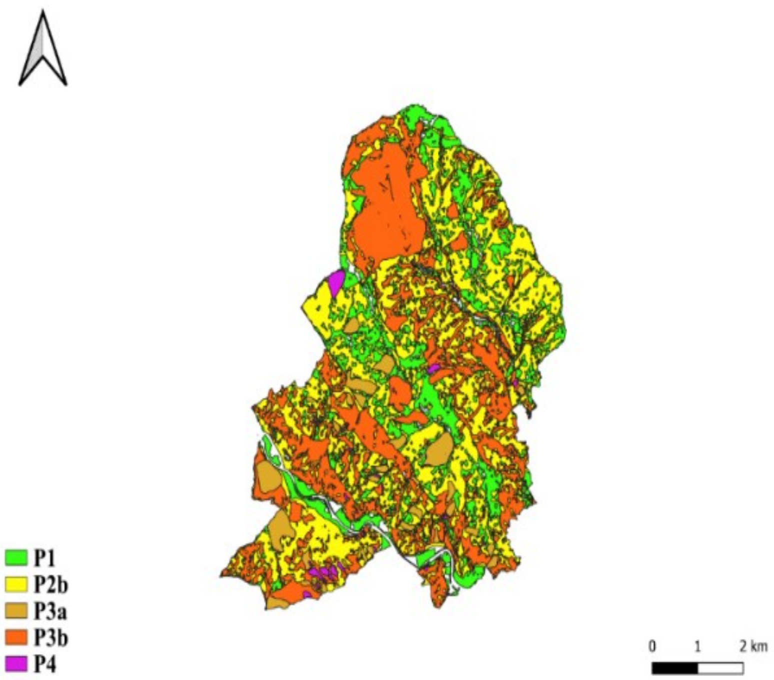


Figure 75: The PAI vector map of San Colombano Certenoli Municipality (5 levels)

By the statistical zoning the chart gives the percentage of landslide movements by following the five levels of susceptibility, as expressed in Figure 77.

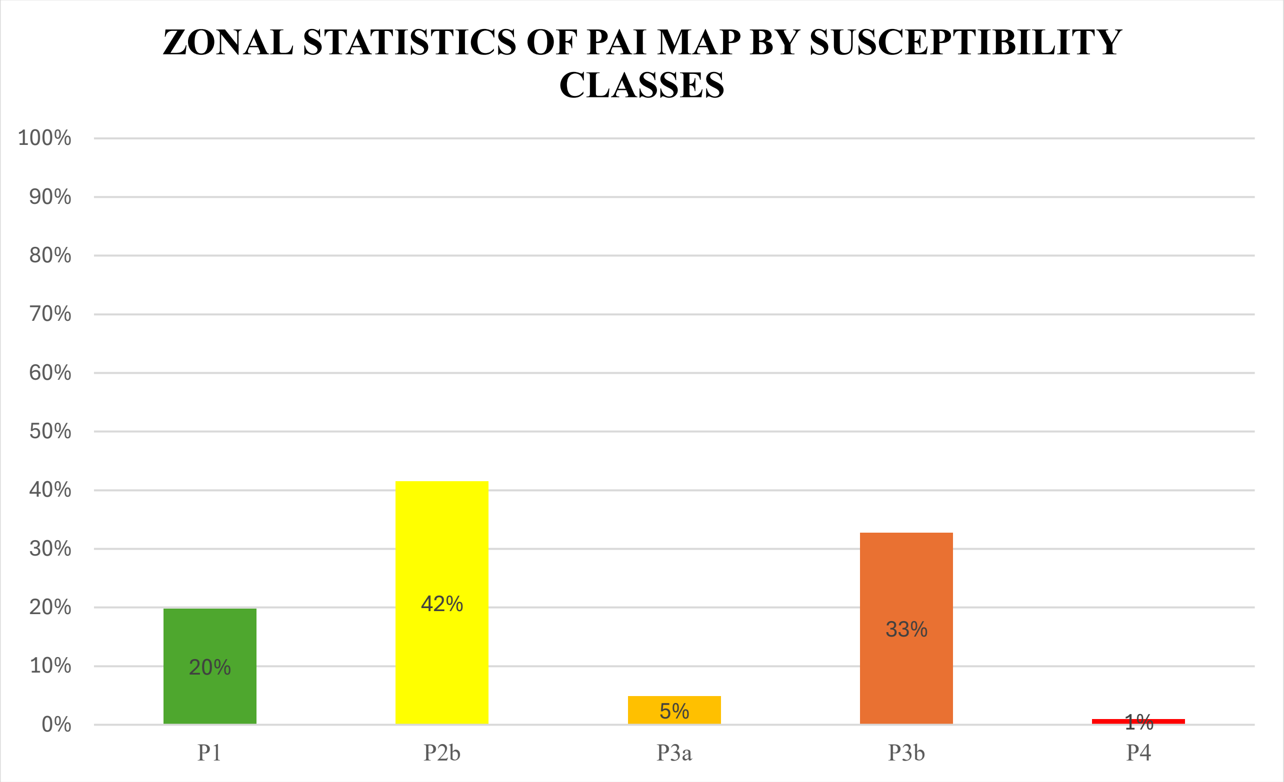


Figure 76: The percentage of PAI landslide susceptibility classes (5 levels) inside San Colombano Certenoli Municipality

By observing the levels of susceptibility, the highest percentage is characterized by 42% of landslides with a mean probability to have a failure; if there is the 33% to have a landslide occurrence inside high probability zones, the number of landslides which are in high critical areas is low with respect the outcomes given by the WOE map.

4.8.4 Landslide quantitative validation by zonal statistics

To validate the areas of landslide's depletion inside the San Colombano Certenoli Municipality, it is necessary the adoption of a quantitative landslide validation by statistics; the IFFI depletion areas are compared with the WOE map and the PAI cartography by counting the pixels inside each susceptibility level, considering only the area at which probably the landslide has its source. The procedure is done by the zonal statistics on GIS support and counting the pixels inside the depletion area, it is possible to understand the landslide susceptibility distribution.

The depletion areas collected as a series of points have been transformed in a series of pixels composing the raster map of 5 meters resolution; the result is properly defined in the map represented in Figure 78:

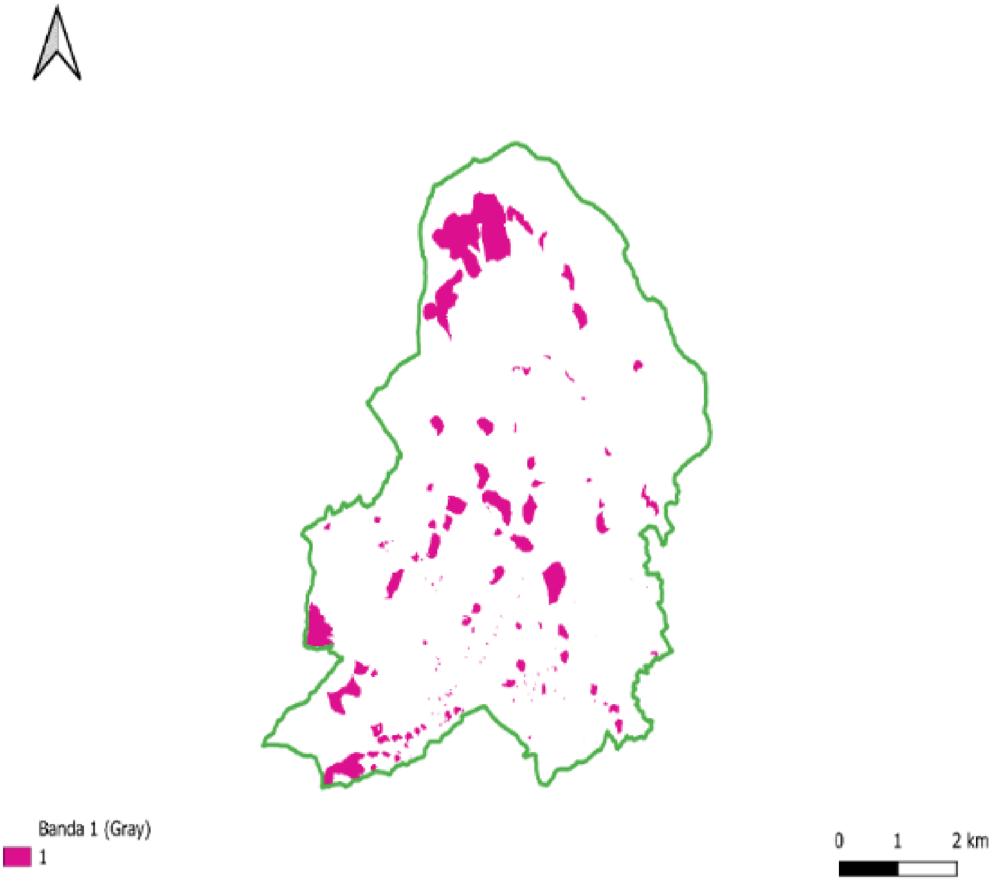


Figure 77: The raster map of IFFI depletion areas inside San Colombano Certenoli Municipality

4.8.4.1 Number of pixels divided by WOE susceptibility categories compared with IFFI inventory

To understand what type of susceptibility areas of WOE are inside the IFFI depletion zone, the landslides are compared with the different levels given by the WOE map to perform the histogram which shows the number of pixels present. It is a statistical count done category by category. The result is shown in the chart (Fig. 79).

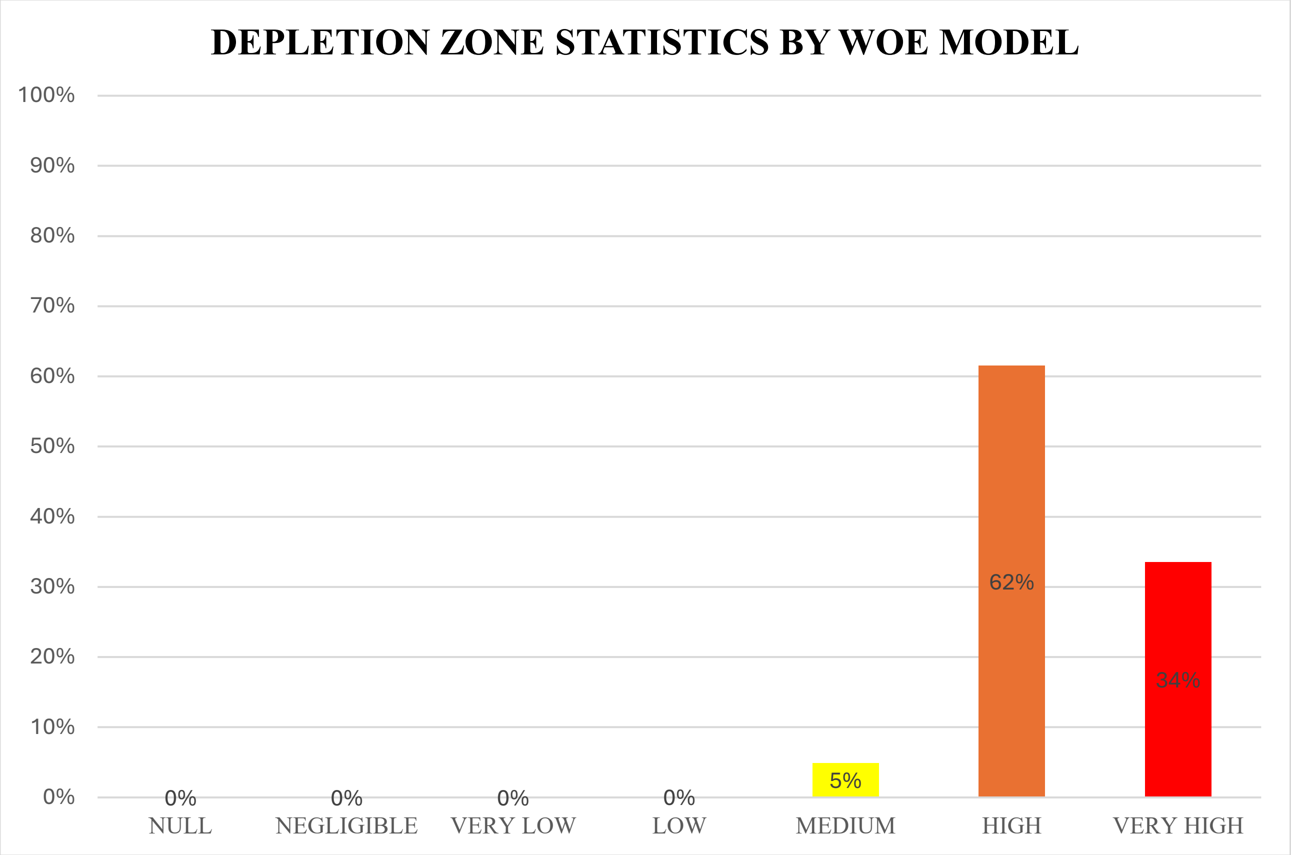


Figure 78: The number of WOE pixels inside the landslide depletion areas

The current histogram shows Weights of Evidence susceptibility levels inside the zones at which a landslide starts to occur; the largest percentage is represented by areas of high susceptibility which cover 62% of landslide bodies. If the average values are marginal (5%), the 34% of landslides is in very high susceptibility areas, which testifies a very high probability to have a landslide movement; the graph therefore provides a critical picture within the territory of San Colombano Certenoli.

Overall, about 96% of the cells fall into high – very high susceptibility classes, indicating that the depletion zone is characterized exclusively by high influence/hazard conditions according to the WOE model. These results can be a starting point for a more accurate and effective analysis of instability; finally, there are no trigger zones where the probability of a landslide movement occurring is low, so the statistical zonation is valid and reliable.

4.8.4.2 Number of pixels divided by PAI susceptibility categories compared with IFFI inventory

In this section, a statistical zonation is described comparing the landslide trigger zone from IFFI Inventory with the PAI regional cartography to identify the most critical aspects in terms of the number of landslides in areas with high susceptibility. The result of the analysis is defined in the histogram (Fig. 80). The goal is to compare the WOE susceptibility map with the PAI cartography to evaluate the different classes of susceptibility and the practical and operational solutions of them.

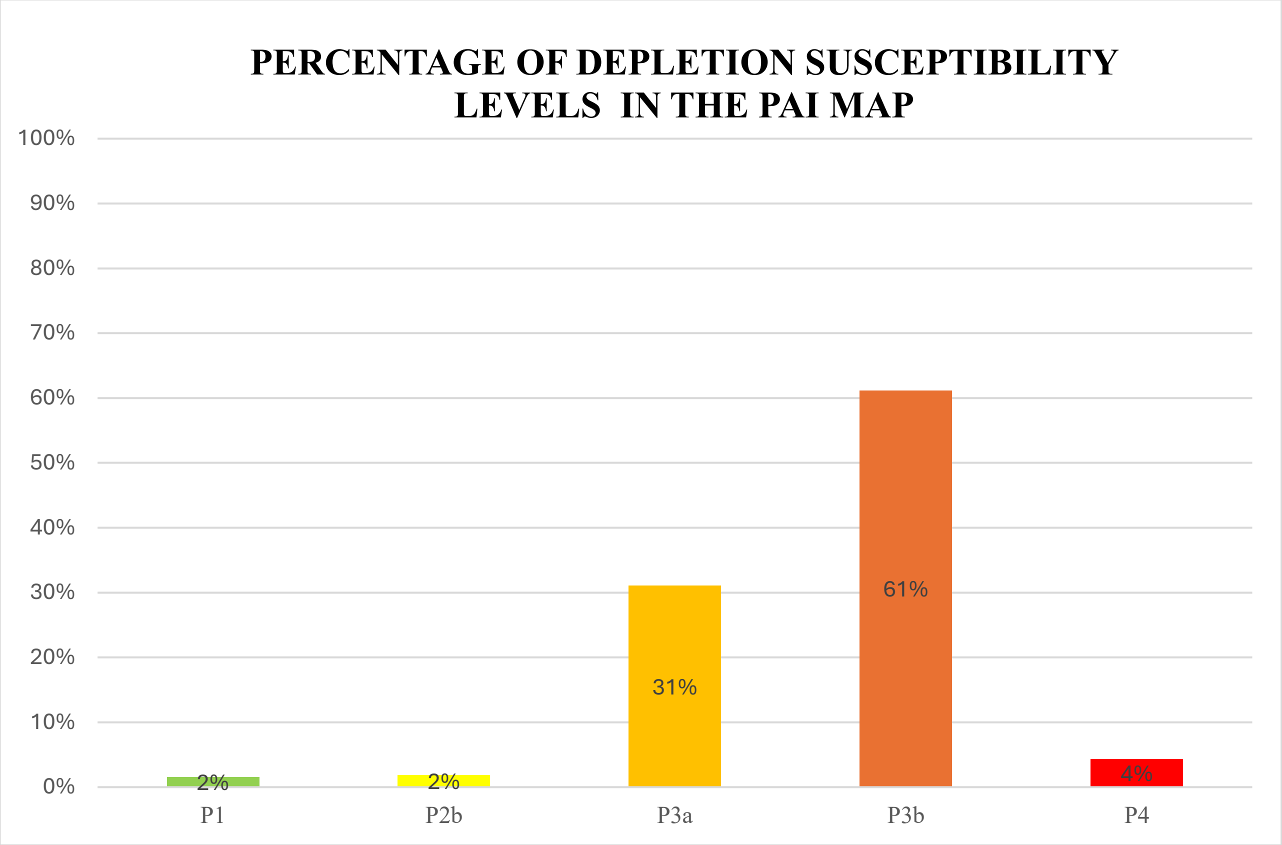


Figure 79: The number of PAI pixels inside the landslide depletion areas

The graph shows the percentage of cells in the PAI map calibration area, broken down by class (P1, P2b, P3a, P3b, P4). A clear predominance of the P3b class is observed, which represents 61% of the total cells. This indicates that most of the calibration area falls into a medium-high susceptibility class. This is followed by class P3a, with 31%, which contributes significantly but much less than P3b. Overall, classes P3a and P3b add up to more than 90% of the cells, showing a strong concentration in the high susceptibility classes. Classes P1 and P2b are marginal, both with about 2%, while class P4, associated with maximum hazard, is limited to 4% of cells. In summary, the calibration area is characterized by medium-high hazard levels, with a very low presence of low hazard classes and a contained, but not negligible, share of maximum hazard.

Finally, the comparison between two graphs shows a general consistency, but also a greater selectivity by the WOE model; in the chart related to the number of pixels located in the ablation zone of the PAI cartography, the distribution is mainly concentrated on the P3a (31%) and P3b (61%) classes, with a reduced presence of P4 (4%); in the WOE model, on the other hand, the distribution shifts decisively towards the higher classes (high and very high). In the lower classes, no pixels are included.

In other words, the PAI cartography shows a prevalence of medium-high probability with a more articulated gradation while the WOE model emphasizes the areas of maximum relevance, concentrating all the cells in the highest classes. This suggests that the WOE model, applied to the depletion zone, acts as a more restrictive filter, selecting the portions of territory with greater significance or risk, while the PAI provides a more distributed representation of susceptibility levels but non always reliable.

4.8.5 On site- qualitative landslide map validation

The qualitative validation of a map describing landslides is a fundamental step in assessing its reliability and usability, especially in the field of territorial planning and risk management.

Unlike quantitative validation, which relies on statistical indicators and numerical comparisons, qualitative validation focuses on the critical and interpretative analysis of the map content. It aims to verify the consistency between the mapped information and the geomorphological reality of the territory, considering the geological, structural, and environmental context.

The aim of the study is to qualitatively validate the WOE map of the territory of San Colombano Certenoli by looking for the correspondence between the mapped landslides and the evidence observable in the field to evaluate the reliability of the map. In this sense, on- site inspections represent an irreplaceable tool to confirm the type, state of activity and limits of landslide bodies.

A qualitatively valid map must not only be scientifically correct, but also understandable and functional to the purposes for which it was created, thus representing an essential step to ensure a conscious and effective use of cartography in decision support. From a qualitative point of view, it is expected that the landslides surveyed, those active or reactivated, fall into the medium-high or very high susceptibility classes. The widespread presence of landslides in areas classified as low susceptibility would represent an inconsistency that requires a critical analysis of the model and the factors used.

4.8.5.1 The analysis of Vignale critical issues

The paragraph shows initially the differences between the Official regional map and the WOE map, to understand how landslide susceptibility changes inside a little portion of San Colombano Certenoli territory. As an example, the landslide bodies of Caruggio di Vignale hamlet are analysed. In Figure 81 and 82 the differences between the two approaches are evaluated.

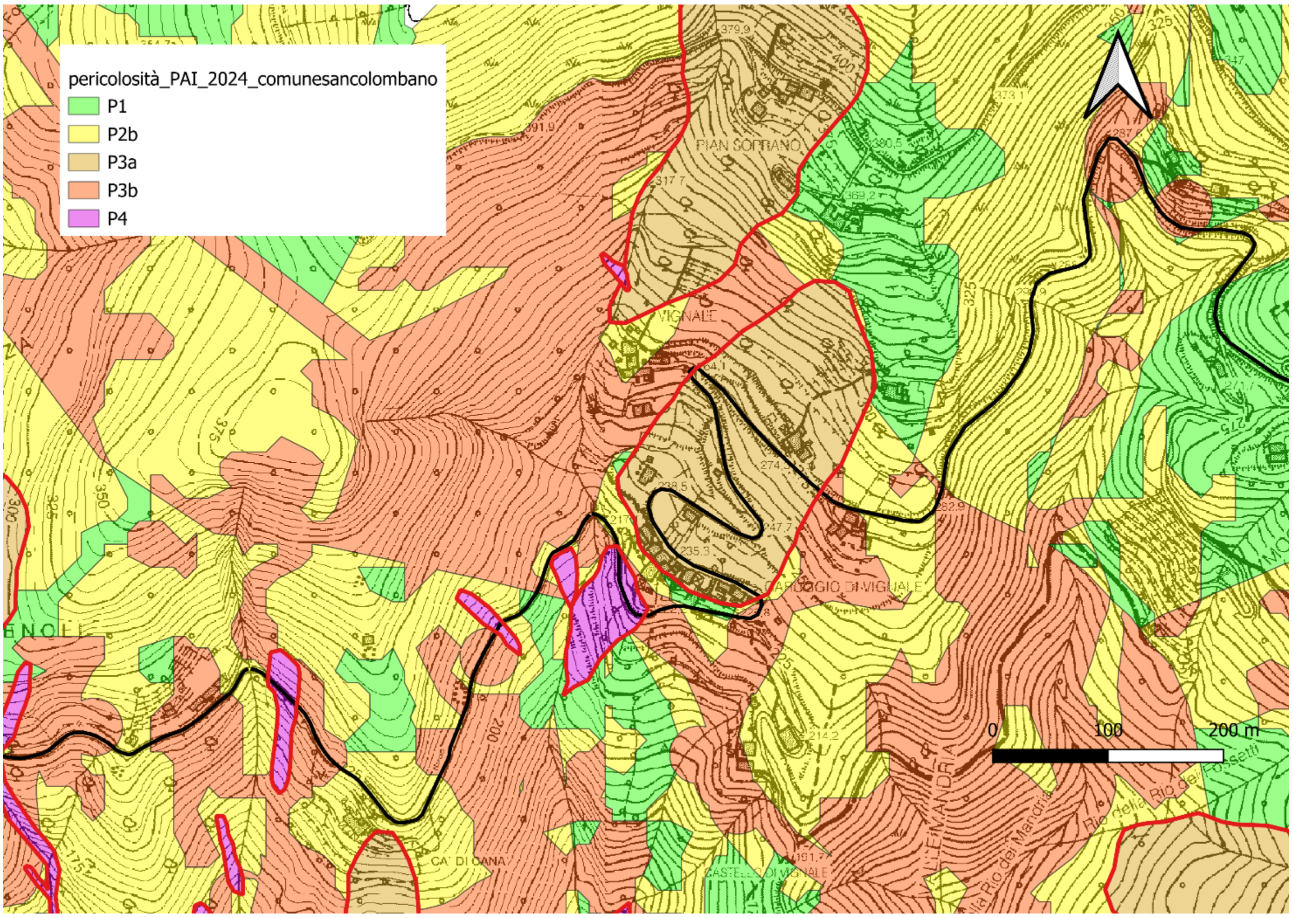


Figure 80: PAI section of Vignale area (5 levels of susceptibility)

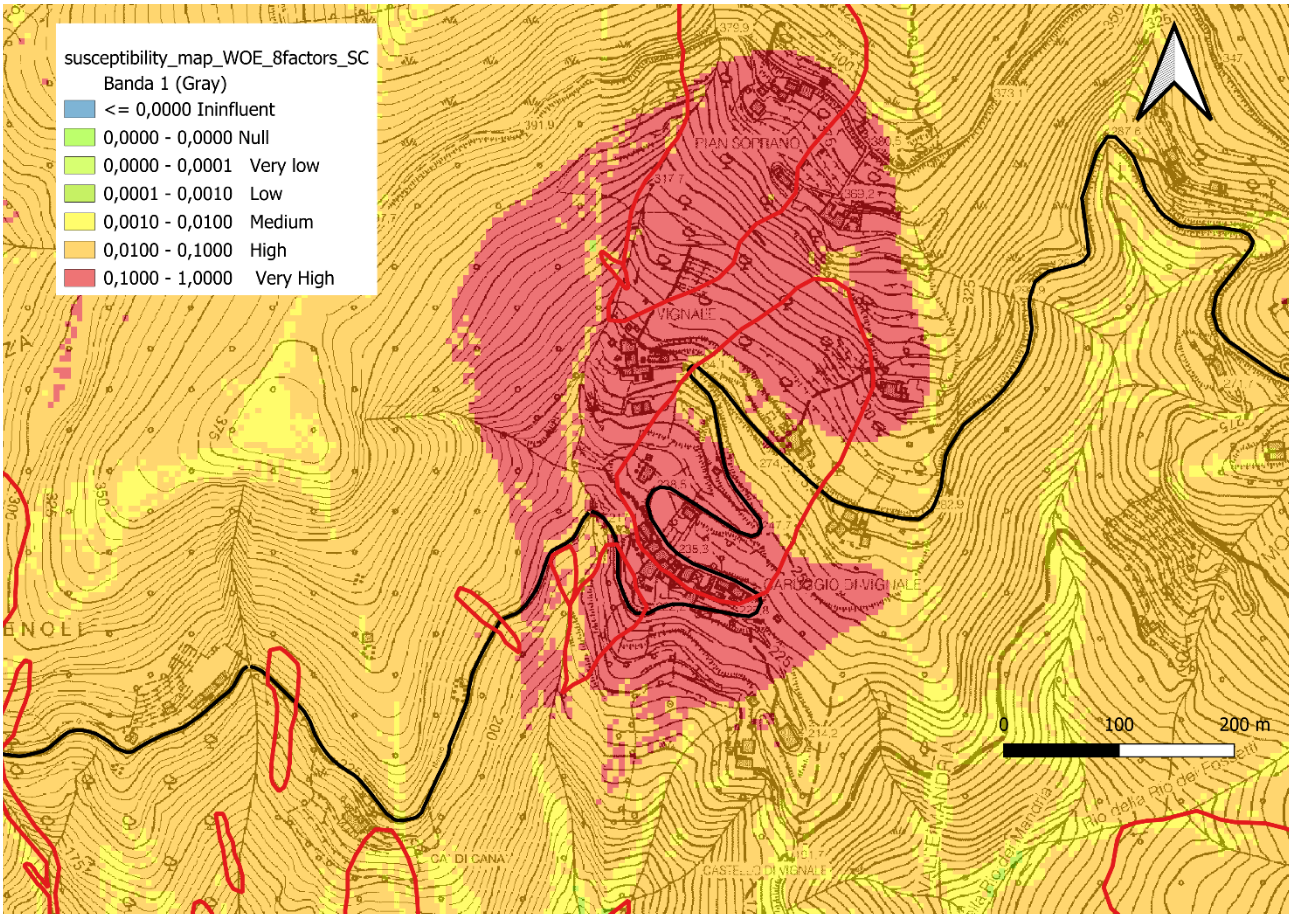


Figure 81: WOE section of Vignale area (7 levels of susceptibility)

The first chart figures out the susceptibility described by the PAI map. The vector map shows a constant and uniform probability to have a landslide inside the entire perimeter of it. There are no variations and changes because the susceptibility remains stable. Looking at the WOE map, the probability to have a failure changes zones by zones; the susceptibility zoning, lets experts to understand the potential critical areas close to infrastructures and surface elements as roads. The raster form of the map helps technicians to evaluate immediately mean and high susceptibility levels to perform efficient landslide mitigation measures with respect the categories given by the map. Another interesting point is that inside the WOE map, the red areas follow the influence of the lithology introduced as predisposing factor inside the model; in correspondence of red areas, there is the presence of colluvial deposits, which are often agents of a landslide occurrence. Indeed, in PAI description there is an intermediate area between the active landslide (purple) and the quiescent landslide (light brown) signed in green, which means a low probability of occurrence. On the contrary, the Weights of Evidence map gives a critical and real view, depicting very high susceptibility levels in correspondence of the road and the exposed assets.

Looking at the WOE map, an on-site qualitative validation has been performed, directly on the field. A series of pictures have been taken pointing out three sections:

- the active landslide involving the road (1)
- an exposed asset of the hamlet (2)
- a portion of dormant landslide above the hamlet (3)

The Figure 83 is a zoom of the landslide body in terms of WOE susceptibility inside the Caruggio di Vignale hamlet. Three key points are identified and shown in Figure 84, 85, 86.

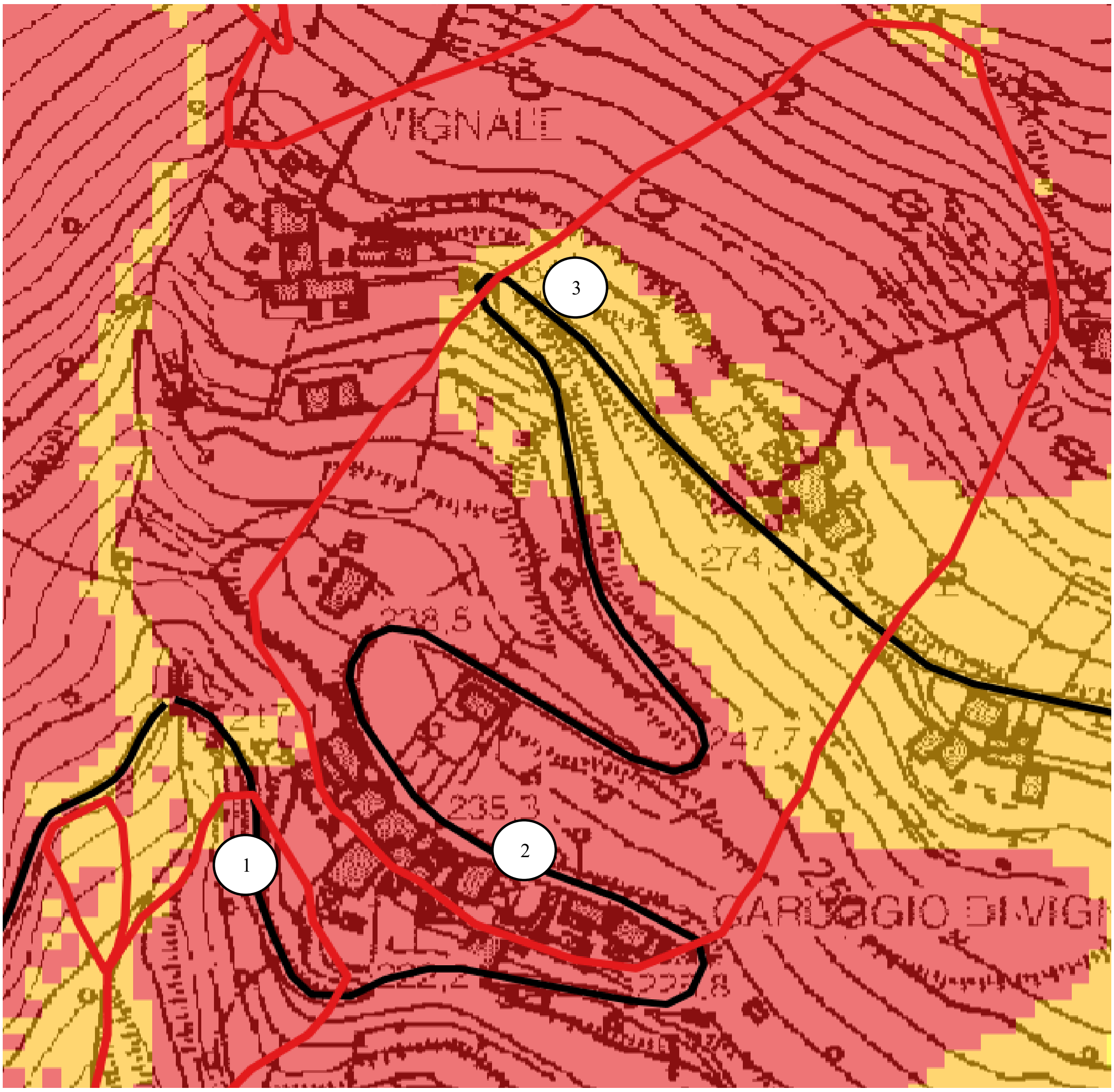


Figure 82: The WOE section map of Caruggio di Vignale susceptibility area; (1) fracture on the road, (2) damage on the wall of an exposed assets, (3) road condition inside the dormant landslide

Figure 83: The surficial fracture on the road (1)

Figure 84: The damage on the exposed asset's wall (2)

Figure 85: A road detail inside the dormant landslide (3)

Figure 83 shows an area characterized by widespread slope instability, with a prevalence of areas with very high susceptibility (in red) and areas with high susceptibility (in yellow), in an engraved morphological context, with significant slopes and infrastructures (roads and built-up areas) that directly interfere with the landslide bodies. The spatial distribution of landslides suggests a complex unstable system, controlled by both natural factors (lithology, structural structure, morphology) and anthropogenic factors (roads, buildings, drainage changes).

In correspondence with Figure 84, the municipal road insists on an active landslide, representing an element of high susceptibility. The active landslide indicates that the deformation processes are underway. The road, in addition to being an exposed element, can also act as a predisposing or aggravating factor, as it alters the regime of surface and underground water and introduces artificial loads and cuts into the slope. The fracture of the road system indicates, as evidenced by the inspection, a picture of high criticality and finds an effective correspondence in the mapping of weights.

In Figure 85, structural damage to a wall is a direct indicator of slow but active ground deformations, often attributable to slow-moving landslides (sliding or landing). Even if the area could formally fall into an area not completely classified as "active", the presence of lesions testifies to an ongoing or in any case recent deformation dynamics with transmission of deformations from the slope to anthropogenic structures. From the point of view of susceptibility, this point highlights that even apparently less critical sectors can manifest significant effects, indicating a very high susceptibility, especially for building elements.

Point (3) in Figure 86 indicates a much better condition of the road surface in the dormant landslide than point (1). The area is in an area of latent susceptibility, which can evolve into activities in response to external factors (prolonged rainfall, changes in drainage, vibrations, anthropogenic interventions). Compared to point (1), the susceptibility is lower, but still not negligible, especially considering the spatial continuity with active landslide areas. This point reinforces the idea of an unstable slope, but less critical than the portion of the road below the exposures of the first photograph.

Overall, field validation proved to be effective. The map of weights allows us to better identify how the coexistence of active and quiescent landslides, combined with the presence of infrastructures and housing, suggests that the slope system is dynamically unstable and that susceptibility cannot be assessed in a timely manner, but must be considered at the slope scale, with a precautionary approach in land planning and management.

4.8.5.2 The road failure in Camposasco area

The last section concerns the validation of another landslide area involving the wide territory of San Colombano Certenoli. In January 2025, the Southwest of the Municipality was affected by adverse climatic conditions which lead to a series of movements which had an impact on some Municipal roads. It is now analysed the case study of Camposasco, a hamlet of the Public Administration.

In January 2025, a significant hydrogeological instability event occurred in Camposasco, impacting on the provincial road (SP 32), a road infrastructure of fundamental importance for connections between the hinterland and the Tigullio district. The phenomenon manifested itself in the form of a slope landslide, which led to a sliding downstream of the road surface, accompanied by the appearance of cracks, lowering and deformation of the roadway.

The causes of the event are attributable to the intense rainfall recorded in the previous days, which increased the degree of saturation of the soil, reducing its resistance and favouring the triggering of gravitational movement. The instability of the slope has led to a rapid deterioration of the safety conditions of the roadway, making it necessary for the competent bodies to make action immediately. The closure of the road has had significant repercussions on the local road network, interrupting the connection between different hamlets of the municipality. Figures 87 and 88 show the levels of susceptibility to instability for the regional cartography and the WOE map, respectively.

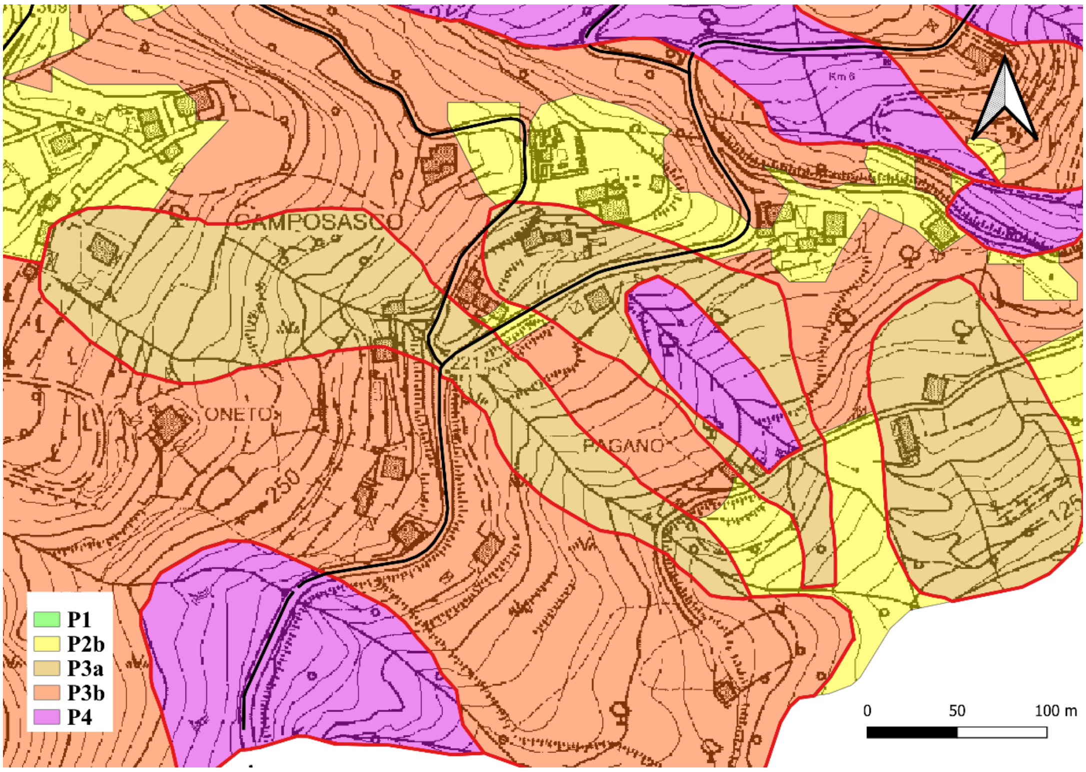


Figure 86: PAI section of Camposasco area (5 levels of susceptibility)

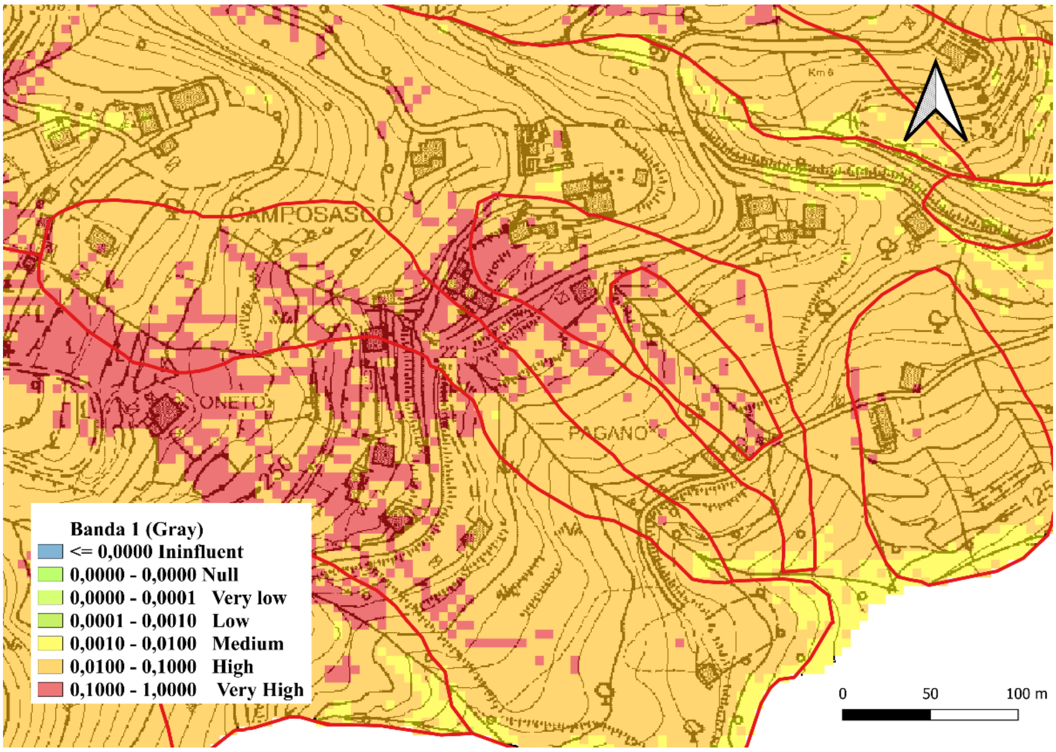


Figure 87: WOE section of Camposasco area (7 levels of susceptibility)

The Figure 87 shows the vector layer of PAI cartography in Camposasco area, as the outcome of geomorphological approach based on landslide bodies previously known by IFFI inventory; the landslide susceptibility is the evaluation of stable and unstable areas with a polygon representation. In Figure 88, the

WOE map is the result of statistical analysis, as the combination between the depletion zone of landslides selected and the predisposing factors; the landslide susceptibility is described by the combination of a sequence of pixels which show the degree of landslide probability.

If the PAI map points out a static and uniform approach, whose sensitivity is low for local changes, the WOE map gives a variable and spatially detailed study of a potential landslide being effective in portions close to linear infrastructures. Indeed, the P4 and P3a (very high and high susceptibility) have some correspondence with red and orange zones highlighted by the WOE, so the maps are convergent but at the same time complementary.

To understand better what happened in January 2025 and to verify the reliability of the WOE map, an on- site validation has been performed. The Figure 89 shows a zoom in the point at which the road started to break down. Three key points have been highlighted as:

- retaining wall split (1)
- the road failure (2)
- the road declivity (3)

The pictures are shown respectively in Figure 90, 91, 92.

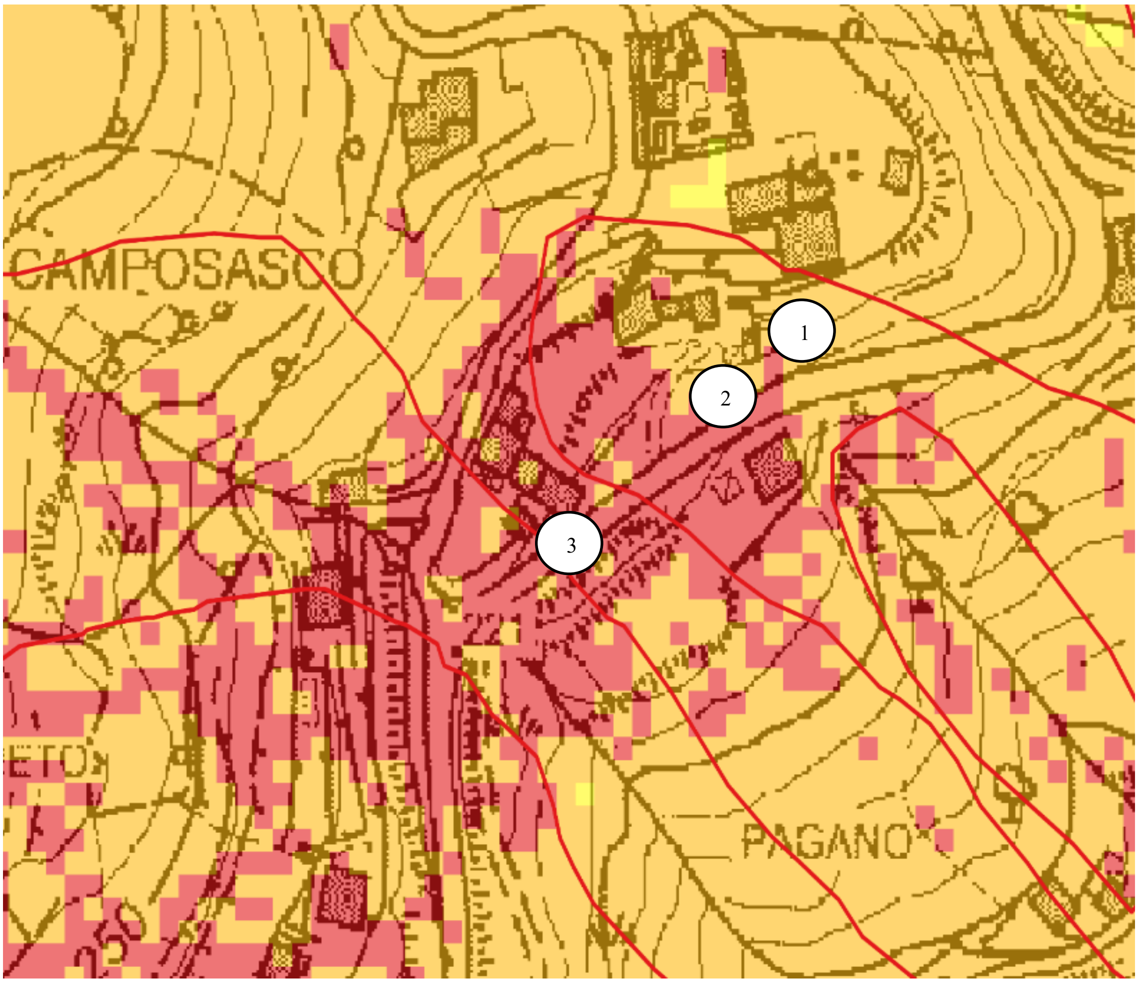


Figure 88: The WOE map section of Camposasco susceptibility area; (1) wall split, (2) road failure, (3) the declivity of the road

Figure 89: Retaining wall split (1)

Figure 90: The road failure (2)

Figure 91: The road declivity (3)

The on – site survey has let to perform a punctual validation of WOE map, pointing out the evidence on the field with the different susceptibility classes. The provincial road is inside a big quiescent landslide and below an active landslide. In point (1), the retaining wall split is the consequence of a translational sliding triggered by adverse climatic conditions. It is interesting to observe that the wall subsidence is localized exactly when the scenario of susceptibility suggests a very high probability to have a landslide (red pixels); this is a clear signal that the instability conditions are coherent with the levels of susceptibility assigned by the WOE map.

In Figure 91, the road crack is localised inside very high levels of susceptibility; the deformation and the subsidence of road level is the clear consequence of sliding effect as the combination between the quiescent and the active landslide action; the critical conditions are punctually described by the WOE map which is valuable and reliable.

The point 3 shows the centre of linear infrastructure localized in very high susceptibility zone (red pixels); observing the WOE map, the road declivity occurs exactly when the levels of susceptibility change from very high to high susceptibility; it can be connected to the morphological response to soil settlement processes which lead to a potential unstable condition. The results of the on- site survey confirm the coherence between the susceptibility classes defined in the WOE map and the landslide conditions observed on the field, supporting the validation of susceptibility model.

4.9 Conclusion

The application of the Weights of Evidence (WOE) method across the different study areas provided consistent and meaningful results, confirming the effectiveness of data-driven statistical approaches for landslide susceptibility assessment at meso-scale. The analyses carried out in both the Alpine context and the Entella basin highlighted a strong correlation between the selected predisposing factors and the spatial distribution of past landslides, allowing the generation of susceptibility maps capable of identifying the most critical areas with good accuracy.

In the Alpine case study, the results showed that specific geomorphological and lithological conditions, combined with extreme rainfall events such as the Alex Storm of 2020, played a decisive role in triggering widespread slope instability. The susceptibility maps produced were able to capture these dynamics, emphasizing areas with high and very high susceptibility that correspond well with the observed landslide patterns. The validation phase, supported by success and prediction curves, demonstrated satisfactory model performance, confirming the reliability of the selected variables and the robustness of the methodological approach.

In the Entella basin and the Municipality of San Colombano Certenoli, the application of different modelling strategies (centroids, depletion zones, and complex landslides) provided a more articulated understanding of landslide processes. The results highlighted how the choice of the landslide representation significantly influences the spatial distribution of susceptibility classes. In particular, the depletion zone approach proved to be more effective in capturing the initiation areas of landslides, while the centroid-based method offered a simplified but still informative representation. The analysis of complex landslides further improved the interpretation of areas affected by multiple or evolving instability phenomena.

Quantitative validation through zonal statistics showed that a significant percentage of observed landslides fall within the highest susceptibility classes, confirming the predictive capability of the models. At the same time, the comparison with existing PAI cartography revealed both consistencies and discrepancies, suggesting that the proposed methodology can complement and, in some cases, refine official hazard zoning. Qualitative on-site validation reinforced these findings, allowing the identification of local critical issues, particularly along municipal road networks and in areas with high exposure.

Overall, the outcomes of Chapter 4 demonstrate that the integration of statistical modelling and GIS tools provides reliable and operational results for landslide susceptibility assessment. The generated maps not only reflect the spatial patterns of past events but also offer a valuable basis for future risk management strategies, supporting both technical analyses and administrative decision-making processes.

CHAPTER 5: FINAL REMARKS

5.1 Synthesis of results

The research demonstrates that the integration of geomatics tools, statistical methods, and administrative frameworks provides an effective approach to support landslide risk management in small–medium municipalities. The application of data-driven models, particularly the Weights of Evidence (WOE) method within a GIS environment, proved to be reliable in identifying areas with higher susceptibility to landslides. The validation procedures, both quantitative (zonal statistics, success and validation curves) and qualitative (field surveys), confirmed the consistency between predicted susceptibility and observed landslide occurrences. The comparative analysis between different case studies, including the Alpine context and the Entella basin, highlighted how the selection of predisposing factors and the quality of input data strongly influence model performance. Moreover, the research underlined the importance of integrating technical results with institutional tools such as PAI cartography and Civil Protection planning. The outcomes show that susceptibility maps can act as operational decision-support instruments, enabling public administrations to prioritize interventions, allocate resources efficiently, and design targeted mitigation strategies. Overall, the study confirms that a multidisciplinary and scalable methodology enhances both the scientific robustness and the practical applicability of landslide risk assessment, contributing to more resilient territorial planning.

5.2 The scientific contribution

This research provides a scientific contribution to the field of landslide risk management by advancing the application of multi-criteria and data-driven methodologies within a geomatics-based framework. The study enhances existing knowledge by systematically integrating statistical approaches, particularly the Weights of Evidence (WOE) method and multivariate regression models, with GIS tools to produce reliable and reproducible landslide susceptibility assessments at municipal scale. A key contribution lies in the comparative implementation of different modelling strategies (centroids, depletion zones, and complex landslides), which allows for a deeper understanding of how methodological choices influence susceptibility outcomes and model performance.

Furthermore, the research contributes to the scientific debate by proposing a structured validation workflow that combines quantitative statistical techniques (such as success/validation curves and zonal statistics) with qualitative field inspections, thus improving the robustness and credibility of susceptibility maps. The adaptation of these methodologies to data-scarce contexts typical of small–medium municipalities represent an important advancement, demonstrating that accurate and meaningful results can be achieved even with limited resources.

Another relevant contribution is the integration of technical susceptibility analysis with administrative and planning frameworks, bridging the gap between scientific modelling and practical decision-making. By aligning susceptibility outputs with existing institutional tools (e.g., PAI cartography and Civil Protection planning), the research promotes a more operational use of scientific results. Overall, the work offers a replicable and multidisciplinary approach that can be transferred to similar territorial contexts, contributing to the development of more effective, data-informed, and sustainable landslide risk management strategies.

5.3 Operational and administrative contributions

Beyond its scientific value, this research provides a concrete operational and administrative contribution by supporting Public Administrations in the practical management of landslide risk, particularly within small–medium municipalities characterized by limited technical and financial resources. The study demonstrates how landslide susceptibility maps, developed through GIS-based statistical methodologies, can be effectively integrated into routine municipal activities, becoming a decision-support tool for territorial planning, infrastructure management, and emergency preparedness.

From an operational perspective, the work offers a structured and replicable workflow that guides technicians in the collection, processing, and interpretation of spatial data related to landslides. The use of accessible tools and standardized procedures enables local administrations to independently update susceptibility assessments, monitor critical areas, and identify priority zones for intervention. This is particularly relevant for road networks and exposed assets, where the timely identification of critical issues can reduce maintenance costs and prevent more severe damage.

From an administrative standpoint, the research facilitates the alignment between technical analyses and existing regulatory frameworks, such as basin planning instruments and Civil Protection procedures. By comparing the results of susceptibility models with official cartographies (e.g., PAI maps), the study highlights discrepancies and potential improvements, supporting more informed decision-making processes. This integration enhances the capacity of municipalities to justify funding requests, prioritize mitigation measures, and comply with regional and national regulations.

Moreover, the work promotes a multidisciplinary and collaborative approach, encouraging interaction between engineers, geologists, and administrative staff. It strengthens the role of Public Administration not only as a recipient of technical analyses but as an active actor in the risk management cycle. The proposed methodology contributes to improving governance, optimizing resource allocation, and increasing the overall resilience of the territory through more effective and proactive landslide risk management strategies.

5.4 Limitations of the research

Despite the methodological robustness and practical applicability of the proposed approach, this research presents some limitations that should be acknowledged to correctly interpret the results and guide future developments.

A first limitation concerns the quality, availability, and temporal consistency of input data. Landslide susceptibility assessments strongly depend on the completeness and accuracy of landslide inventories and predisposing factors. In the case of small–medium municipalities, data are often heterogeneous, not regularly updated, or derived from different sources and scales. This may introduce uncertainties in the modelling process and affect the reliability of susceptibility maps, particularly in areas where past landslides are underreported or poorly documented.

A second limitation is related to the intrinsic assumptions of data-driven statistical methods, such as the Weights of Evidence and multivariate regression models. These approaches are based on the hypothesis that future landslides will occur under conditions like those observed in the past. While valid, this assumption may not fully account for changing environmental conditions, such as climate change, land-use modifications, or extreme events, which can alter slope stability dynamics and lead to unexpected phenomena.

Moreover, the spatial resolution and scale of analysis represent another constraint. The adopted methodologies are well suited for meso-scale applications but may not capture local-scale variability and site-specific conditions, which are crucial for detailed engineering design. Consequently, the susceptibility maps produced should be considered as screening tools rather than definitive instruments for project-level decisions, which require more detailed geotechnical investigations.

From an operational perspective, although the proposed workflow is designed to be replicable, its implementation still requires a minimum level of technical expertise in GIS and statistical analysis. This may limit its immediate adoption by all municipalities, particularly those lacking adequately trained personnel or technological resources.

Finally, the validation procedures, while comprehensive, are partly constrained by the availability of independent datasets and field verification opportunities. On-site validation may be limited by time, accessibility, and logistical factors, potentially affecting the completeness of qualitative assessments.

Overall, these limitations do not undermine the validity of the research but rather highlight the need for cautious interpretation of results and continuous updating of data and models. They also open pathways for future improvements, including the integration of dynamic variables, higher-resolution data, and more advanced modelling techniques.

5.5 Future perspectives

The outcomes of this research open several perspectives for future developments, both from a scientific and an operational point of view, with particular attention to the transferability of the proposed methodology to different territorial contexts. The approach developed in this study, based on the integration of GIS tools, statistical modelling, and administrative frameworks, has demonstrated a high degree of flexibility and scalability, making it suitable for application beyond the specific case study of the Entella basin and the Municipality of San Colombano Certenoli.

One of the main future perspectives concerns the improvement of data quality and availability through the integration of emerging technologies. The use of higher-resolution remote sensing data, real-time monitoring systems, and open-access geospatial platforms could significantly enhance the accuracy and timeliness of landslide susceptibility assessments. In particular, the incorporation of dynamic variables, such as rainfall thresholds, soil moisture conditions, and climate projections, would allow the transition from static susceptibility mapping to more advanced hazard and risk forecasting systems.

Another relevant development is the potential integration of the proposed methodology into Decision Support Systems (DSS) for Public Administrations. By embedding susceptibility maps within digital platforms, local authorities could benefit from interactive tools capable of supporting planning decisions, emergency management, and resource allocation in a more efficient and transparent way. This would further strengthen the link between scientific analysis and policymaking, fostering a proactive rather than reactive approach to landslide risk management.

The applicability of the methodology to different territorial contexts represents a key strength of the work. Although developed in a Mediterranean environment characterized by complex geomorphological and climatic conditions, the approach can be adapted to other regions, including mountainous areas, urbanized slopes, and regions affected by different triggering factors such as seismic activity. The modular structure of the workflow allows for the selection and customization of predisposing factors according to local conditions, ensuring its relevance across different geographical settings.

From a broader perspective, the impact of this research in the future lies in its contribution to enhancing territorial resilience and sustainable land-use planning. By providing accessible and scientifically sound tools, the work supports Public Administrations in making informed decisions, optimizing the use of financial resources, and reducing the socio-economic impacts of landslides. In the context of increasing climate variability and extreme weather events, such approaches will become increasingly important for risk prevention and adaptation strategies.

Finally, the research encourages a cultural shift towards a more integrated and multidisciplinary management of natural hazards, where technical expertise, administrative processes, and community awareness converge. Future studies could expand this work by incorporating socio-economic vulnerability assessments, cost–benefit analyses of mitigation measures, and participatory approaches involving local stakeholders. In this way, the proposed methodology can evolve into a comprehensive framework for landslide risk governance, contributing to safer and more resilient territories at both local and regional scales.

CONCLUSIONS

This doctoral research has addressed the complex issue of landslide risk management by proposing an integrated, multidisciplinary approach that combines scientific analysis, geomatics tools, and administrative frameworks. Starting from the recognition of landslides as a major natural hazard affecting vulnerable territories, particularly in small–medium municipalities, the work has highlighted the need for effective and accessible tools to support both technical assessments and decision-making processes.

The study has first established a solid theoretical foundation by reviewing the state of the art in landslide susceptibility assessment methods, with particular attention to statistical and GIS-based approaches. It has then examined the legislative and institutional context, underlining the importance of regulatory instruments and the role of Public Administrations in managing hydrogeological risk. The integration of these perspectives has been essential to frame the research within a real operational context.

Through the analysis of case studies, including the Municipality of San Colombano Certenoli and the Entella basin, the research has demonstrated the applicability and effectiveness of data-driven methods such as the Weights of Evidence model. The results have shown that these approaches can produce reliable landslide susceptibility maps, especially when supported by accurate input data and rigorous validation procedures. The comparison between different modelling strategies has further contributed to understanding the strengths and limitations of each approach.

A key outcome of the research is the recognition of landslide susceptibility maps as valuable decision-support tools. When properly validated and integrated with official cartographies and planning instruments, these maps can guide Public Administrations in identifying critical areas, prioritizing interventions, and allocating resources more efficiently. In this sense, the work has demonstrated how scientific outputs can be translated into practical applications, bridging the gap between research and governance.

At the same time, the study has acknowledged the limitations related to data availability, methodological assumptions, and scale of analysis, emphasizing the need for cautious interpretation and continuous updating of models. These aspects, together with the proposed future perspectives, highlight the dynamic nature of landslide risk assessment and the importance of ongoing research and technological innovation.

In conclusion, this work contributes to the advancement of landslide risk management by providing a replicable, flexible, and operational methodology tailored to the needs of local administrations. It reinforces the idea that an integrated approach—combining technical, administrative, and territorial knowledge—is essential to enhance resilience and support sustainable planning strategies. The results achieved represent a step forward towards more informed, proactive, and effective management of landslide-prone areas, with potential benefits extending to a wide range of geographical and institutional contexts.

The use of advanced technological tools such as GIS systems, capable of integrating heterogeneous data and supporting spatial and complex statistical analyses, can provide solid support to territorial planning activities, spending many economic sources in an efficient and aware way. In this context, the combination of administrative criteria, technical-engineering aspects, and data analysis with ICT technologies, contributes significantly to strengthening the resilience of San Colombano Certenoli Municipality and territories with similar needs, giving the right tools to perform efficient and sustainable strategies necessary to manage the delicate phase of landslide risk management.

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