Landslide information for land management and planning: Examples from Italy and Croatia

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Abstract Landslide information and derived mapping products are relevant tools to support local authorities in land use management and planning. Landslide inventory maps are the basis to evaluate landslide susceptibility, hazard, and risk at different scales. Accurate landslide mapping and geotechnical characterisations can be of paramount importance for the comprehension and set-up of landslide forecast models. In addition, information on landslide spatial occurrence (i.e., susceptibility) is fundamental to evaluate the instability of the territory and can be a relevant component of early warning systems, which focuses on the forecast of multiple or populations of landslides over large areas based on the monitoring of a potential landslide trigger (e.g., rainfall). The article presents different landslide maps produced at different scales for scientific, technical, or institutional purposes in Croatia and Italy. The maps at national, regional and local scales can be relevant tools and scientific support for land management and planning.

Keywords Landslide maps, Croatia, Italy, land management and planning

Introduction

Landslides are widespread phenomena that cause casualties and extensive damage worldwide. Landslides can be caused by different triggers, including rainfall, earthquakes, rapid snowmelt, and human activities. The approach of avoiding landslide-prone areas is rarely feasible, and it is neither possible nor desirable to proscribe development in all landslide-prone areas. The challenging task is to choose and apply, implement and finance the most effective mitigation approaches. For this, it is necessary to have information on landslides spatial occurrences in the form of landslide inventory and susceptibility maps. Significant reductions in potential losses and damages can be achieved by combining landslide hazard mitigation measures through spatial planning with emergency management measures.

In Italy, intense or prolonged rainfall is the primary trigger of landslides. Damaging failures occur every year in this country, where they have caused more than 6 300 casualties in the 60-year period, 1950–2009 (Salvati et al., 2010). Consequently, research to determine the amount of rainfall necessary to trigger landslides is of scientific and social interest. In Italy, there are several examples of landslide maps prepared at different scales: (i) the IFFI catalogue compiled at a national level, by the Italian Institute for Environmental Protection and Research for the entire Italian territory; (ii) a mosaic of landslide hazard maps, originally prepared by the regional administrations following national criteria. As an example of the use of landslide maps, the prototype SANF system (Sistema per l'Allertamento Nazionale da Frana), developed by CNR IRPI for the Italian Civil Protection Department, forecasts the possible occurrence of landslides by comparing rainfall measurements and forecasts with rainfall thresholds for the possible occurrence of failures.

In Croatia, despite the long tradition of landslide mapping in Zagreb city (1950-today), there is a lack of suitable, officially accepted landslide maps, which is the main problem with the current landslide risk management practices at all levels, from national to local (Mihalić Arbanas et al., 2016). Since landslides are widespread in different parts of Croatia, and thus the risk of possible accidents and catastrophic consequences, it is necessary to establish a systematic of landslide maps to mitigate landslide hazards and risks. Important results were achieved in the framework of two scientific projects (2020-2023) that provided prototypes of different types of landslide maps for land management and planning at all levels (Mihalic Arbanas et al., 2023; Bernat Gazibara et al., 2023). Besides mapping methodologies, the research projects were also focused on multiple aspects related to map uses and were conducted together with spatial planners, developers and administrations at all levels in the Republic of Croatia.

The aim of this paper is to describe two approaches and experiences of multi-level landslide mapping: the Croatian derived from national scientific projects and the Italian from current practices and trends. The first part presents all landslide maps required by potential users dealing with the creation and implementation of spatial and urban plans in Croatia. The second part illustrates different landslide maps produced in Italy at different scales for scientific, technical, or institutional purposes.

Landslide maps in Croatia

Background

In Croatia in the past decade, various types of landslide mapping and modelling have been applied for the purpose of land management and planning. Several recent examples of inventory maps were prepared at large scale (1:2 000) using visual interpretation of LiDAR DTM (Digital Terrain Model) morphometric derivatives. The EU-funded project PRI-MJER (https://pri-mjer.hr/) explored the optimal landslide inventory required at the municipal level. Large-scale landslide susceptibility zonations were derived using statistically based methods in the framework of the scientific research project LandSlidePlan (https://landslideplan.eu/), funded by the Croatian Scientific Foundation. To ensure a rational approach to landslide mapping in the entire Croatian territory, a prototype of a landslide susceptibility map was produced at a medium scale (1:25 000) with areas classified into three levels (Fig. 1a).

Large-scale inventory maps

The large-scale inventory maps for different study areas were compiled in the period 2017-2023 (Đomlija, 2018; Bernat, 2019; Jagodnik et al., 2023; Krkač et al., 2022; Bernat Gazibara & Mihalić Arbanas, 2023). Identification and mapping of landslides was carried out for six study areas (total area of about 194 km²) by visual interpretation of morphometric maps derived from LiDAR DMT of 0.3 - 1-m resolution (Airborne LiDAR Scanning in the periods 2012-2020). The results are representative landslide inventories containing precise and reliable landslide contours on a detailed scale for the entire study area, including densely vegetated areas. Landslide inventory maps on a 1:2,000 scale can be used to prepare maps of special restrictions for the development and implementation of spatial plans, but they are also input data for landslide susceptibility evaluation, as well as hazard and risk assessments.

Table 1 shows a summary of information about landslide types and dimensions derived from the inventory maps. Landslide area statistics performed for study areas in different geomorphological environments in Croatia provided useful information on the number and dimensions of the phenomenon. For example, the landslide density in Zagreb is 33.3 landslides/km², but the total area is only 0.5 km² or 2.43% of the area because the phenomena are small and shallow. Figure 1c presents an example of information derived from the landslide inventory map showing the spatial distribution of all historical landslides in Zagreb hills (Pannonian Basin).

Large-scale landslide susceptibility maps

Landslide susceptibility assessment was performed to produce zoning maps on 1:5,000 scale for six study areas (total area of about 194 km²) using LIDAR-derived landslide inventories. The assessment was performed by statistical analysis of random forests using relevant factor maps belonging to morphological, geological, hydrological, and anthropogenic conditions. The research was also focused on the influence of different modelling methods, cartographic units and graphical representations of landslides used in analyses (Bernat Gazibara et al., 2023). The optimal results were derived using a regular grid of 5x5 m and 50 % of randomly selected landslide polygons.

Figure 1d shows examples of landslide information from the landslide susceptibility map of the study area in Zagreb: 45.9 % of low susceptibility zone (9,7 km²), 39.3 % of medium susceptibility zone (8.3 km²), 14.7 % of high susceptibility zone (3.1 km²). Unlike the Pannonian basin environments, the spatial distribution of susceptibility zones in flysch areas in the Dinarides and Adriatic Plate (Istrian Peninsula) is strongly related to erosion phenomena and deep fossil landslides.

Table 1 Information on landslide type and dimension derived from inventory maps

Study area	Landslide types	Total number of landslides	Landslide density (number per km²)	Landslide area (m²)				
				Min.	Max.	Mean	Median	St. dev.
Hrvatsko Zagorje (20 km²)	Soil slide, soil flow	912	45	3	13,778	448	173	879
Podsljeme Hils (20 km²)	Soil slide	702	33	43	8,064	730	427	942
Karlovac (50 km²)	Soil slide	1,069	21	13	8950	224	131	420
Vinodol Valley (20 km²)	Soil slide, soil slide-debris flow	627	31	65	49,462	2337	1218	4498
Rječina River Valley (19 km²)	Soil slide, soil slide-debris flow	1300	68	14	78,364	720	179	3122
Buzet (20 km²)	Soil slide, soil slide-debris flow	1,782	89	-	-	-	-	-

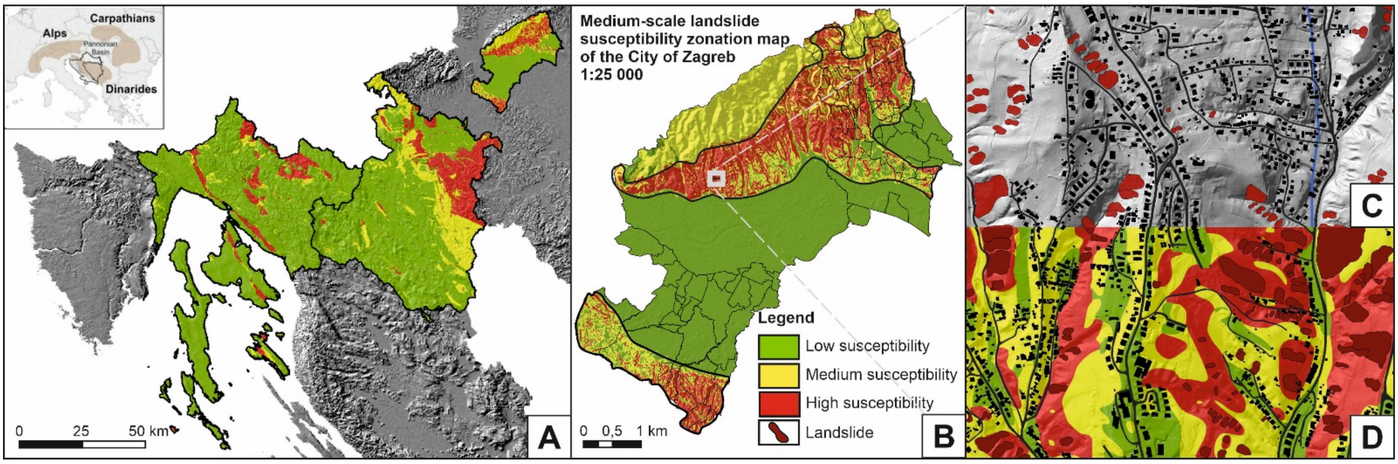

Figure 1 Examples of landslide maps in Croatia: (a) regional level mosaic susceptibility map; (b) susceptibility map of the City of Zagreb (regional level, County status) at 1:25,000 scale; (c) local level susceptibility map at 1:5,000 scale; (d) local level inventory map at 1:2,000 scale.

Medium-scale landslide susceptibility maps

Another important piece of information for land management and planning is the susceptibility map at 1:25,000 scale that subdivides the territory into three zones according to the probability of landslide occurrence across three counties (Fig 1a). Spatial probability is estimated using a Fuzzy heuristic approach because of the lack of representative landslide inventory (Bernat Gazibara et al., 2023). Verification performed by incomplete landslide inventory (about 2,000 phenomena) showed satisfactory prediction results for regional scale landslide modelling (86 % of mapped landslides fall in high and very high susceptibility zones in Karlovac County and 89 % in Primorje-Gorski Kotar County).

The medium-scale susceptibility map shows the proportion of the area potentially prone to landslides for counties. For example, approx. 12% of the Primorje-Gorski Kotar County, approx. 32% of the Karlovac County and approx. 48 % of the City of Zagreb belongs to zones of medium and high susceptibility. Due to the lower precision of susceptibility assessment, the information provided by this map is recommended for use in spatial planning to identify where a more detailed susceptibility assessment is needed. Fig. 1b shows an example of how to outline areas where susceptibility mapping on a large scale is necessary for the City of Zagreb based on medium-scale zonation.

Landslide maps in Italy

Background

In Italy in the past decades, various types of landslide mapping and modelling have been produced at different scales for scientific, technical, or institutional purposes. For the entire national territory, institutional landslide maps have been mosaicked by the Italian Institute for Environmental Protection and Research (ISPRA) and the Basin Authorities (AdB, now organized into Hydrographic Districts), starting from cartographic products realized by Regions and the Autonomous Provinces. Recently, ISPRA has implemented IdroGEO, a national web platform, that allows the navigation, social sharing and download of data, maps, reports of the Italian landslide inventory, national hazard maps, and risk indicators (Iadanza et al., 2021).

The IFFI landslide inventory map

The most detailed landslide inventory map for the entire Italian territory (IFFI), was harmonized by ISPRA in the framework of a dedicated project (www.progettoiffi.isprambiente.it; https://idrogeo.isprambiente.it/app/). The IFFI map (Fig. 2) was realized by Regions and Autonomous Provinces following standardized and shared methods (Trigila et al., 2007) and includes 620,808 landslides, affecting an area of approximately 23,700 km²,

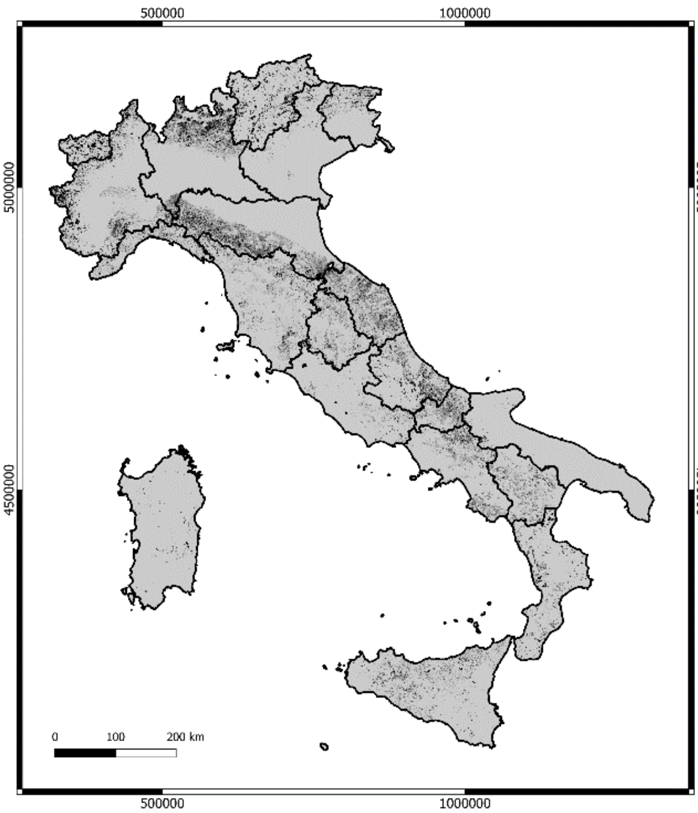

Figure 2 The map shows the IFFI landslide data (black polygons) for the Italian regions (black lines).

equal to 7.9% of the national territory. Landslides are available in vector format, as polygons with several associated information (e.g., locality, date, and type of landslide).

An analysis carried out by Trigila et al. (2010) attempted to verify the completeness and homogeneity of this national landslide map using three different methods of analysis: (a) areal frequency statistics; (b) analysis of the proximity of surveyed landslides to urban areas; and (c) analysis of the variation of the landslide index within the same lithology. The analysis revealed that IFFI is highly heterogeneous, with areas that are representative in terms of homogeneity and reliability and that can potentially be used for further assessment (for example, as training and calibration data for landslide susceptibility modelling) and areas where the collected information is underestimated or inaccurate. The IFFI data aim to facilitate the widest dissemination and use of landslide information to local governments, research institutions, technicians working in the field of land use design and planning, and citizens. Figure 2 shows the spatial distribution of the IFFI inventory for the entire national territory.

The PAI landslide hazard maps

The PAI landslide hazard maps (Fig. 3) were prepared for the Italian regions in the framework of a national project (www.isprambiente.gov.it) that was focused on identifying areas of possible evolution of existing landslides and areas where new landslides potentially may occur. In some regions, the original PAI maps prepared by the regional administrations were updated with local studies and investigations, recent landslide occurrences, and structural risk mitigation interventions. The PAI mapsshow polygons classified in five levels of severity: AA (area of attention), PAI1 (low), PAI2 (moderate), PAI3 (high), and PAI4 (very high). Figure 3 shows the spatial distribution of each level for Italy.

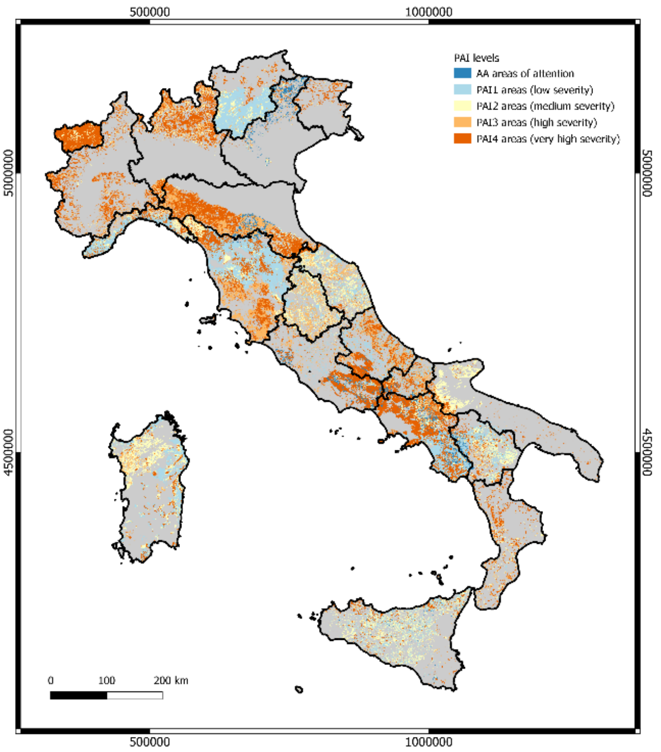

Figure 3 The map shows the distribution of the five PAI hazard levels (AA, H1, H2, H3, and H4) for the Italian regions (black lines).

The PAI maps were carried out, according to the criteria of the Act of Guidance and Coordination of the DPCM of 29/09/1998, by the Basin Authorities (now merged into the Hydrographic District Authorities according to the provisions of Law No. 221 of December 28, 2015), for the preliminary design of soil defence interventions and infrastructure networks and the drafting of Civil Protection Emergency Plans.

Large-scale landslide susceptibility maps

Another important information for land management and planning is the susceptibility map that subdivides the territory according to the probability of landslide occurrence across a given geographic space (Reichenbach et al., 2018). This probability is usually estimated by using a binary classifier which is informed of landslide presence/absence data and associated landscape characteristics. In Italy, the IFFI landslide inventory map was used to prepare slope-unit based landslide susceptibility maps. For each type of mass movement of the IFFI inventory (Complex, Deep Seated Gravitational Slope Deformation, Diffused Fall, Fall, Rapid Flow, Shallow, Slow Flow, Translational), a different susceptibility zonation was prepared using a Bayesian version of a Generalized Additive Model. The landslide susceptibility maps were prepared considering the following three aspects: (a) spatial homogeneity/ heterogeneity of landslide inventories, (b) a solid approach to the susceptibility estimation, and (c) the use of SU as geomorphologically sound mapping units (Loche et al., 2022).

SANF system - example of the use of landslide maps

In the context of the scientific activities carried out for the Italian National Department for Civil Protection, IRPI has designed and implemented an early-warning system to forecast the possible occurrence of rainfall-induced landslides in Italy. The system named SANF (an Italian acronym for National Early Warning System for Rainfall Induced Landslides), forecasts the possible occurrence of landslides by comparing rainfall measurements and forecasts with rainfall thresholds for the possible occurrence of landslides (Fig. 4). For this purpose, a national rain gauge network provides rainfall measurements, and numerical weather models provide synoptic-scale quantitative rainfall forecasts. The landslide forecasts are based on rainfall thresholds of the mean Intensity-Duration type that are used to define critical levels for the possible occurrence of landslides, in different classes (Rossi et al., 2012).

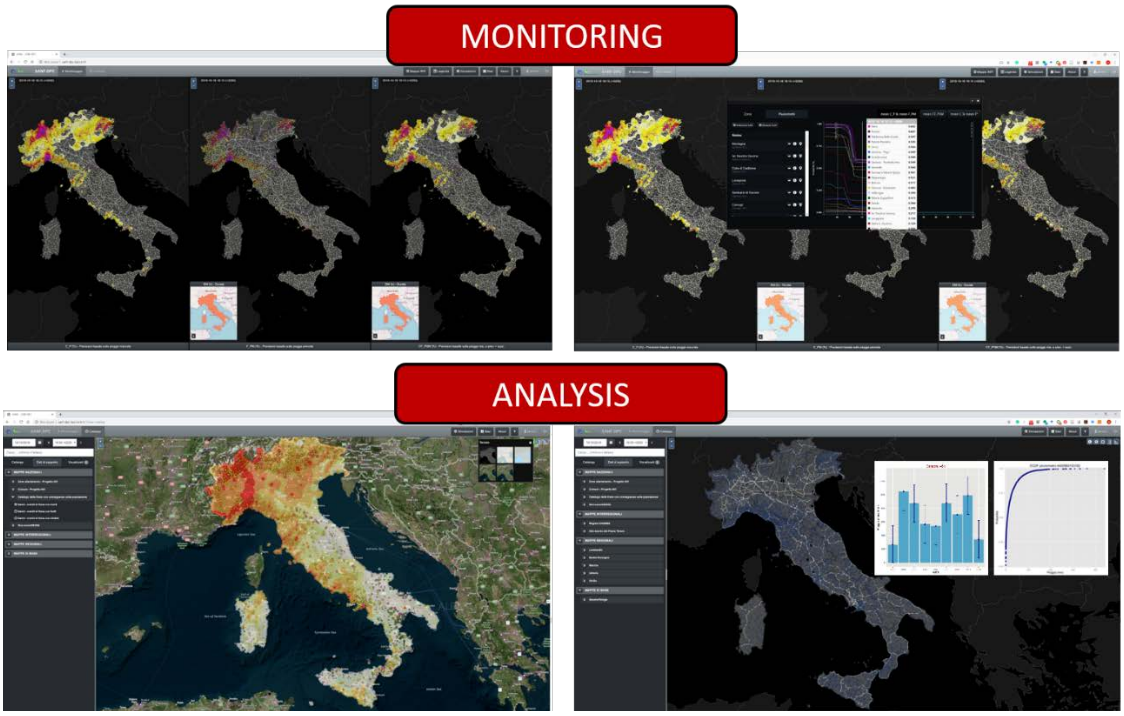

Figure 4 Monitoring and analysis interfaces of the SANF system designed and implemented to forecast the possible occurrence of rainfall-induced landslides in Italy.

Discussion and conclusions

Landslide mapping and zoning can be prepared at national, regional, and local levels using different and heterogeneous approaches, depending on techniques and methods used for landslide data collection (i.e., inventory maps) and hazard and risk assessment. Landslide inventory maps are important to document the extent of landslide phenomena in a region, to investigate the distribution, types, pattern, recurrence, and statistics of slope failures, to determine landslide susceptibility, hazard, vulnerability, and risk, and to study the evolution of landscapes dominated by mass-wasting processes (Guzzetti et al., 2012). Moreover, high-quality landslide inventory maps have positive effects on all derivative products and analyses, including erosion studies and landscape modelling (Tucker and Hancock, 2010), susceptibility and hazard assessments, and risk evaluations.

A critical literature review on landslide susceptibility modelling (Reichenbach et al., 2018) revealed a considerable heterogeneity of the landslide and thematic data types and scales, the modelling approaches, and the criteria used to evaluate the model performance, which highly influence the zonation. The quality of the susceptibility models has improved over the years, but top-quality assessments are still not common. In addition, common standards and recommended practices to construct, validate, and evaluate the susceptibility models and the associated zonation are not available.

The presented cartographic products from Italy encompass the following: national landslide inventory maps (IFFI inventory), regional landslide hazard maps (PAI maps), and large-scale landslide susceptibility zonation maps for different landslide types. The current practice shows the use of maps at national, regional, and local levels for water management (through soil defence interventions), infrastructure management and civil protection, including landslide forecasts at the national level (SANF system). The different cartographic products described above may constitute a starting point for landslide hazard and risk analysis at the national level and an important tool to support mitigation policies through the identification of intervention priorities, allocation of funds, programming of mitigation measures and planning of civil protection measures.

The presented cartographic products from Croatia encompass the following prototypes of landslide maps developed through scientific projects: mosaicked regional landslide susceptibility maps (scale 1:25,000); large-scale landslide susceptibility maps (scale 1:5,000); and large-scale landslide inventory maps (scale 1:2,000). The recommended use of all maps in spatial planning is derived from research conducted with numerous spatial planners dealing with the creation and implementation of spatial plans at national, regional, and local levels. The main purpose of the Croatian large-scale maps is to obtain special restrictions for the development and implementation of spatial plans. All presented maps are also important tools to support mitigation policies through the identification of intervention priorities, allocation of funds, programming of mitigation measures through water and infrastructure management, as well as planning of civil protection measures.

From the two multi-level landslide mapping approaches and experiences carried out in Croatia and Italy, the following points can be derived:

1) Landslide maps and zonation are still not associated with regulations/laws, and consequently, they are rarely considered by planners. This hampers the distribution of these cartographic products among professionals and private companies dealing with spatial planning.
2) Inventory and susceptibility maps need to be associated with different levels/types of regulation/restriction because of different types of information (i.e., evidence vs prediction).
3) Landslide maps (landslide inventory, landslide susceptibility, landslide hazard and risk maps) prepared at small, medium and large scale, cannot be used for construction design or other engineering purposes that require engineering-geological mapping at a detailed scale.
4) The interaction between the scientific community and spatial planning institutions/actors is of crucial importance, and it needs to be strengthened both in Croatia and Italy because of the relevant use of landslide inventory and zonation maps in spatial planning.
5) Stakeholders require regulations/restrictions associated with the recognized landslide phenomena and the classes of the zonation maps that can only be achieved through the cooperation of scientists and spatial planners.
6) The two different scientific experiences can be used to start a discussion on the use/application of landslide maps.

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