Multi-hazard Analysis and Mapping of Infrastructure Systems at National Level Using GIS Techniques: Preliminary Results

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Abstract. Preliminary results of the multi-hazard (seismic, landslide, floods) analysis, conducted on some Critical Infrastructures (CI), are presented. Lifelines an CI such as roads, railways, gas and power networks are essential for the Country's economy, but also to ensure the overcoming of emergencies in those territories in case of natural disasters. ENEA CIPCast platform, an innovative Decision Support System (DSS), has been used for the GIS-based analysis of physical impacts induced by natural hazards on CI. It has been exploited in several projects, including RAFAEL that, by means of analytical and geoprocessing tools, was focus on the extensive assessment and mapping of CI hazard. Geospatial layers, describing and classifying the different hazards in Italy, has allowed to produce a set of specific hazard maps for each CI considered. Multi-hazard values were assigned by using a suitable matrix having four classes. Preliminary results are discussed focusing on the impact on CI exposed to different level of seismic, flood and landslide hazard.

Keywords: Hazard analysis · Hazard mapping · Critical Infrastructures · Lifelines · Geoprocessing

1 Introduction

1.1 The Italian Territorial Context

Italy is among the countries at greatest geological risk in the Mediterranean area, where seismicity is strongly gathered [1] and with some seismically active zones particularly worthy of note [2]. The position of the Italian territory in the convergence zone between the African and Eurasian plates causes strong compressive forces, which have allowed the formation of mountain belts of Alps and Apennines during Mesozoic. From Neogene, a distensive tectonic phase was activated, resulting in numerous high-intensity and long-lasting seismic events. The frequency of earthquakes that have affected our

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country throughout history, as well as the energy that some events have reached, have a considerable impact on infrastructures [3]. Landslides and floods can expose lifelines and infrastructures to hazard [4, 5].

Risk is a measure of the expected damage over a period of time, based on the type of catastrophic event, building resistance and level of anthropization. Risks related to flooding, landslides and earthquake in Italy are correlated to the high vulnerability of Critical Infrastructures (CI) and their exposure to different catastrophic events [6]. The dangerousness is given by the frequency and strength of the catastrophic event that affects an area: it will be higher in case of high intensity and high probability of occurrence in a given time interval. The susceptibility of structures or infrastructures to being damaged is called vulnerability. Finally, exposure is determined by the possibility to have economic damages, injuries or loss of life and damage to assets in due to the presence of structures or infrastructures (e.g., lifelines) exposed to the event.

In case of calamitous event, depending on its extent and on the territorial ability to respond, the decision-makers (according to the reference legislation, deriving from EU Directives) are appointed to manage the emergency and to provide support to the population affected, by activating the national civil protection system (Italian Civil Protection Code [7]. This system regulates all the expertise involved and the activities to be carried out, aiming at the protection and physical integrity of citizens, assets, settlements, livestock and, more in general, the environment from hazards or damages caused by calamitous events of natural origin or resulting from human activity [8].

The knowledge and awareness of the territorial hazard and vulnerability, allow to identify, before an event occurs, the most suitable guidelines to be adopted at National level for the subsequent definition at local level of emergency planning to be implemented when the event actually occurs.

Therefore, Italian territory has been classified into different hazard zones in order to prevent the effects of earthquakes, floods, landslides and other natural disasters. Intensity and frequency of past earthquakes, for example, are considered in the definition and application of specific standards for buildings. To this end, Italian anti-seismic legislation prescribes technical standards on the basis of which to design structures and infrastructures. The census of areas prone to landslides or flooding is also carried out and the entire territory has Hydrogeological Master Plan (called PAI, *"Piano di Assetto Idrogeologico*"; [9].

In this framework, a crucial issue is related to the Critical Infrastructure Protection (CIP). This aspect is at the heart of the European and International Agenda since several years. Natural disasters affecting CI are able to cause huge damages and consequences, both from social and economic points of view [10]. Thus, the use of effective tools and approaches should be pursued to support Public Administration and Operators in their tasks concerning the hazard and risk assessment, especially to carry out an effective protection of their assets from impacts arising from natural disasters, which can harm the infrastructures and reduce the continuity of services delivered.

In particular, for the aims of the activities described in the present paper, we focused on the hazard analysis and mapping of CI systems represented by energy, gas and transportation (road and railway) networks.

The study carried-out represents a fundamental step to develop an extensive approach aiming at the reduction of the vulnerabilities and the mitigation of the risks, facing the threats to which these complex systems, essential for the everyday life, are exposed.

There is a large number of studies that illustrates the effects of natural phenomena on CI systems. Many researchers have proved that an integrated and multi-hazard approach can support effective measures in both prevention and quantitative analysis of risk assessment enhancing the capacity for disaster risk reduction [11–14]. The aim is to support the risk analysis related to the CI of interest and provide a quantitative analysis based on overlapping of seismic, floods, landslide hazard with essential infrastructure systems.

1.2 The CIPCast Platform

To perform the study described in the present paper, the ENEA CIPCast platform has been employed. It is an innovative Decision Support System (DSS) and interoperable platform for the operational 24/7 monitoring of CI and for the prediction of physical and functional impacts induced by natural events on CI. It can also support risk analysis and mapping [15]. The CIPCast platform has been developed as a combination of free/open-source software (FOSS) environments including GIS features, which play a major role in the construction of a Spatial DSS. In order to store and share all data and information available, a PostGIS-based [16] GeoDatabase for data storage and management has been implemented. The Geodatabase can be directly accessed by means of different desktop GIS software suites (e.g., QGIS). In addition, by means of the server stratum, represented by the GeoServer suite [17], data can be accessed via web by using OGC standards (WMS, WFS and WCS) [18]. Thus, in the GeoDatabase numerous (more then 400) maps and information layers are stored and constantly updated:

- Basic data and maps describing the territory;
- Environmental hazard maps (floods, landslides, earthquakes);
- Data about the location and topology of the main National CI systems and networks (i.e., High Voltage, gas, transportation networks, etc.)
- Outputs from forecast models (weather, nowcasting, flooding);
- Real time seismic data (INGV National Earthquake Observatory) and meteorological data (National Civil Protection);
- Data from distributed sensors (ground sensing) located on specific CI.

The geospatial data used to carry out the activities described in the present paper will be specifically listed and detailed in Sect. 3.1.

CIPCast can run in operational mode (on a 24/7 basis, as an alert system) [19] and in offline mode by performing hazard/risk assessments and/or simulating events [20]. In the first case, CIPCast gets external data from many different sources (e.g., seismic network, meteo/hydrological models), to establish the current conditions and elaborate an expected “damage scenario” for the area in which is located the CI of interest. In the second case, CIPCast can be employed as a GIS tool enabling risk mapping and assessment for each element of the CI considered, depending on the type of event expected (hazard) and the specific vulnerabilities [21]. A specific WebGIS

application has been implemented in order to be used as geographical interface of data and information provided and/or produced within CIPCast.

1.3 The RAFAEL Project

The study and the related applicative cases presented in this paper have been carried out in the framework of the RAFAEL Project ("system for Risk Analysis and Forecast for critical infrastructure in ApenninEs dorsaL regions", PNR 2015–2020, co-funded by the Italian Ministry of University and Research, Grant no. ARS01_00305, ended in November 2021, https://www.progetto-rafael.it/). The Project aimed at integrating different approaches and technologies, developed within its activities, into the CIPCast platform [21]. RAFAEL was focused on the risk assessment and monitoring of numerous infrastructural systems, by evaluating the impacts and the damages deriving from natural disastrous events. Among its objectives, the RAFAEL project has implemented new capabilities in CIPCast, by means of analytical and geoprocessing tools able to assess and map the hazard for CI as described in the present paper.

2 Study Area Characteristics

Hazard analyses and researches can be considered as a set of studies that quantitatively determine how the territory in which we live is subject to the effects of various natural disasters. The starting point to implement such approach is to describe and map the hazards, by distinguishing the various phenomena to which a portion of territory may be exposed (i.e., earthquakes, hydrogeological disruptions, etc.) and to characterise them into different levels by using a proper classification.

2.1 Hazards

In this Section, the three main hazard typologies considered in the present study (flood, landslide and seismic hazards) are described, with a specific focus on the Italian situation.

Flood Hazard. In Italy there are several areas prone to hydraulic hazard, due to flooding caused by rivers, streams, canals, lakes and, for coastal areas, by the sea. In Italy, the Legislative Decree 49/2010 has implemented the Directive 2007/60/EC (Floods Directive - FD), aiming at the definition of a framework for the assessment and management of flood risks.

The Italian territory is particularly exposed to flood events due to its geographical, morphological and geological characteristics. These include, for example, flash floods, which are triggered by rainfall phenomena of short duration but of considerable intensity. Although these natural phenomena are impossible to be predicted, a series of human activities have contributed to increasing the probability of occurrence of floods and have also amplified their impact on structures/infrastructures and consequently on the population. Destructive flood events, such as those that have affected several areas of Italy [22] in recent years, are paradigmatic of floods with similar characteristics.

Firstly, the destructive consequences of floods are intensified by the expansion of urban settlements and production sites. Such anthropic interventions resulted in an

increase of impervious surface areas (roads, buildings, etc.), causing detrimental hydrologic changes, stream channel erosion and habitat degradation. Secondly, the probability of occurrence of extreme flood events has increased due to the combined effect of the climate change (which alters the thermo-pluviometric regime) and the increasing land consumption [22].

In 2017, ISPRA released the new National Mosaic (v. 4.0 - December 2017) [23] of the flood hazard zones mapped by the River Basin District Authorities according to the following three scenarios defined by Legislative Decree 49/2010 (implementation of the Flood Directive 2007/60/EC) as follows:

– high probability scenario (P3) with a return period of 20–50 years (frequent floods);
– medium probability scenario (P2) with a return period of 100–200 years;
– low probability or extreme event scenario (P1).

Since flood hazard refers to the probability of occurrence of an event of a given intensity in a given period of time and over a given area, the cited hazard maps show the delimitation of the areas that could be affected by floods according to the three probabilities (i.e., hazard) scenarios listed above [24].

Landslide Hazard. Considering the landslides, Italy is one of most affected Countries in Europe [14, 25]. On the basis of the data surveyed and archived by the Italian Landslide Inventory (IFFI Project), there are about 621,000 landslides affecting an area of 23,700 km^2, equal to about 8% of the entire National territory [22]. About one third of these landslides is represented by rapid phenomena (falls/topples, mud flows and debris flows), having a high speed and able to produce destructive consequences on structures/infrastructures as well as to cause loss of human life. On the other hand, landslides characterised by moderate or slow speed (e.g., complex landslides, rotational/translational slides, slow earth flows), not only are able to damage structures in built-up areas, but can also cause significant damages to linear lifelines, such as - for example - roads, or other infrastructures such as railways, buried pipelines, etc.

Among the most important factors for triggering landslides [26–28] can be considered: short and intense rainfall, continuous and persistent rainfall, earthquakes (ground shaking caused by earthquakes can destabilize the slope directly (e.g., by inducing soil liquefaction) or can weaken the material and cause cracks that could eventually produce a landslide).

In this framework, the reference dataset is the National mosaic (v. 3.0 – December 2017) of landslide hazard zones of the River Basin Plans (PAI), mapped by the River Basin District Authorities and released by ISPRA in 2017 [23, 24]. Such mapping is based on the landslides already occurred, the areas of possible evolution of the existing landslide phenomena, and the areas potentially susceptible to new events.

According to this approach, the National territory has been classified into five hazard classes:

– very high H4;
– high H3;
– medium H2;

– moderate H1;
– attention zones AA.

Seismic Hazard. As stated in the Introduction Section, seismicity in Italy is distributed in the entire territory [1]. Due to the rich historical documentation in Italy, several databases have been compiled to integrate all the available data about historical seismicity [29, 30]. One of the last compilations is represented by the Parametric Catalogue of Italian Earthquakes of INGV (CPTI15 [31], which covers the entire Italian territory. It includes 4,894 earthquakes in the time interval 1000–2020, characterized by maximum intensity equal or greater than 5 (and instrumental magnitude greater or equivalent to Mw = 4.0). In the last twenty years, 49 seismic events with Mw greater than 5 have been recorded in Italy: among these, is worth to mention the 2009 L'Aquila earthquake and the 2016–2017 Central Italy seismic sequence [32–35].

A new hazard map of the national territory was released in 2004, based on the most up-to-date information, for which periodic revisions are required by law. An assessment of the most dangerous areas of the National territory is provided by the seismic hazard map [36].

Peak horizontal acceleration (PGA) is a parameter traditionally used in the design of the elastic response of buildings. The PGA value refer to a hypothetical homogeneous soil foundation of the infrastructure with good characteristics. Designers apply appropriate corrections to consider the different nature of the soil on a local basis, if necessary. A design of an infrastructure must consider zonation of the National territory.

Four seismic zones are defined [38], based on ground acceleration values g (acceleration of gravity is equal to 9.81 m/s^2):

– Zone 4 (0.25–0.3 g) has the strongest shaking values and is expected throughout the central-southern Apennines (with maximum peaks in Calabria and south-eastern Sicily, and in Friuli Venezia Giulia);
– Zone 3 (0.15–0.25 g) has moderate values as reported on the Salento Peninsula, along the Tyrrhenian coast between Tuscany and Latium, in Liguria, within the Po Valley, and along the entire Alpine arc;
– Zone 2 (0.05–0.15 g) has low value of ground acceleration and is expected along western Alpine Arch and all-around Zone 3 in Central Apennine;
– Zone 1 (< 0.025–0.05 g) is located in Sardinia that, among the Italian regions is the least dangerous, and statistically very low shaking values are statistically expected.

3 Materials and Methods

In this Section the datasets used and the methodological steps implemented in CIPCast in order to evaluate the multi-hazard (hydrogeological and seismic) in Italy are presented.

3.1 Datasets

To carry out the multi-hazard (flood hazard; landslide hazard; seismic hazard) analysis and mapping, a series of geo-referenced information layers were integrated in the

CIPCast GeoDatabase. Those data were acquired from open/public sources or gathered within the RAFAEL Project activities. Thus, data stored into the CIPCast GeoDatabase and used for the purposed of the present study can be subdivided according to their typology, as follows (Table 1 and Table 2):

Table 1. Data describing and characterizing the Italian territory in terms of hazards

#	Description	Source
A-1	National mosaic of flood hazard - PAI 2017	ISPRA Idrogeo [24]
A-2	National mosaic of landslide hazard - PAI 2017	ISPRA Idrogeo [24]
A-3	Italian Seismic Hazard Maps - 2004	INGV [37]
A-3	National seismic classification of municipalities - 2021	Civil protection Dpt. [38]

Table 2. Geographic location, topology and characteristics of the CI of interest within the Italian territory

#	Description	Source
B-1	Road network, containing information on main roads (topology, length, hierarchy and corresponding management authority	ANAS -DBPrior10k
B-2	Railway network, containing topology and main characteristics (track length, type, etc.)	DBPrior10k
B-3	Location and topology of the elements of the Italian national transmission grid: lines, substations and plants	S&P Global Platts
B-4	Location and topology of the elements of the Italian national gas transmission network: pipelines, facilities and storages	S&P Global Platts

3.2 Hazard Mapping

To map and evaluate the specific hazard of the CI systems considered, the related geospatial data describing them (Table 2) were spatially processed (by means of GIS intersection and join) along with the geospatial layers describing and classifying the different hazards in Italy (Table 1). In this way, it has been possible to produce a new set of hazard maps for each CI considered, according the processing steps reported in Fig. 1 and described the following.

In the present study QGIS Desktop and Esri ArcGIS software suites have been used in order to generate:

1. single-hazard maps describing and classifying the different hazard values for each part/element of the CI considered;
2. multi-hazard map, synthesising and combining the three hazard typologies analysed for each part/element of the CI considered.

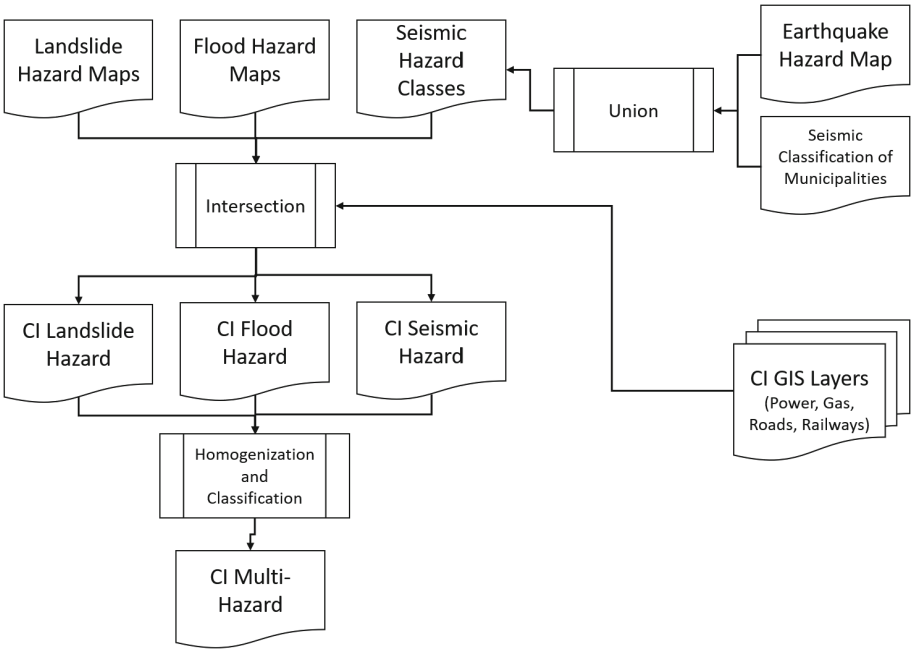

Fig. 1. Multi-hazard analysis.

Firstly, the single-hazard maps (flood, landslide and earthquake separately) and the geospatial layers about CI have been selected (see Sect. 3.1) and pre-processed in order to be used in the subsequent steps. In particular, all the layers have been homogenised in the same geographic reference system: UTM-32 coordinates on the WGS84 Datum (EPSG:32632).

Additional pre-processing steps were needed for the flood hazard maps coming from PAI and for the seismic hazard map. In the first case, the three different original GIS layers (one for each specific probability scenario P_x) were merged (by using Esri ArcGIS geoprocessing tools) in a synthetic GIS layer, in which the hazard classes are jointly mapped and hierarchically organised. In the second case, the geoprocessing was used to join and homogenise the seismic hazard map in terms of PGA [37] with the GIS layer containing the Seismic Classification of Municipalities [38], in order to have an extensive description of the seismic hazard for the entire Italian territory (including the Sardinia Region and the Northern part of Italy), subdivided into the four zones listed in Sect. 2.1. Another pre-processing task was devoted to exclude specific areas (e.g., marine ones or zone with missing data) from the computation. In particular, to deal with the lack of data regarding the flood hazard (PAI [24]) in the Marche Region and the related border areas (especially with the Emilia-Romagna Region) it was decided to remove from the multi-hazard GIS layer the segments of the road network falling into the Marche Region. Such assumption was also justified by the need to process reliable statistical data, not affected by a miscalculation of multi-hazard values deriving from inaccurate and/or missing data.

The next task has regarded the organisation and harmonisation of the attribute tables associated to each GIS layer processed. Attributes titles were (if necessary) cleaned/renamed and redundancies deriving from the multiple geoprocessing steps were eliminated. Such procedure has the scope to allow the comparison of the three different hazards scales and to classify the results according a synthetic multi-hazard value. Moreover, a specific attribute related to the code of each Administrative Region in which Italy is subdivided has been inserted, to make possible performing statistics both at National and Regional level.

Once the pre-processing steps have been accomplished, the next geoprocessing step performed was the spatial intersection between each of the above-described single-hazard maps with each GIS layer related to the CI considered (roads, railways, power and gas networks) within the entire National territory.

4 Results

The single-hazard maps obtained as intermediate result have been merged in new synthetic GIS layers, combining and classifying the three hazards with the CI of interest. In such a way, the final results are represented by four multi-hazard maps, one for each of the four CI systems analysed.

In order to assign the multi-hazard values in a coherent way, a specific matrix was created (Table 3) with four overall classes, spanning from 1 to 4 (where 1 is the minimum value that can be assigned and 4 is the maximum). In particular, flood hazard is described by means of its three increasing-probability classes (P1, P2 and P3) and with a 0 value for the areas not prone to flood. In the case of the landslide hazard, it has been assumed to merge into a unique class the attention zones (AA, for which, by definition, a precise zoning is still not clearly defined) and the H1 zones (moderate hazard). Similarly, the H3 and H4 zones (High and Very High hazard) were merged in the same class. Areas not prone to landslide phenomena have been classified with 0 value. For seismic hazard the four classes defined in the matrix fully reflect the national 4-zones subdivision.

The multi-hazard matrix allows to assign to each element/part of the CI considered an overall hazard value, which can account for each specific single-hazard value in a synthetic and extensive way.

Table 3. Multi-hazard matrix

Flood hazard values	Landslide hazard values	Seismic hazard zones	Multi-hazard index values	Hazard levels
0	0	Zone 4	1	Low
P1 (300–500y)	AA + H1	Zone 3	2	Moderate
P2 (100–200y)	H2	Zone 2	3	High
P3 (20–50y)	H3 + H4	Zone 1	4	Very high

All the GIS layers produced according the above-described processing steps (see Sect. 3.2) have been uploaded into the CIPCast GeoDatabase (PostGIS). Thanks to such data organisation, a statistical analysis has been carried out in order to calculate, both at National and Regional level, the length of each CI network classified according the different classes of hazard.

Subsequently, all the layers were loaded to GeoServer in order to be published within the CIPCast WebGIS application and made available to the users via WMS. In particular, geospatial data were styled (colour, thickness and other visible attributes) to properly render them into the WebGIS.

The following images show some examples of the results of the analysis and mapping: the elements and/or parts of CI classified at different hazard levels are suitably thematised. As an example of the results obtained for a lifeline system, in Fig. 2 the National Road network exposed to flood hazard is reported.

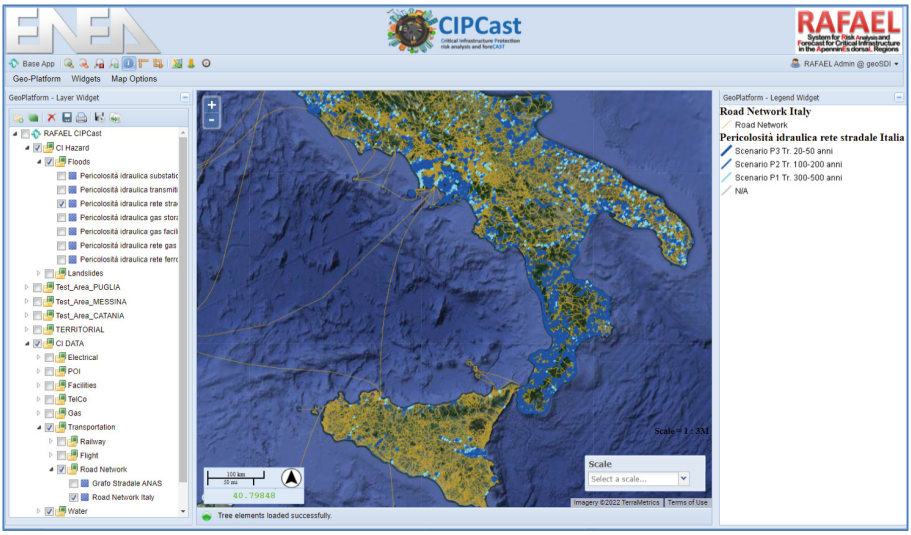

Fig. 2. Flood hazard mapping for the main Italian road network (colour scale indicates the severity of the expected flood scenario regarding the affected portion of road network).

In addition, for the road network the relative statistics were also calculated (i.e., the kilometres classified in each hazard class), according to the following percentage values of total length (Fig. 3): 79.5% not at risk, 6.5% Scenario P1, 6.8% Scenario P2, 3.5 Scenario P3, 3.7% data not available (Marche Region).

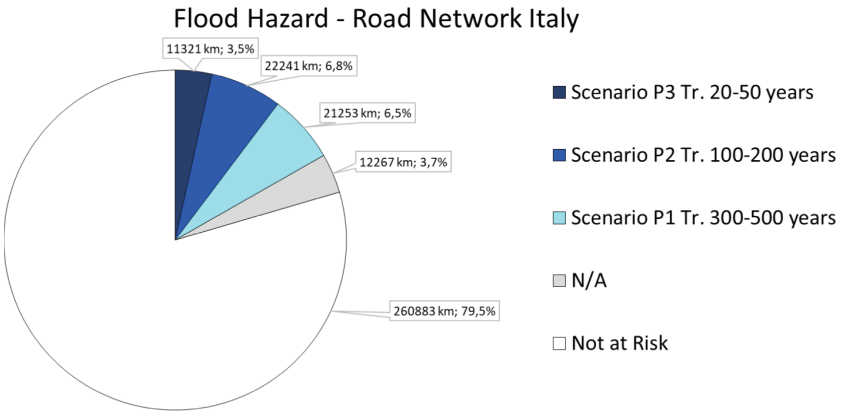

Fig. 3. Statistical analysis of the kilometres of road network falling in areas classified at different levels of flood hazard

In Fig. 4 the map of the National Road network exposed to landslide hazard is reported. In Fig. 5 a chart with the kilometres and the percentage values of total length classified for each hazard level is depicted.

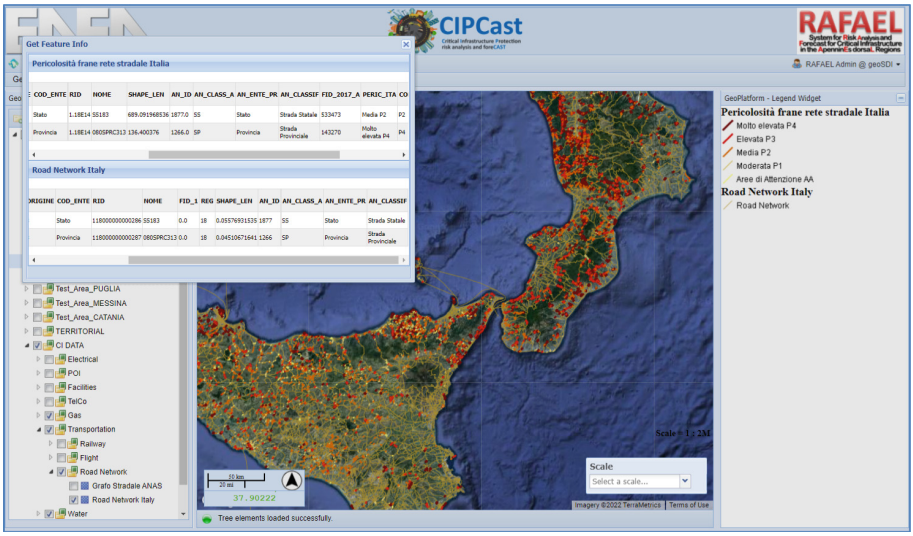

Fig. 4. Landslide hazard mapping for the main Italian road network (colour scale indicates the hazard level regarding the affected portion of road network)

Another example of the results obtained is depicted in Fig. 6, where different charts with the values (kilometres or total number) and percentages of the corresponding infrastructures exposed to seismic hazard are reported.

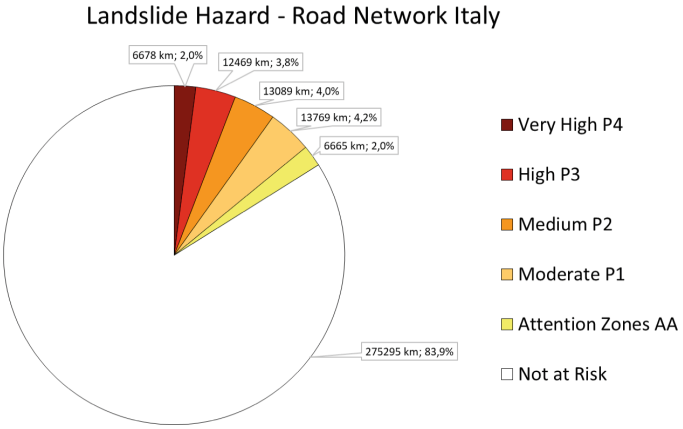

Fig. 5. Statistical analysis of the kilometres of road network falling in areas classified at different levels of landslide hazard

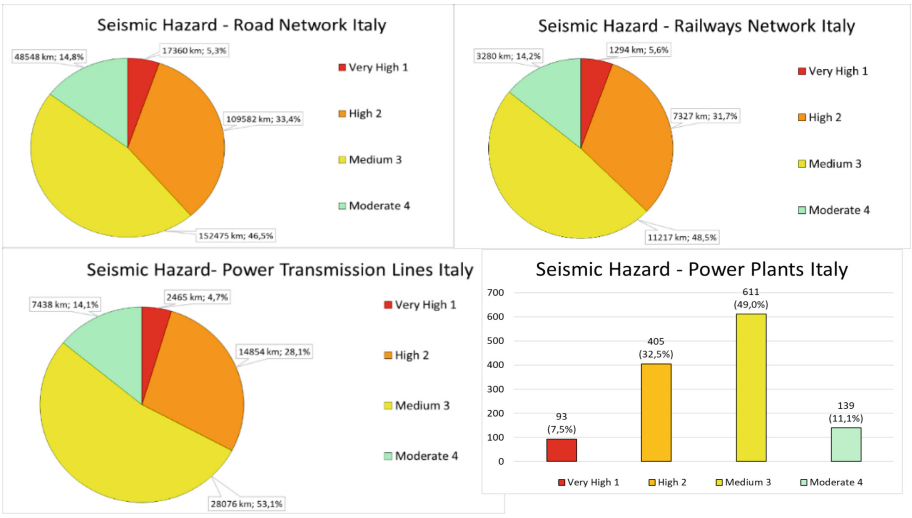

Fig. 6. Statistical analysis of the kilometres of road, gas and railway networks and number of power plants falling in areas classified at different levels of seismic hazard

In Fig. 7 the multi-hazard mapping for the entire Italian road network, as represented within the CIPCast WebGIS interface is reported. In Table 4 the kilometres of road network classified according the 4-classes multi-hazard defined (Low, Moderate, Medium, High) are reported.

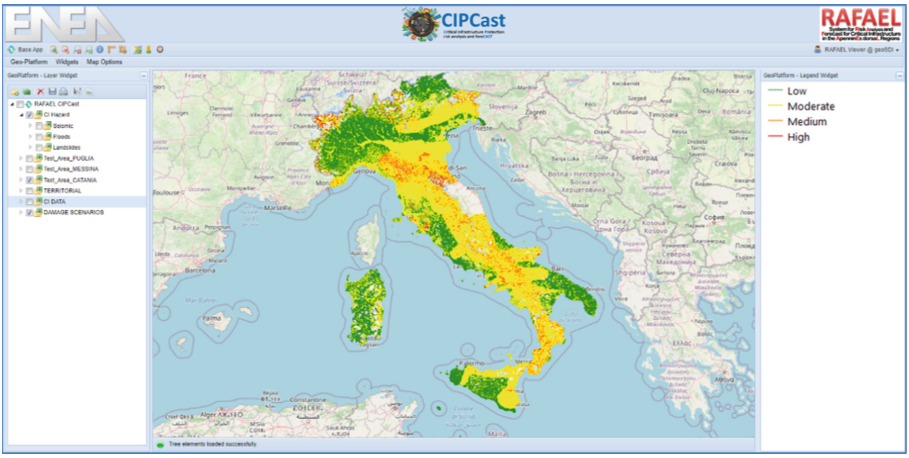

Fig. 7. Multi-hazard mapping for Italian road network: visualization within the CIPCast Web-GIS interface

Table 4. Kilometres of Italian Road Network subdivided for multi-hazard classes

Multi-hazard index	Km
Low	39,716
Moderate	232,876
Medium	42,825
High	489

5 Discussion and Conclusions

Critical Infrastructures play a fundamental role for the economy and development of a Country. Among the different CI, road and power networks are certainly the strategic ones, especially considering the essential and fundamental services provided to the citizens.

For example, the analyses carried out in the present study show that the National Road network (which has a linear extension of about 328,000 km) is exposed to seismic hazard for about 5.3% of its length, 3.5% to flood hazard and 2% to landslide hazard. Thus, considering the multi-hazard (Fig. 7 and Table 4), the majority of National Road network is exposed to moderate-medium values, about 40,000 km are exposed to low values and about 490 km are exposed to high values of multi-hazard.

It is important to observe that the interruption of the road network caused by calamitous events also leads to the production of waste, sludge and debris in the case of floods and landslides, rubble in the case of earthquakes. Those issues can interfere with a prompt response by the operational structures of the Civil Protection System, which relies on such lifeline in order to help the affected population.

An extensive hazard assessment and, above all, a territorial knowledge of the most vulnerable areas can favour the prompt response in case of emergency or support the proper definition of contingency plans. GIS-based approaches are fundamental to perform the above-mentioned hazard assessments. In addition, the availability of an interoperable tool such as the CIPCast platform can provide an effective support to deal with the issue related to hazard analysis and mapping.

The future work should implement the subsequent processing steps necessary to perform an extensive risk assessment: to this end, the hazard mapping obtained in the present study will represent the basis for a multi-risk analysis, including coastal risk, taking into account also the information about the specific vulnerabilities of the asset exposed.

Moreover, the hydrogeological hazard mapping will be update considering the latest versions of the datasets recently issued by ISPRA [24]: the National mosaic of landslide hazard (v. 4.0 – 2020–2021) and of the National mosaic of flood hazard (v. 5.0 – 2020).

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