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Article

Rainfall-Induced Shallow Landslide Susceptibility for Risk Management of the Underground Services in a Mediterranean Metropolitan City

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Abstract

Shallow-landslide susceptibility assessment is an essential research activity for land management and risk assessment. In this research, a GIS-based approach has been developed to assess the rain-induced landslide susceptibility in the Municipality of Genoa, a Mediterranean anthropized area historically characterized by intense rainfall events triggering shallow landslides with high destructive power. Based on a detailed inventory of landslide phenomena, a semi-quantitative method has been applied to assess the role of seven natural and anthropogenic landslide causal factors. The areas of differing rain-induced shallow landslide susceptibility have been discriminated into five classes indicative of areas on slopes where newly triggered landslides may occur. The landslide susceptibility map was subsequently cross-referenced with the map of gas and water utilities, whose features have been used to assess their vulnerability. Finally, a early-stage risk assessment of the two utility networks has been realized obtaining a decision support tool for adequate planning and integrated asset management in a context of climate change.

Keywords: shallow landslides; landslide susceptibility mapping; risk assessment; underground services; Genoa Municipality

1. Introduction

Among the natural hazards categories, landslides are the ones that cause damage and significant socio-economic losses in the territory every year [1–3]. Shallow landslides and debris/mudflows are the most frequent processes that cause damage to buildings and infrastructures, inducing often the loss of human lives [4]: triggering is caused by intense rainfall and usually generates limited volumes landslides, which are often spread on the territory and characterized by a sudden evolution and high speed of propagation [5–7]. The high kinetic energy of small but quickly moving masses may cause serious damage to buildings and infrastructures.

Landslide risk may be defined as the probability of occurrence of a potentially damaging event in a defined area and for a determined return period [8,9]. Risk assessment requires estimation of landslide volume, time frequency and location [10]. The extent and recurrence time of the event are difficult parameters to predict, as they are linked to the natural processes that control gravity dynamics. Besides, landslide inventories are relatively recent [11–13].

The spatial distribution of potentially unstable areas can be obtained through the probability of an event occurrence based on local geological and physical-geographical features [14]. The definition of landslide susceptibility represents the first step in risk assessment [15]: the identification and mapping of areas in which slope instability processes have occurred in the past or with similar

geotechnical characteristics are useful information for predicting the location of first-born shallow landslides [16]. Landslide susceptibility assessment therefore becomes an essential tool for risk management, supporting authorities and decision-makers in sustainable spatial planning and for the definition of mitigation measures, including monitoring and warning activities [17–19].

Over the past decades, several methods have been developed to assess landslide susceptibility, combining parameters in a GIS environment and collecting data with precision remote sensing techniques such as ALS (Airborne Laser Scanning) surveys [20–24]. The methods used to assess landslide susceptibility can be distinguished into [25–28]: 1) geomorphological survey and inventory map of landslide phenomena; 2) semi-quantitative approach based on the combination of partial parameters, linked to geomorphological processes and landslide factors; 3) physically-based methods [29], linked to the constitutive laws of the geomaterials that characterize the stratigraphic sequence of the investigated slopes.

The definition of rainfall-induced shallow landslide susceptibility is thus the first key step in risk assessment, which is done through subsequent cross-referencing with hazard-exposed elements. Much research has been carried out for rainfall-induced shallow landslide risk assessment with reference to buildings and large infrastructures.

Rainfall-induced shallow landslides are also an important element of risk for vulnerable elements such as underground services. Scientific research over the past 20 years has been conducted mainly on oil and gas pipelines, with interesting case studies in China, Turkey, Albania and Romania, related to transcontinental oil and gas pipelines affected by landslides.

Research was focused on the strains of underground gas pipeline subjected to landslide movement [30], on expert determination approach to define a consensus for the estimate of the risk for a gas pipeline [31], on a quantitative model for regional risk assessment through an analysis of the patterns of historical landslide disasters along oil and gas pipelines, with an interesting dual approach both on susceptibility and vulnerability assessment [32], an appropriate methodology for using the Tunnel Boring Machine to construct a micro-tunnelling to bury a natural gas pipeline beneath an active landslide [33], on the assessment of landslide susceptibility at a damaged gas pipeline, through the application of both statistical index and weightings factor, in a GIS environment [34], on a risk assessment model performed for buried pipeline geohazard like landslide, sinkhole phenomena and running water processes [35], on the geotechnical finite element approach for a landslide hazard case for an underground gas pipeline [36], and on what maximum susceptibility conditions an underground pipeline subject to leakage and rupture as a result of a landslide can reach [37].

An interesting scientific contribution is addressed on the susceptibility assessment of soil erosion for shallow underground pipelines; the method analyses geotechnical soil parameters and through an AHP procedure, the susceptibility values of potential erosion are assessed [38].

There is no research in the scientific literature on risk assessment for underground services, such as gas and water networks, in urban areas located in hilly and mountainous environments, which represent an important criticality in terms of land management.

In this research, a semi-quantitative method was adopted to assess the shallow landslide susceptibility in the municipality of Genoa, located in NW Italy: this is a hilly-mountainous territory close to a narrow fluvial-coastal strip (Figure 1) internationally known for its cultural and landscape heritage, but also historically affected by natural hazards such as landslides, debris flows and floods [39].

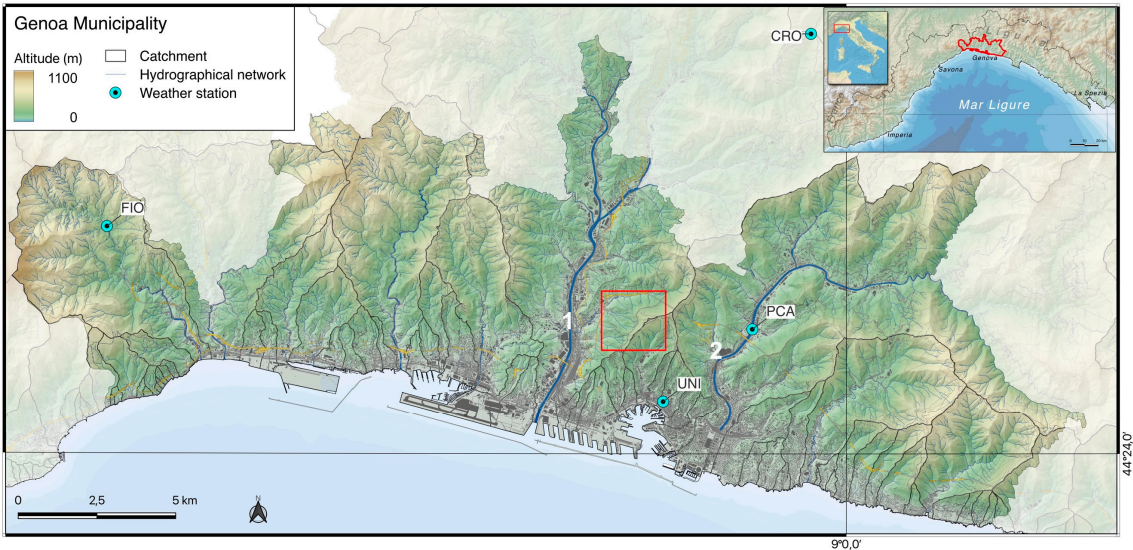


Figure 1. The study area, i.e., the Municipality of Genoa, is characterized by fairly developed hydrographic networks, small catchments, and an elevation between sea level and more than 1,000 m above sea level at a reduced distance as the crow flies from the sea. The red box is the reference for Figure 10. In 1 the Polcevera stream and in 2 the Bisagno stream.

Starting from the landslide inventory map, seven landslide causal factors were selected and classified according to the statistics of recent events. The weighted combination of the predisposing factors resulted in five different landslide susceptibility classes, whose reliability was tested by means of a model calibration process. Finally, the landslide susceptibility map obtained was cross-referenced with the gas and water sub-services vulnerability maps (Figure 2), categorized according to pipe diameter (and thus directly related to the exposed value), thus obtaining a preliminary geo-hydrological risk assessment.

These results are a useful decision support tool for an adequate planning and integrated asset management in a context of climate change.

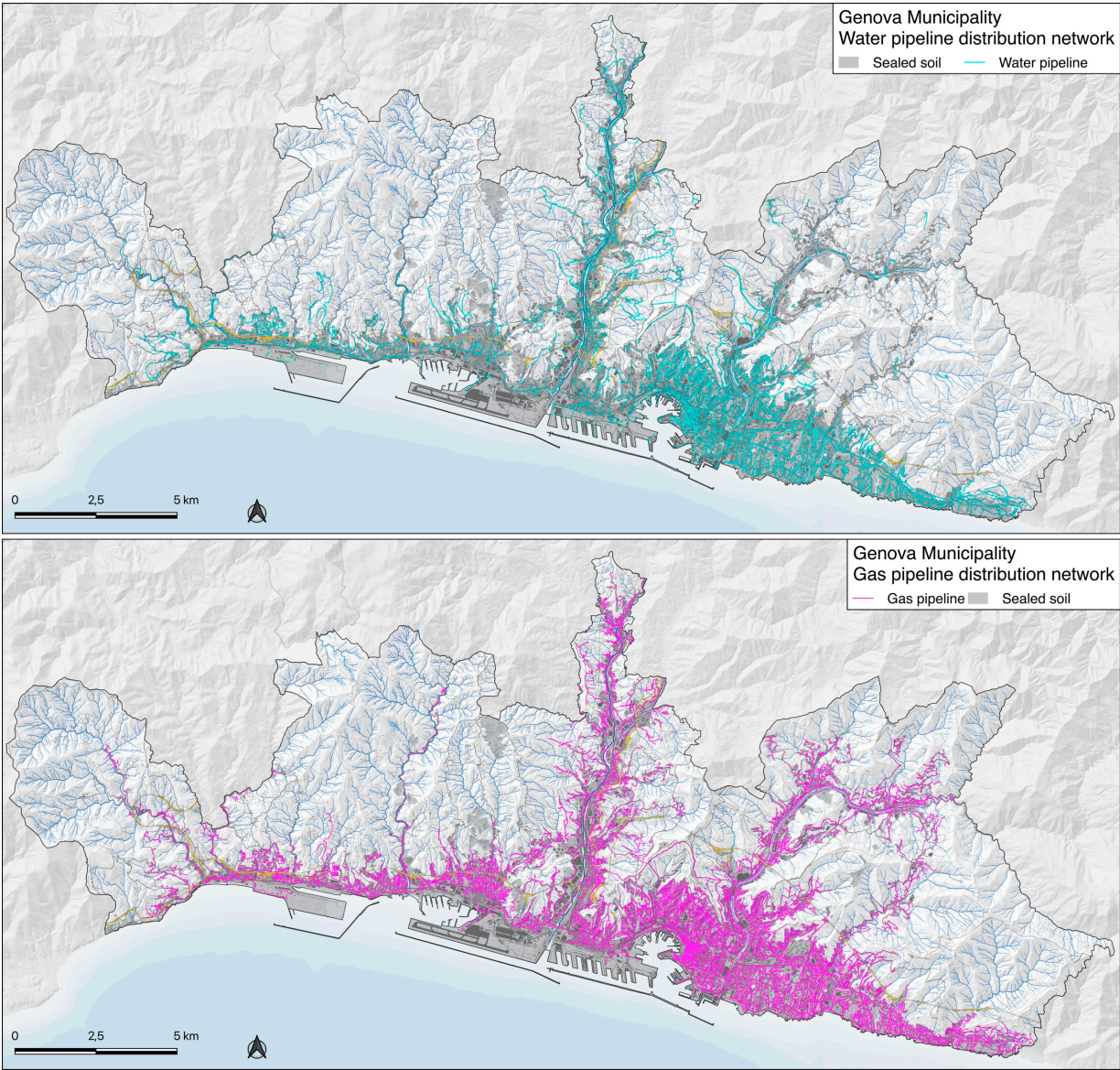


Figure 2. Development of the water (A) and gas (B) distribution network in Genoa Municipality.

2. Materials and Methods

2.1. Geographical and Geological Outline

Genoa is a coastal city and the capital of Liguria region, located in the north-western Italian macro-region (Figure 1); it extends over approximately 240 km², mostly distributed along a coastal strip stretching for 30 km from east to west (Figure 1). Only subordinately the city also extends along the two main drainage axes that are orthogonal to the coastline: the Bisagno and Polcevera streams (Figure 1), which limit the morphological amphitheater on which the historic city center has been built over time [40].

The resident population of Genoa is about 560,000, but in the 1970s, when the industrial sector especially related to the port was at its peak, it reached 800,000. In that condition the urban planning had already foreseen a city of 1 million inhabitants.

The port area is one of the most important in the Mediterranean: it is the original settlement of the city and still today represents the main focus of industrial, commercial and transport activities. The extensive waterfront, which has been achieved by land filling and the consequent advancement

of the coastline since historic times, clearly shows the anthropic transformations of the city that have occurred over the last 150 years due to the socio-economic growth and evolution.

From the administrative point of view, Genoa is divided into nine municipalities (Middle-East, Middle-West, Lower Bisagno Valley, Middle Bisagno Valley, Polcevera Valley, Middle-West, West, Middle-East, East) and 71 census sections. The population density reaches the highest values in the central part of the municipal area, particularly in the final stretch of the alluvial plain of the Bisagno stream, in the historical amphitheater behind the port area and near the mouth of the Polcevera stream. The highest value reaches 25,000 inhabitants/km² in Marassi (Lower Bisagno Valley) at the east from the amphitheater in an area of high flood hazard, and west from it in Sampierdarena district (Middle West).

The physical-geographical features of Genoa are peculiar, both in terms of meteorological-climatic aspects and for the landscape. The meteo-climatic structure of Genoa is particular and has long been studied by researchers and meteorology experts. Due to its location at the northern apex of the western Mediterranean, in the late summer-autumn period the depression over the Gulf of Genoa is frequent, bringing intense and high intensity rainfall: the metropolitan city of Genoa in fact shows rainfall records at a Mediterranean scale. The highest values have been topped in occasion of the major flooding events: on 7-8 October 1970 (948 mm/24 h), 4 November 2011 (181 mm/h) and 4 October 2021 (883.8 mm/24 h, 740.6/12h, 496 mm/6h and 377.8 mm/3h).

This last event, which was particularly intense, affected the hinterland to the west of the city but avoiding the municipal territory, causing many shallow landslides. During this event, the maximum values recorded over 12, 6 and 3 h exceeded the previous maximums that had been measured during the 1970 and 2011 phenomena.

On average, winters are mild and summers warm, with significant rainy periods in autumn and spring. The average annual rainfall is 1250 mm in the city center and varies significantly with altitude. Figure 3 shows the average monthly values recorded at the Genoa University station, which has been operating since 1833. The higher value of the annual rainfall corresponds to some catastrophic events that occurred in the past, while the higher monthly values mainly occur in fall and, secondarily in spring.

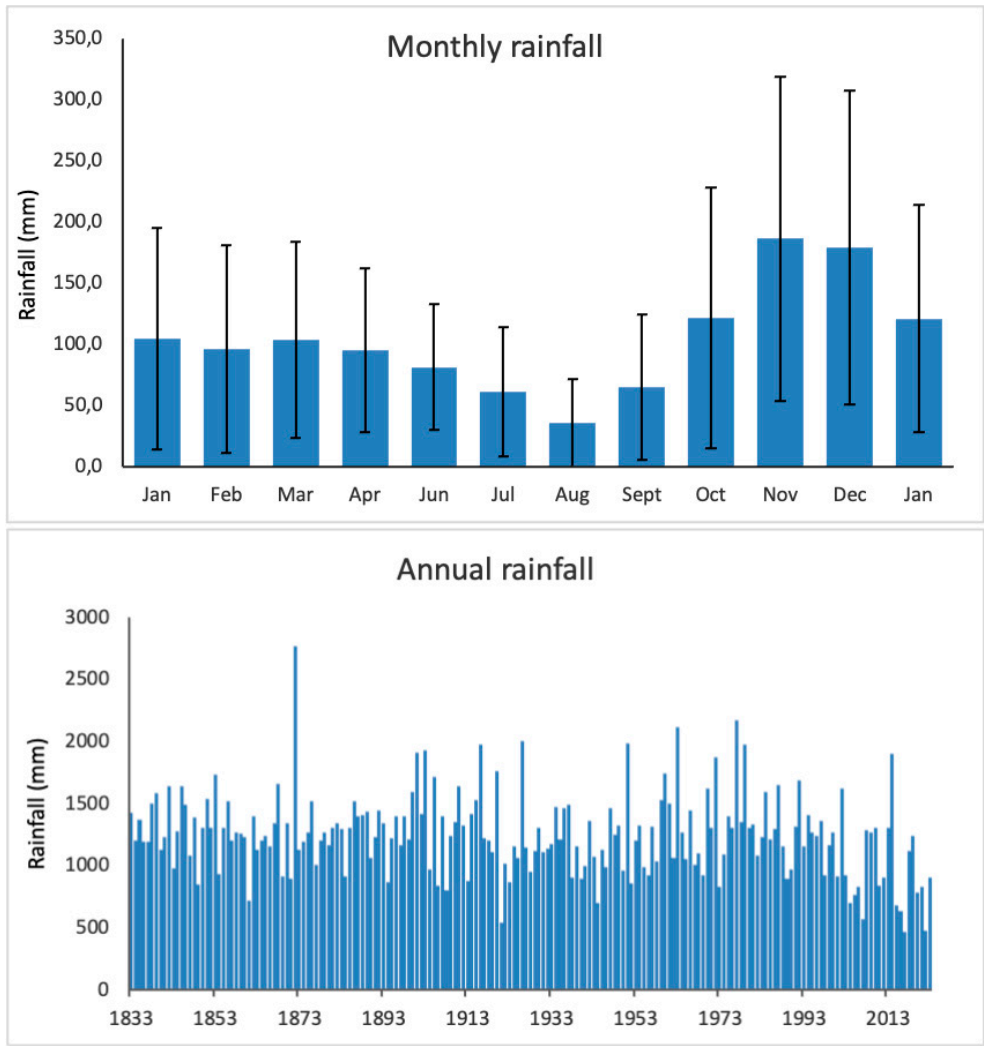


Figure 3. Monthly mean rainfall recorded at Genoa University weather station (35 m a.s.l.) in the 1833-2023 period and annual rainfall.

Evidence of climate change in Genoa can be witnessed by an increase in the average annual air temperature and a decrease in the number of rainy days, resulting in an increase in the intensity of rainfall, leading to more frequent occurrences of floods and landslides [41, 42]. Besides, proxies related to extreme rain events shows statistically significant increase over the period 1979-2019 [43]. The last significant events occurred in December 2022 triggering a rock-fall that affected some buildings in the central-eastern sector of the city and in August 2023 when a very intense but highly concentrated rainfall in terms of space and time caused heavy ground effects in Genoa’s historic center [44].

The Apennine Mountain range surrounds the city of Genoa with peaks reaching a maximum altitude of almost 1200 m in the eastern sector (Mt. Reixa, 1183) and over 1000 m in the eastern sector (Mt. Candelozzo, 1036 m). The area includes a large number of catchment basins mainly oriented perpendicular to the coastline. Not all the watersheds belong entirely to the municipality of Genoa: for example, both the upper Bisagno basin and the upper Polcevera one are included in other municipalities.

Based on the distance of the watershed from the coastline and the nature of the rock masses, slope gradients are generally high, especially in the eastern and western sectors of the municipal area (e.g., basins of the Nervi, Leira and Cerusa streams) where values above 50% are prevailing.

The morphometric and elevation features of the basins (Figure 1) represent one of the most significant landslide factors, which results in a widespread hazard: during heavy rainfall, the reduced

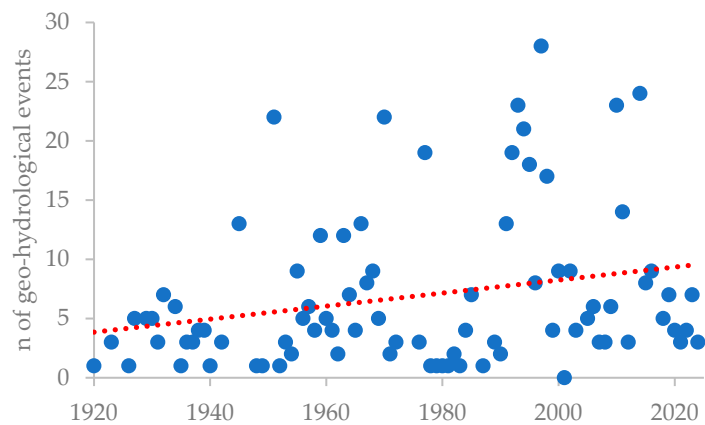
runoff time of small basins results in extremely rapid runoff (even less than 30') and flash floods hit the floodplain resulting in high risk due to the high urbanization.

During flood events, often of flash flood type, shallow landslides are triggered and, depending on the morphological features of the territory, also debris-mudflows. These quickly moving masses cause a high hazard to the directly exposed elements such as buildings and infrastructure, and an indirect one related to the saturation of the culverts which are diffusively present in the urban area. The effects on the ground can be very serious and also include loss of life as well as substantial economic damage.

Table 1 shows the geo-hydrological hazard events that have characterized the Genoese territory in the last 100 years based on AVI project database [59] properly updated.

Table 1. Rainfall events triggering geo-hydrological phenomena with ground effects occurred in the City of Genoa in the 1920-present day period, organized in decades (database AVI project available at <https://sici.irpi.cnr.it/storici.htm>). For each year, the number in round brackets represents the number of rainfalls events that triggering geo-hydrological phenomena.

Period	Date, Number of Events
1920-1929	1920(1), 1923(1), 1926(1), 1927(5), 1929(5)
1930-1939	1930(5), 1931(3), 1932(7), 1934(6), 1935(1), 1936(3), 1937(3), 1938 (4), 1939(4)
1940-1949	1940(1), 1942(3), 1945(13), 1948(1), 1949(1)
1950-1959	1951(32), 1952(1), 1953 (3), 1954(2), 1955(9), 1956(5), 1957(6), 1958(4), 1959(12)
1960-1969	1960(5), 1961(4), 1962(2), 1963(12), 1964(7), 1965(4), 1966(13), 1967(8), 1968 (9), 1969(5)
1970-1979	1970 (22), 1971(2), 1972(3), 1976(3), 1977(19), 1978(1), 1979(1)
1980-1989	1980(1), 1981(1), 1982(2), 1983(1), 1984(4), 1985(7), 1987(2), 1989(3)
1990-1999	1990(2), 1991(13), 1992 (19), 1993(23), 1994(21), 1995(18), 1996(8), 1997(28), 1998(17), 1999(4)
2000-2009	2000 (9), 2002 (9), 2003(2), 2005(2), 2006(6), 2007(3), 2008(3), 2009(2)
2010-2019	2010 (12), 2011 (10), 2012(1), 2014 (24), 2016(2), 2018(2), 2019 (4)
2020-2024	2020 (2), 2021(1), 2022 (3), 2023 (3)



The city of Genoa geologic features contribute substantially to the slope instability processes, then inducing the natural hazard: Figure 4 schematically shows the rock masses of the Genoa area, predominantly of sedimentary type in the East (limestone-marly flysch), and of ophiolitic type in the West (serpentinites and calcareous schist). The central sector is particularly complex and characterized by argillitic and siltitic flysch, basalts, and dolomites.

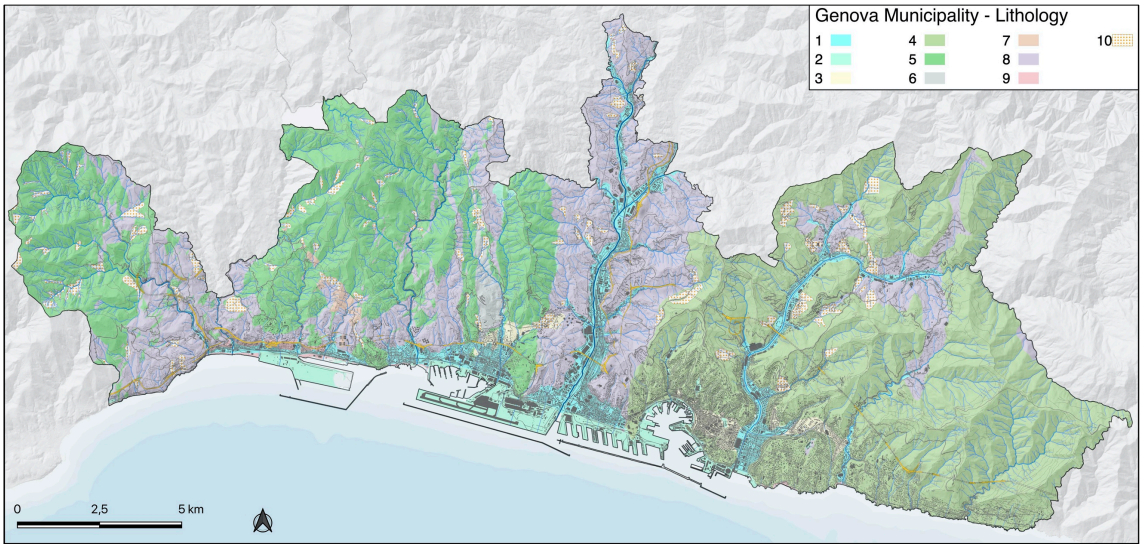


Figure 4. Lithological sketch map of the Municipality of Genoa area. 1 alluvial deposit; 2 coastal deposits; 3 Plio-Quaternary deposits; 4 Flysch rock masses; 5 Ophiolitic rocks; 6 Carbonate rocks; 7 Conglomerate; 8 Shales and schists; 9 quartzite and cherts; 10 ancient landslides.

The geological history undergone by the rock formations, both ductile and brittle, and the consequent pattern of deformations occurred, together with the frequent coupling of geomaterials with different strength and deformability, is an additional predisposing element for slope instability and for triggering landslides characterized by different kinematics processes.

2.2. Research Methods

The susceptibility assessment for shallow landslides on the territory of the Municipality of Genoa was carried out by employing a semi-quantitative approach, which means combining a quantitative and a qualitative method. This approach makes it possible to combine numerical criteria with subjective analysis skills and experience. The objective component is based on descriptive statistics of census phenomena at the regional scale, while the subjective component is based on geomorphological analysis and evaluation.

The method, schematized in Figure 5, is based on identifying a set of descriptive parameters of the area as predisposing factors for the triggering of rapid runoff phenomena and related descriptive statistical evaluation. Then, the results of the descriptive statistics are assigned as weights to the different classes into which each predisposing factor has been divided, and the different factors are appropriately reclassified [45].

The different factors are combined by means of other weights, the identification of which is done by applying the heuristic method AHP Analytic Hierarchy Process [46–49] by combining subjective evaluations by experts [50,51]. This methodology is a modified version of the one already proposed and tested in Mediterranean environment [17] in a previous research. Further, the susceptibility analysis results are applied to the risk assessment of the gas and water distribution pipelines in the Genoa Municipality.

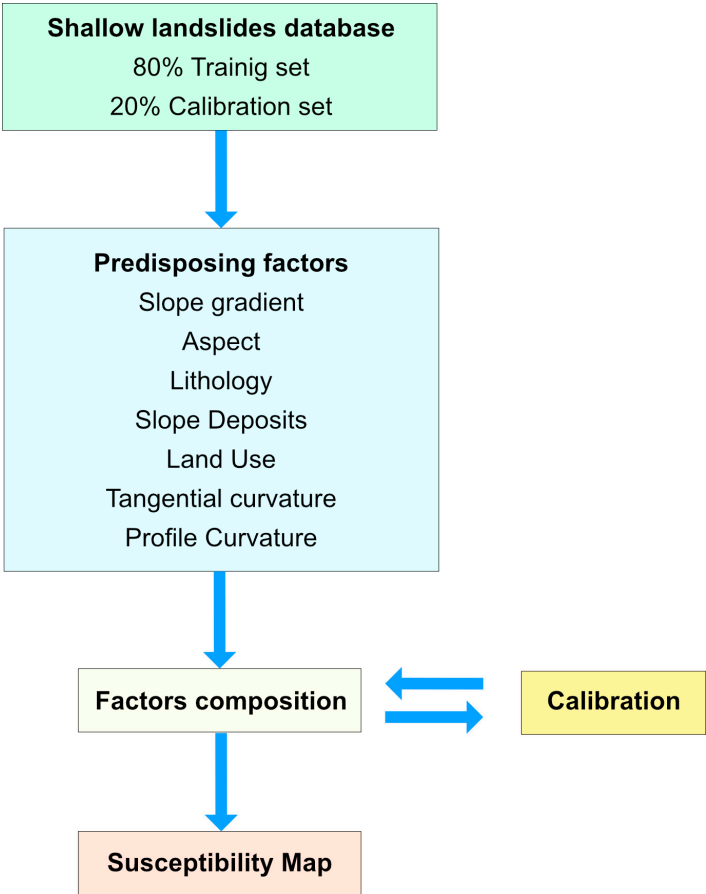


Figure 5. Logical flow of the process of landslide susceptibility map evaluation: the database of 485 shallow landslides identified in the Municipality of Genoa area was randomly divided into two subsets corresponding to 80% and 20%, respectively, used to estimate the occurrence according to the seven causal factors and to calibrate the susceptibility evaluation model.

AHP is a semi-quantitative multi-criteria decision-support technique used to compare heterogeneous physical quantities and widely applied in natural hazard management [52] and landslide susceptibility analysis [6,7,17,53–56]. The assignment of weights to each identified factor and their subsequent normalized combination allowed to obtain a shallow landslide susceptibility map [57,58].

The basic data used is the inventory of landslide phenomena in Italy from the IFFI project, from data collected through the Copernicus system following the most recent intense events, and from data acquired by the governing authority of the basin plans involving the municipal area [59]: from the combination of several geodatabases, 485 phenomena of rapid landslides and fast-developing shallow landslides that occurred in the municipal area were extracted.

The case history of such phenomena in Liguria and beyond is wide and increasing since the year 2000 [43]: the events that occurred in western Liguria in 2000, the hundreds of shallow landslides triggered during the flash flood that affected the Cinque Terre/Vara Valley in 2011, the events of October/November 2014 in Genoa Province, and the landslide that in Leivi, in the hinterland 50 km east from Genoa, claimed two lives, the 2016 Lavina di Rezzo (Imperia) rapid flow and the 2019 landslides in Cava Lupara (Genoa), Cenova di Rezzo (Imperia) and Madonna del Monte (Savona) that caused the collapse of the viaduct along the A6 highway.

The set of census events at the municipal scale was divided by random extraction into two subsets: a training set of 388 phenomena accounting for 80 percent of the total and a calibration set of 97 phenomena accounting for the remaining 20 percent (Figure 6).

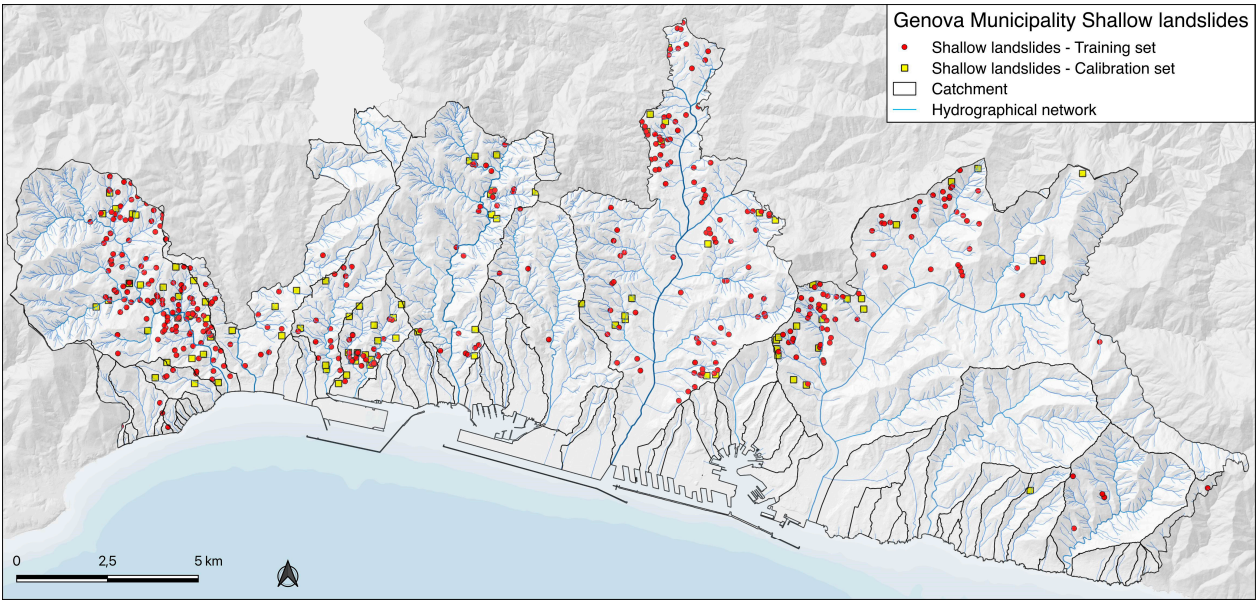


Figure 6. Representation of the 485 surface landslides recorded in the municipal area, distributed by a random extraction process between a training set (80%) and a calibration set (20%).

The first set has been used to obtain descriptive statistics of phenomena with respect to the seven identified predisposing factors (Figure 7): slope gradient, slope aspect, lithology, land-use, planar curvature and tangential surface curvature, and presence of slope debris cover.

These data, whose characteristics are summarized in Table 2, were partly obtained from the available data of regional databases at the scale 1:10,000, and partly obtained by application of processing algorithms to the 5 m mesh DTM made by the Region of Liguria. Debris covers are also considered to play a major role in terms of the probability of triggering shallow landslides. Therefore, basing on evidences of recent phenomena occurring in the area, it was decided to additionally include the slope cover factor in the analysis of shallow landslide susceptibility: this geomorphological data was obtained by composing the informative layer included in the geological map made by the Municipality of Genoa, with original field surveys and remote sensing analysis that allowed a more detailed recognition and mapping of the anthropogenic terraces widely spread in the Ligurian territory.

The presence of anthropogenic terraces has often been found to be crucial in triggering the phenomenon that have affected the region over the past 20 years. Their identification has been conducted through a dedicated analysis according to the methods identified in the same morpho-climatic environment [60–62] in other researches. The analysis has been fulfilled using the DTM obtained from the ALS survey acquired by the Municipality of Genoa in 2018 with 1m resolution. The analysis is based on the computation of the SVF -Sky View Factor (SAGA GIS algorithm), whose reliability and accuracy was deemed satisfactory for the purposes at hand [63].

Table 2. list of data, in raster and vector formats, used in the assessment of shallow landslide susceptibility.

Name	Source	Scala/Pixel	Date	Type
Administrative Unit	Liguria Region	1:5,000	2018	V
Aspect	Liguria Region	1:10,000	2007	V
CORINE Land Use (II Level)	Liguria Region	1:10,000	2018-2019	V
CTR (Regional Technical Map)	Liguria Region	1:5,000	1990-2006	R
DEM (Digital Elevation Model)	Liguria Region	5 m	2016	R
Hydrographic Network and Catchments	Liguria Region	1:10,000	2019	V
Landslide—Project IFFI	Liguria Region	1:10,000	2014	V

Lithology	Liguria Region	1:10,000	2017	V
Slope	Liguria Region	1:10,000	2016	V
DEM	Genoa Municipality	1 m	2018	R
Geomorphological map	Genoa Municipality	1:5,000	2015	V

The predisposing factors identification has been conducted according to the extensive bibliography available and allows the evaluation of both geological-morphological-morphometric characteristics and anthropogenic influence through land use. Descriptive statistics made it possible to objectively assign different weights to the relevant classes into which each factor has been divided. The weights in the combination of the seven factors were assigned by adapting the values obtained through the AHP technique developed and applied in recent research in a surrounding area [17]. The weights between factors used are shown in Table 3. The reliability of the result was subsequently verified by the calibration process, i.e., by checking the susceptibility classes corresponding to the 97 landslides in the calibration set.

Table 3. Weights assigned to the 7 causal factors for shallow landslide susceptibility assessment.

Landslide Factor	Weight
Lithology	0.08
Aspect	0.06
Slope gradient	28.0
Land Use	13.0
Slope deposits	29.0
Tangential curvature	0.09
Profile curvature	0.07

The risk assessment of the water and gas distribution networks has been approached evaluating the vulnerability of the twos through the local diameter of the pipes and then calculating the related risk [64–66]. The following Table 4 identifies the 5 vulnerability classes that have been defined according to the pipe’s diameters, which ranges from 10 to 900 cm for the water network, and from 15 to 800 cm for the gas one. Then, the 5 risk classes have been obtained combining the vulnerability classes with the hazard ones identified by the susceptibility computation: figures in the risk matrix have been obtained after the product of the hazard score and the vulnerability score. Finally, the results have been conservatively classified in the 5 risk classes in Figure 8.

Table 4. The water and gas networks vulnerability classes according to the pipe’s diameters.

Pipe Diameter (cm)	Vulnerability Class
$d \leq 50$	1
$50 < d \leq 100$	2
$100 < d \leq 200$	3
$200 < d \leq 300$	4
$d > 300$	5

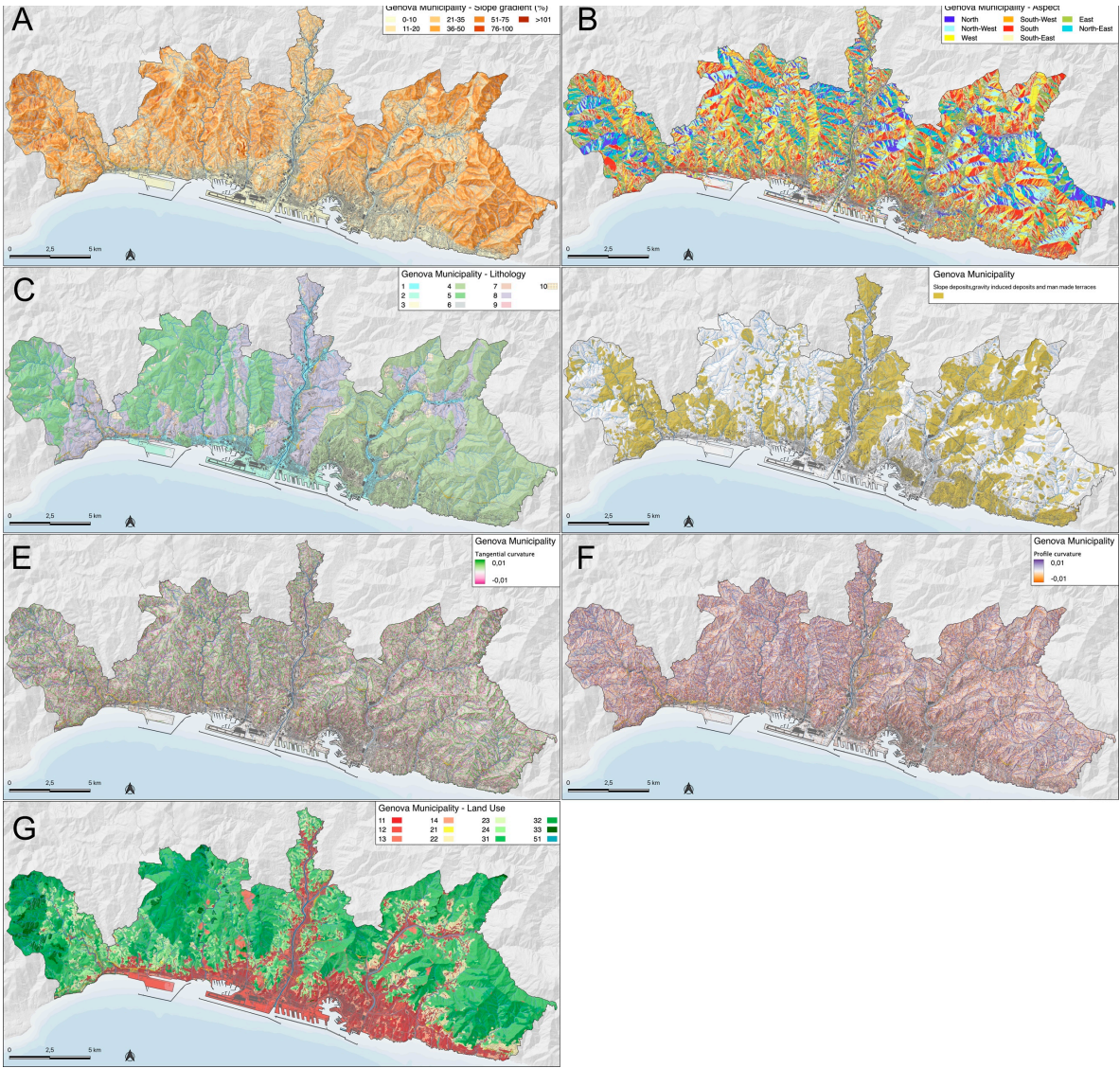


Figure 7. Cartographic representation of causal factors used in the assessment of shallow landslide susceptibility: (A) slope gradient; (B) slope aspect; (C) lithotype; (D) slope and terrace deposits of estimated thickness greater than 1m; (E) tangential surface curvature; (F) profile surface curvature; (G) land-use.

		Hazard class						
		1	2	3	4	5		
Vulnerability class	1	1	2	3	4	5	1	
	2	2	4	6	8	10	2	
	3	3	6	9	12	15	3	
	4	4	8	12	16	20	4	
	5	5	10	15	20	25	5	

Figure 8. The risk matrix, obtained by the combination of the 5 hazard and 5 vulnerability classes.

3. Results

Statistical analysis of the shallow instability phenomena belonging to the training set produced the results shown in Table 5. Statistics have been used as weights for the reclassification process of every predisposing factor. As it can be seen from Table 5, the highest occurrence frequency of shallow landslides for the area of Genoa municipality is related to: exposures to the southern quadrants, slopes of intermediate classes, cultivated land uses, i.e., the presence of terraces, meadow and forest,

and lithotypes of schist, quarzitic, flysch and ophiolitic rock masses. In addition, the possibility of development even in the absence of cover, as its presence was defined, i.e., for thicknesses greater than 1 m or in the presence of terraces, although it may seem incongruent, is to be attributed to the development of phenomena of modest size or to cases in which the presence of cover was not precisely recognized.

Table 5. Occurrence of shallow landslides for the 7 identified causal factors grouped into classes and corresponding weights used to assess landslide susceptibility.

Slope (%)	Shallow landslides	Weight
0-10	2	0.0052
11-20	36	0.0935
21-35	153	0.3974
36-50	139	0.3610
51-75	54	0.1403
>75	1	0.0026
Aspect	Shallow landslides	Weight
South	67	0.1740
East	44	0.1143
West	59	0.1532
North	22	0.0571
North-East	34	0.0883
South-East	69	0.1792
South-West	68	0.1766
North-West	22	0.0571
Lithology	Shallow landslides	Weight
Schists and shales	103	0.2675
Carbonate rocks	5	0.0130
Alluvial deposits	18	0.0468
Conglomerate	2	0.0052
Flysch	72	0.1870
Quartzite and cherts	91	0.2364
Ophiolitic rocks	94	0.2442
Land Use	Shallow landslides	Weight
Artificial areas	8	0.0208
Crop and meadows	119	0.3091
Wood	195	0.5065
Scrub and herbaceous areas	61	0.1584
Peri-fluvial areas	2	0.0052
Tangential curvature	Shallow landslides	Weight
< -0,025	0	0.0000
-0,025/-0,01	55	0.429
-0,01/- 0,0025	92	0.2390
-0,0025/0,0025	98	0.2545
0,0025/0,01	85	0.2208
0,01/0,025	47	0.1221
>0,025	8	0.0208
Profile curvature	Shallow landslides	Weight
< -0,025	0	0.0000
-0,025/-0,01	44	0.1143
-0,01/- 0,0025	97	0.2519

-0,0025/0,0025	134	0.3481
0,0025/0,01	86	0.2234
0,01/0,025	23	0.0597
>0,025	1	0.0026
Slope deposits	Shallow landslides	Weight
Presence	359	0.9325
Absence	26	0.0675

The network of underground utilities, shown in Figure 2, was cross-referenced with the susceptibility mapping obtained according to the aforementioned procedure. Areas made impermeable by urbanization were excluded from the assessment because they substantially lack potential source material for rapid runoff phenomena. This type of phenomena shows the highest capacity to generate damage on structures and infrastructures [67–69] because of the high speed of movement that, even in the presence of relatively moderate masses, results in high kinetic energy. Moreover, their evolution, whose triggering is driven by high rainfall intensities, occurs extremely rapidly, preventing any kind of intervention during the event. Sealed surfaces can play the role of concentrating the runoff and thus possibly contribute to the triggering of a downstream runoff phenomenon, as may occur through “gutter effect” by a road with inadequate or possibly occluded surface drainage.

The achieved susceptibility map (Figure 8) shows a large concentration of areas in the highest class at Polcevera and Bisagno Valleys and in the small catchment areas of the western portion of the municipality. The latter are developed in the proximity of the municipality’s highest elevations, which exceed 1,000 m above sea level at a very short distance from the coastline, thus in the presence of extremely high slope gradients. In addition, also due to these morphometric characteristics, they are historically affected by higher and more intense rainfall values than the eastern parts of the municipal territory.

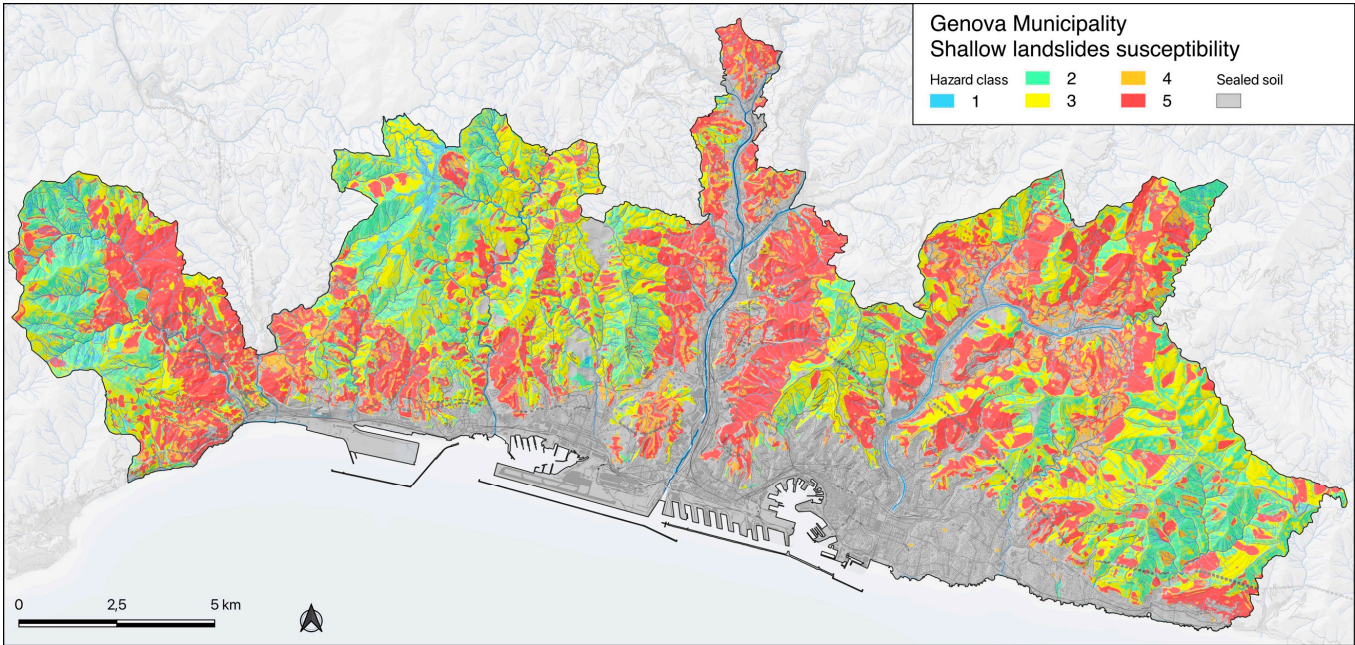


Figure 8. The shallow landslide susceptibility map.

More generally, the susceptibility classes and their spatialization can also be ascribed to the different proneness to the triggering of fast-developing landslides by the different lithologies that make up the geological bedrock, which emerged from the statistics of the phenomena, as well as the lower presence of cover, including terraces. The high slope gradient also results in a high erosive power, preventing or significantly reducing debris and soil accumulations.

The calibration process made it possible to verify the reliability of the susceptibility assessment model. The results, obtained by cross-referencing the events in the calibration set (Figure 6) with the landslide susceptibility mapping, are shown in Table 6: 92 percent of the landslides in the calibration set fall in landslide susceptibility zones of classes 4 and 5, and 73 percent fall in class 5. These results testify the reliability of the developed model.

Then, the obtained landslide susceptibility map has been used as an assessment of the hazard to which the underground utilities are exposed to in relation to the development of fast shallow landslides. Considering the association of vulnerability to the pipe’s diameters defined in Table 4 and the following definition of risk classes in Figure 8, the networks risk maps are presented in Figure 9. In Figure 10 a detail related to a hilly area is shown, while Figure 11 exposes the distribution of length in percentage for the different risk classes.

Table 6. A majority of the landslides in the calibration set, 92 per cent of the total of 97 landslides, fall into the two maximum susceptibility categories, testifying to the model’s level of reliability.

Susceptibility Class	Shallow Landslides— Calibration Set
1	0
2	3
3	5
4	18
5	71
Total	97

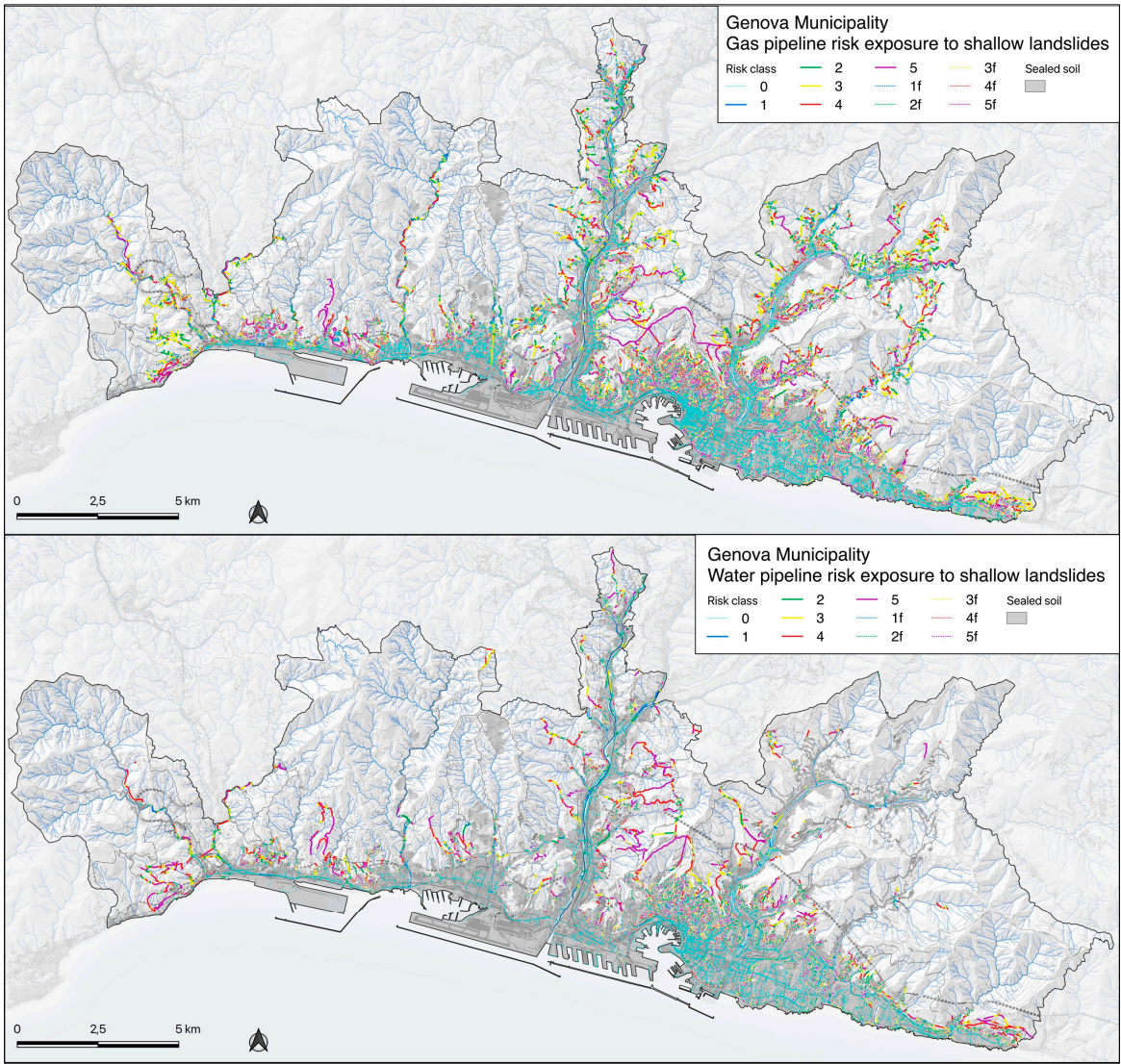


Figure 9. Risk map for the gas (A) and water (B) distribution network, obtained considering the vulnerability as a unit and using the susceptibility map for hazard assessment. The networks are classified into sections corresponding to increasing risk classes 1 to 5. The suffix f denotes rockfall or collapse risk classes.

In urban areas, where the shallow landslides hazard is absent (class 0), in order to highlight the potential presence of risk factors determined by falls or wall collapses, pipes sections have been classified as follows: i) where the slope gradient is under 5° the hazard is absent and then the associated risk; ii) in areas steeper than 5° the fall hazard has been considered belonging to one class and the associated risk has been obtained considering the vulnerability as previously identified (Table 4). Then, in Figure 9 is present the classification of the two networks in terms of risk for shallow landslides occurrence in classes form 1 to 5 and the one in terms of fall risk from 1f to 5f. The 0 class denotes absence of the two risk factors.

The detail maps in Figure 10 belongs to steep slopes and highlights the mixing and co-penetration between natural cover areas and scattered built-up ones: high risk zones are present at the edge of areas of intermediate or even low risk. In addition, Figure 10 shows the assessment of running water concentration, as obtained by the application of the corresponding algorithm (SAGA GIS) to the DTM: this parameter represents the potential triggering factor of potential fast-developing landslides, and its spatial analysis in relation to the landslide’s susceptibility allows a further assessment of the shallow landslides induced risk. Then, the combination of the two analysis helps in identifying both a potential shallow landslide and its development path, allowing to point out, through the subsequent spatial analysis, the potential exposed elements.

Finally, in Figure11 the percentage distribution of gas and water networks in Genoa Municipality exposed to the risk is shown. The performed calculation evidences that 12% of the water network and 11% of the gas network belong to risk classes 4 and 5, then are exposed to the highest risk. Considering Figure 9, these high-risk stretches are widely spread along the slopes where the networks expand from the urban sealed soil area to the sparse buildings one.

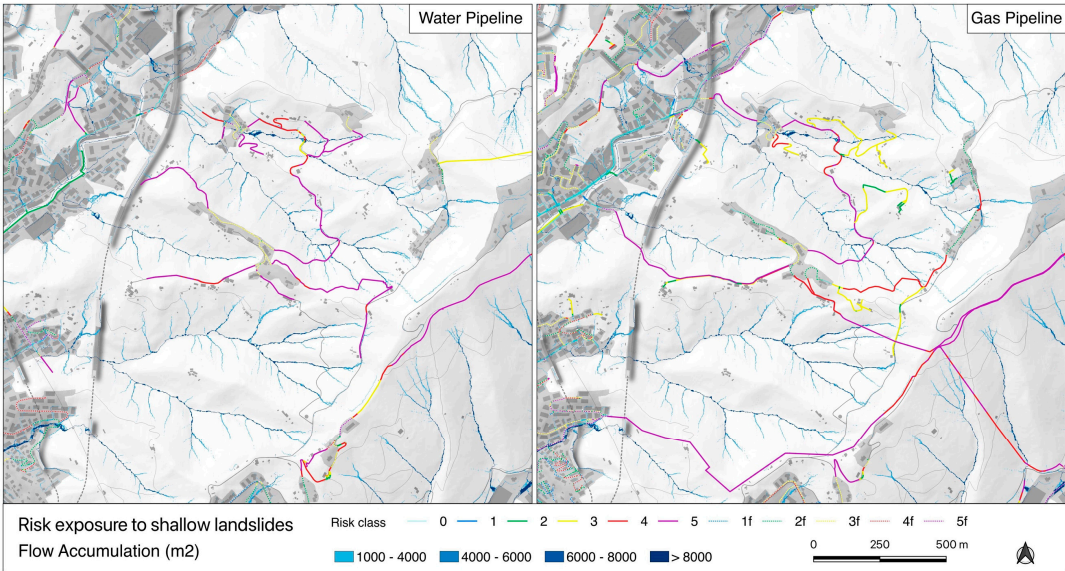


Figure 10. Details of the risk assessment for the water and gas distribution network. The networks are subdivided into sections corresponding to increasing risk classes from 1 to 5 for both the shallow landslides risk and the rockfall or collapse one.

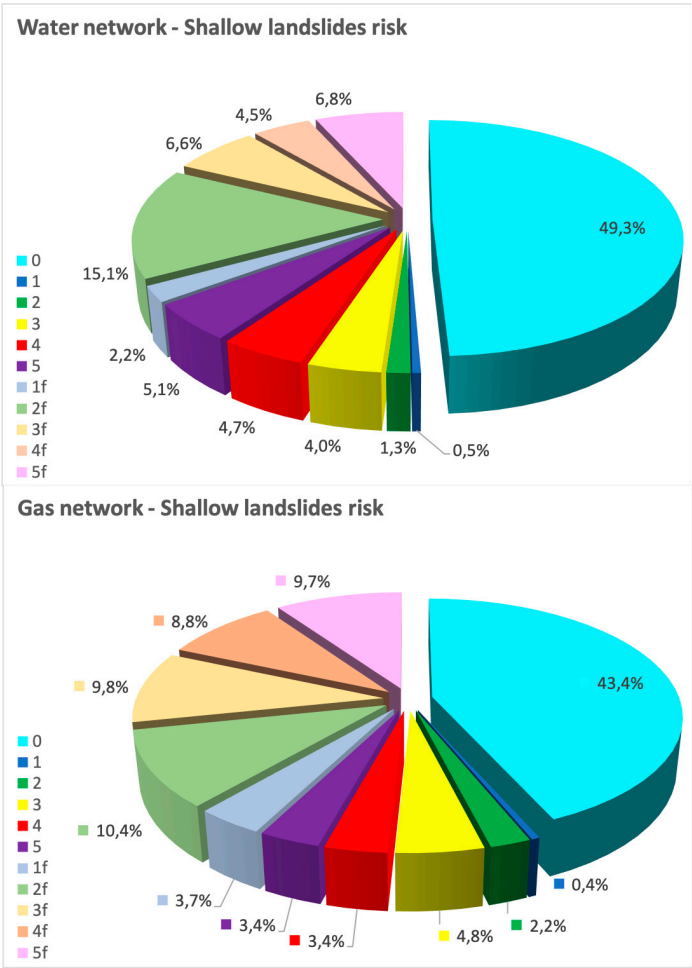


Figure 11. Distribution of the gas and water networks according to the different risk classes.

5. Discussion

The research activity allowed to obtain the susceptibility map for rainfall-induced shallow landslides in the Municipality of Genoa, following a qualitative-quantitative approach and then the risk related map for the water and gas networks. The descriptive statistics method, based on the evaluation and analysis of 485 rapid-developing surface landslide events recognized in the municipal territory, was combined with the AHP method, which is part of the heuristic techniques for evaluation and decision support. The methodology was applied by employing seven predisposing factors for the initiation of rain-induced surface landslides and using baseline and remote sensing survey data combined and analyzed in a GIS environment. The model was tested with a calibration process that confirmed its good reliability: 92% of the calibration set, which include 97 landslides, belonging to the that two highest susceptibility classes.

The result was subsequently cross-referenced with the underground utility networks vulnerability as defined in terms of the pipe’s diameter, in order to evaluate the risk and provide an early prevention tool. This first assessment can be further refined and developed by including the analysis of runoff water flow accumulation, i.e., by including the triggering factor for rainfall-induced shallow landslides and by carrying out periodic on-site checks in the most critical areas. The possible approach is presented in the detail Figure 10. The availability of detailed information on the characteristics of the networks, and especially on how they are laid, may allow subsequent refinement of the risk assessment by assigning further differentiated vulnerability values. The potential risk related to wall’s collapse or rockfall in urban areas, where shallow landslides hazard is considered absent, has been included in the risk evaluation in order to give a more complete evaluation of the two networks.

Furthermore, it is necessary to highlight how the susceptibility map for the fast-developing shallow landslides was obtained basing on the events that occurred on the municipal territory over the past 2-3 decades [39; 41-42]. Although their number represents a robust statistical basis, it should be emphasized that their occurrence is determined by intense rainfall, which in the area and for the short duration intervals present the maximum at the national and European scale with 180 mm/1h recorded in 2011 [70]. Such high-intensity phenomena exhibit strong spatial localization, then it is possible that the areas where the landslide phenomena have developed less frequently (Figure 6) have not yet been affected by extremely high rainfall intensities, but they could be in the future. Further research developments may additionally investigate both this aspect and include more descriptive parameters of utilities network vulnerability to risk. Besides, the presented approach to the vulnerability assessment and then the following risk evaluation, represents an evolution of previous research activities dedicated to the hazard assessment [5,6,17,24,55].

The performed analysis allows to plan and design a possible mitigation strategy. At first, the distribution of the two networks in risk classes constitutes a priority scale of attention along the very long networks. Then, depending on the local situation, and considering the shallow nature of the considered landslides, the necessary prevention measures may include NBS—Nature Based Solutions—techniques [71–75]. These measures are successfully used to improve slopes’ stability in particular in presence of abandoned man-made terraces which represent a possible source of risk [60,62,63,76,77]. Besides, NBS prevention measures present other co-benefits: i) the small and low-cost measures may be widely adopted along the Municipality with a proper planning of resources and interventions; ii) the short extension of the measures allows to overcome access issues that may arise in some steep or critical areas.

Finally, the importance of prevention activities is increasingly necessary and urgent considering the rainfall trend in the study area that sees a reduction in rainy days in the face of annual averages that remain substantially unchanged [78]. Figure 12 shows the annual maximum rainfall intensities in 1h, 3h and 6h registered between 1960 and 2024 by 3 rain stations whose localization is shown in Figure 1. The absolute values are relevant for all the time intervals and for all the stations, underlining the high hazard for pluvial induced phenomena in the area. Table 7 shows the statistics for the intervals and for the stations: the maximum exceeds 120 mm/1h, 260 mm/3h and 330 mm/6h. Besides, the trends look to be increasing in the 64 years period: Table 8 shows the Mann-Kendall trend test performed at 95% of significance and the Sen’s slope trend estimation with the relative confidence intervals. The analysis shows that the 1h yearly maximum intensity increase is statistically significant for the Fiorino station, which is located in the western portion of the Municipality (Figure 1). All the other diagrams present an increasing trend, even if not statistically significant. Finally, these results are coherent with other research conducted on extreme pluvial events meteorological proxies [43].

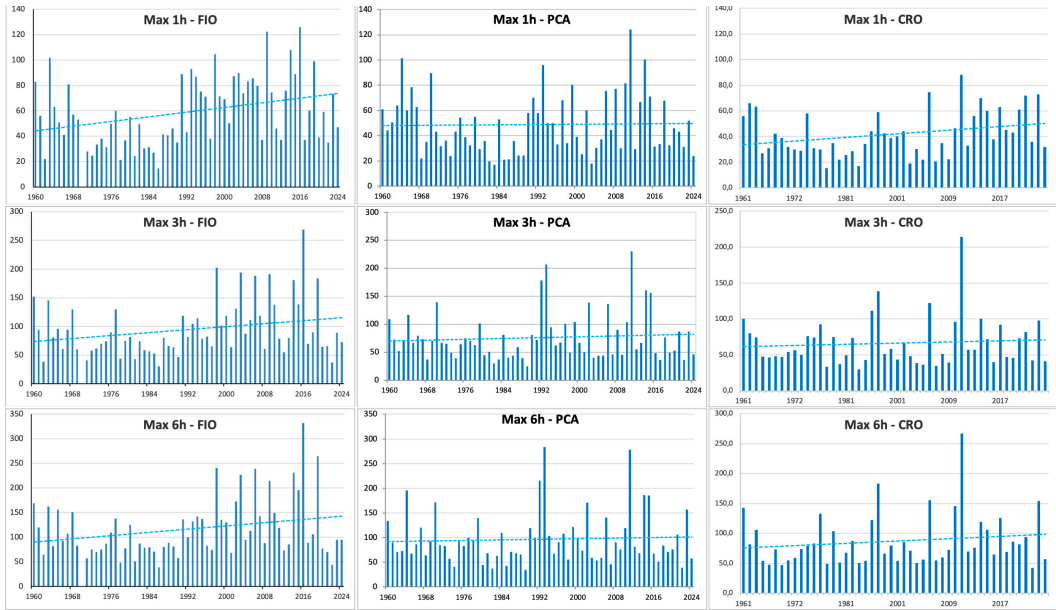


Figure 12. annual rainfall cumulative amounts for FIO. PCA and CRO rain gauge stations.

Table 7. Descriptive statistics of hourly rainfall at Fiorino (FIO 1960–2024), Ponte Carrega (PCO 1960-2024) and Crocetta d’Orero (CRO 1961–2024) rain gauges.

Statistics	FIO			PCA			CRO		
	1 h	3 h	6 h	1 h	3 h	6 h	1 h	3 h	6 h
Mean	59.1	95.0	116.5	48.9	75.9	96.8	42.1	66.3	86.9
Median	54.2	80.5	94.7	43.0	66.4	83.0	38.4	55.1	73.7
Maximum	126.0	269.0	332.0	124.2	230.0	283.6	88.0	214.0	267.0
Minimum	14.8	31	38.8	17.0	24.6	35.0	15.2	29.6	42.0

Table 8. Mann-Kendall trend test results at 95% confidence for hourly rainfall series at Fiorino (FIO 1960–2024), Ponte Carrega (PCO 1960-2024) and Crocetta d’Orero (CRO 1961–2024) rain gauges.

Statistics	FIO			PCA			CRO		
	1 h	3 h	6 h	1 h	3 h	6 h	1 h	3 h	6 h
z-stat	2.40470	1.73823	1.54695	-0.12457	-0.283092	-0.192505	1.92901	-0.04445	1.29781
p-value	0.01619	0.08217	0.12188	0.90086	0.777101	0.847347	0.05373	0.96455	0.19435
trend	yes	no	no	no	no	no	no	no	no
Sen’ slope	0.44721	0.42311	0.39500	-0.01847	-0.051355	-0.03333	0.31623	-0.01456	0.34170
Lower	0.09268	-0.07143	-0.13600	-0.31111	-0.426229	-0.50345	-0.01053	-0.45000	-0.23125
Upper	0.82857	0.98571	1.05625	0.28	0.333333	0.51429	0.70769	0.50625	0.94595

4. Conclusions

The research allowed to assess the shallow landslides risk for the two water and gas distribution network in the Genoa municipality. The assessment has been conducted evaluating the hazard according to a methodology previously developed in a contiguous area [17,55] which has been modified and adapted to the territory features. Besides, the methodology has been adapted to the study area using a statistically robust set of 485 events which has been randomly split between a training set and a calibration set of, respectively, 80% and 20% of the total events. The large number of events and the rigorous approach allowed to perform a good evaluation of the occurrence of the shallow landslide in relation to the considered seven conditioning factors. The high percentage obtain after the calibration test attests the reliability of the adopted model.

Moreover, it must be underlined that, comparing to previous works [17,55], the conditioning factors set has been modified decreasing its number and introducing new ones related to the morphometry features. The conditioning factors number reduction, obtained including all the anthropogenic features into the land use factor, allows a more agile model application without losing the reliability, as testified by the calibration process result. Besides, the crucial factor related to the presence of man-made terraces that belong to the human modification of the landscape, has been maintained as their presence has been precisely identified using results belonging to previous researches [62,63] and including them into the slope deposit factor. Finally, the availability of a recent and precise LiDAR derived 1 m resolution DTM allowed an accurate evaluation of the landscape morphometric features, and the presence of terraces.

The increasing instability of the slopes due to shallow landslides triggering and the effects in the peri-urban areas causes more and more damages every year and often involves the water and gas distribution networks. The effect is related to the increasing intensity of rainfall that hit the study area, as it has been underlined by the 95% statistically significant increase of the 1h duration maximum intensity at one meteorological station in the studied area.

Then, these results contribute to underline the necessity of adopting prevention measures for the ground effects related to high intensity rainfall [79] in order to mitigate the risk level of the two vulnerable networks, which represent critical exposed elements. The developed risk assessment tool represents the basis of a decision support tool for planning and adopting a series of small prevention measures at the Municipality scale. A further development of the obtained results may eventually implement other network's technical data for an additional vulnerability assessment.

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