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Morphometric Analysis of Trail Network and Tourist Vulnerability in a Highly Frequented Protected Area

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Abstract: Increasing interest in the natural environment and greater hiking activity have resulted in higher anthropogenic pressure in areas characterized by a geographic/physical setting that could present hazardous conditions. The development of these activities is influenced by the peculiar geomorphological and climatic conditions of the area. Visitors and hikers do not always have adequate cultural background and full awareness of natural dynamics, including the possibility of incurring hazardous conditions. For its cultural and landscape value and extraordinary trail network, the Portofino Promontory is frequented by more than a hundred thousand of hikers a year. However, due to the geomorphological characteristics of the area, the morphological features of the trail network (i.e., exposed paths, steep ups and downs, rocky sections with cables, etc.) and the peculiar meteo-climatic conditions, the number of accidents involving hikers has increased in the most recent years. This research uses a detailed LiDAR survey, a morphometric analysis, and a significant dataset of information on the frequentation of the hiking trail network and on the number of rescue operations carried out by the National Mountain Rescue and Speleological Service (CNSAS). These data have been related to the physical-geographical characteristics of the area. The results can be a useful tool for land management by the Park Authority.

Keywords: trail network; natural hazard; tourist vulnerability; hiking; morphometric analysis; natural parks

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1. Introduction

Growing interest in the natural environment and its resources, anthropogenic pressure on cities, and the spread of outdoor sports have led, in recent years, to the intense grow of nature tourism—a form of tourism that encompasses various activities in which nature is the primary setting or attraction [1–3]. Nature-based tourism can take many forms, ranging from the passive enjoyment of landscape to hiking activities, even in areas characterized by natural hazard processes in various environments, from high mountains to the coast (cf. [4,5]).

Moreover, the recent COVID-19-related pandemic and additional viral diseases such as swine fever seem to have contributed to an additional boost in outdoor activities, with a greater emphasis on protected areas and areas of high scenic and naturalistic-environmental value in general [6–8].

This phenomenon may induce an array of impacts on vegetation, soils, animals, and water as evidenced by the extensive literature on use-related trail impacts (cf. [9–11]). In fact, the trampling effect due to the use of slopes and rangelands for recreational activities may increase soil erosion, reduce and alter the vegetation cover, or disturb wildlife (e.g., [12–15] and reference therein). Extensive research has focused on soil erosion in mountain trails, especially in protected areas, as evidenced by the abundance of scientific publications occurring since 2010 (cf. [16] and reference therein).

The increasing frequency of tourists and hikers has also led to a rise in the number of accidents involving these individuals and park visitors along the trails. This increase is substantiated by data collected by the National Mountain Rescue and Speleological Service (CNSAS) over more than two decades of surveys, with a significant upswing in recent years. This is related to the growing number of people who, lacking sufficient technical skills, equipment, and knowledge of the terrain and its natural hazards, venture into areas characterized by active processes and unique climatic-environmental conditions.

In fact, the development of nature-based tourism and hiking activities is often linked to the presence of singular geological and geomorphological features, as well as meteorological and climatic. Perry [17] underscores that tourism frequently occurs in dynamic environments and "it is often the high risk components of the landscape that are the most attractive from the tourist point of view". However, the physical-geographical dynamics of an area can result in significant natural hazards and consequent risk which, sometimes, does not seem to correspond to a proper perception and awareness [18–20]. Cui et al. [21] approached the risk perception considering the subjective and the objective components and the cognition of exceeding a threshold risk level. When dealing with hiking activity, perception assumes a crucial aspect and the self-judgment capacity may result critical.

Ongoing climate change [22,23], rising average air temperature and changing rainfall regime, of short duration and high intensity [24–27], contributes to worsening natural hazard scenarios and increasing the vulnerability of the human component at the same time. Tourists/hikers are not always prepared to deal with situations of sudden climatological and meteo-hydrological processes that have been significantly intensified in recent decades (e.g., heat waves, flash floods, mud flow) and also tend to be more vulnerable than locals because they are unfamiliar with the place they are visiting [17].

In natural areas with a high tourist attendance, in particular along the hiking trail network, the risk is defined as the product of geomorphological hazard, meteorological hazard, and tourist vulnerability [28–31]. The geomorphological hazard is associated with: (i) geomorphological processes which can interfere with the paths; (ii) the characteristics of the existing phenomena, such as typology, geometry, extension, state of activity, frequency [32–35]. Meteorological hazard [36,37] is given by sudden changes in meteorological conditions, heavy rainfall, fog, humidity, very low or high temperatures in winter and summer, etc. Tourist vulnerability includes: (i) the structural characteristics of the hiking trails, such as the type of path, the exposure, the steepness, the state of maintenance, the presence of adequate waymarks; (ii) the human element, such as physical and psychological preparation, technical skills, hiking experience, equipment, level of knowledge of the area and awareness of natural hazards that may be present, etc. [38–41].

Extensive research has been recently undertaken in trail science, a branch of recreation ecology aiming to characterize common trail impacts and pinpointing significant factors affecting the severity of these impacts, and promoting sustainable approaches to trail design and management (e.g., [42–44] and reference therein). In this context, some authors have successfully applied GIS [45–47], ALS [48], dendrochronology [49], or logistic regression analysis [50] to assess and model trail stability and erosion or explored the relationships between trail conditions and the experiences [51]. Other authors pointed out the importance of a proper design of trails in order to mitigate erosion [52–54]. A much less explored topic in this domain has been the assessment of the risk along hiking trails, which, nevertheless, is of paramount importance for ensuring safe and sustainable tourism in protected areas over time. Brandolini et al. [55] assessed risk considering factors relating to geomorphological hazard and factors relating to tourist vulnerability along trails in Portofino Park (Italy). More recently, Giordan et al. [56] proposed a codified procedure for the effective management of geo-hydrogeological risk to be applied after relevant meteorological events affecting the Cinque Terre National Park (Italy). However, study on relationships between morphometric conditions and the trail risk remain scarce. In this paper, to fulfil this gap, we present a methodology for recognize the factors that have led to accidents along a trail network basing on high detail DTM and on the accidents database and for assess the degree of risk along the trails. The proposed methodology was tested in the Portofino Natural Park (Liguria, Italy), a highly frequented park (Figure 1) that, in recent decades, has become the practical example of the interaction between natural hazards and high tourist frequency [57–60], and, consequently, high number of accidents involving hikers. The research is developed through the following highlights: analysis of accidents that have occurred in the park area in recent decades; analysis of tourist and hiking frequency in the protected area through pedometers installed by the Park Authority; three-dimensional reconstruction of the trail network and its immediate surroundings through remote-sensing surveys; evaluating a series of morphometric parameters along the trails; assessment of natural hazards that have characterized the park area in recent decades and in previous periods; assessment of the degree of risk along the trail network due to both natural processes and structural features of the trail; and definition of guidelines for the mitigation of natural hazards and related tourist vulnerability.

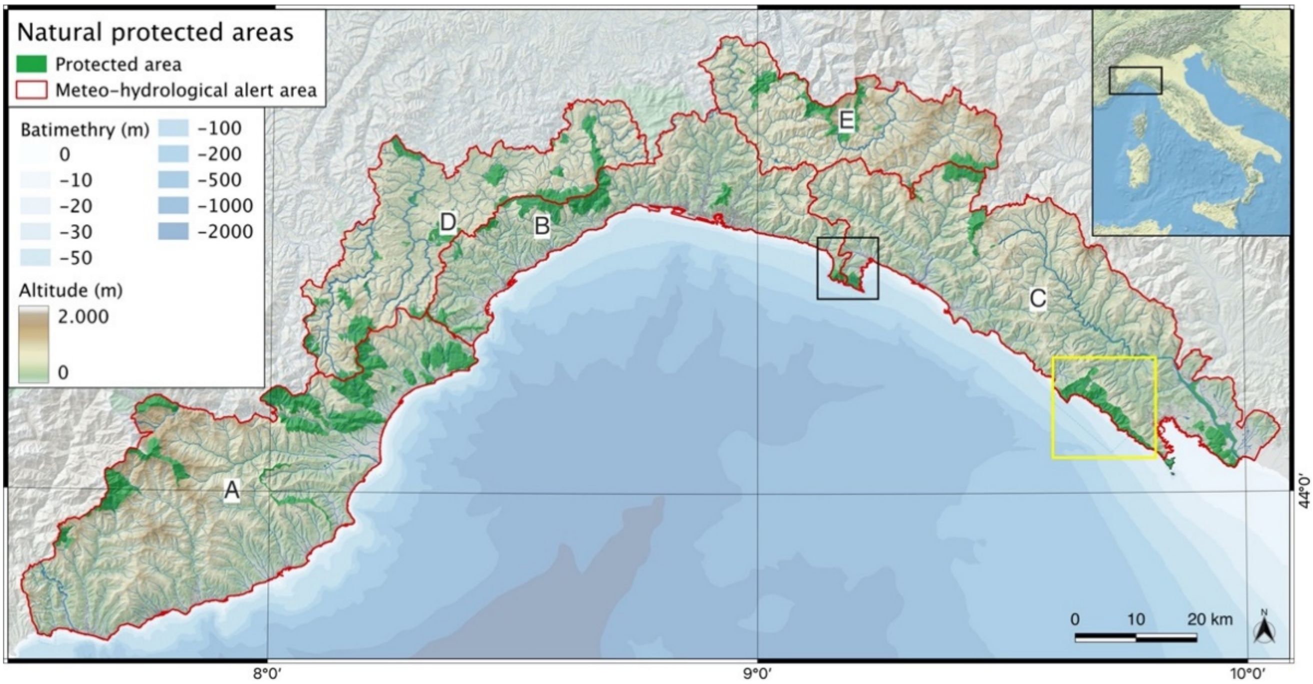

Figure 1. Physical map of the Liguria region. A, B, C, D, and E are the hydrometeorological alert zones. The black square highlights the Portofino Promontory and the yellow one the Cinque Terre National Park.

2. Materials and Methods

2.1. General Settings of Portofino Promontory

The Portofino Promontory, located in eastern Liguria (Northern Italy) and protected since 1935 by the natural park of the same name, is internationally known not only for its valuable landscape, and naturalistic and cultural-historical heritage, but also for a hiking tourism attracted by the extensive network of trails that cross the protected area. It is an area of recognized cultural and landscape value, renowned at an international level.

The park has an area of 18 km^2, and it comprises an integral reserve, a general reserve, a protection area, and an economic promotion area. The variety of attractions that distinguish the Park area, from scientific-naturalistic (fauna, flora, geology, geomorphology) to environmental (landscape), from historical-cultural and architectural (The Batteries, Monumental Complex of the Abbey of San Fruttuoso, the Valley of the Mills, the seaside village of Portofino) to socio-economic (accommodation activities, local, etc.), as well as recreational-sports (hiking, cycling, diving in the marine protected area and other water sports), and easy access even from the sea, combine to make the category of users of the trail network very composite in terms of age, origin, level of preparation, equipment, and degree of knowledge of the area. This factor contributes significantly to increased vulnerability along the Park's trails and worsens existing risk situations related to natural hazards and structural elements of the trails.

Its trapezoidal shape breaks the continuity of the coastline between Genoa and La Spezia, representing the watershed between the Paradiso Gulf and the Tigullio Gulf (Figure 2). The promontory is configured as a mountain ridge with a NW–SE orientation, culminating with the peak of Monte di Portofino (610 m) [61]. Short streams, mainly of the first order, originate from the main watershed (Figure 2). The mountain ridge determines an abrupt and significant orographic elevation in relation to the proximity to the coastline, which lies at about 1 km from the main watershed. This has a strong influence on the climate conditions of the whole compartment. In fact, the Portofino Promontory represents the border between zone-B and zone-C of the Ligurian meteo-hydrological alert subdivision (Figure 1).

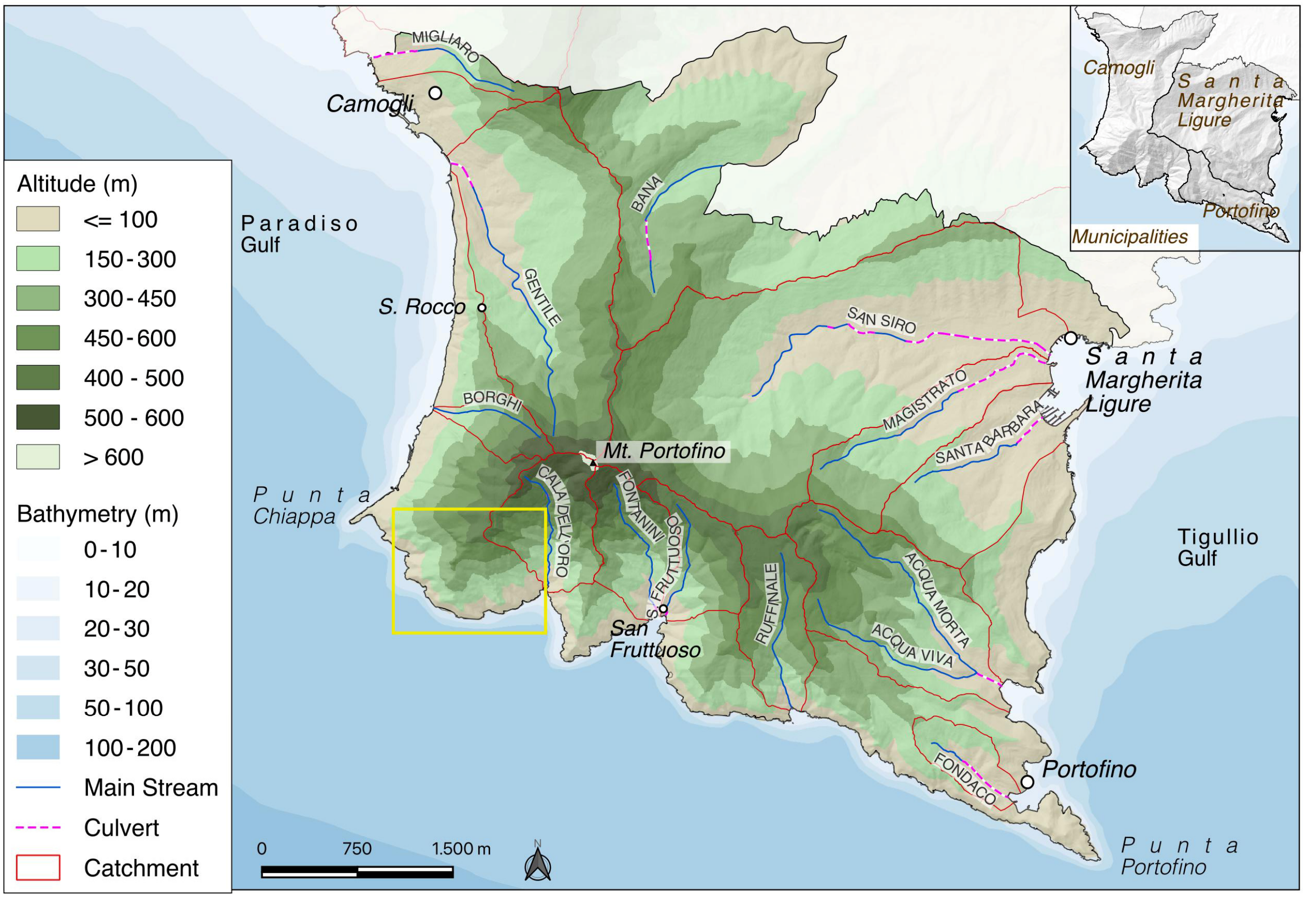

Figure 2. Geographical sketch map of Portofino Promontory; the yellow rectangle denotes the detail area in Figure 6.

Temperature and rainfall values determine a middle latitude temperate climate of the Mediterranean type [62,63]. The average rainfall cumulate in a year varies from 900 to 1300 mm, depending on the orographic features of the territory. The wettest season is autumn, while summer is the driest. The mean annual temperature is 12–13 °C, with a summer peak of 24–25 °C and a winter low of 8–9 °C. On the peak of the Monte di Portofino, summer air temperatures up to 35 °C are recorded, with more than 75% of relative humidity, while the lowest temperatures in the winter can drop below 0 °C.

Different factors, like altitude, aspect, air humidity, and land cover, determine different microclimates [64–67]. Three areas can be differentiated: (i) the southern slopes, with very hot summers and mild winters, long insolation periods and exposition to warm southern winds; (ii) the northern slopes, characterized by mild summers and cool and wet winters, favored by the exposition to the northern currents; (iii) the summit area, affected by frequent rainfall and mists, originated by the interaction between the warm and wet air that comes from the sea and the dry and cool air coming from the inland.

The geology of the Portofino Promontory is characterized by two different formations: the Portofino Conglomerates, outcropping in the summit area and the southern slope of the promontory and the Mt. Antola Formation, outcropping in the northern sector (Figure 3).

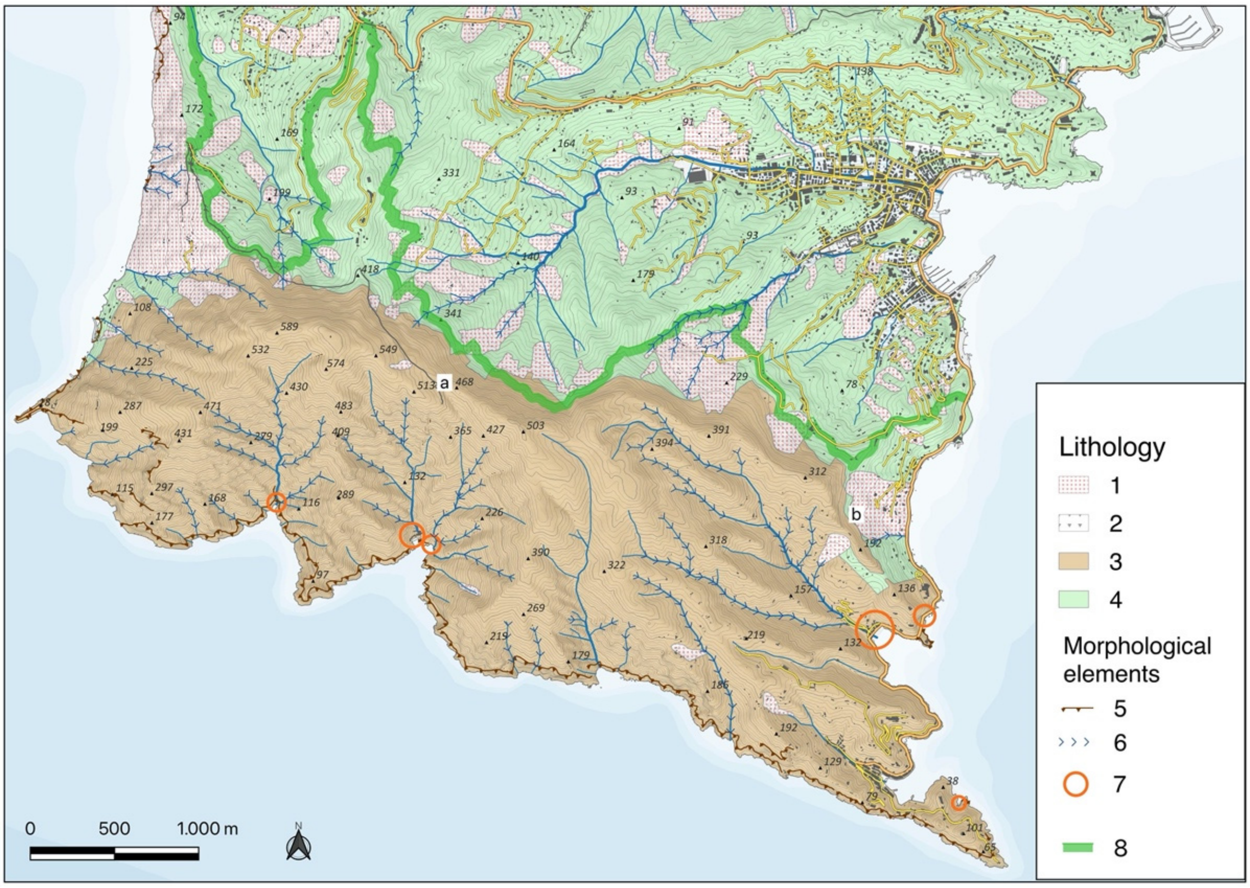

Figure 3. Geological and geomorphological sketch map of Portofino Promontory. (1) Landslides, quaternary deposits; (2) Fills; (3) Portofino Conglomerates; (4) Mt. Antola Formation. (5) Cliffs; (6) V-shaped valleys; (7) Pocket beach (8) Border of the Portofino Natural Park; a. Pietre Strette; b. Le Gave.

The Mt. Antola Formation (Late Cretaceous-Paleogene; [68]) is a marly-limestone flysch, with intercalations of sandstones, marls, and shales. It shows polyphase deformation, both ductile and fragile, with strata and folds characterized by variable orientation. The Portofino Conglomerates (middle-late Eocene-early Oligocene [69]) are made of heterometric pebbles, from centimeters to meters in size, in a sandstone matrix. The pebbles are of different lithologies: marly-limestones, sandstones, ophiolites, cherts, and schists [69–71]. The conglomerates have a roughly N-NE dip direction and a 10–30° dip. In the conglomerates, there is evidence of fragile deformation, with fault systems oriented WNW-ESE and NNE-SSW. These fault systems control the hydrographic network, the orientation of the coastline, and the direction of the watersheds [72].

The southern side of the promontory, carved in conglomerates, shows very steep slopes and subvertical rocky cliffs. The coastline is composite due to the alternation of capes and coves. The western side, on which the Mt. Antola flysch outcrops, has similar features, and it is subject to erosion by waves during storms with SW winds (Libeccio). The eastern side, mainly carved in flysch and only marginally in conglomerates, is gentler. There, the coastline is articulate, with rocky cliffs alternated with beach deposits, subject to wave motion originated by SE winds (Scirocco).

Among geomorphological features, one can recognize landforms due to gravity, to fluvial and runoff processes and due to wave erosion. These processes determine potential danger and risk for human settlements and for the many frequenters of the Park [29,73,74]. At the same time, geology and geomorphology are the basis for the scenic landscape and the richness of geosites [75].

Landslides can be observed along the contact between conglomerates and flysch, and can be classified as lateral spreads (e.g., Pietre Strette) or complex landslides (e.g., Gave) [76]. Active landslides, with rock fall and rockslide cinematics are found on the western side, between Camogli and San Rocco; they are favored by the wave erosion acting at the bottom of the cliffs. In general, rock falls are frequent along all the active cliffs of the promontory, from Camogli to Santa Margherita Ligure.

Colluvial deposits are widespread on all the slopes of the promontory. They are variable in thickness, and sometimes they are reworked in anthropic terraces. Water courses are short, very steep, and present a torrential water regime. In case of heavy rainfall, they can give rise to debris flows with high destructive potential.

2.2. Research Methods

The study has been divided into the following phases: (i) bibliographic research of existing works concerning the geomorphological hazard and risk in protected areas and natural parks or parks of considerable landscape and naturalistic-environmental value with a high tourist attendance, both in hilly, mountain areas and coastal; (ii) characterization of the geological, geomorphological, climatic-meteorological, and environmental structure of the Portofino Park territory and identification of the main situations of geomorphological danger along the paths; (iii) a geomorphometric assessment of the trails features through a dedicated algorithm and others, applied to a high resolution LiDAR DTM; (iv) assessment of tourist vulnerability through the analysis of the path network and data relating to the tourist flow and accidents that occurred along the hiking trail network of the Park in the period 2010–2021; (v) analysis of risk scenarios along the path network of the Portofino Park and identification of possible strategies for the mitigation of situations of geomorphological danger and the reduction in tourist vulnerability along highly used paths.

Geomorphometric assessment has been performed using the 0.5 m DTM derived from the ALS survey performed within the monitoring activities of the project RECONECT [77]. A LiDAR system Riegl VQ 1560-II with two 2 MHz sensors coupled to a Phase One IXM-RS150MF camera was used to obtain a point density of up to 20 m^{-2} from a flight altitude of 5000 ft. The subsequent point classification allowed us to obtain a 0.5 m DTM; an orthophoto mosaic at a 5 cm resolution in both RGB (red, green and blue) and CIR (color infrared) were also obtained.

A vector layer of trails, realized by the Park Authority after a direct GPS survey (https://www.geoportal.regione.liguria.it/ accessed on 15 September 2022), has been used as the basis for a trail geodatabase: raster maps obtained after the calculation of six geomorphometric parameters have been associated to the trails at a resolution of 0.5 m. A dedicated algorithm has been developed to calculate the fall hazard along the trails within a distance of 2 m, while five more algorithms have been selected and applied to the DTM in order to outline the morphometric features of the landscape. The five algorithms have been applied using the free software QGIS (ver. 3.20), Whitebox (v2.1.0), and SAGA-GIS (: (i) TRI terrain ruggedness index, which gives the variance of elevation change across the 3 × 3 cells [78]; (ii) Vector Roughness Measure (VRM), which combines the variability of slope and aspect to quantify terrain ruggedness [79]; (iii) ANVAD (Angular Normal Vector Angular Deviation), which gives a measure of the surface roughness quantifying the angular deviations in the direction of the normal vector [80]; (iv) slope gradient; (v) gradient along the trail. In order to estimate the hiking frequentation and the tourist vulnerability, data have been analyzed regarding the number of presences within the park and the number of rescue operations, in the years 2010–2021.

Since 2006 the Park has installed a total of nine eco-meters of different types that allow to count the daily passages (Figure 4; Table 1). Eight eco-meters record the passages on foot, while the ninth records the passages by bike. Each eco-meter is composed of two separate counters ('IN' and 'OUT') that detect the direction of the passages. The number of hikers along the trail network has been taken from the technical reports by Eco-Compteur.

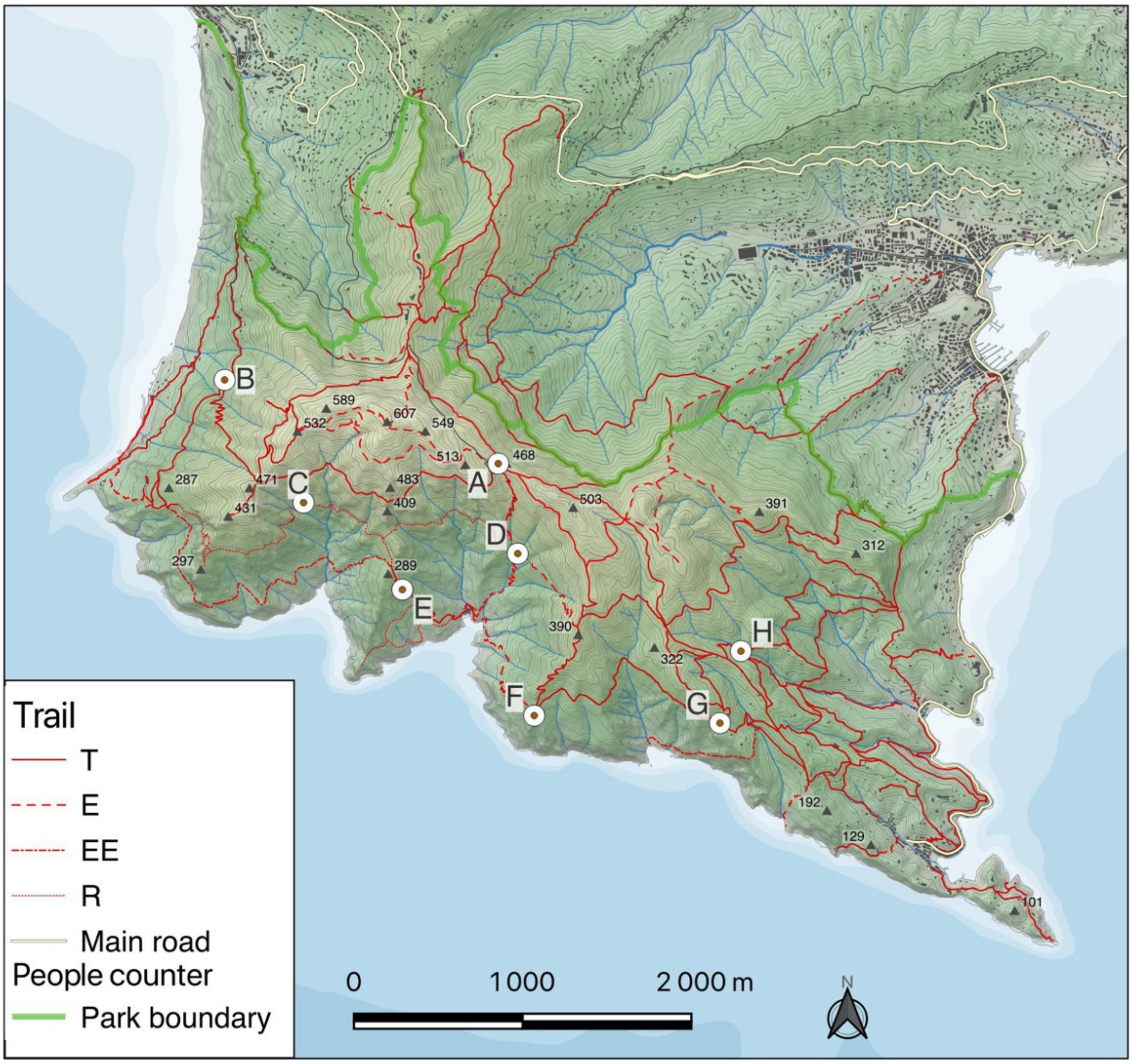

Figure 4. The network of hiking trails of the Portofino Promontory and people counters, identified with letters (see Table 1 as a reference).

Although it is not possible to define with certainty the number of daily presences along the trail network, due to its complex planimetry, it is, however, possible to determine a minimum number of presences within the Park in a given period of time. The minimum number of presences has been estimated taking into account the passages on the eco-meters 'Pietre Strette IN', 'Fornelli IN', 'Prato IN', and 'Mulini'. The passages on these stations on the same day can reasonably be ascribed to different people.

The data regarding the rescue operations are taken from the technical reports by the National Alpine and Spelaeological Rescue Corps (CNSAS).

Table 1. The nine eco-meters installed by the Portofino Natural Park; letters denote the position in Figure 4.

Place	Type of Transit	Type of Data
A—Pietre Strette	Foot, bike	Number of passages, direction (IN = to S. Fruttuoso/OUT = to Portofino Vetta)
B—Fornelli	Foot	Number of passages, direction (IN = to Batterie e S. Fruttuoso/OUT = to S. Rocco)
C—"Via dei Tubi"	Foot	Number of passages, direction (IN = to Caselle/OUT = to Batterie)
D—Caselle	Foot	Number of passages, direction (IN = to S. Fruttuoso/OUT = to Pietre Strette)
E—S. Fruttuoso (W)	Foot	Number of passages, direction (IN = to S. Fruttuoso/OUT = to Batterie)
F—S. Fruttuoso (E)	Foot	Number of passages, direction (IN = to S. Fruttuoso/OUT = to Base O)
G—Prato	Foot	Number of passages, direction (IN = verso S. Fruttuoso/OUT = verso Portofino Mare)
H—Mulino Gassetta	Foot	Number of passages

3. Results

3.1. Natural Hazards

The main geomorphological processes that persist in the park territory are the processes related to gravity, fluvial and runoff processes, and coastal processes. Among the landslides, the best known and most significant are found on the western slope of the Promontory, between San Rocco and Mortola, and consist of different types of processes (rock falls, rock topplings, debris flows, complex landslides with slow kinematics) influenced by the dynamics of the cliff operated from the sea to the foot of the slope. Rock falls and topplings are widespread along all the cliffs of the promontory. Debris flows and earth flows can also develop along the incisions of the watercourses, which are very short and steep.

A very important component of natural hazard is the meteo-climatic component. Extreme conditions are reached in the summer months, between the end of May and the end of September, where the combination of high temperatures (which can exceed 35 °C in the central hours of the day) and high relative humidity lead to very high heat index values, indicating prohibitive conditions for visitors. During the autumn and, to a lesser extent, the winter season, a risk is constituted by extreme rain events, which can lead to several hundred mm of accumulated rain in a few hours. Fogs are relatively frequent in the summit of the Monte di Portofino. Due to the low altitudes, the mild winter temperatures, and the proximity of the sea, snow is infrequent.

3.2. Morphological and Morphometric Features of the Hiking Trail Network

The Portofino Natural Park is characterized by a dense hiking trail network, with a total length of 80 km. The main access points to the Natural Park are the coastal towns of Camogli and Santa Margherita Ligure; the villages of San Rocco, Paraggi, and Portofino; the Portofino Vetta hotel; and the maritime landings of San Fruttuoso and Punta Chiappa. The main crossroads of the hiking trail network is the Pietre Strette pass; minor crossroads are found in Fornelli, Sella Toca, Gaixella, le Bocche, and Olmi.

The hiking trails have different lengths, heights, technical characteristics, and levels of difficulty (Figure 4; Tables 2 and 3). Generally, they are ancient stone-paved paths or tracks with bare earth surface. Most of the paths are waymarked with painted trail marks, signs at the crossroads and explicatory panels. Along the trails classified as 'EE' (i.e., for experienced hikers), one can find exposed stretches, rocky sections, and easy scrambles, usually equipped with fixed cables and chains. The most difficult trails in the Park area are the so-called "Via dei Tubi", which follows the route of an ancient aqueduct carved in vertical conglomerate cliffs, and the "Passo del Bacio" path, which goes from Batterie to

San Fruttuoso crossing the high conglomerate cliffs of Cala dell'Oro. The "Via dei Tubi" is the only trail for which a special permit is needed; all the other trails are freely walkable.

Table 2. Main hiking trails of the Portofino Promontory. The difficulty scale is explained in Table 3.

#	Trail	Length (km)	Elevation Gain (m)	Difficulties Scale
1	San Rocco—San Fruttuoso	4.3	450	EE
2	San Rocco—Punta Chiappa	2.1	0	T
3	San Rocco—Punta Chiappa	2.0	0	E
4	Valle dei Mulini	2.6	250	T
5	Anello alto	6.7	400	T
6	Anello basso	6.0	250	T
7	Ruta—San Fruttuoso	5.0	210	E
8	Santa Margherita—Portofino Mare	5.5	250	T
9	San Fruttuoso—Portofino Mare	3.2	300	E
10	San Rocco—Toca—Pietre Strette	3.6	300	E
11	Ruta—Bocche—Portofino	6.5	220	T
12	"Via dei Tubi"	2.8	100	EE

Table 3. Official classification of the difficulty of the hiking trails, by the Central Commission on Hiking of the Italian Alpine Club.

Grade	Code	Description
For Tourists	T	It includes itineraries on dirt roads, mule tracks, or easy paths; the routes are generally not long, take place below 2000 m.a.s.l. and do not present any orientation problems. They develop in the immediate vicinity of towns, tourist resorts, and communication routes. They do not require specific training.
For Hikers	E	It includes paths or traces in various types of terrain (pastures, debris, stony ground, screes, etc.); sometimes they can develop on open ground, without obvious tracing, but not problematic and always with adequate signaling. They can take place on steep slopes or have single, short, and not exposed passages on rocky terrain that do not require the use of specific climbing equipment. The great majority of hiking trails fall into this category. They require a sense of direction and knowledge of the mountain environment, walking training, suitable footwear, and equipment.
For Experienced Hikers	EE	It includes generally waymarked trails that imply an ability to move easily on rough and treacherous terrain (steep and/or slippery grass slopes, or mixed rocks and grass, or rock and debris, etc.), mixed terrains at relatively high altitudes (stone fields, short non-steep snowfields, open slopes without reference points, etc.), or rocky stretches with slight technical difficulties (equipped routes etc.) that do not require climbing gear. They require good training and adequate physical preparation, sure-footedness and absence of vertigo, a good knowledge of the mountainous environment, and adequate gear and equipment.

In Figure 5A–F, the morphometric characteristics of the hiking trails are shown; in Figure 6A–F, a detail in the south-west promontory. In general, the most unfavorable conditions are found on the southern and western slopes of the promontory, and around the summit of the Monte di Portofino, as the spatial distribution of the calculated parameters show values describe the fall hazard, surface roughness, and gradient, then reflect the terrain morphometry along the trails with a possible link with the hazard. In particular, Figure 5A highlights the danger if falling along the path: the purple color, which denotes a fall height over 2 m evidences the most critical zones. These are located in the southern facing trails and in the western and eastern ones besides the coastline. The area between San Rocco, Batterie, San Fruttuoso, Monte di Portofino, and Pietre Strette, where the Portofino Conglomerates crop out, is characterized by steep, rocky, and value-derived articulated slopes. Consequently, the hiking trails are generally steep, rough, and with a notable height drop on the down side. The northern and eastern slopes of the Promontory, as well as the summit area of Monte Pollone and Monte delle Bocche, are gentle. This influences greatly the morphometry of the hiking trails, which are characterized by low values of the morphometric indices.

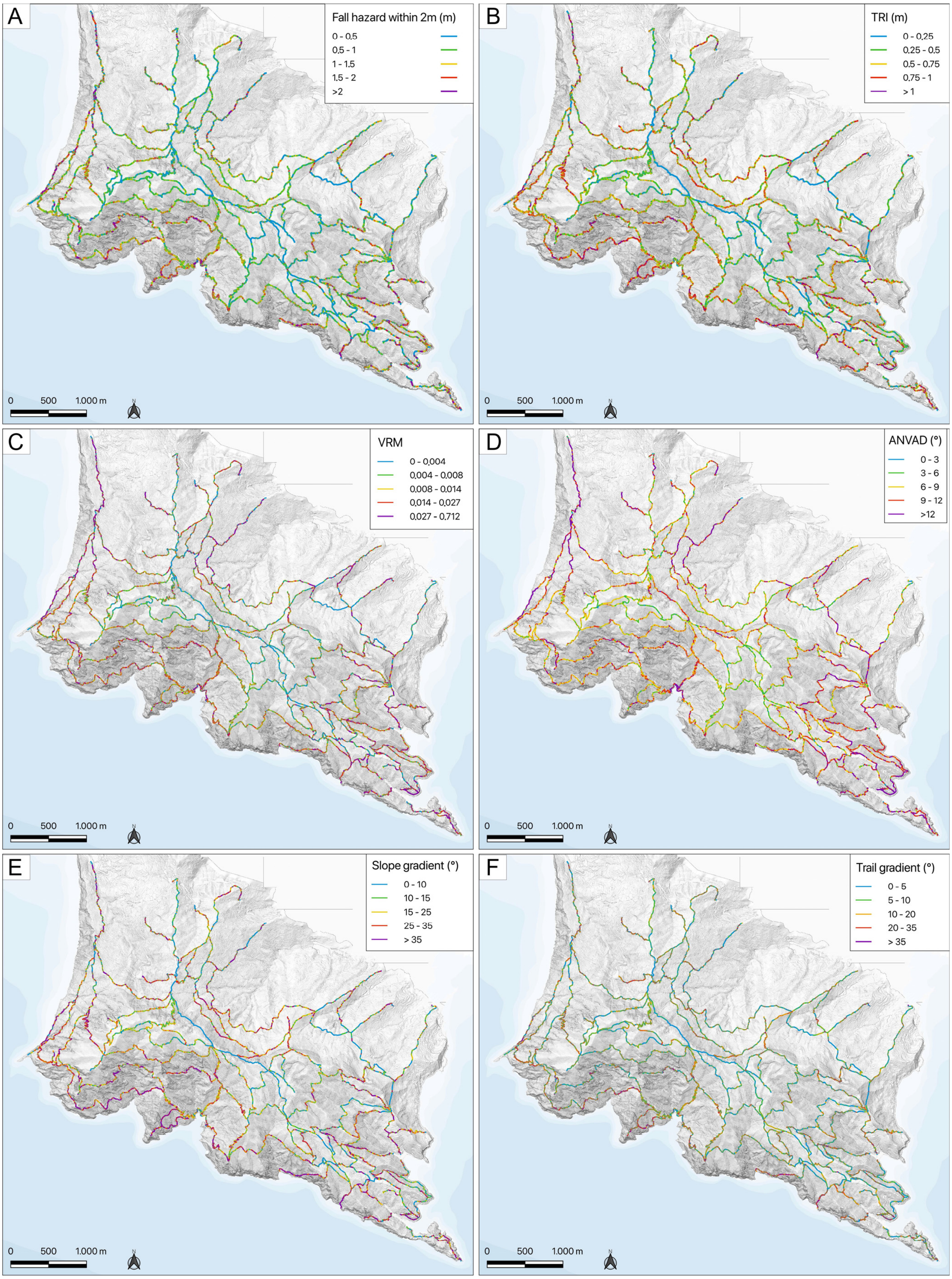

Figure 5. Morphological features of trails: (**A**) Fall hazard within 2 m; (**B**) TRI; (**C**) VRM; (**D**) ANVAD; (**E**) slope gradient; (**F**) trail gradient.

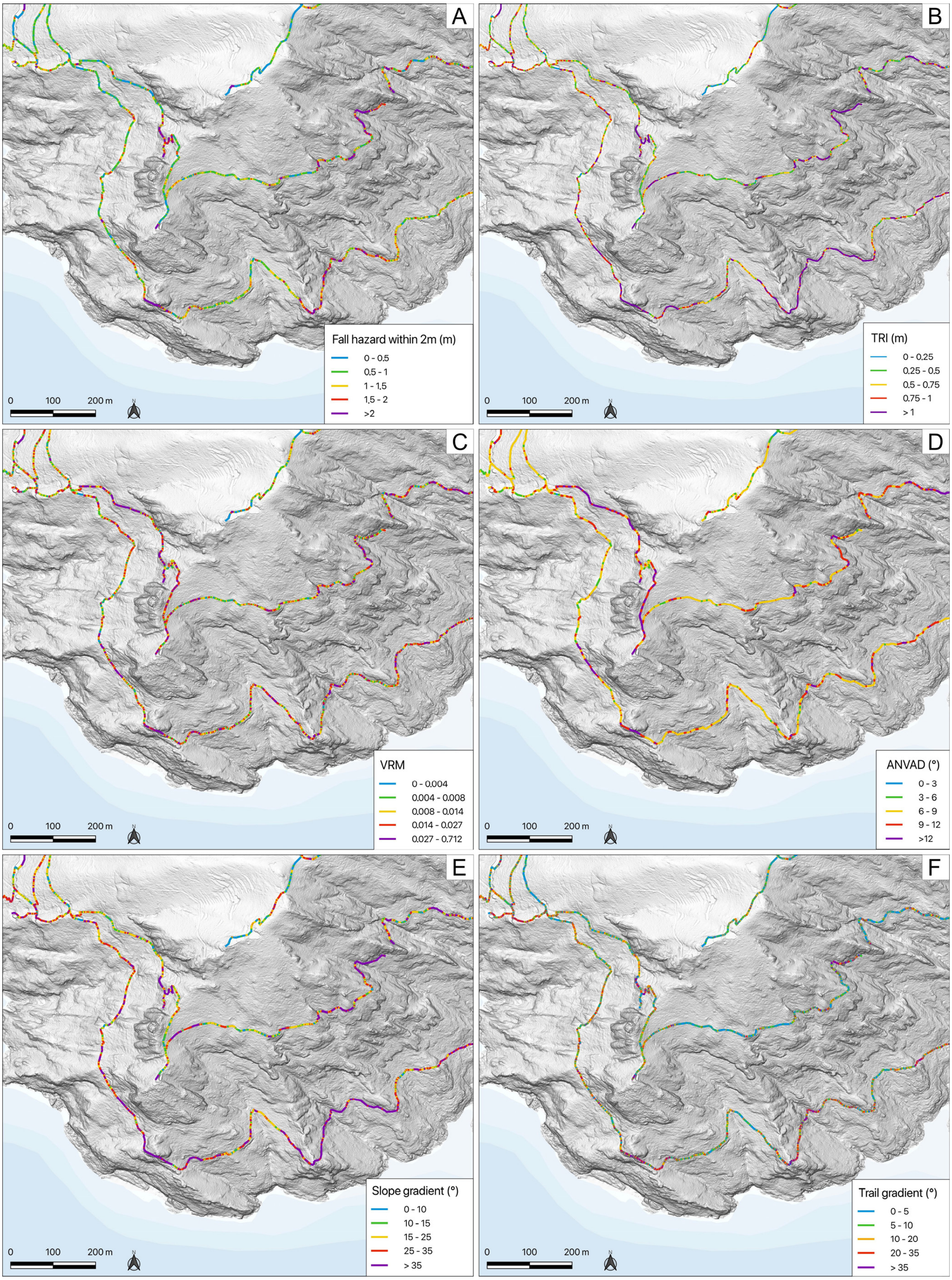

Figure 6. Morphological features of trails, detail: (**A**) Fall hazard within 2 m; (**B**) TRI; (**C**) VRM; (**D**) ANVAD; (**E**) slope gradient; (**F**) trail gradient.

Finally, Figure 7 shows the diagram of the trails' length distribution among the five respective classes of the different calculated parameters. Fall hazards within 2 m represent 18% of the total trails' length in the two higher classes and the corresponding trails develop along the south facing slopes. TRI, VRM, and slope gradient are almost equally distributed in the respective 5 classes, while ANVAD and trail gradient present a distribution similar to the Fall hazard within 2 m, with values mostly concentrated in the lower 3 respective classes.

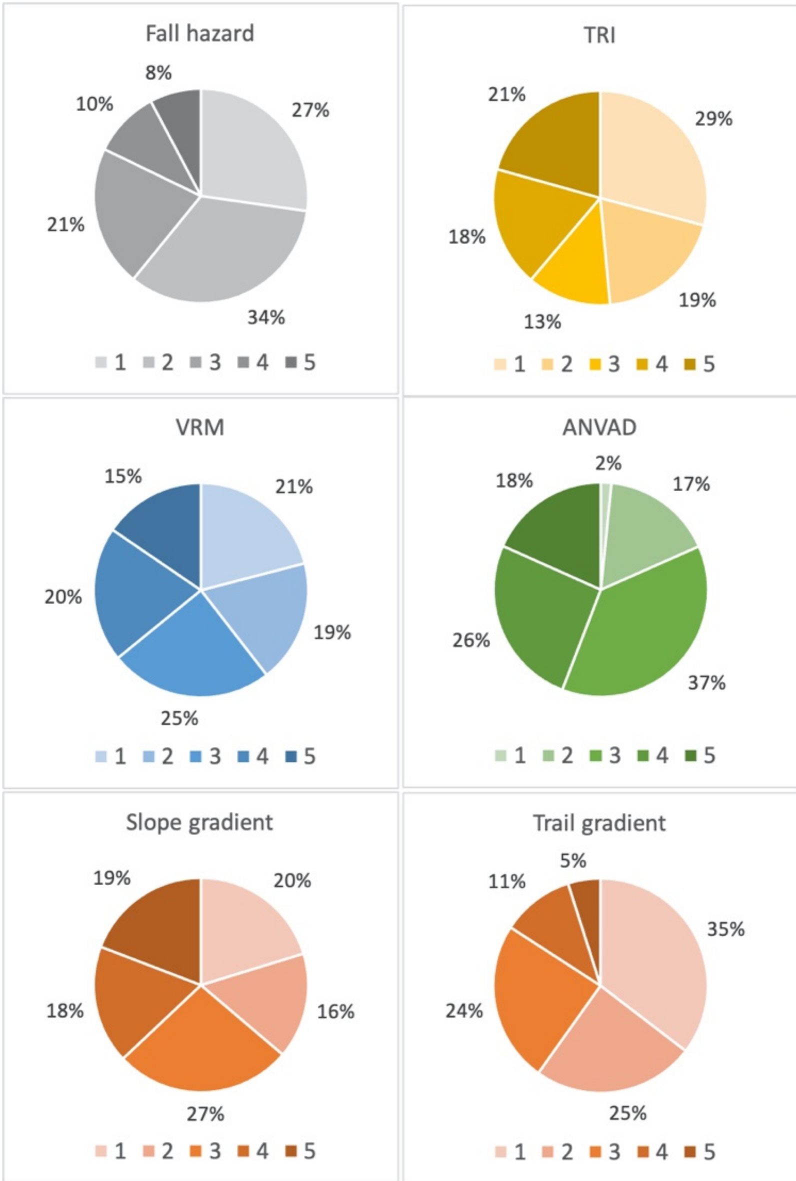

Figure 7. The distribution of the trails length in the 5 classes defined in Figure 5A–F and Figure 6A–F.

3.3. Hiking Frequentation and Vulnerability

Data collected from the nine eco-counters installed in the Natural Park allow estimation of the frequentation of the hiking trails in the years 2010–2022. The minimum number of total yearly presences within the park shows a light increase in the second part of the study period (Figure 8). In the year 2020, a great drop in the total presences can be observed due to the restrictions due to the COVID-19 pandemic. In 2021, with no more restrictions, the total presences were similar to the pre-pandemic years, while in 2022, the total presences further increased.

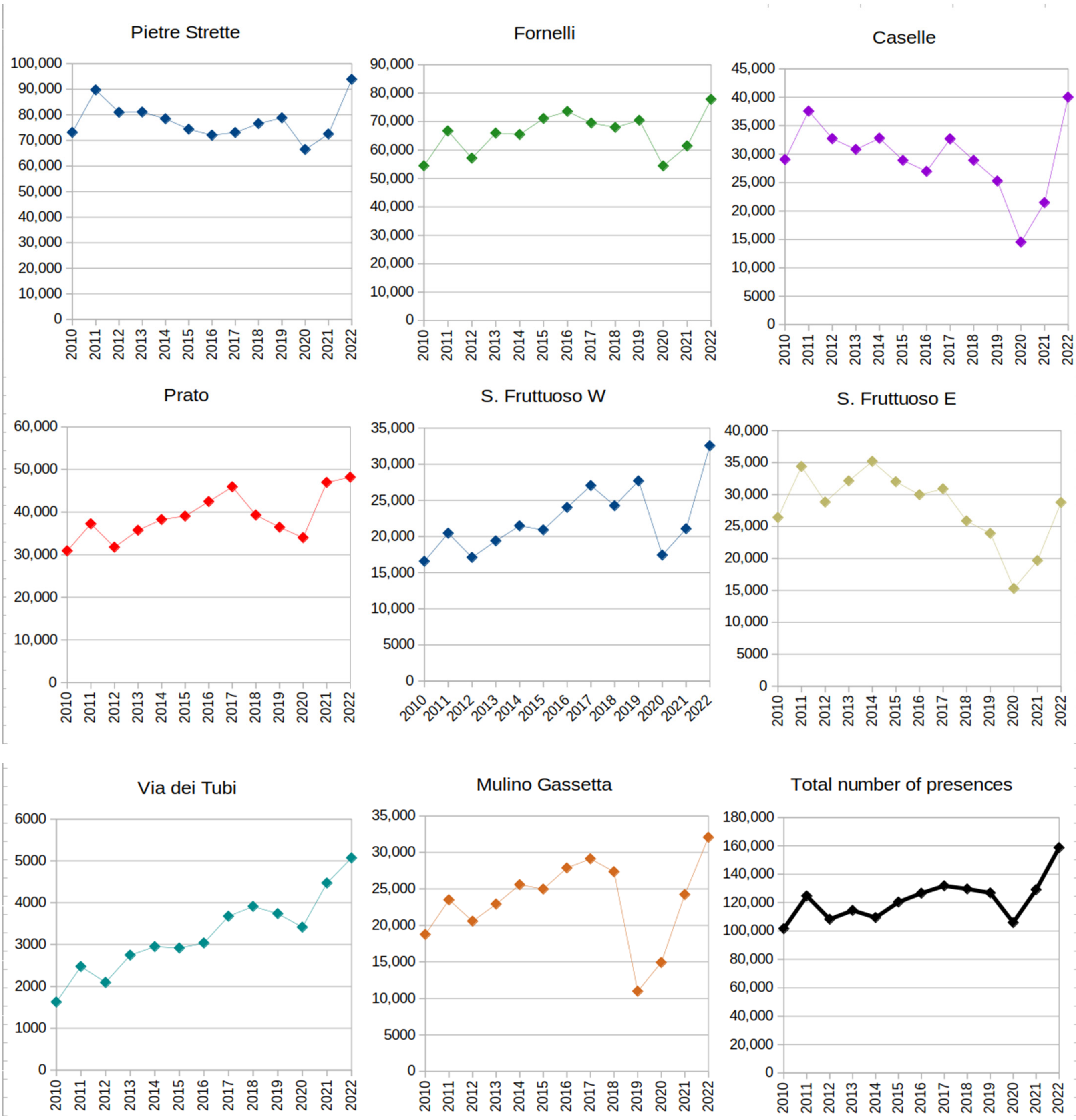

Figure 8. Total minimum number of presences in the Portofino Natural Park for the 2010–2022 period (Pietre Strette, Fornelli, Caselle, Prato, San Fruttuoso W, San Fruttuoso E, Via dei Tubi, Mulino del Gassetta eco-counters) and number of passages per year on the Park.

Among the nine stations, the most frequented is Pietre Strette, with an average of about 76,000 passages per year. Second is the Fornelli station, with 65,000 average passages per year, while the other stations record from 20,000 to 30,000 passages per year. An exception is the Via dei Tubi station, which is much less frequented (3000 passages per year). The Fornelli, Prato, San Fruttuoso West, Via dei Tubi, and Mulini stations show an increasing trend in the yearly number of hikers within the study period. The Pietre Strette, Caselle, and San Fruttuoso East stations show a decreasing trend instead.

In addition to the hikers, it should be remembered that every year, a very high number of tourists arrive in Punta Chiappa and in the villages of San Fruttuoso and Portofino from the sea, with 50,000, 1,000,000, and 2,000,000 yearly presences, respectively.

In Figure 9, the passages per month in the study period are shown for the San Fruttuoso W station. The station recorded the highest frequentation in mid-spring (April and May). However, while the number of passages in the winter, spring, and autumn months has remained relatively stable, the number of passages in the summer months (especially June and July) has strongly increased from 2010 to 2022.

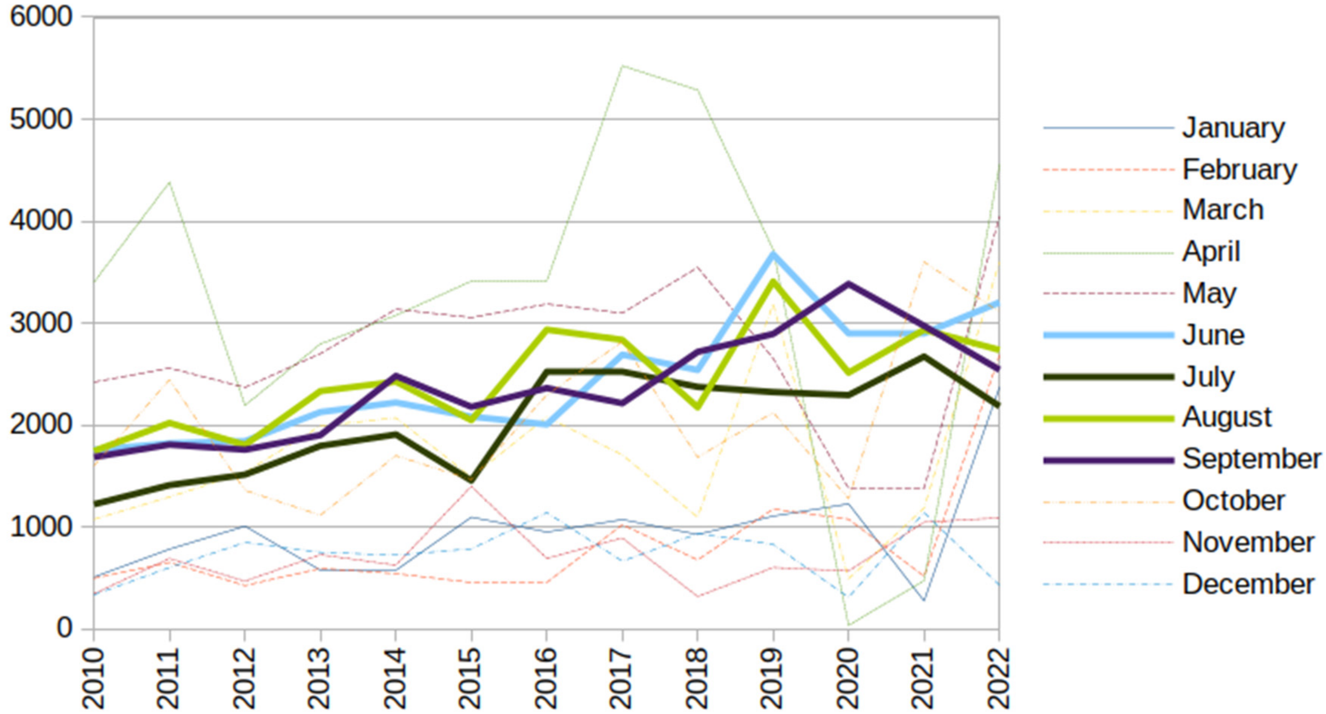

Figure 9. Breakdown by month of the passages on the San Fruttuoso W eco-counter. Summer months are highlighted.

In the years 2010–2022, the National Alpine and Spelaeological Rescue Corps (CNSAS) carried out 191 rescue operations. Most of them concerned the recovery of exhausted or injured people (80.6%) due to more or less serious accidents occurring along the hiking trails; 13.1% of the CNSAS operations regarded the search for missing persons, while the remaining 6.3% concerned other activities (e.g., veterinary interventions, defusing of explosive devices, etc.).

About 63% of the accidents occurred in the late spring and summer months, from May to September, in which the greatest tourist presence within the Park area is recorded. Accidents are more frequent from Thursday to Sunday (68%) than in the first days of the week.

The CNSAS interventions are not distributed evenly in the Park area. About half of the rescue operations (50.2%) have been carried out along the "Passo del Bacio" path, from le Batterie to San Fruttuoso, which is the most difficult of the freely walkable paths of the Park. Other paths that have seen a notable number of rescue operations are the one from Pietre Strette to San Fruttuoso (8.3%) and the one from Base O to San Fruttuoso (5.2%). The remaining operations were scattered among all the other trails of the network (Figure 10a). The number of interventions per year has strongly increased in the second part of the decade, growing from 3 to 8 per year in 2010–2015 to 24 to 38 per year in 2018–2022 (Figure 10b).

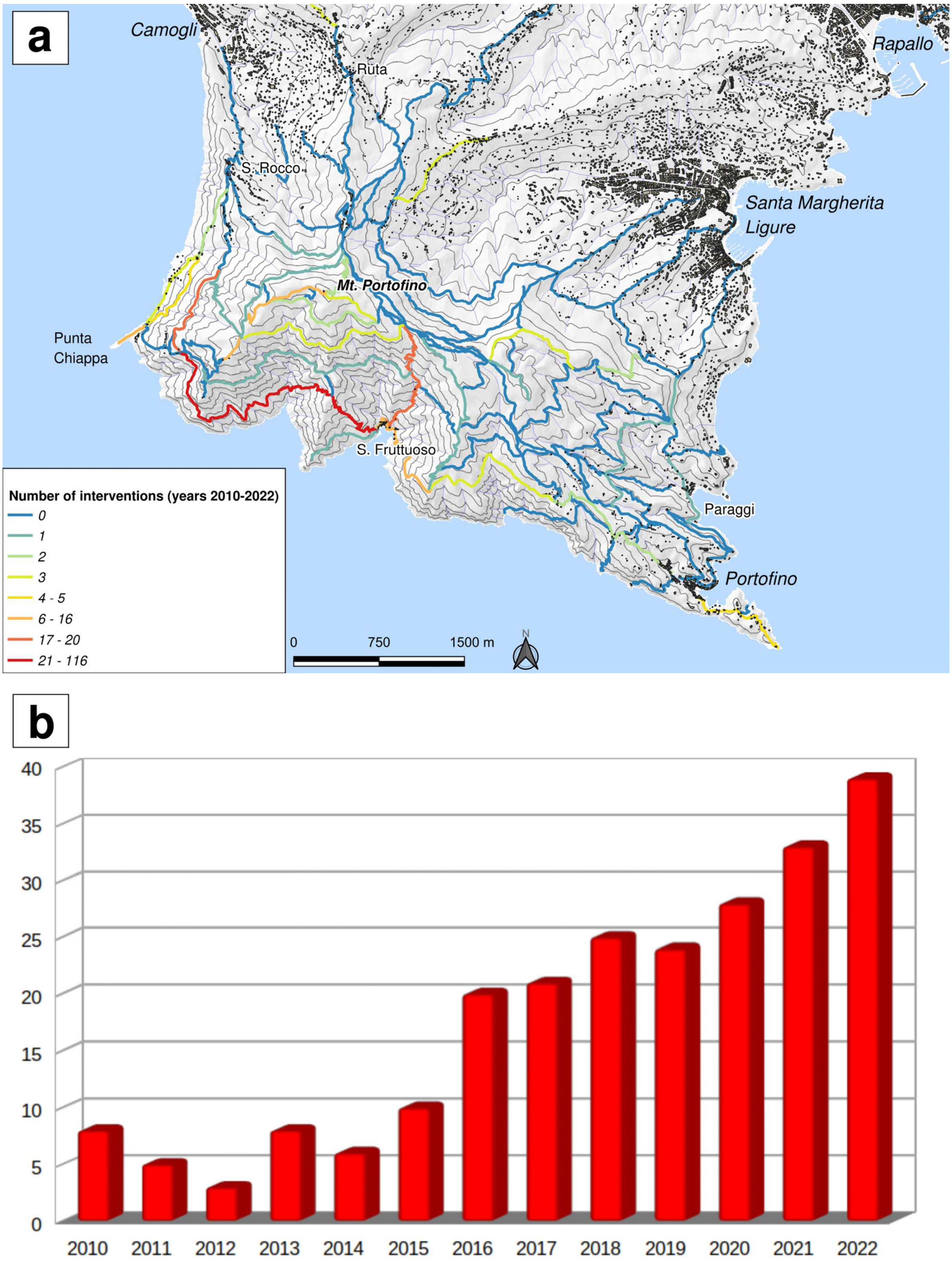

Figure 10. (**a**) Number of rescue interventions by the CNSAS in the years 2010–2022 by path. (**b**) Number of rescue interventions per year by the CNSAS.

4. Discussion

The analysis carried out allowed identification of the possible risk scenarios along the hiking trail network in the Portofino Park. The analysis has taken into account geomorphological hazard, meteorological hazard, and tourist vulnerability through a detailed morphometric analysis along the trails.

In the last twelve years, the Portofino Park has seen a sharp increase in the number of visitors, and, consequently, an increase in the number of accidents and rescue operations.

None of these accidents seem related to geomorphological hazard. The accidents are related to meteorological hazard and to tourist vulnerability instead.

The main risk factors are due to the climatic-environmental aspects that characterize the area: prolonged insolation, high temperatures and relative humidity in the summer season (also late spring and early autumn), heavy rains and strong thunderstorms in the autumn and winter season, low-level clouds, storm surges. On the other hand, the hiking trails present a wide variety of situations and difficulties: some are steep, winding paths, with sometimes irregular bottoms and narrow, exposed stretches, equipped with metal chains and ladders. Tourist vulnerability depends also on the preparation of the hiker: the physical fitness, the level of knowledge of the territory, of natural phenomena and paths, the ability to assess environmental conditions, adequate clothing and equipment.

The number of presences on the hiking trail network of the Portofino Natural Park has seen a steady rise in the last 11 years. Only in 2020 did the presences decrease, due to the restrictions of the COVID-19 pandemic. This increase in presences coincides with a steady increase in accidents, and, consequently, of interventions by the CNSAS. It is frequent that unprepared people, without adequate footwear, clothing, and equipment, venture along the hiking trails on the southern slopes of the Promontory. These trails are among the most demanding of the entire network of the Portofino Natural Park.

In particular, the absolute majority of accidents occur on the "Passo del Bacio" trail, which is one of the most notorious of the promontory. During the development of this research, we unfortunately experienced the tragic event of 12 March 2023 in which a hiker lost his life when he fell from the path between Batterie and San Fruttuoso (Passo del Bacio). This trail connects the Batterie with San Fruttuoso, and is quite physically demanding: it is about 4 km long, with continuous and steep ups and downs, exposed and rocky stretches equipped with chains and cables, and no water. The yearly number of hikers who attempt the "Passo del Bacio" trail has doubled in the study periods: in 2010 the eco-meters recorded about 16,500 passages, while in 2022, there were about 32,500 passages. The most notable increase was recorded in the summer months, which have the most unfavorable conditions to walk in: hot temperatures, high humidity rates, and continuous insolation can severely put the hikers in trouble. From 2010 to 2022, the CNSAS performed 116 rescue operations on the "Passo del Bacio" trail (five operations in the January–March 2023 period). The CNSAS reports that most of the rescue interventions on the "Passo del Bacio" trail are due to exhausted, worn out, or dehydrated hikers, and people who get lost or get injured from accidents along the rocky stretches of the trail.

Previous research focused on the impact of trails frequentation [16,81] or on spatial analysis of trails through the profile [82]. The performed detail morphometric analysis along the trails represents a new way of approaching the accessibility assessment by hikers: it is a support to the assessment of paths both from the risk point of view and from the landscape perception. In fact, thanks to the high detail DTM, a precise calculation of 6 parameters along the trails gives information about the local features in terms of possible hazard related to a hiker fall or about the roughness along the path. In addition, other relevant information about the complexity of the surface and about the steepness along the path may be used to point out critical points in terms of fall risk and of hiker's fatigue. The results of the calculations (Figure 5) are confirmed by the spatial distribution of rescue interventions (Figure 10). The more critical stretches are located along the trails in the southern slopes of the promontory, where the morphometry is characterized by high roughness and steeper slopes. No previous research considered the hazard assessment along the trails in a quantitative way through the morphometric analysis, then the actual results may open a new approach to the accessibility evaluation of trails and of the identification of critical points along them.

The morphometric analysis, performed with the calculation of the parameters in Figures 5 and 6, point out quite clearly the high hazard along some of the examined trails. In particular, along the "Passo del Bacio", the Fall hazard within 2 m (Figure 6A) points out the high hazard in the two more critical points. Similarly, the other parameters put in evidence critical zones related to a particularly steep morphology, characterized by high surface roughness. It must be underlined that in some cases, like along the trails by the coastline in the eastern part of the Promontory, close to Portofino, or along the one approaching to Punta Chiappa on the opposite side, the trails are definitively less hazardous as some border protections are present. Falling occurrence is then strongly reduced.

To reduce tourist vulnerability, it is essential to establish an adequate programming of structural interventions and information campaigns, aimed at making tourists and hikers aware of the characteristics and difficulties of the hiking trail network.

Among the essential interventions to ensure safety conditions along the hiking trails, it is necessary to provide for the periodic maintenance of the trails, the arrangement of protective structures in the most exposed or demanding passages and the affixing of clear and easily recognizable signs even in adverse weather conditions (poor visibility due to fog or low-level clouds, snow, etc.). At the start of the "Passo del Bacio" trail, particular signs and panels are posed, highlighting the difficulties and the dangers of the hike, and the necessary equipment to walk through it (Figure 11).

Other measures could include the lock of particular trails, or regulating the hikers' presence. The "Via dei Tubi" trail, which is as physically and technically demanding as the "Passo del Bacio" trail, is closed to the general public to avoid a similar increase in frequentation and accidents. The "Via dei Tubi" does not have waymarks, and even its entrances are not marked; thus, it is only accessible by means of guided tours, or requiring a special permit provided by the Portofino Natural Park. These measures have kept the frequentation low, about 40,000 total presences in 11 years. In the study period, only three rescue interventions have been carried out on the "Via dei Tubi".

Moreover, the morphometric analysis highlights the trails portions where the landscape may offer to the hiker a scenic landscape, whose importance as been previously considered by other researchers (Gavrilă, 2012). The stretches with higher value of the morphometric parameters overlap quite well with viewpoints that have been pointed out in other studies in terms of geomorphological and scenic landscape [61].

The results of the research may be used to improve the safety level and the general information of the area. An environmental education program and the communication of its physical-geographical features could be developed at various levels: from school centers to local authorities and sporting associations related to all those open-air activities that may involve interaction between man and the natural environment. The training initiatives must first and foremost provide for the production and dissemination of scientific and informative texts accompanied by thematic maps explaining the itineraries in relation to the natural environment and the landforms and processes that characterize it, whether static or dynamic. It is, therefore, considered essential to produce geo-hiking maps showing: (i) natural hazard situations, (ii) the features of the trail and the vulnerability situations present along the route, (iii) the meteo-climatic conditions that may aggravate and/or trigger already present hazard and vulnerability situations, and (iv) the main tourist attractions in the area (naturalistic, scientific, historical-cultural, architectural, landscape, etc.). A fundamental aspect of the educational activities is to increase the level of knowledge and awareness of the users of the trail networks of the climatic processes, in order to ensure the understanding of local meteo-hydrological conditions.

Finally, the research offers a new approach that may be furtherly developed considering: (i) different parameters sets; (ii) the aggregation of parameters to obtain a synthetic index of evaluation; (iii) performing the application in different physiographic contexts. The comparison of results in other areas along the seaside or in the mountains may result crucial in the identification of a new standard or synthetic index to give clear information about both the trail hazard and difficulty, and the presence of scenic landscape to hikers. Then, the morphometric approach main limitation may be identified in the availability of a sufficiently detailed DTM: in the research a 0.5 m DTM covering a wide area has been used but such a detail is not easily available.

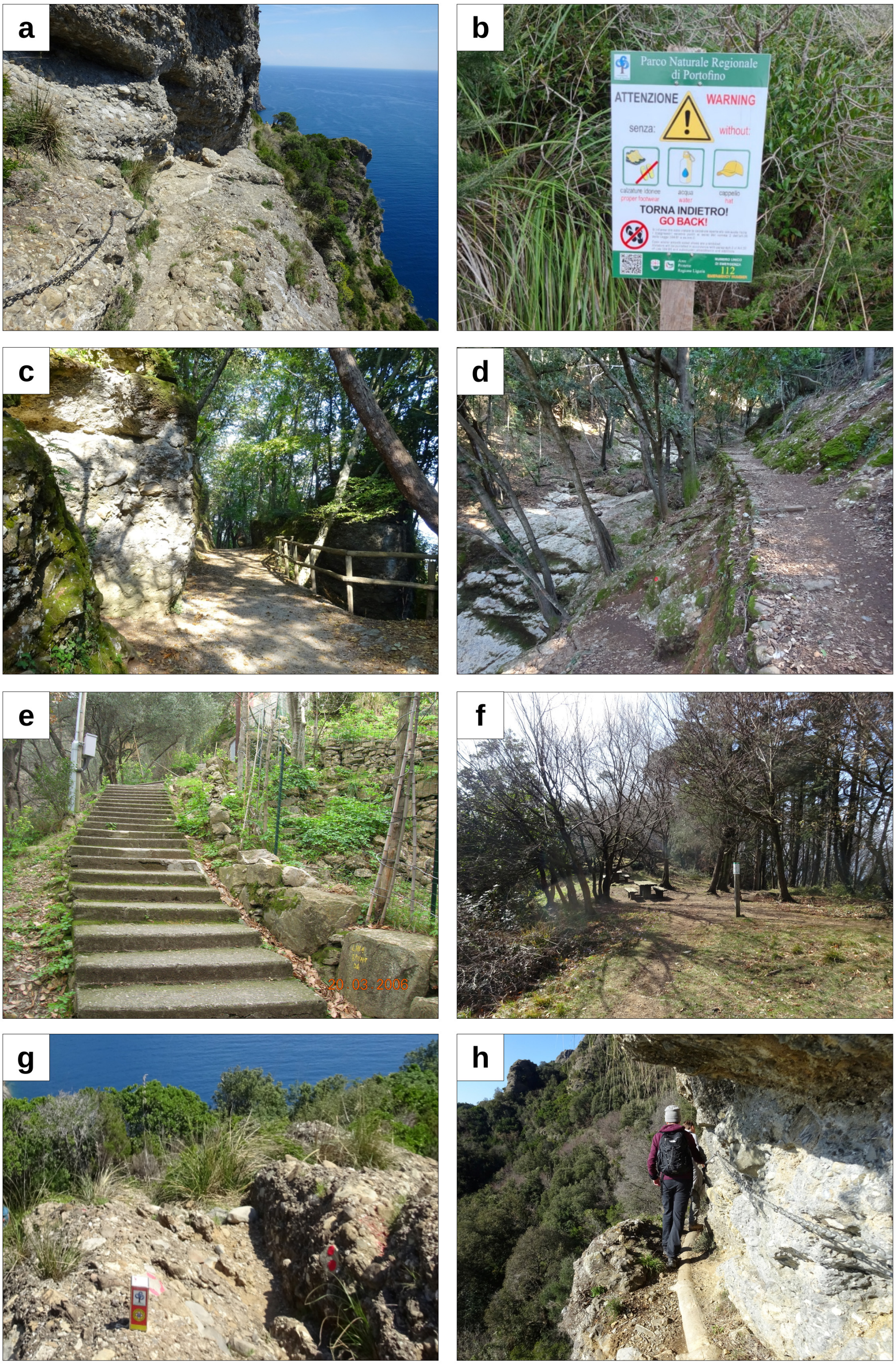

Figure 11. The hiking trail network of the Portofino Natural Park. (**a**) Exposed path with cables at the Passo del Bacio. (**b**) Warning sign near the Passo del Bacio. (**c**) Dirt road at Pietre Strette. (**d**) Ancient, cobbled mule track between Pietre Strette and San Fruttuoso. (**e**) The stairway from San Rocco to Punta Chiappa. (**f**) Crossroads and picnic area at Sella Porcile. (**g**) SOS marker along the path from Passo del Bacio to San Fruttuoso. (**h**) Exposed stretch of the Via dei Tubi.

5. Conclusions

This research has led to the identification of the main risk factors along the hiking trails of the Portofino Natural Park, by analyzing its geomorphological and morphometric features, meteo-climatic setting, the characteristics of the hiking trails, the number of presences (i.e., hikers and tourists), and the nature of accidents in the last twelve years.

In this period, the presences along the trails of the natural park have steadily increased, as did rescue operations for hiker accidents. If this trend continues, risk scenarios are expected to become even worse. Thus, it is important for the Park authority to understand the main risk factors, to better manage the hiking trail network and the flux of visitors. It is also foreseeable that, in the light of climate change, which in this area has brought variations in the rain regime and an increase in temperatures, the meteo-climatic hazard conditions will become more common. The risk is not correctly perceived by tourists even for the hardness of the hiking trails. Some of them, particularly the ones that go to San Fruttuoso, are steep, sometimes exposed, and strenuous, requiring good training.

Therefore, it will be necessary for the authorities to activate initiatives aimed at reducing tourist vulnerability, by making people aware of the level of difficulty of the trails and the hazards connected to particular meteorological conditions. It could be of interest for the Park authority to know something about the characteristics of the hikers themselves. This information could be collected by means of targeted questionnaires or interviews.

Moreover, the detailed morphometric analysis allowed a quantitative approach of both the geomorphology related risk along the trails and the landscape features. The new methodology presented in this research allows precise identification of the risk related features through the fall risk and a set of indicators related to the roughness of the surface through a 0.5 m DTM analysis and algorithms application. Finally, this approach may result as a basis for the assessment of landscape features along the trail as it may be perceived from the hikers. The research may be further developed considering different morphometric parameters sets, identifying a synthetic assessment index and comparing its application to different physiographic contexts. The main limitation of the studied approach is in the availability of enough detailed DTM covering the studied area.

In conclusion, forms of conscious and sustainable tourism can only be guaranteed by combining the correct knowledge of the territory and its dynamics, the ability to evaluate environmental and climatic conditions, and full awareness of one's own abilities and degree of hiking and physical preparation of the users of the hiking trails that cross protected areas and natural parks.

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