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Lorenzo Boccia[1]; Alessandra Capolupo, Ph.D.[2]; Marina Rigillo[3]; and Valentina Russo[4]

Abstract: The phenomenon of the abandonment of terraced landscapes compromises environmental well-being and is a preamble to hydrological instability and, consequently, the collapse of terrace retaining walls, soil erosion, and loss of agricultural lands. These problems will escalate in the coming years because of climate change (CC), especially in areas in which a rise in rainfall events is expected, such as the coastline of the Campania region, which is exposed to extreme rainfall events. This study identifies a landscape management guideline for Crapolla Fiord on the Amalfi coast (Campania region), a typical cultural landscape characterized by the presence of archaeological ruins. Potential hazards were evaluated and quantified, taking into account the flow rate and the rain intensity both at the mountainside and micro-basin scale. This study shows that potential hazards have increased because of the loss of terraces and may further increase due to the abandonment of agriculture. This paper points out that supporting measures are necessary in areas in which agricultural land use is still present and that the introduction of small interventions designed to raise the infiltration capacity of the soil and/or to regenerate vegetation in areas in which terraces have been lost is a best practice. **DOI:** 10.1061/(ASCE)HZ.2153-5515.0000473.

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Introduction

The UNESCO World Heritage Convention (UNESCO—World Heritage Center 2017) describes "cultural landscapes" as particular landscapes characterized by "combined works of nature and of man," illustrative of the evolution of human society and settlement over time, under the influence of physical constraints and/or opportunities presented by the natural environment and successive social, economic, and cultural forces, both external and internal. The Sorrento-Amalfi Peninsula is included among these, and the site of Crapolla, located in that context, may be recognized as an "organically evolved landscape" (Di Fazio and Modica 2018). This category involves landscapes that "descend from an organization of the land components initially guided by social, economic, religious/administrative reasons, the form of which was determined over time by answering the needs of the community in such a way that is coherent with the given environmental context and that has left perceivable traces of this evolutionary process" (Di Fazio and Modica 2018). Indeed, Crapolla Fiord was described by Russo (2014) as a "symbiosis between building and nature" that "expresses and communicates values of aesthetic quality, historical sedimentation and collective memory." It is an archaeological site composed of the ruins of Pietro Abbey (dating from before the 12th century) and monazeni, structures used by local fishermen for boat sheltering. Although its landscape is still heavily terraced, some areas, widely spread out, show land use predominately governed by bare soil on a limestone rocky substratum, with slight signs of old terraces. Moreover, extreme rainfall events are not unknown on the Amalfi coast, such as the one that occurred on October 25, 1954, when 500 mm of rainfall occurred in about 4 h, causing loss of life (318 people dead) and huge damages to the built environment (Tessitore et al. 2011). Such cloudbursts are possible in the Mediterranean climate, and it seems that they will be even more frequent in the coming years. Some examples have already been seen in other Italian areas, such as 350 mm in 6 h at Cinque Terre (Liguria region) on October 25, 2011 (Agnoletti et al. 2019), about 250 mm in 4 h at Giampillieri (Sicilia region) on October 2, 2009 (Lombardo et al. 2014), and other events.

The most important and widespread factors affecting cultural and environmental heritage have been investigated by scientists in order to identify initiatives that should be undertaken to safeguard these vestiges (Cassar 2005; Sabbioni et al. 2008, 2009). Among these factors, hydrogeological conditions, climate change, and the abandonment of terraced landscapes, which is widespread throughout the world (Agnoletti et al. 2019), are the most relevant. The phenomenon of terrace abandonment is a result of their inadequate competitiveness in terms of production and of a lack of interest in this kind of agriculture, which is still practiced with traditional technologies. In summary, abandonment is related to the cost of maintenance compared to the value of agricultural productivity, to climate change, which increases the stress on plants during arid periods, and to the probability of catastrophic rain events in the Mediterranean context (Sabbioni et al. 2009) and, consequently, to the vulnerability of goods exposed to debris floods (Agnoletti et al. 2019). The runoff increment, as a consequence of these natural factors, will increase the probability of the occurrence of debris flows. This enhances the potential hazard for underlying zones, which should be preserved by adopting proper mitigation plans. This becomes even more important when the danger zone

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is characterized by the presence of archaeological ruins, as in the Crapolla Fiord.

The term *natural hazard* is here intended (UN/ISDR 2004) to refer to the probability that a harmful event will occur. The concept of vulnerability is closely linked to the notion of natural hazards, because it is related to consequences, considered in terms of damages and losses (Fuchs et al. 2007). A synthetic definition of a vulnerability was given in the glossary of IPCC (2014): "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." Wilson et al. (2005) specified the main components of vulnerability as (1) exposure, defined as the probability that a damaging event will occur in a specific time period; (2) impact, defined as the consequences of a specific harmful process on some particular feature; and (3) intensity, defined as the magnitude, duration, and frequency of particular elements.

Hence, in order to properly evaluate hazard potential and its consequences, forecasting risk potential is becoming a pressing need. Further, natural hazard assessment is largely influenced by the scale adopted for analysis of slope morphology and surface, because, as demonstrated by Capolupo et al. (2015b), scale should be always adapted to the object under investigation.

The essential baseline for morphological analysis is the digital elevation model (DEM), as shown in Florinsky (1998). Therefore, DEM resolution is an essential factor to be considered in improving hazard analysis, and the finest scale of DEM is not always the best fit (Pawłuszek et al. 2017); however, a high resolution is a good choice for an accurate natural hazard assessment. Several techniques have been introduced to generate precise DEM over the years, such as photogrammetry or laser image detection and ranging (LIDAR).

The current paper evaluates potential natural hazards in the area of Crapolla Fiord on the Amalfi coast, Campania region, which is famous worldwide for its outstanding landscape and the presence of historic heritage and cultural goods. This area is potentially subject to extreme rainfall events and land abandonment. Hence, an empirical analysis of its vulnerability is also introduced. The paper also aims to identify some landscape management guidelines for coping with potential hazards. The evaluation and quantification of potential hazards was carried out taking into account the flow rate and rain intensity both at the mountainside and microbasin scale. Its value has increased because of the loss of terraces; therefore, the introduction of small interventions, designed to increase the infiltration capacity of the soil or to regenerate the vegetation, are recommended as the best practices for reducing potential hazards.

Materials and Methods

Study Area

Crapolla Fiord is an inlet on the Sorrento-Amalfi Peninsula located at geographical coordinates 40°35′35″ N, 14°22′51″ E. The peninsula is a promontory, interposed between the Gulf of Naples and the Gulf of Salerno, in the Campania region in southern Italy (Fig. 1). It covers an area of 121.14 km^2 and includes nine municipalities. Although differences in elevation are less than 400 m, the vegetation at the lower elevations, which are characterized by typical Mediterranean greenwood and scrublands, differs from the vegetation at the upper elevations, which is characterized by temperate forests (Tessitore et al. 2011; Pindozzi et al. 2015). The two sides of the promontory have many characteristics in common, such as the presence of terraced landscapes, which feature in the local agricultural economy. The climate is Mediterranean, characterized by mild temperatures, but there are fairly frequent rainfall events, which in some cases can produce catastrophic consequences (e.g., the aforementioned cloudburst on October 25, 1954).

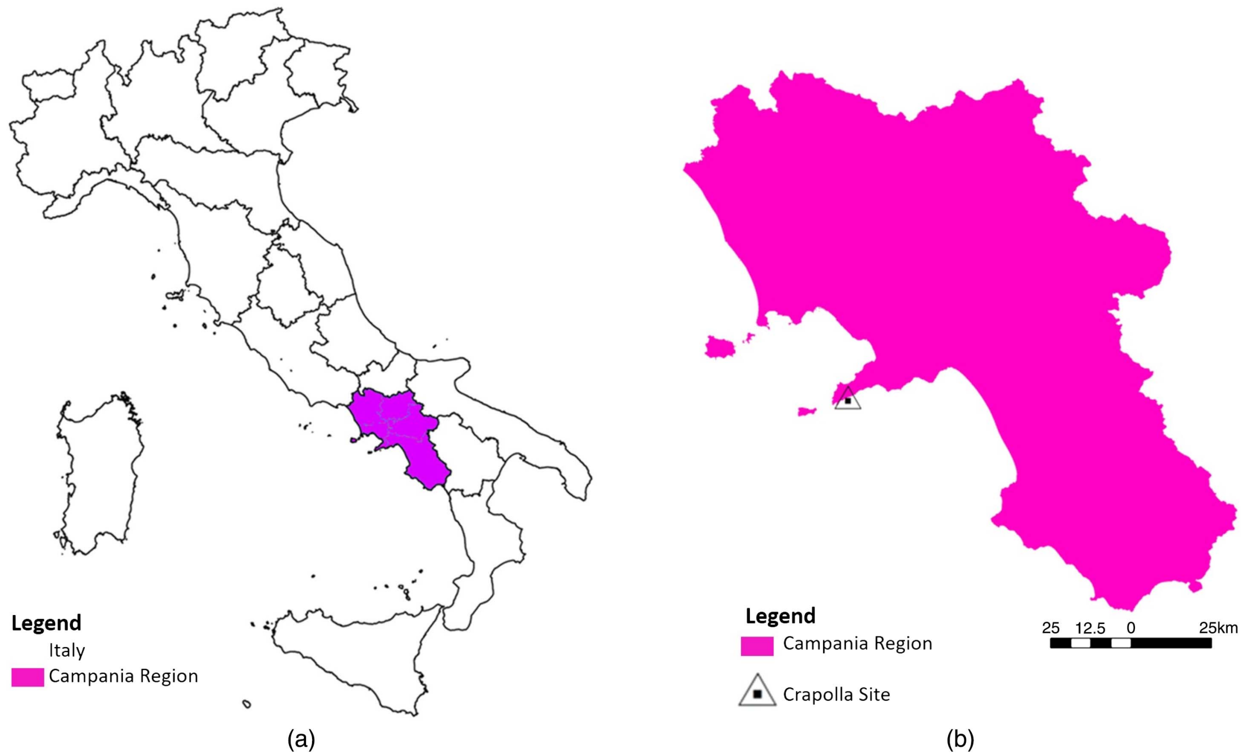

Fig. 1. Study area: (a) Campania region in Italy; and (b) Crapolla Fiord in Campania region.

Fig. 2. Details of the study area. (Images by Lorenzo Boccia.)

Crapolla Fiord has been inhabited since the Roman period, as evidenced by archaeological ruins of storage rooms and other proofs found in the area.

An abbey in the area, which belonged to the Benedectine Order, was built before the 12th century (Russo 2014). Unfortunately, the abbey has been continuously pillaged and damaged; therefore, only a few ruins have survived (Fig. 2). A watchtower, built around 1570 in response to a Turkish invasion 10 years earlier, is still on the east side of the bay. The area has been intensely used over the years, as evidenced by the presence of some terraced landscapes, which shape the slope from the top down to the bottom. The terraces are in danger of falling down because of the abandonment of agriculture on their steps; the abandonment of agriculture is due to the difficulty of accessing the terraces and their inadequate competitiveness in terms of production efficiency (Capolupo et al. 2017, 2018). Therefore, only a small portion of the terraces is weakly recognizable on the slope morphology in the eastern part of the bay (Fig. 2).

Data Sources

In order to meet the purpose of this research, the dataset refers to two data sources: rainfall information provided by Italian National Hydrographic Service in the hydrological annals, and landform mapping provided by a digital surface model (DSM) and digital terrain model (DTM), both commissioned by the Department of Territorial Information Systems (SIT) of Città Metropolitana di Napoli.

The annual maximum precipitation from 1928 to 1999 was extracted from the hydrological annals. These events were classified into five data classes j according to durations of 1, 3, 6, 12, and 24 h. The weather stations (Fig. 3) useful for the investigation were selected considering two criteria: (1) the distance between the weather stations and the study area, and (2) the amount of available data. In the first phase of the study, all the weather stations located at distance less than 20 km from the site have been considered (Fig. 4). Next were picked out only the weather stations with an adequate continuity of the series of data. The names of the weather stations used in the study, with indication of the number of year of observation, are reported in Table 1.

DSM and DTM were obtained by a LIDAR survey from 2009–2012. Their resolution was 1 m^2, and their elevation accuracy was 0.15 m. They were scanned using 4 points/m^2. Because their raster cells may show some small imperfections (commonly called pits), which can create discontinuities in the hydrographic scene, both DTM and DSM were preprocessed with the ArcGIS hydrology tool (version 10.1) in order to fill the pits (Infascelli et al. 2013).

Rainfall Data

The rainfall data were analyzed hypothesizing Gumbel distribution, which is considered one of the most widespread hypotheses for meteorological purposes. This approach defines the meteorological probability curves for a specific return period for each class of rainfall data for each selected weather station. It was applied in the current research because the rainfall events considered have a relatively short return period T. However, to take into account exceptional events (such as the event that occurred in 1954), the two component extreme value (TCEV) procedure was used for very long return periods; conceptually, TCEV is a combination of two Gumbel distributions.

Therefore, the average μ and standard deviation (SD) were computed for each class of information for each weather station, which allowed the calculation of the parameters needed to describe the Gumbel probability distributions (α and u)

$$\alpha = \frac{\pi}{\mathrm{SD} \times \sqrt{6}} \quad (1)$$

$$u = \mu - 0.45 \times \mathrm{SD} \quad (2)$$

Rainfall intensity h_{ij} was computed for each data class j for each weather station i for different return times ($T = \mathrm{RT}$) using Eq. (3)

$$h_{ij(T=\mathrm{RT})} = u_{ij} - \frac{1}{\alpha_{ij}} \times \ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \quad (3)$$

To assess flood risk, considering the limited extent of the mountainside (about 1,500 m) and the difference in altitude (about 400 m), a concentration time of less than 1 h was preferable for the current analysis. Therefore, it was realistic to focus on concentration times equal to 0.5 h. Consequently, the rainfall intensity on $j = 30$ min was estimated using the Bell's formula (Bell 1969) [Eq. (4)], which is usable for short duration rainfall of $5\ \mathrm{min} < j < 120$ min (Minh Nhat et al. 2006)

$$h_{j(T=100)} = h_{60'(T=100)} \times (0.54 \times j^{0,25} - 0.50) \quad (4)$$

Flow Rate Computation

To assess potential hazards, flow estimation was carried out considering two different levels: (1) related to Crapolla Fiord, characterized by the presence of monazeni and Roman-age structures, and (2) related to the ruins of the Abbey of San Pietro in Crapolla. The steps are illustrated in Fig. 4.

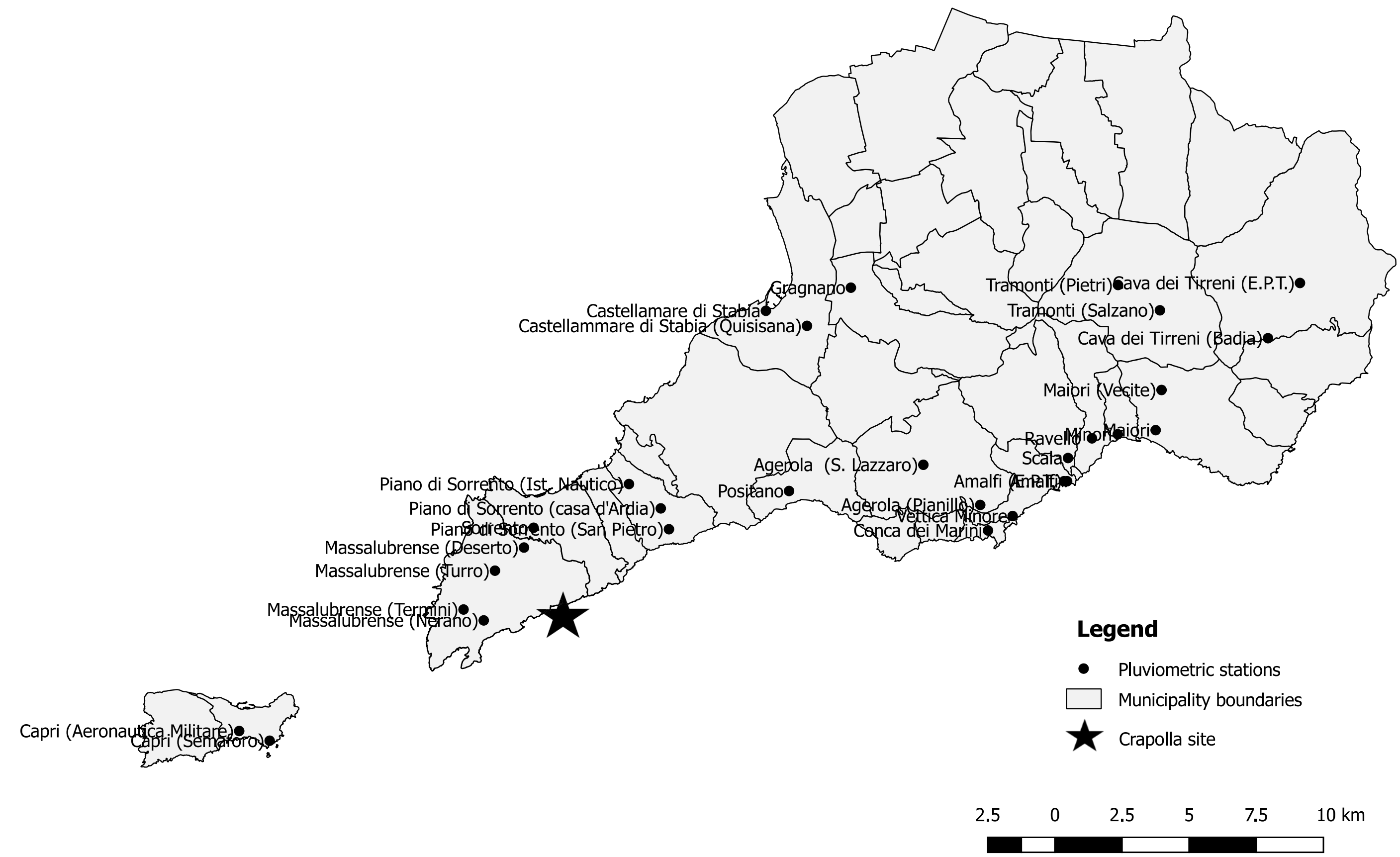

Fig. 3. Weather stations (circles) close to the study area (star).

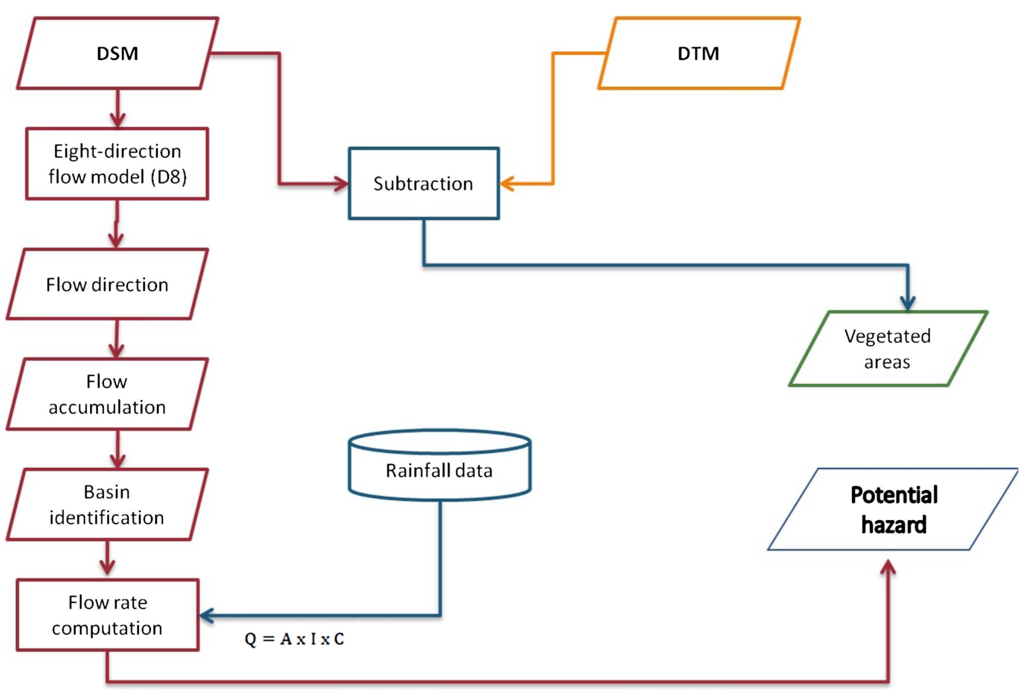

Fig. 4. Potential hazard assessment.

Vegetated areas were detected by subtracting the DSM and DTM (Fig. 5), and microrill network shaping was carried out using the eight-direction flow model (D8) at field scale, implemented in ArcGis (version 10.1) (Capolupo et al. 2014; 2015a). After identifying surface flow directions, an outlet (pour point) was located on the microrill, close to the abbey; another was located on the rill corresponding to the Crapolla Fiord. Therefore, two microbasins were identified (Fig. 6). The smallest one (about 3,500 m^2)

Table 1. Weather stations useful for the analysis

Weather station	Height AMSL (m)	Distance from the study area (km)	Period of available data	Number of useful data
Piano di Sorrento San Pietro	309	5	1957–1996	28
Piano di Sorrento Ist. Nautico	122	5.5	1950–1998	28
Massa Lubrense Fraz Turro	250	4	1977–1999	19
Positano	195	10	1928–1943	11
Agerola San Lazzaro	683	16	1928–1966	19
Ravello	315	21	1928–1995	30
Maiori	60	23	1928–1985	34
Cava de Tirreni–Badia	367	23	1955–1984	23
Cava de Tirreni–Ente Turismo	199	21	1956–1996	21

Note: AMSL = height above sea level.

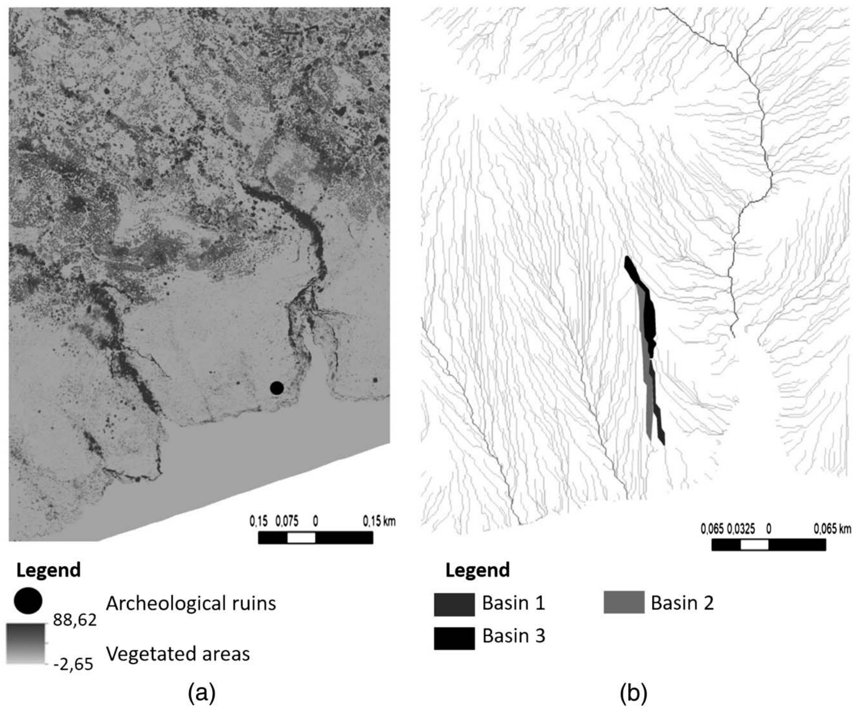

Fig. 5. (a) Detection of vegetated areas (subtraction between DSM and DTM); and (b) flow accumulation in the area.

was introduced because it may induce a local flow directly onto the ruins of the abbey. The larger basin (about $1.25 \times 10^6\ m^2$) was considered because it flows directly into the narrow fiord, between the Roman ruins and the monazeni, which belong to the same historical and rural heritage.

Thus, flow rate was calculated for both conditions by applying the rational method [Eq. (5)]:

$$Q = A \times I \times C \tag{5}$$

where A = basin area; I = rain intensity; and C = runoff coefficient, which was defined considering the texture and type of soil. The most vegetated and cultivated areas were characterized by a sandy loam, while the zone close to the abbey was mainly rocky and the soil was almost completely gone. Taking a pragmatic approach, the runoff coefficient C was assumed equal to 0.15–0.2 for sandy loam soil with a slope greater than 7%, as has been commonly reported in the literature (Chow 1980; Leone 2011), according to the rain intensity: $C = 0.2$ for rain intensity with a return period of 100 years ($T = 100$) and $C = 0.15$ for rain intensity with a return period of 10 years ($T = 10$).

Climate change (CC) modifies the probability of the occurrence of factors able to trigger debris flows. CC studies have led to contrasting conclusions regarding the consequences of expected rainfall in the future. CC will introduce nonstationary climate conditions, changing (1) the duration of rainfall events, (2) the depth of rainfall, and (3) the return period of extreme events. A simplistic approach takes into account the reduction of annual precipitation and the increase in the depth of the largest events, but does not consider the return period of extreme events. Peres and Cancelliere (2018) estimated the probability of the occurrence of landslides in a similar Mediterranean context (Sicilia region) using Montecarlo simulations. Comparing different CC scenarios [representative concentration pathway (RCP) 4.5 and RCP 8.5] and prediction models, Peres and Cancelliere (2018) concluded that CC will decrease landslide hazards.

Results and Discussion

Considering a return period of 100 years ($T = 100$), cumulative precipitation for all of the weather stations employed in the current

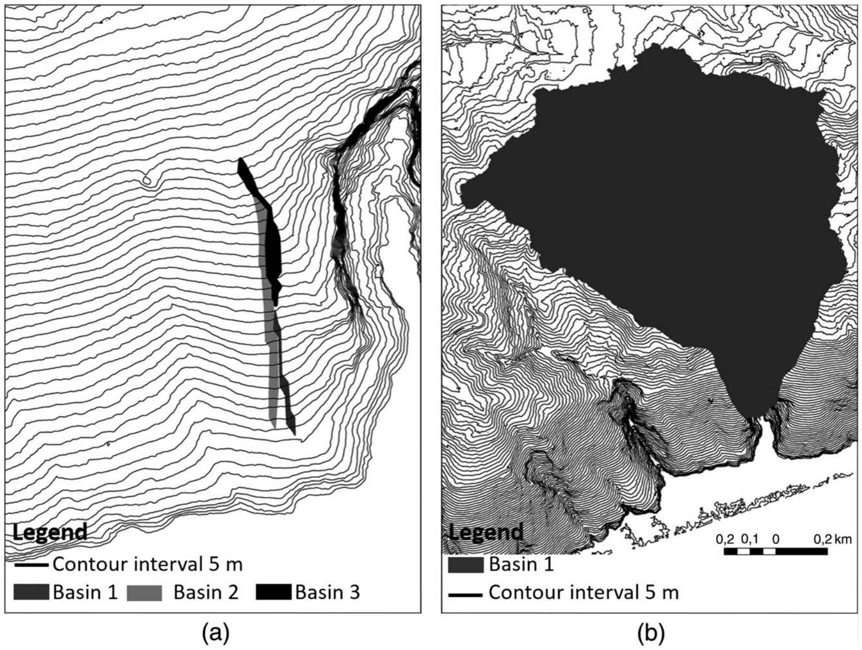

Fig. 6. Microbasins identified in the study area close to (a) the abbey; and (b) the monazeni.

Table 2. Predicted cumulative rain H considering return period of 100 y ($T = 100$)

Weather station	Rain in 1 h (mm)	Rain in 3 h (mm)	Rain in 6 h (mm)	Rain in 12 h (mm)	Rain in 24 h (mm)
Ravello	54	81	124	153	180
Piano di Sorrento (Istituto Nautico)	76	104	125	140	156
Piano di Sorrento (S. Pietro)	69	83	96	129	151
Massa Lubrense	130	139	142	151	158

research is reported in Table 2. The weather station at Massa Lubrense, the closest station to the site under investigation, had a very high value for rainfall for the duration of 1 h compared to the other stations. This resulted from the presence of an exceptional event with 192 mm of rainfall in 1 h, which occurred in 1992; this event had a great influence on the final results, because the series for this station was characterized by a limited number of recorded values (19 events).

Taking into account that the microbasin is characterized by a very short length (about 1,500 m with a slope of about 300 m), the concentration time is very short (about 15 min). For meeting that purpose, we considered a rain event of maximum intensity, that is able to reach a stationary condition of hortonian flow. We consider that the shorter rainfall event, with the maximum intensity that reach this condition is that one of 30 min.

The rain intensity in 30 min was obtained using Bell's equation, which is an approximation suitable to data with such a large dispersion. The results for each weather station are shown in Table 3. Therefore, the intensity of rain was equal to 60 and 23 mm in 30 min for return periods of 100 and 10 years, respectively.

Table 3. Predicted rain in 30 min considering return periods of 100 and 10 years

Weather station	Rain in 30 min, T = 100 years (mm)	Rain in 30 min, T = 10 years (mm)
Ravello	41	28
Piano di Sorrento (Istituto Nautico)	58	37
Piano di Sorrento (S. Pietro)	52	38
Massa Lubrense	99	60

Because of the proximity of the weather station at Massa Lubrense to the study area, it seems that we should take into account a rain event of 99 mm in 30 min; indeed, such an event is compatible with events that sometimes occur in Mediterranean climates. The average value of 63 mm of rain in 30 min for the 4 evaluated station, is influenced by the value of 99 mm in 30 min calculated for the weather station of Massa Lubrense, that is supported by a short series of data. With a pragmatic approach, taking into account the purposes of the paper, and the doubt on the calculated value for Massa Lubrense, we considered with a return time of 100 years, at least one event of rainfall greater than 60 mm in 30 min (rain intensity $I = 0.033$ mm/s) instead of 63 mm. Similarly, for a return period of 10 years, at least one event greater than 40 mm with a duration of 30 min, has be taken into account (rain intensity $I = 0.022$ mm/s).

Fig. 5 shows the overall distribution of vegetation in the study area. Vegetation is rare around the archaeological ruins of the abbey, but it is more prominent on the steep mountainside.

Thus, processing the digital surface model, was obtained the flow accumulation presented in Fig. 5(b) and was carried out the identification of the basins (Fig. 6). Fig. 6(a) shows the microbasins of about 3,500 m^2 in the proximity of the abbey, while Fig. 6(b) shows the basin of about 1,250,000 m^2 near the fiord, in the proximity of the Roman ruins and the monazeni.

Considering the microbasin flow on the ruins of the abbey [Fig. 6(a)], the maximum predicted flow rate is equal to 0.4 m^3/s

for $T = 10$ years and about 0.9 m^3/s for $T = 100$ years. For the larger basin, the maximum predicted flow rate is equal to 41 m^3/s ($T = 10$ years) and 82.5 m^3/s ($T = 100$ years) [Fig. 6(b)].

The abbey was built on a ridge, and consequently the basin identified is very small. Nevertheless, although the ratio between the surfaces in the two situations is greater than 1:350, the ratio between the predicted flow rates is about 1:100. Moreover, the entire area of the abbey was originally terraced; currently, the soil is completely lost. Nevertheless, the predicted flow rate for a rain event with a return period of 100 years does not seem to be a danger to the ruins of the abbey.

The situation in the area around the monazeni and the Roman ruins is very different. In this case, an event with a return period of 100 years may produce a catastrophic event, with a flow on the order of 80 m^3/s. It is impossible to control the outfall area where are the archaeological goods; therefore, taking into account that anything have to be placed in the outflow area is essential.

In addition, the phenomenon of the abandonment of terraced areas was evaluated in the larger microbasin. This phenomenon will produce, in a short time, conditions identical to those in the area of the abbey. Undoubtedly, after a few years the soil will be lost and the flow rates will increase by 2–4 times. The abandonment of terraced landscapes due to social evolution, climate change, and inadequate policies will produce flows on the order of 200–300 m^3/s. The depth and path of such flows would be enough to destroy all the ancient ruins.

In such a scenario, not only would the identity of the landscape be lost (Di Fazio and Modica 2018), but all vestiges of the past would be lost as well.

Related to the larger basin, it is mandatory to maintain the actual land use and the terraces. Regarding the smaller basins, an anachronistic reconstruction of terraced landscapes on an area of hundreds of hectares is not feasible; it would be more reasonable to control the foreseeable flow by introducing some smaller interventions aimed at diverting the outflow at the side of the abbey or creating some areas suitable for incrementing the infiltration capability. Therefore, focusing attention on improving the situation of the microbasins is more appropriate. Because the surface of the microbasins is about 3,500 m^2, a significant improvement can be achieved by creating 20 areas of about 5 m^2, characterized by the presence of shrubs and Mediterranean vegetation. These would not be true terraces but would be shells of stones aggregated with modern binders and jointed in the first phase with nets of degradable plastic or with other techniques suited to these slopes (about 60%). These interventions would increase both the infiltration rate and the amount of Mediterranean scrub.

As suggested by Agnoletti et al. (2019), terraced slopes should be converted to vegetated areas full of woody species when they are abandoned. Moreover, Agnoletti et al. (2019) showed that the introduction of shrubs and woody species can be controlled, reducing maintenance and monitoring activities.

Conclusions

Not only potential hazards but also vulnerability assumes a different significance for the two microbasins, since it is different the exposed value (Wilson et al. 2005). Vulnerability includes the value of intangible assets, such as historical landmarks and archaeological ruins and also the value of the infrastructures such as the 700 stairs and the paths for improving the accessibility. Even if vulnerability assumes a different value at the two levels, it is significant in both cases; consequently, some actions are required in order to mitigate potential hazards. Fragmenting the flow directions in order to minimize flow rates is a possible solution for reducing potential hazards in the first microbasin, but action should be focused on building a gutter at the sides of the ladder, because it is the main feature guiding the flow on the archaeological ruins. At the main microbasin scale, it is necessary to preserve vegetated and cultivated areas in order to not change the permeability of the soil, which influences the coefficient of runoff. Indeed, changes in the soil as a consequence of abandonment, from sandy loam to rocky, will increase the runoff coefficient.

Even if it appears inappropriate to take climate change into account in terms of empirical forecasts of rain events and consequent hazards, it is clear that CC will affect temperature and stress vegetation in Mediterranean climates. The value of agricultural activities and the maintenance of terraced areas is increased by nonstationary climatic conditions. Therefore, agricultural activities should be supported both for their social value and for hazard reduction purposes.

It was considered the idea of recovering the remains of terraced landscapes that are currently only visible on the ground, but the idea is considered anachronistic, considering the trend to the abandonment of the terraced landscapes in Mediterranean context. It is to seriously considering the introduction of techniques aimed to preventing the degradation that follow the abandonment of the terraces. In the occurrence that the actual agricultural system on the terraces develops into abandonment, the best solution is a land-use change versus shrubs and woody vegetation, avoiding a sudden cessation of maintenance and monitoring activities. This can be achieved by applying forestation interventions on the terraces, such as those presented for the Cinque Terre (Agnoletti et al. 2019).

For the condition of the smaller basin in the critical areas of the abbey, the concept is to create shells of soil, using innovative techniques at detailed scale. The benefits of this course action are twofold: (1) potential risks are reduced to a minimum, and (2) the original landscape heritage is safeguarded.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request, including (1) rainfall data selected from the *Annali Idrologici*, and (2) LIDAR data (DTM and DSM) for the study area.

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