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Addressing land use planning: A methodology for assessing pre- and post-landslide event urban configurations

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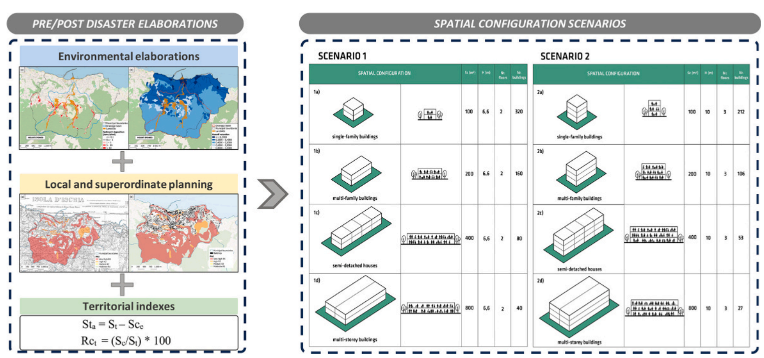
HIGHLIGHTS

- A landslide event occurred in Casamicciola Terme Municipality (Italy).
- A methodology to support landslide risk management has been proposed.
- Environmental, planning, and configurational spheres have been connected.
- Urban configurations in free prone risk areas have been identified.

GRAPHICAL ABSTRACT



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ABSTRACT

With urban areas projected to accommodate 68 % of the global population by 2050, the imperative for inclusive, safe, and sustainable cities becomes paramount. In the timeline of urban centers, landslides represent one of the most destructive phenomena, involving several resources allocation with private and public investments, sometimes claiming human lives. By synergically connecting environmental, planning, and configurational spheres, this study seeks to support the proactive management of landslide risk. The proposed three-step methodology allowed to quantify the environmental features involved in landslide occurrence, evaluate planning framework vulnerabilities, and suggest alternative configurations for urban areas that experienced landslides.

The methodology has been applied to the case study involving a tragic landslide in Casamicciola Terme (Italy) in November 2022.

First, the stream network and the drainage basin corresponding to confluence point of the landslide into the sea have been calculated (environmental elaborations). Subsequently, these elaborations have been overlapped with the runoff mitigation and the sediment deposition layers, extracted through the INVEST software. Secondly, the reconnaissance of the local and superordinate planning levels has been realized, to deepen planning tools cogency on the study area, contextually deepening the constraints that characterize it. From the overlapping of these two steps, free landslide risk areas have been located. Finally, based on the available territorial surface (St_a) and the territorial cover ratio (Rc_t), two territorial configuration scenarios have been proposed, envisaging the relocation of the buildings involved into the landslide. Results show that landslide originated by three out of five

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gullies. Some portions of the urban areas of Casamicciola Terme are still under high and very high hydrogeological risk. Contextually, it emerges poor attention from the local planners to the superordinate planning framework. Historic settlement has an Rct of 33.64 %, while areas in which relocate the built up show an Rc_t of 32,45 % for scenario 1 and 27,9 % for scenario 2.

The methodology resulted useful to address planning vulnerabilities, supporting the realization of alternative configurational scenarios. We expect our research to contribute to the evolving field of disaster risk reduction, by providing a systematic approach to manage landslide risk.

1. Introduction

In a world in which urban areas are expected to host 68 % of the global population by 2050, cities need to be inclusive, safe, resilient, and sustainable (United Nations, 2015, 2018).

Urban areas are human settlements in which social, economic, and environmental phenomena occur (Lejano, 2019; Orimoloye et al., 2019; Verma and Raghubanshi, 2018a). This anthropogenic system fits into a territorial framework in which the presence of human activities pushes ecosystems beyond their natural carrying capacity (Angel et al., 2020; Dembińska et al., 2022). From a different point of view, it can be stated that ecosystems depletion, caused by the exploitation of natural resources, brought to a self-feeding negative feedback mechanism for which land degradation and natural extreme events occurring in urban areas are strictly correlated (Foley et al., 2005; Munang et al., 2013).

In this context, landslides represent one of the most destructive events affecting urban areas. It is well known how these disruptive phenomena involve several resources allocation with private and public investments (Winter et al., 2016). From 1980 to 2013 an estimated annual average of 20 billion dollars has been claimed globally due to landslides, the 17 % of the annual global disaster losses in the period of reference (Klose et al., 2016). Additionally, between 1995 and 2014, 1370 deaths have been recorded in the European countries, associated to 476 landslide events (Haque et al., 2016).

Landslides can be triggered by extreme rainfalls, i.e. enormous and extraordinary amounts of raining water. Simultaneously, global warming contributes to raise the frequency, intensity, and duration of these events (Pendergrass et al., 2017). Hence, in a condition of climate instability and urbanized areas expansion, landslide risk and exposition are meant to increase.

On this basis, the need to dispose of methodologies aimed at predicting and mitigating increasingly frequent emergency situations is of fundamental importance (Balogun et al., 2020; Javan et al., 2023). Additionally, the challenges set by global warming and human activities contribute to raise the issue of climate resilience and risk mitigation, looking at territorial transformations both pre and post-disaster occurrence (Arnell, 2022; Dibs et al., 2023a; Dibs et al., 2023b; Heinzlef et al., 2022; United Nations, n.d.; Xi et al., 2023).

To face up landslides, several methodologies have been developed. Specifically, to map and frame landslide susceptibility and landslide risk assessment, Geospatial models (Sharma et al., 2024), Remote sensing techniques (Sarkar and Kanungo, 2004), Geographic information systems (GIS) (Podolszki and Karlović, 2023) and, more recently, machine learning models (Gnyawali et al., 2023) are some of the most widespread technologies. At the same time, the cross-sectional nature of landslide risk management inherently recalls several government aspects (Cheung, 2021; Santos et al., 2021). To be effective, the above mentioned elaborations must be able to influence local and superordinate planning policies. Indeed, the elements that play a key role in defining landslide susceptibility and risk, such as land use/land cover (LULC) changes, geomorphology and socioeconomic factors, are managed or conditioned by national and local policies, whose will is expressed through local planning tools. Simultaneously, planning policies must be able to rely on a methodological approach capable of connecting the information derived from landslide risk analysis (Roy and Ferland, 2015). Wherever this is absent, the result is a planning framework that doesn't fulfill the objective of a government action based on a real strategic asset (der Sarkissian et al., 2022; Garrido and Saunders, 2019). To this regard, ecosystem services (ES), territorial configuration and planning tools cogency are some of the analyses that can help deepen the level of integration and interaction between anthropic and natural systems, strengthening landslide risk management into land government (Canesi and Marella, 2022; Giaimo and Salata, 2019; Verma and Raghubanshi, 2018b).

Nevertheless, due to the sectoral thinking still prevailing in local planning, landslide risk assessment and management lacks a procedure able to make these elements conjointly influence land policies (Sandholz et al., 2018). In 2014 Begum et al. provided different conceptual frameworks to promote the integration of disaster risk reduction (DRR) as a fundamental step to reduce the negative impacts of flooding, landslides, heat waves, temperature extremes, droughts, and intense storms. Similarly, Riddell et al. (2019) proposed a methodology in which the integration of different elements (scenario timelines, socio-economic component, LULC data and hazard modeling) through exploratory scenarios is used to help reduce disaster risk. More recently, Mateos et al. (2020) analyzed the regulation of landslide hazard into urban planning across Europe, finding inadequate mapping tools and weak or absent governance tools to manage this phenomenon. To help bridging these gaps, the present study aims to connect environmental, planning, and configurational spheres related to landslides, with the final objective of setting free risk urban configurations, both pre and post phenomenon occurrence. To do this, the proposed methodology articulates into three main steps: (1) Environmental elaborations. It encompasses a series of analyses aimed at deepening the main features that contribute to locate the areas potentially vulnerable to a landslide event (mainly the areas susceptible of triggering the landslide event and the entity of the sediment subject to transport). To do this, the elaborations focused on two ecosystem services: the runoff retention and the sediment delivery ratio. (2) Local and superordinate planning cogency analysis. The reconnaissance of the local and superordinate planning frameworks is fundamental to deepen the level of integration between hydrogeological risk management and land development policies. Environmental elaborations in point (1) have been overlapped with the local and superordinate planning tools envisaged for the study area, allowing the methodology to show possible incongruences with the regulatory framework. Furthermore, this comparison allowed the identification of suitable free risk areas, a fundamental step to set free risk urban and territorial configurations. (3) Territorial configuration scenarios. The last step of the methodology focused on the previously located free risk areas. Indeed, whenever the maintenance and monitoring actions to be done on the areas located in step (1) are not sufficient, it is necessary to move all the elements (people and buildings) that could be heavily harmed or damaged by a potential landslide event. To do this, territorial indexes help find the most suitable areas among the free risk ones. The principle behind the identification through the above-mentioned indexes is the limitation of land take, considered as one of the causes that contribute to lower environmental quality and, contextually, to increase vulnerability to landslides (Pacheco Quevedo et al., 2023; Simoniello et al., 2023).

Procedural steps have been applied to the case study represented by the landslide that occurred in the night between 25th and 26th November 2022 in the municipality of Casamicciola Terme (Center Italy), in which twelve people died (https://emergency.copernicus.eu/

mapping/list-of-components/EMSR643).

Open-source software and data have been used to assure replicable, integrated, and multiscale analyses (Hamel et al., 2021; Idrizi et al., 2018).

2. Study area

The study area is represented by the municipality of Casamicciola Terme, situated in the island of Ischia, in the Campania region (Fig. 1).

Ischia, such as Italy, has a long history of landslides and floods (Mateos et al., 2020). These events have also interested the municipality of Casamicciola Terme since the half of the XVI century, occurring continuously until today (Del Prete and Mele, 2006).

The major reason for these episodes lies into the geological structure of the island of Ischia, specifically in the northern part of the Epomeo Mount, which interest the municipalities of Casamicciola Terme and Barano d'Ischia. The tectonic volcano surrection of the Epomeo Mount set a condition for which the municipality of Casamicciola Terme is characterized by debris accumulations from debris flow and alluvial debris deposits. The result is a conformation characterized by sub-vertical walls with a strong bank erosion, which is cause of several landslide phenomena. Here, the instability of the slopes, together with the alluvial events, lead to a high level of solid transport along the incision ditches. The resulting gullies directly flow towards the coastline, passing through the city of Casamicciola Terme (Del Prete and Mele, 2006).

Due to its location in the Mediterranean basin, Ischia is a temperate – warm climate Island. Despite this, the precipitations along its territory are not equally distributed. Indeed, data from meteorological stations show an average annual quantity of rainfalls which is lower in the South West part of the island, compared to the North East one (Mennella, 1944). The average annual precipitation (period of reference 2011–2021) is equal to 875.7 mm (Romeo et al., 2023).

The municipality extends for 5,8 km^2 and it occupies about the 12 % of the island of Ischia (46,4 km^2), which is part of the Flegree Islands in the Gulf of Naples. Ischia is among the most populated Italian islands, with a resident population of about 62,323 inhabitants (year of reference 2021). The studied municipality accommodates 12 % of the population of the island, with a density of 1339 inhab/km^2, about seven times the national mean value (200 inhab/km^2).

In 2019 Ischia recorded a population of 64,126 inhabitants. This value, after a strong increase in the 1990s, decreased in the last years. Specifically, the Island lost a population of about 1800 inhabitants, of which 282 (15 %) in Casamicciola Terme, between 2019 and 2021 (https://www.istat.it/it/censimenti/popolazione-e-abitazioni).

The structural aggregates for the studied municipality are 3236 and occupy 507,500 m^2, equal to the 8,6 % of the municipality surface.

The number of buildings, according to the censuses of Istat (National

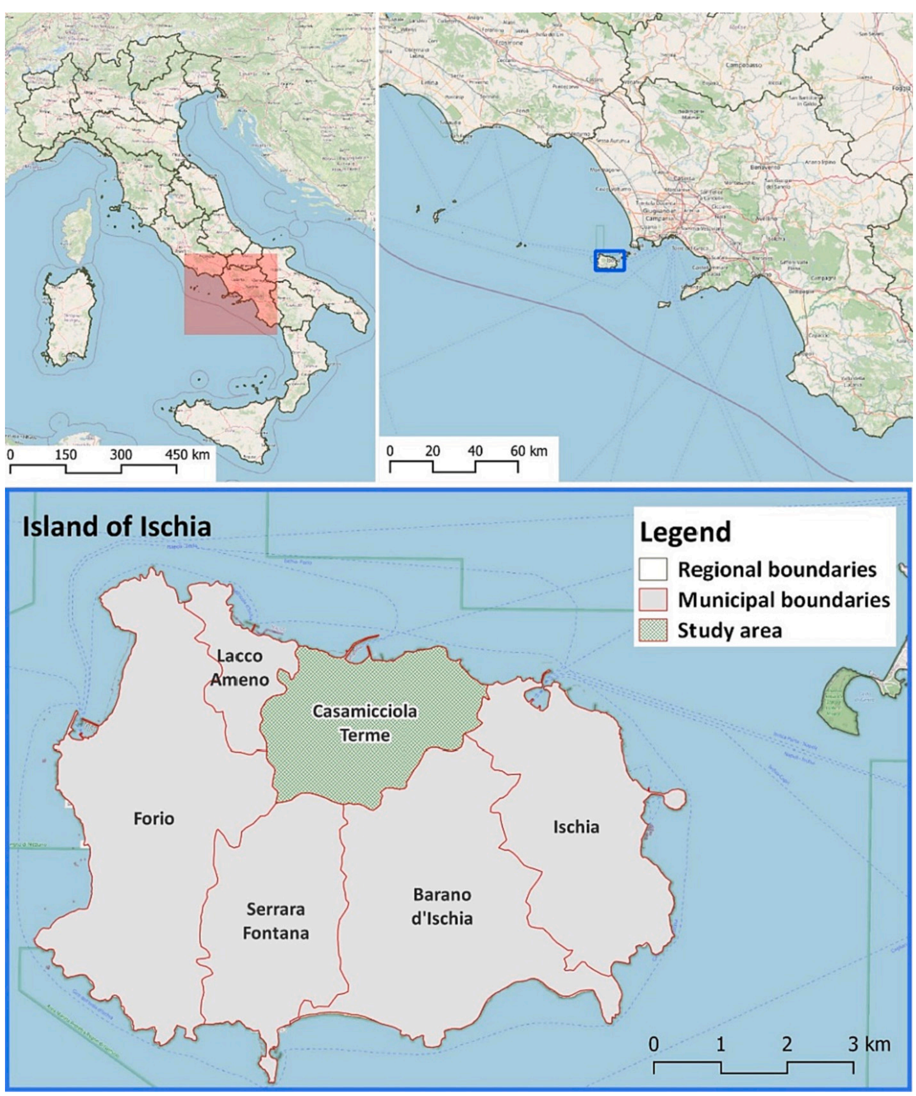


Fig. 1. Study area.

Institute of Statistics), has grown up from about 500 in the fifties to more than 2000 in 2011 (https://www.istat.it/it/censimenti/popolazione-e-abitazioni).

The night between 25th and 26th of November 2022 the Casamicciola Terme municipality experienced an episode of extremely abundant rainfall event. A quantity of 126 mm of rain have fallen on the municipality in a timelapse of 6 h, triggering a huge landslide event (https://www.cnr.it/it/nota-stampa/n-11543/frana-a-ischia-i-dati-di-cnr-irpi) (Fig. 2). The debris flow originated from three distinct points outside the urban area, near the Epomeo Mount, reaching the coast and passing through the city of Casamicciola Terme (https://emergency.copernicus.eu/mapping/list-of-components/EMSR643).

The area covered by the catastrophic event is equal to 28.2 ha and comprehends three main branches that converge into one point inside the urban area, then flowing directly to the sea through the port area.

Twelve people died, with hundreds of residential and commercial buildings destroyed in the city.

3. Materials and methods

The approach followed in this study comprehends three different dimensions of territorial dynamics. First, an environmental approach has been used. In this part of the work the concept of ecosystem service has been used to deepen two environmental features involved into the analyzed event: the runoff mitigation and the sediment delivery ratio. Despite the modern elaborations available worldwide in the scientific literature, the attention has been focused on ESs declined not only as the potentiality of ecosystems to give some services in terms of good and benefits (runoff mitigation values), but also to act as proxy of potential territorial fragilities outside and inside the urban areas (sediment deposition values) (Cortinovis and Geneletti, 2020).

Secondly, local and superordinate territorial planning tools have been deepened, to investigate the fifties and the actual built up configurations, based on the regulatory constraints that characterize it.

All these information layers have then been overlapped to highlight territorial vulnerabilities such as built-up areas under hydrogeological risk.

Finally, based on the evidence emerged, two spatial reconfiguration scenarios of the areas affected by the landslide event have been developed, to help decision makers addressing configurational changes (Fig. 3). To relocate the portion of the urban fabric involved in the landslide event, the attention has been focused on well-established territorial indices (Romano, 2014).

All these operations have been made using open-source software and well-known indicators, to assure the replicability of the standardized procedure and allow to implement new analyses and tools into the workflow structure.

3.1. Environmental elaborations

To comprehend some of the main causes and dynamics involved in the catastrophic event of Casamicciola Terme some preliminary elaborations have been made. Using the Digital Elevation Model (DEM), with a resolution of 10 m/pixel (Tarquini et al., 2012; Tarquini and Nannipieri, 2017), the stream network inside the municipality has been extracted. Additionally, the drainage basin associated to the confluence point of the landslide into the sea has been calculated. Finally, the drainage basin has been overlaid with two ESs elaborations: the Sediment Delivery Ratio (SDR) and the urban flood risk mitigation (UFRM). Both SDR and UFRM modules have been retrieved through the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software, which aggregates and compute ESs based on Land Use Land Cover (LULC) classes (Sharp et al., 2014). To do this the Urban Atlas (UA) dataset has been used. This product has been created to deeply describe urban areas (Montero et al., 2014), with a higher class resolution (minimum mapping unit: 0.25–1 ha) compared to the broader used Corine Land Cover dataset (minimum mapping unit: 25 ha) (https://land.copernicus.eu/user-corner/technical-library/urban-atlas-mapping-guide).

The elaboration considered in this study for the sediment delivery ratio (SDR) model, to deepen the potential debris flow that originates outside the urban area, is the sediment deposition.

To extract the SDR related values, the InVEST software relies on the universal soil loss equation (RUSLE) (Benavidez et al., 2018). The sediment deposition, reported in tons per pixel with a resolution of 10 m/pixel, expresses the quantity of sediment deposited from the upslope

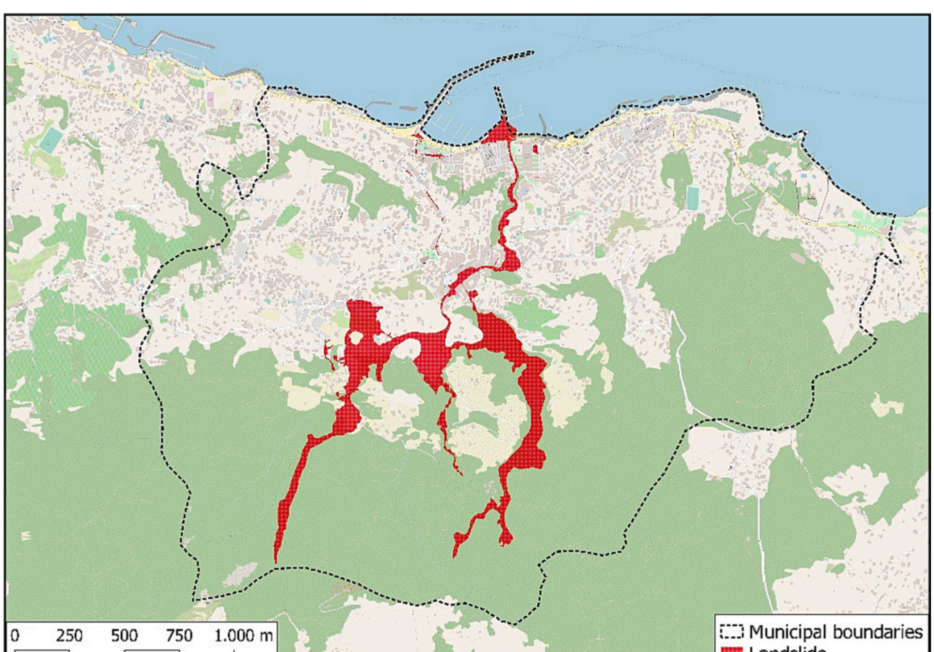


Fig. 2. Landslide footprint (red) inside the Casamicciola Terme municipality. The landslide originated from three different point, then converging inside the urban area of Casamicciola Terme city, then reaching the porta area (retrieved from Copernicus emergency service).

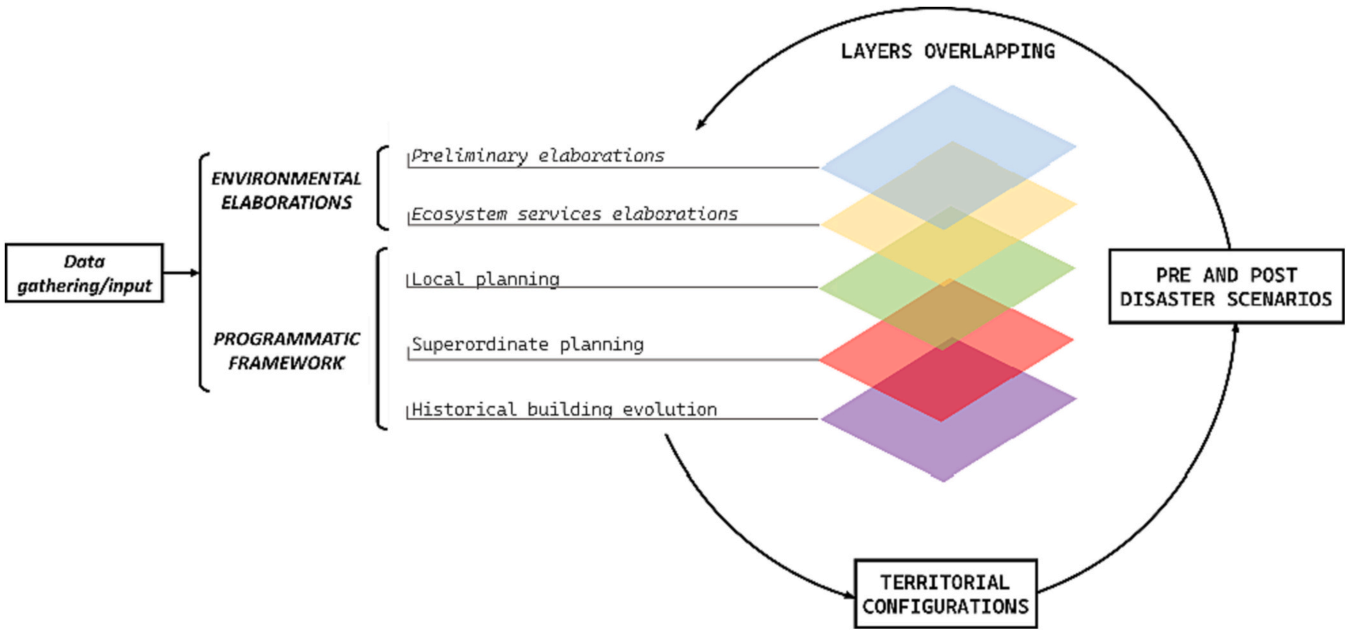


Fig. 3. Flowchart of the applied methodology. The chart shows the three main steps: (1). Environmental elaborations to deepen the features that contribute to locate potentially vulnerable areas. (2) Local and superordinate planning cogency analysis to spot the level of integration between hydrogeological risk management and land development policies. The comparison between steps (1) and (2) allows the identification of suitable free risk areas to develop (3) Territorial configuration scenarios.

sources as a result of trapping. As opposed to the runoff mitigation, the sediment deposition is not an ecosystem service indicator, rather one of the outputs that can be used to evaluate the avoided erosion and the avoided sediment export in the SDR InVEST module. Nevertheless, it is a useful elaboration when considering the landslide event under which the population or the built-up areas are potentially exposed.

To compute sediment deposition, the InVEST SDR module relies on the sediment delivery ratio (SDR), defined as the proportion of sediment that reaches the pixel i (Vigiak et al., 2012):

$$SDR_i = \frac{SDR_{max}}{1 + exp\left(\frac{IC_0 - IC_i}{k}\right)} \quad (1)$$

in which, SDR_{max} is the maximum sediment delivery ratio (default value 0.8), IC_0 and k are respectively the Borselli IC_0 parameter and the Borselli k parameters (Vigiak et al., 2012).

SDR values are then used to calculate the sediment retained on any i-pixel in the flowpath as:

$$\mathrm{T_i} = \mathrm{dT_i}^* \left(\sum_{j\epsilon\{\text{pixels that drain to i}\}} \mathrm{F_j}^* \mathrm{p(i,j)} \right) \quad (2)$$

here, F_j is the amount of sediment export that does not reach the stream flux. $p(i,j)$ is the proportion of flow from pixel i to pixel j and dT_i is considered as:

$$\mathrm{dT_i} = \frac{\left(\sum_{k\in\{\text{directly downslope from i}\}} \mathrm{SDR_k}^* \mathrm{p(i,k)}\right) - \mathrm{SDR_i}}{1.0 - \mathrm{SDR_i}} \quad (3)$$

here, SDR_k is the sediment delivery ratio ok the pixel k, SDR_i is the sediment delivery ratio of the pixel i and $p(i,k)$ is the proportion of flow from pixel i to pixel k.

Based on the Eqs. (1), (2) and (3), the InVEST SDR module requires different inputs. First, the erosivity values are needed. Erosivity indicates the erosive capacity of the rain in the specific area of interest, depending on the LULC classes.

Secondly, erodibility values are required. Erodibility indicates the sediment transport due to runoff and rainfall, based on the Land use/ Land cover classes. These inputs have been added as raster with a resolution of 500 m/pixel (erosivity raster) and 100 m/pixel (erodibility raster) (Panagos et al., 2015a; Panagos et al., 2014). Finally, the biophysical table reporting C (soil erosion cover management) and P (Support practices) factors is required. These data were obtained by the European soil data center (ESDAC), from two works of Panagos et al., 2015b and Panagos et al., 2020.

Together with these inputs, the model enquires the setting of the parameters specified in the above equations. Specifically, the threshold flow accumulation, i.e. the number of upslope pixels that must flow into a pixel before it is classified as a stream (it works based on the DEM), has been sat at 500. This value allowed to obtain a stream network coherent with the one extracted in the preliminary elaborations. The Borselli IC_0 and K parameters have been set at 0.5 and 2 respectively, which are the default values proposed in the InVEST user's guide. Finally, the maximum SDR value has been set at 0.8. Also this value is considered the default one for the model.

The output considered for the Urban Flood Risk Mitigation (UFRM) model is the runoff map.

The runoff values have been retrieved as:

$$\mathrm{R_i} = 1 - \frac{\mathrm{Q_{p,i}}}{\mathrm{P}} \quad (4)$$

here, the i pixel's runoff retention (R_i) is considered as the ratio between the pixel's runoff ($Q_{p,i}$) and the design storm P. Simultaneously, the runoff ($Q_{p,i}$) is calculated as:

$$\mathrm{Q_{p,i}} = \left\{ \begin{array}{c} \frac{(\mathrm{P} - \lambda \mathrm{S}_{max,i})^2}{\mathrm{P} + (1-\lambda)\mathrm{S}_{max,i}} \text{ if } \mathrm{P} > \lambda^* \mathrm{S}_{max,i} \\ 0 \text{ otherwise} \end{array} \right\} \quad (5)$$

in which, P is the design storm depth in mm (in this case the mm of rainfall that triggered the landslide), $S_{max,i}$ is the potential retention in mm, calculated through the curve number method (NRCS, 2004), λ^* $S_{max,i}$ is the rainfall depth needed to initiate runoff (for simplification, λ is set at a default value of 0.2).

The UFRM model also requires several inputs. Specifically, the area of interest is represented by the watershed map obtained from the DelineateIt InVEST model (DelineateIt — InVEST® Documentation, 2023). For the specific event 126 mm rainfall depth has been set. The latter comes from the National Research Council (CNR), reporting the quantity of rain fell in a time frame of 6 h the night between the 25th and 26th of November (https://www.cnr.it/it/nota-stampa/n-11543/frana-a-ischia-i-dati-di-cnr-irpi). The Soil Hydrologic Group dataset (raster file, 250 m/pixel resolution) has been retrieved from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (Ross et al., 2018). This data has been used to calculate the $S_{max,i}$ value, together with the curve number (CN) values, defined for each LULC class into the biophysical table. The CN values have been retrieved from the Simulsoil software, realized in the context of the LIFE SAM4CP project, to assess different ESs in the Italian context (Giaimo and Salata, 2019). Due to the different classifications of the LULC classes, the Curve number values have been converted into the urban atlas classes (for specific data see supplementary material).

3.2. Local and superordinate planning

From the local planning level the programmatic framework of the study comprehends the historical map showing the urban fabric dated back to the 1950, derived from the IGM 25 V series (https://www.igmi.org/geoprodotti#c2=%2Fpunti-geodetici&b_start=0&c4=1540967.43%2C4966149.95%2C1555751.46%2C4978623.97&c4=intersects). From this map the fifties built-up has been retrieved.

Secondly, the urban plan (PRG) drafted between the end of sixties and the beginning of seventies, and approved in 1982 (D.P.C.R. n. 11389, 12.29.1983) has been considered.

Also the preliminary PRG, dated back to January 2020 and still not approved, has been taken into account (https://www.comune.casamicciolaterme.na.it/home/preliminare-di-piano-urbanistico-comunale/). Specifically, the cognitive framework has been retrieved, deepening the timeline of routes and buildings ("QC14 Cronologia dei tracciati e dell'edificato"). By deepening these local planning tools together with the historical map, it has been possible to highlight the built-up expansion occurred throughout the years, leading to the actual urban spatial configuration, contextually looking at future territorial development scenarios, represented by the in draft PRG.

From the superordinate planning level the Hydrogeological Structure Master Plan (PAI) (http://www.pcn.minambiente.it/mattm/servizio-di-scaricamento-wfs/) adopted by the Institutional Committee Resolution n.11, 05.10.2002 has been retrieved. From the PAI the maps of the hydrogeological hazard and risk have been retrieved.

Considering the PAI, only areas under R3 and R4 hydrogeological risk have been considered. Here, the hydrogeological risk is defined as the entity of the damage expected in a given area, in a certain interval of time, following the occurrence of a hydraulic and/or gravitational slope phenomenon:

$$R = D \times E \times V \tag{6}$$

in which D is the danger, defined as the probability of the occurrence of the phenomenon in a specific area, E is the exposition of people or goods to the phenomenon and V is the vulnerability, i.e. the capacity of a system or element to resist the phenomenon.

Specifically, only areas under R3 (high) and R4 (very high) hydrogeological risk have been considered. These categories subtend the following definitions:

R3 - High Risk, for which there are possible problems for the safety of people, functional damages to buildings and infrastructures, with consequent unusability of the same. There could also be significant damages to the environmental heritage and interruption of the functionality of the socio-economic activities.

R4 - Very High Risk, for which there is possible loss of human life, serious damages to buildings, infrastructure, environmental heritage, and the destruction of socio-economic activities.

3.3. Territorial configurations

First, it is essential to implement a new planning strategy, not linking the location of new settlements to the design of land ownership. Indeed, this way of thinking land planning can lead to considerable difficulties in achieving efficient spatial configurations. The latter could allow to save land, improve local economies, and better provide common services through equalization and compensation actions (Munafò et al., 2013; Romano et al., 2010).

To operate on the identified free risk areas, two indexes have been used: the available territorial surface (St_a) (7) and the territorial coverage ratio (Rc_t) (8) (Romano, 2014).

$$St_a = S_t - Sc_e \tag{7}$$

$$Rc_t = (S_c / S_t)*100 \tag{8}$$

where:

S_t = Territorial surface (m^2)
St_a = Territorial available surface (m^2)
Sc_e = Existing building covered surface (m^2)
S_c = Covered surface (m^2)
Rc_t = Territorial coverage ratio (%).

Here, St is the territorial surface area, representing that part of the territory that includes all buildable surfaces, i.e., those intended for private residential or productive building interventions, all surfaces for primary urbanization (roads and network services) and surfaces for secondary urbanization (collective social services).

Sta is the territorial area available for new construction, i.e., the St land area from which Sc_e (the covered area derived from the projection to the ground of the outer perimeter of existing buildings) is subtracted.

Rc_t is the territorial coverage ratio, which is the ratio between the Sc (covered surface) and the St (territorial surface), expressed as a percentage.

Additionally, a shapefile containing the buildings for the Municipality of Casamicciola Terme, retrieved from the civil protection department, has been associated. For this dataset commercial, transport, residential, and residential/commercial units have been considered.

(https://rischi.protezionecivile.gov.it/it/approfondimento/dataset-nazionale-degli-aggregati-strutturali-italiani).

The information about the type of use of buildings comes from different data sources: Open Street Map, POIGPS, and Google Satellite Hybrid.

To calculate the volumetry of the buildings to be relocated, data of the covered surface have been used. Through OpenStreetMap dataset a recognition on the mean height of the built up has been conducted, resulting in about 2 floors. Estimating an average floor height of about 3.3 m, the built–up of two floors has been set at 6.6 m.

To limit land use, areas with a compatible land cover ratio and close to the already developed urban axis were chosen. Together with this, some of the practices to implement the de sprinkling process through densification and infilling were implemented (Romano et al., 2017a).

In addition, to cause the least socio-psycho-economic stress to the population, that is, to avoid opposition to the plan and/or claims of owners' rights, it has been assumed to relocate all volumes, including the abusive ones.

All these assumptions have led to the creation of two scenarios. In the first case, densification practices have been envisaged. In the second scenario, also a verticalization of the built-up areas has been envisaged.

4. Results

4.1. Ecosystem services and their distribution

Preliminary results show that the drainage basin corresponding to the debris flow encloses both the urban and natural systems, up to the Epomeo Mount, from which the landslide occurred in late November. It has an extension of about 278 ha (312 ha also considering the extension to the neighbor municipality of Barano d'Ischia), corresponding to the 47,5 % of the total extension of the municipality (585 ha). Finally, it can be seen how part of the Drainage basin includes the neighboring municipality of Barano d'Ischia (Fig. 4a and b).

The sediment deposition values, i.e. the quantity that is deposited on every pixel from the upslope sources as a result of trapping, range between 1 and 10 tons per pixel, directly involving the historic settlement, parts of the peri-urban areas under requalification and the widespread urban settlement (Fig. 4a).

It can be also seen the sediment deposition correspondence with the landslide footprint of the event that occurred in Casamicciola Terme, retrieved from the Copernicus emergency service (https://emergency.copernicus.eu/) (Fig. 4a).

Three out of the main five strands were the ones from which the landslide originated. Furthermore, the branches not subject to landslide only partially follow the path of the occurred event, affecting also other portions of land that were not interested in late November 2022.

UFRM model returns high values of runoff in the inner urban areas. Shifting into a natural context, near Epomeo mount, these values tend to lower (Fig. 4b). One of the highest runoff values is registered at the convergence of the branches resulted by the footprint of the landslide (between 92 and 119 mm of runoff, corresponding to 73–94 % of the precipitation fallen). The lowest runoff values are registered in agricultural and forestry systems, with runoff values ranging from about 32 mm (25 %) to 55 mm (43 %).

The risk map overlapped with the historic urbanized areas shows that in the fifties the built-up was not located in areas under hydrogeological risk, except for some portions on the coast, characterized by level of dangerousness P4. Relatively to the areas subject to hydrogeologic risk, Casamicciola Terme has about 60 % of the municipal extension subject to landslide and flood risk. Specifically, areas under landslide risk occupy 3.3 km^2, of which 3 km^2 are at high risk level (Fig. 5a). From the evaluation of the existing building, it results that 651 buildings are in risk areas, 642 of which are under high and very high hydrogeological risk (525 in very high-risk areas and 117 in high-risk areas). Currently 1/5 of the structural aggregates of the municipality are in unbuildability areas with an occupied surface of 50 ha (Fig. 5b).

Considering the historic and the actual built-up there are significative changes. First, as reported in the 14th table of the cognitive framework of the preliminary PRG "QC14 Cronologia dei tracciati e dell'edificato", the actual built-up has grown over time (Fig. 6). The historic urban fabric is the densest area, distributing in parallel to the coastline and wedging southward in front of the port of Casamicciola. This urban fabric has an irregular mesh that follows the land orography, thickening in the flat areas and fragmenting along the slopes of the hilly ones.

The latest built-up comprehends isolated buildings (residential and turistic functions), with a thinning of the building fabric that doesn't follow any urban regulation. In addition, single units are distributed unevenly along the terracing of coastal and inland hilly areas. This kind of distribution is an example of sprinkling, a typical Italian settlement model also present in the Iberian Peninsula and Balkan area (Romano et al., 2017b).

From the comparison between the in force PRG with the supra-ordinate PAI, as showed in Fig. 7, the 20 % of the PRG zones is in high and very high hydrogeologic risk areas. Specifically, F zones "spaces for public facilities of general interest" is the most affected (25,8 %), followed by A zones "Historic center zone and areas of special environmental value" (22,5 %). It is also interesting to see that 10 % of C zones "Areas for new public and private housing" are placed under hydrogeological risk. A similar value (13 %) is registered for the subzone F6 "Land designated for school or public facilities".

From the programmatic document of the preliminary PRG, drafted in January 2020, the elaborate 3 of the structural frameworks "QS3 Indirizzi per le aree Urbanizzate" subdivides the territory into 5 classes: 1) Historic settlement recovery; 2) Valorization of rural areas; 3) Valorization of the coast and urban waterfront, 4) Diffuse settlement fabrics to be requalified and 5) Peri-urban urbanized areas to be requalified. For the "diffuse settlement fabrics to be requalified" and the "Peri-urban urbanized areas to be requalified", the envisaged requalification operations are based on building and urban redevelopment, with an additional focus on the infrastructures, to improve usability of these areas.

From the overlap of these data with the PAI it emerges that 40 % of urban waterfront is under very high and high risk, 18 % of the diffuse urban fabric to be requalified and 12 % of the Peri-urban urbanized areas to be requalified are under very high and high risk.

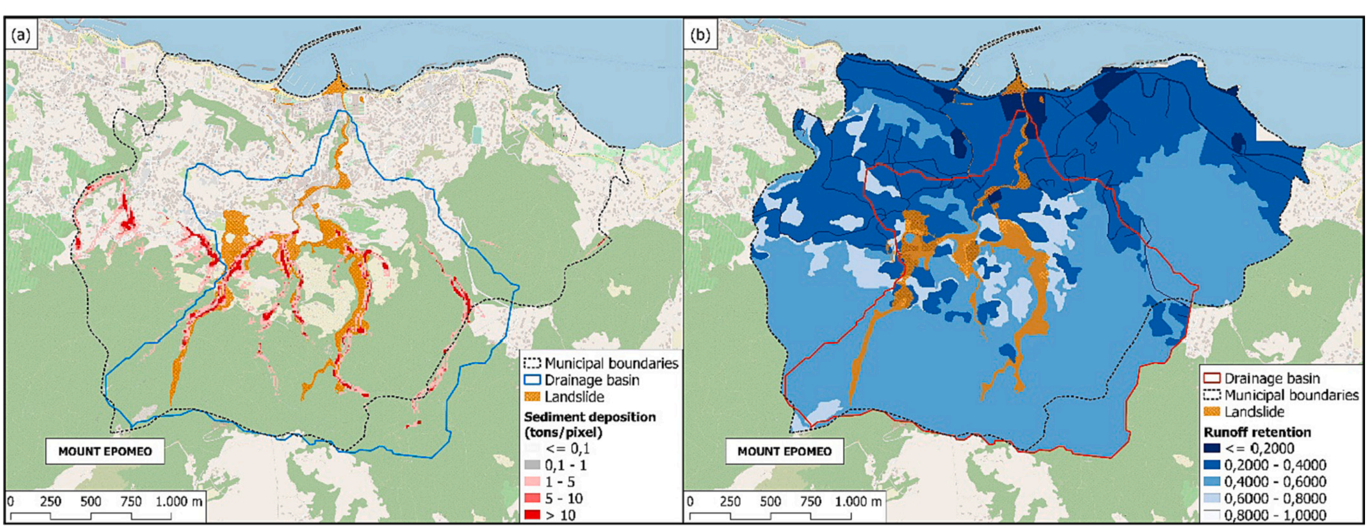


Fig. 4. (a) Map of sediment deposition in tons per pixel. The darkest is the red the highest is the deposition value. (b) Runoff retention map. The darkest is the blue the higher is the value of runoff retention. On both maps are indicated the drainage basin, the municipal boundaries and the landslide footprint, occurred in November, 22th 2022 (b).

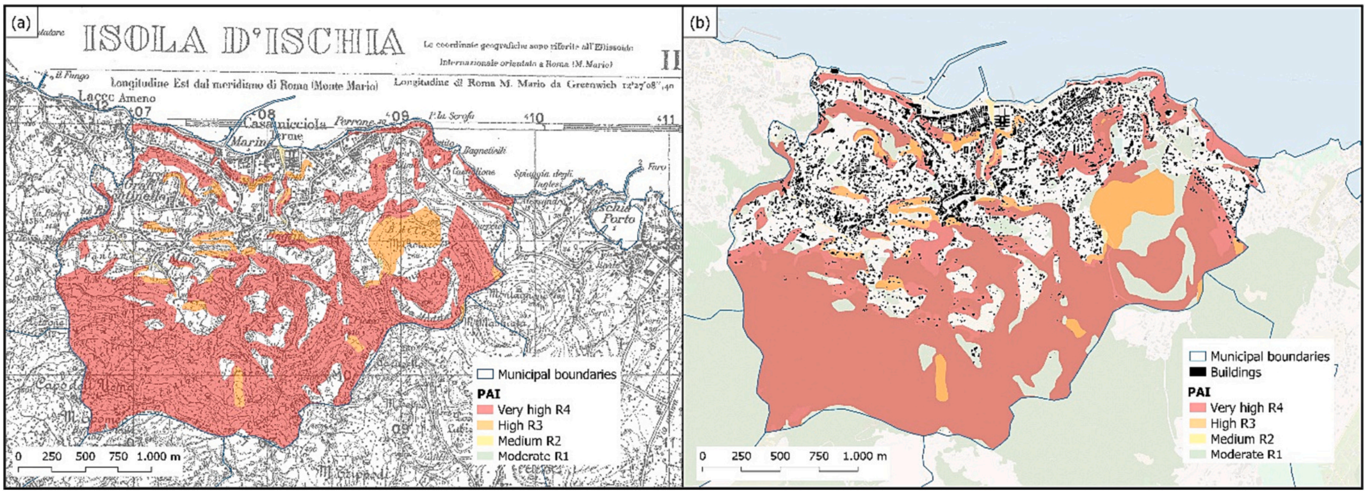


Fig. 5. (a) Overlapping of Hydrogeological Structure Master Plan (PAI) risk map and historic cartography. (b) Overlapping of built-up and PAI risk map.

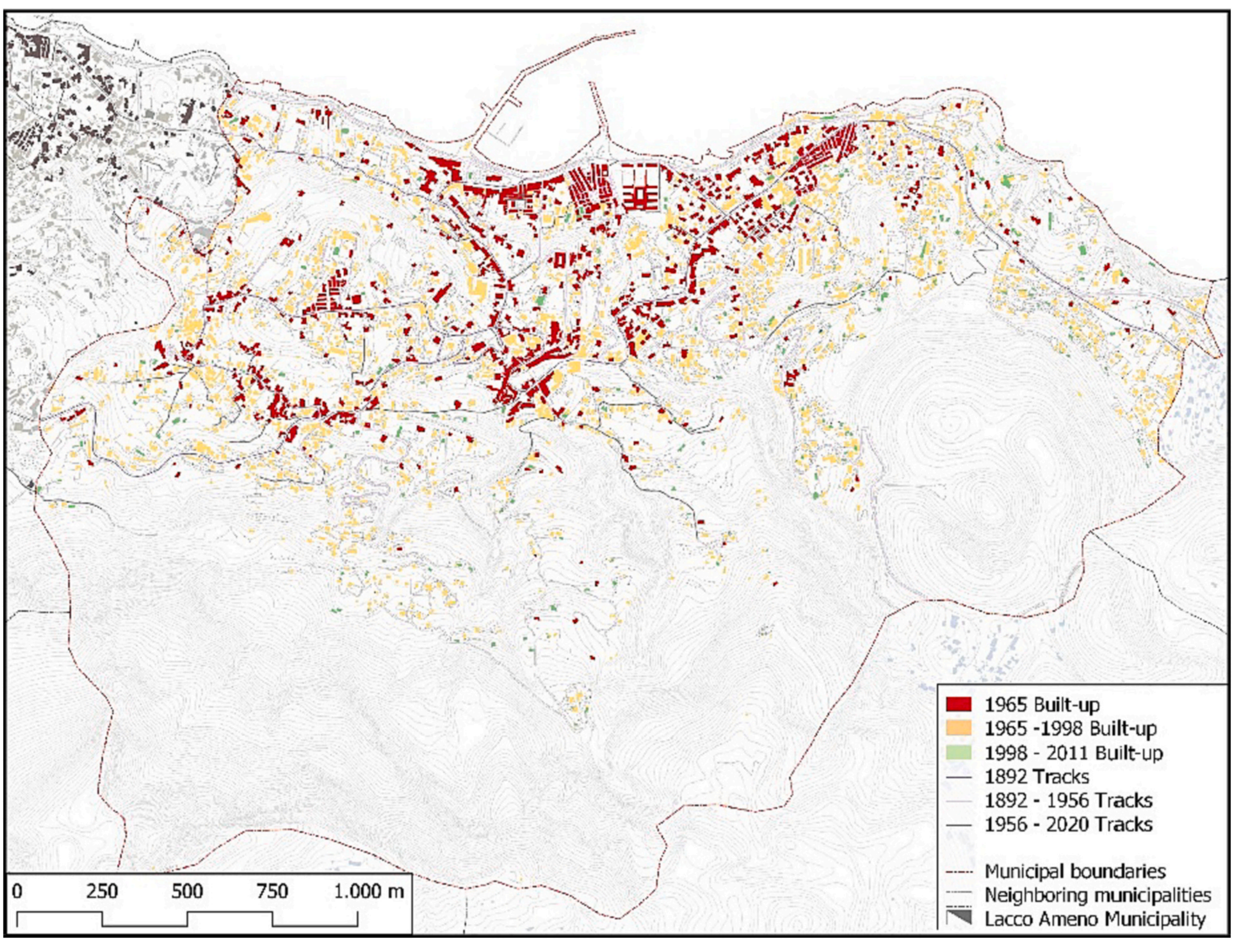


Fig. 6. 14th table of the cognitive framework of the preliminary PRG “QC14 Cronologia dei tracciati e dell'edificato”.

4.2. Spatial reconfigurations

The landslide, partially occurred in a designated PAI flood risk zone, involved several buildings with predominantly residential use, totally destroying or otherwise damaging them beyond repair.

Overlapping the landslide and the built-up areas, the number of buildings involved is 138, which correspond to a surface of 32,122,3 m^2 and a volume of 212,007 m^3 (Fig. 8).

It is therefore necessary to reconstruct these buildings and find non-risk areas in which to relocate them. Thereby, following the procedure previously described, free risk areas have been identified through the overlapping of various informative layers: landslide footprint, stream network, urbanized areas, landslide risk, runoff, and sediment delivery ratio (Fig. 9).

The choice of the areas has fallen on those whose indexes values were as close as possible to the ones derived from the historic built-up.

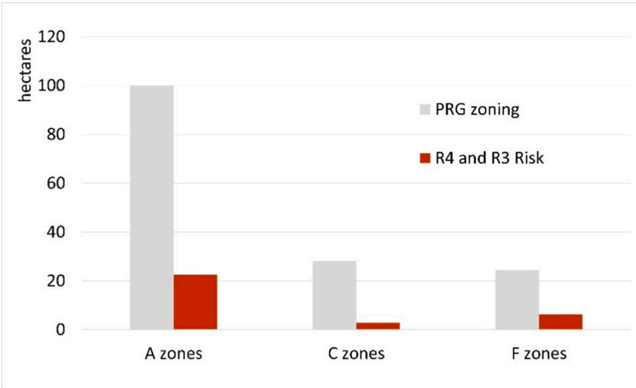


Fig. 7. Bar chart reporting PRG zoning extension (grey) and the relative areas under R4 and R3 PAI risk (red).

In our case study, the most suitable areas to relocate the new buildings resulted to be the ones identified by the preliminary PRG "diffuse settlement fabric to be redeveloped", being adjacent to the more heavily urbanized areas identified in the Strategic Plan as " Historic settlement recovery".

The historic settlement has a territorial surface of 606,720 m^2. Here, the existing buildings cover a surface of 204,113 m^2. From Eq. (8), territorial coverage ratio turns out to be 33,64 %.

The extension of the located risk-free areas is 240,910 m^2. In these areas existing buildings occupy a surface of 46,048,3 m^2.

Using the expressions (7), the territorial available surface is 194,861,6 m^2.

Starting from these values, to relocate all the buildings involved in the landslide, two different scenarios have been developed (Fig. 10):

Scenario 1 (two-story buildings) shows a progressive building densification moving from configuration 1a to 1d, resulting in buildings decrease (from 320 to 40, with a percentage of 87 %).

Here, adding up the existing building covered surface to the area covered by the buildings to be reconstructed, it results in 78,170,6 m^2, and a territorial coverage ratio of 32 %.

In Scenario 2, like in the previous one, the number of buildings decreases from configuration 2a to 2d (212 to 27, with a percentage of 87 %). Here, together with compacting of configurations, a verticalization of the built-up area has been envisaged (three-story buildings).

Adding the value of the new built-up area to that of the existing one, the covered surface turns out to be 67,249 m^2 with a territorial coverage ratio of 28 %.

5. Discussion

Starting form environmental elaborations, the implementation of the Runoff retention and the sediment deposition values allowed to preventively quantify the landslide event. Contextually, synergies between the aspects of soil impermeabilization and potential sediment transport have been deepened, to highlight potential vulnerabilities affecting the analyzed territorial scope. Thanks to the elaborations based on the INVEST software, the fundamental link between LULC and the expression of ESs has been realized. As already stated by Roy et al. (2024) and Viglizzo et al. (2012), this is a long time wanted aspect inside the territorial planning research field, to help decision makers value the nature and the consequences of territorial transformations. Nevertheless, such technologies are poorly integrated at the local administrative level, where their employment is still in its embryonal phases (Di Dato et al., 2021; Romano et al., 2018).

In the case study of Casamicciola Terme the extension of the drainage basin, associated to the confluence point of the landslide into the sea, leads to different considerations. First, as already stated by Romeo et al. (2023), incision ditches whose confluence points occur into the most anthropized zones of the municipality of Casamicciola Terme, expose urban areas to potential landslide events. In this context, the results provided describe a condition in which the incision ditches are characterized by average runoff mitigation and high sediment deposition

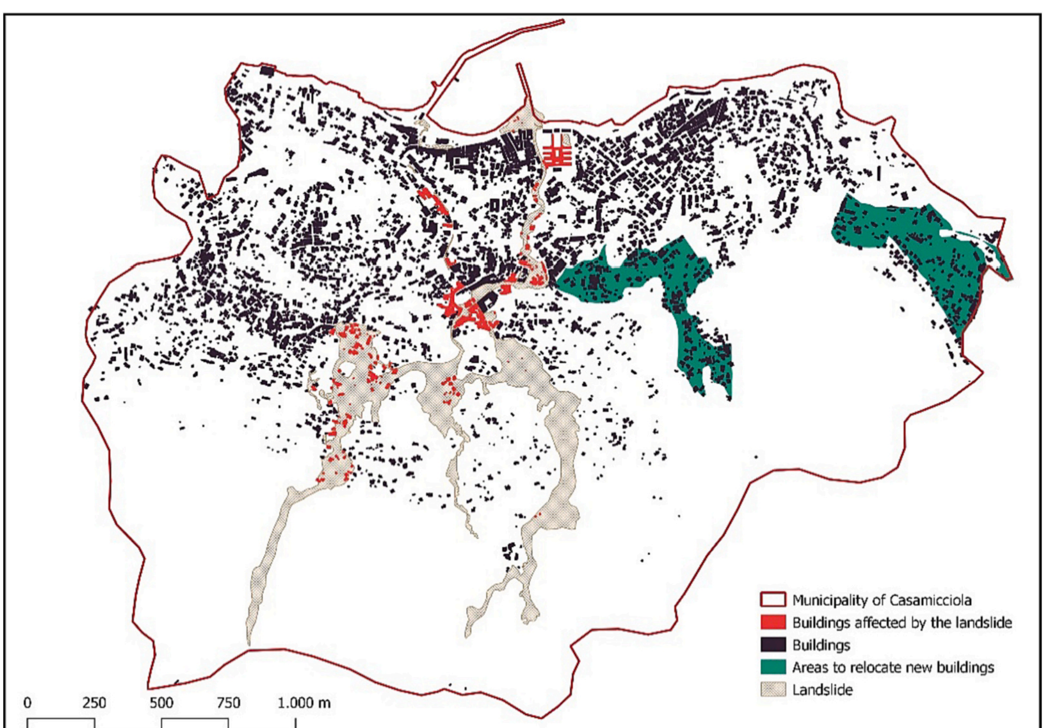


Fig. 8. Map of Casamicciola Terme buildings. In red the buildings affected by the landslide, in black the other buildings. The green areas represent the ones in which relocate the new buildings.

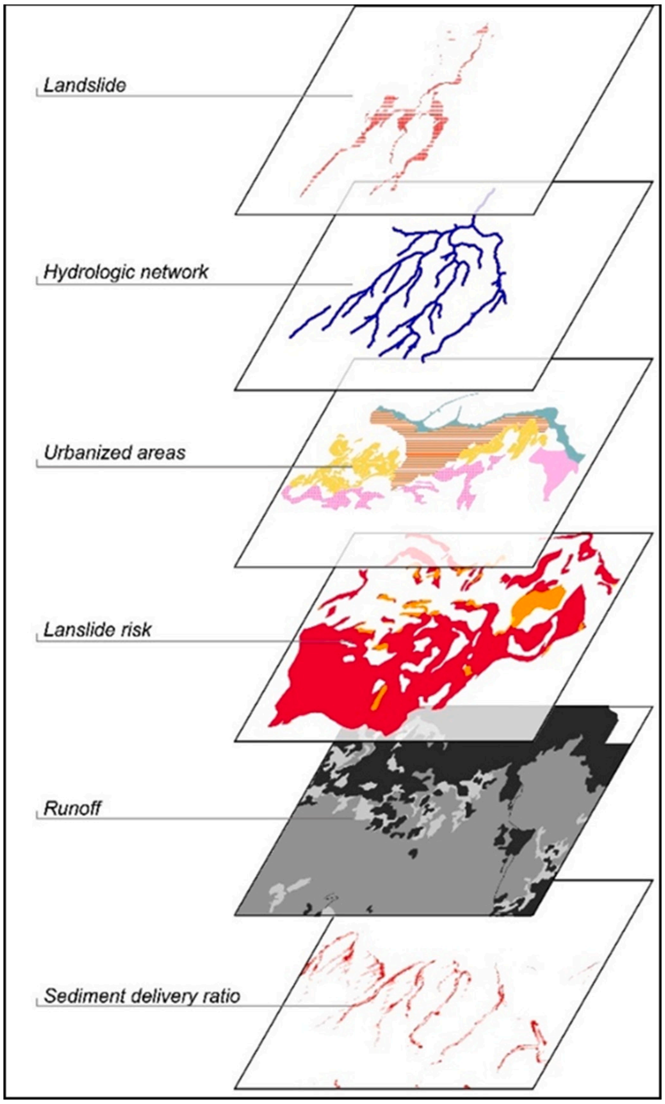
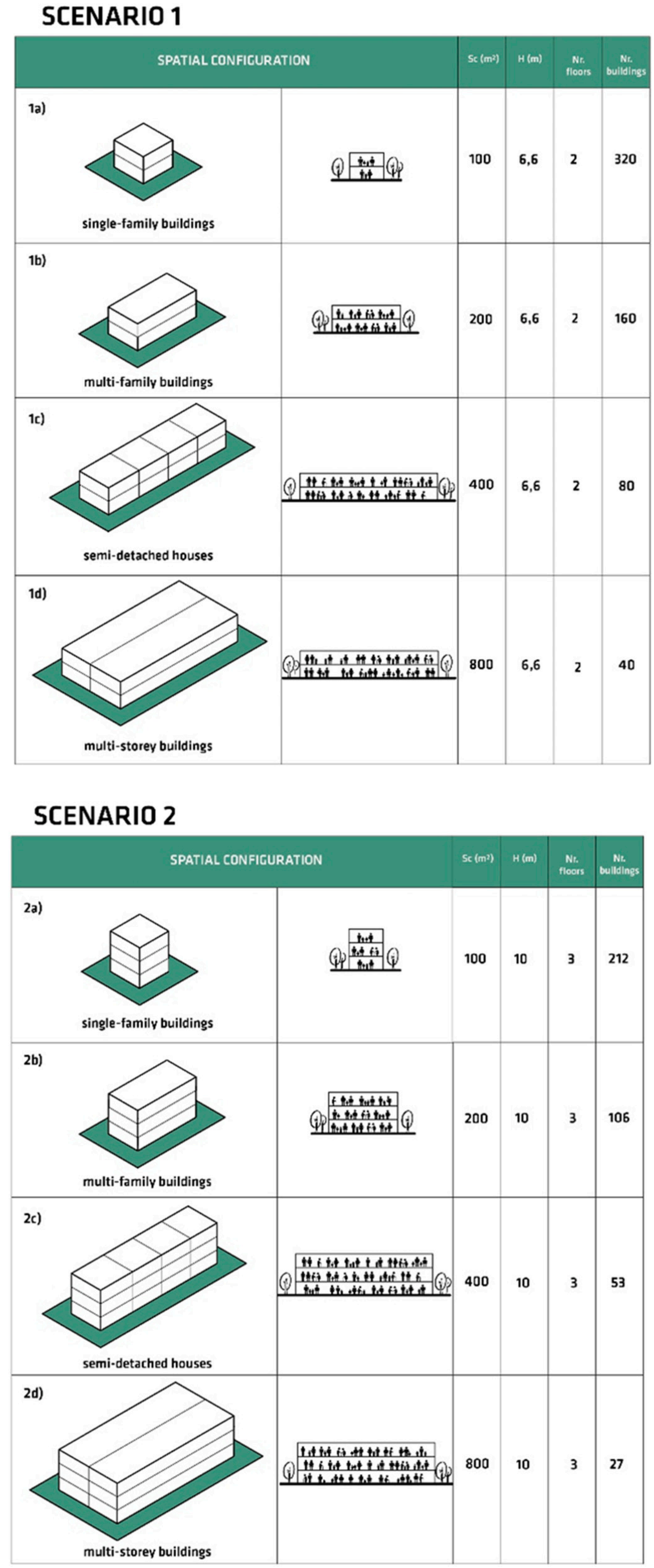


Fig. 9. Overlapping of the informative layers to locate the area in which relocate the new buildings.

values. As already demonstrated by other studies (Arrogante-Funes et al., 2022), low runoff (32 mm) values correspond to areas characterized by permeable land cover (agricultural areas, pasture, forests and so on), while high runoff values (123 mm of runoff, compared to the 126 mm of precipitation) are mostly registered in urban areas. Here concrete, asphalt and similar materials used to build roads and buildings lead to soil impermeabilization, contributing to raise runoff values (Ivits et al., 2022).

From a morphological point of view, the main flow veins originating from the Epomeo Mount directly intersect the urban fabric. This result is further supported by the overlap between the runoff retention, the sediment deposition, the drainage basin and the stream network layers. Additionally, it is possible to see that, among these five veins, only three triggered the landslide that reached the urban areas of Casamicciola Terme. Considering the high slope instability already described by Santo et al. (2012), the other two veins could still cause landslide events due to abundant precipitation (Gariano and Guzzetti, 2016; Rong et al., 2023), directly involving portions of the urbanized areas. Furthermore, the drainage basin extension encompasses both the municipality of Casamicciola Terme, and the neighboring municipality of Barano d'Ischia. This aspect has huge consequences on the planning policies that must be adopted when managing landslide risk. Indeed, the peculiar territorial



SCENARIO 1

SPATIAL CONFIGURATION	Sc (m²)	H (m)	Nr. floors	Nr. buildings
1a) single-family buildings	100	6,6	2	320
1b) multi-family buildings	200	6,6	2	160
1c) semi-detached houses	400	6,6	2	80
1d) multi-storey buildings	800	6,6	2	40

SCENARIO 2

SPATIAL CONFIGURATION	Sc (m²)	H (m)	Nr. floors	Nr. buildings
2a) single-family buildings	100	10	3	212
2b) multi-family buildings	200	10	3	106
2c) semi-detached houses	400	10	3	53
2d) multi-storey buildings	800	10	3	27

Fig. 10. Spatial configuration (scenario 1 and scenario 2) for buildings relocation. The scenarios show the spatial configuration of the modules, the vertical section of the modules and the associated value for the identification of each of the modules. The used indexes are Covered surface (Sc), Height of the buildings (H), number of floors and the consequent number of buildings. Scenario 1 and 2 differs for the height of the buildings. Scenario 2 is more compact than the Scenario 1 configuration.

context represented by the Island of Ischia entails a landslide risk also potentially originating outside the municipal boundaries, hence, to be manage by two local planning tools.

From the local planning framework reconnaissance, little consideration of the superordinate planning levels emerges. Although the in force PRG predates the current PAI, in the new municipal masterplan (that is now in its draft form) the requalification of *peri* urban areas and diffuse urban fabric under high and very high-risk areas has been envisaged. In these areas, although constraint of unbuildability exists, the expansion of the built up denotes poor attention from the local planners, and a transformative framework mainly driven by local interests (Romano et al., 2019; Fiorini et al., 2021).

These results support the findings of Romano et al. (2018), who very clearly highlighted one of the major problems affecting the Italian municipalities, whose territorial governance is often unrelated by the upper planning levels, resulting in a lack of a real strategic management of land dynamics. This aspect is also partially due to the repeated unauthorized building, followed by illegal building amnesty and uncontrolled land take that characterizes Italy since the end of WWII (Fiorini et al., 2019; Romano et al., 2021; Zanfi, 2013). The above findings also apply to other international contexts such as Belgium, Denmark and Croatia, in which Local planning still does not correctly deal with hydrogeological risk, due to the lack of a detailed landslide risk mapping and to unsuitable planning tools (Mateos et al., 2020).

After environmental elaborations and programmatic framework reconnaissance, the methodology moved to the "configurational scenarios" section. Thanks to the information retrieved in the previous steps, suitable areas have been located.

From the spatial configuration scenarios, it emerges that scenario 1 has an Rct value (32,44 %) that is near the one of the historic settlement (33,64 %). In this case a compaction of the built-up has been hypothesized, leading to less land use. Indeed, as demonstrated by Angel et al. (2020), dispersed forms of urban settlement imply an augmented demand for infrastructures and services, leading to land use and fragmentation of the natural matrix. For the same reason, scenario 2, together with a compaction phenomenon, envisages a verticalization of the built-up, with even less land use and a lower Rct value (28 %).

Hence, to reduce land use, simultaneously assuring public health protection, planning policies should also consider the requalification of the urban fabric and a partial delocalization of the actual built-up interested by the catastrophic event, preferring compaction and verticalization practices (Conticelli et al., 2023; Ferrante et al., 2020; Reale, 2011; Tozzi, 2012).

Although being conceptualized to be applicable in different territorial contexts, the present study has different limitations. First, InVEST software relies on models which imply certain simplifications. Specifically, the SDR model strongly relies on the RUSLE which, thus being widely used, only consider overland (rill/inter-rill) erosion processes. Hence, to have a more complete quantification, it could be useful to rely on models that comprehend also other sources of sediment such as gully erosion and streambank erosion. Additionally, values used to calculate the sediment deposition are default values, which are useful when providing preliminary elaborations, but may be too little specific when there is necessity to deepen local areas under study (Sougnez et al., 2011). To this regard, future directions will be aimed at deepening also other models to rely on more complete elaborations. Even the urban flood risk mitigation model, although being useful in describing different LULC classes characteristics, involves uncertainties due to the use of the SCS-Curve Number approach. For example, the model does not include the water flow, drainage and flood velocity. These aspects can be useful when addressing potential flood damage costs (Quagliolo et al., 2023). Limitations and simplifications in using the InVEST models have been well deepened in the software user's guide (Sharp et al., 2014). Despite these implications, models have been chosen due to the wide spread of data used for the elaborations, as well as their ease of calculation using InVEST software also by non-expert users. Whenever necessary, models can be substituted with more complex and specific elaborations, paying attention to use always open-source data and software to not sacrifice the implementability of the approach. Finally, the study does not consider some factors that could be critical in relocation practices. For example, it has not been considered the historic and architectonic value of the buildings involved in the areas under analysis. Indeed, it could happen that some buildings cannot be moved due to their specific historic value. Furthermore, political and local will could be strongly opposed to the relocation of the buildings, due to the extremely elevated costs of such operations, and to socio economic motivations (Sangasumana, 2018). In this case, monitoring and warning systems should be preferred. Following these considerations, further studies will need to be done to enhance the methodology, providing other types of interventions such as landslide defense works or land maintenance actions. Additionally, socio economic aspects of building relocation actions will need to be implemented.

6. Conclusion

The research focused on landslides, one of the most destructive phenomena for urban areas. Through its findings, this paper can support land redevelopment actions necessary for planning policies to manage landslide risk.

Specifically, the methodology supports spatial planning both pre and post disaster. First, hydrological analyses, together with an evaluation of the ecosystem services values, allowed to deepen the runoff mitigation and the sediment deposition values associated to each LULC class. Before landslide occurrence, these elaborations can be useful to quantify future potential landslides. Furthermore, through the connections between LULC and the associated ecosystem services elaborations, decision makers can better value the nature and the consequences of territorial transformations. Secondly, the local and superordinate planning tools cogency analysis has been realized. From this step, the overlap between planning tools and environmental elaborations allowed to highlight potential territorial vulnerabilities, such as areas under hydrogeological risk, and planning tools actions inconsistent with the susceptibility of some areas to landslides.

Finally, territorial indexes through which address spatial configurations of the areas in which relocate new buildings have been proposed. By doing this, the possibility of combining different planning tools and intrinsic environmental characteristics allows to correctly address government policies both pre and post disaster, transforming the uncontrolled phenomena of land take and indiscriminate urbanization into a conscious management of the risk component originating inside and outside urban boundaries.

In addition, this research yields considerations of practical importance for the case study represented by the municipality of Casamicciola Terme. (1) The event occurred the night between 25th and 26th November 2022 is not the only one that could be potentially triggered in the analyzed areas. Two gullies could still activate landslides, directly involving portions of the urban areas. (2) Local planning policies and tools poorly consider the superordinate planning framework, making land planning actions susceptible of raising the exposition to landslides. (3) After landslide occurrence in November 2022, free risk areas in which relocate the affected buildings are the ones that belong to the nearest part of the urbanized axis. Here, densification and verticalization procedures should be prioritized to limit land take.

CRediT authorship contribution statement

Federico Falasca: Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Camilla Sette:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Cristina Montaldi:** Conceptualization, Investigation, Methodology, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171152.

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