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Geomorphological mapping and anthropogenic signature along the rocky coast in the Tigullio Gulf (Eastern Liguria, Italy)

Abstract: Pietrogrande S., Mandarino A., Azzoni R.S., Forti L., Faccini F., Pelfini M., Brandolini P., *Geomorphological mapping and anthropogenic signature along the rocky coast in the Tigullio Gulf (Eastern Liguria, Italy).* (IT ISSN 0391-9838, 2025). This paper describes the geomorphology of the coastal stretch between Zoagli and Chiavari, and presents the annexed geomorphological map at the scale of 1:5000. The study area, a dramatic rocky coast facing the Ligurian Sea, has been severely impacted by anthropogenic morphogenesis. It is historically prone to landslides and characterized by (i) a geological setting markedly conditioning the geomorphological evolution, (ii) small valley bottoms that have been entirely artificialized, (iii) hillslopes almost completely terraced, and (iv) a hydrographic network that is largely modified by channelization and culverting. Unlike many other areas worldwide where agricultural terraces have been abandoned over the past century, in this sector they have partially preserved their agricultural function and have been partially transformed by urban expansion, especially during the 1960s-1970s. Urbanization involved the construction of large settlements and scattered buildings associated with residential and tourism infrastructure, in some cases extending up to or beyond the sea cliff edge. This landscape setting, combined with high relief energy and the ubiquitous presence of infrastructure and facilities, makes the area highly exposed to geo-hydrological hazards such as mass movements, flash floods, and storm surges. The geomorphological map was produced through collection and review of archival data, geomorphological field surveys and indirect survey techniques based on the photointerpretation of aerial photographs, orthophotos, and satellite images, and the analysis of digital elevation models, all managed in a GIS environment. The outcomes of this research provide further insights to enhance both public awareness of geomorphological processes and risk perception, and represent a solid base for sustainable land management and adaption planning.

Key words: Geomorphological mapping, Anthropogenic landforms, Terraced slopes, Land use change, Coastal slope instability, Mediterranean Sea.

Riassunto: Pietrogrande S., Mandarino A., Azzoni R.S., Forti L., Faccini F., Pelfini M., Brandolini P., *Cartografia geomorfologica e tracce dell'impronta antropica lungo la costa rocciosa del Golfo del Tigullio (Liguria orientale, Italia).* (IT ISSN 0391-9838, 2025). Questo lavoro descrive la geomorfologia del tratto costiero compreso tra Zoagli e Chiavari e presenta la relativa carta geomorfologica in scala 1:5000. L'area di studio, una spettacolare costa rocciosa affacciata sul Mar Ligure, è stata fortemente influenzata dai processi di morfogenesi antropica. Si tratta di un settore storicamente soggetto a fenomeni franosi e caratterizzato da: (i) un assetto geologico che condiziona in modo marcato l'evoluzione geomorfologica, (ii) piccoli fondovalle completamente artificializzati, (iii) versanti quasi interamente terrazzati e (iv) un reticolo idrografico ampiamente modificato attraverso canalizzazioni e tombinature. A differenza di molte altre aree del mondo in cui i terrazzamenti agricoli sono stati abbandonati nel corso dell'ultimo secolo, qui essi hanno in parte mantenuto la loro funzione agricola e in parte sono stati trasformati dall'espansione urbana, in particolare tra gli anni Sessanta e Settanta del Novecento. L'urbanizzazione ha comportato la realizzazione di grandi insediamenti e di edifici sparsi associati a infrastrutture residenziali e turistiche che, in alcuni casi, si estendono fino al ciglio della falesia e talvolta oltre lo stesso. Questo assetto territoriale, combinato con l'elevata energia del rilievo e la diffusa presenza di infrastrutture e manufatti rende l'area altamente esposta a pericolosità geoidrologiche, quali frane, alluvioni improvvise e mareggiate. La carta geomorfologica è stata realizzata attraverso la raccolta e l'analisi di dati d'archivio, rilievi geomorfologici sul terreno e tecniche di indagine indiretta basate sulla fotointerpretazione di fotografie aeree, ortofoto e immagini satellitari, nonché sull'analisi di modelli digitali del terreno, il tutto elaborato in ambiente GIS. I risultati di questa ricerca contribuiscono a migliorare la comprensione dei processi geomorfologici, a rafforzare la consapevolezza pubblica nei confronti del rischio e a fornire una base solida per la gestione sostenibile del territorio e per la pianificazione di strategie di adattamento.

Termini chiave: Cartografia geomorfologica, Forme antropiche, Versanti terrazzati, Variazione di uso del suolo, Instabilità dei versanti costieri, Mar Mediterraneo.

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INTRODUCTION

Human activities have affected geomorphic processes across all climatic contexts for millennia, resulting in landforms directly or indirectly shaped by anthropogenic processes (Brown *et al.*, 2017; Steffen *et al.*, 2007). Along coastal areas, where population is densely concentrated, anthropic activity has significant impact on natural resources (Ferrer-Valero *et al.* 2017). As a result, geomorphological processes have undergone severe alterations and landforms have been modified or have completely disappeared (Del Monte, 2017; Reynard *et al.* 2017; Faccini *et al.*, 2021; Forti *et al.*, 2023). These landscape changes have often increased geohazard levels and vulnerability, leading to higher geo-hydrological risks (Polemio *et al.*, 1999; Morelli *et al.*, 2024; Mandarino *et al.*, 2023). These dynamics have also involved sites of geomorphological, geocultural and touristic interests, posing serious challenges for their conservation (Brandolini *et al.*, 2011; Coratza *et al.*, 2021). Understanding Earth surface processes and landforms through geomorphological maps is essential under a land management perspective, namely, to support the development of risk mitigation and environment recovery measures (Bishop *et al.*, 2012; Dramis *et al.*, 2011). Geomorphological mapping enables the reconstruction of the recent evolution of a landscape and the processes that have shaped it, including anthropogenic processes (Forti *et al.*, 2022; Kamal and Midorikawa, 2004; Pica *et al.*, 2024; Prampolini *et al.*, 2017; Wierzbicki *et al.*, 2021). Furthermore, geomorphological maps represent an effective tool for assessing human impact on landforms (Latocha, 2009). However, the urban environment poses relevant challenges in geomorphological mapping, as landforms are severely modified and often largely buried (e.g., Mandarino *et al.*, 2021). Thus, specific approaches and methodologies based on fieldwork, remote sensing, engineering-geological investigations, and historical data analysis are required to overcome the challenges (Mohapatra *et al.*, 2014; Nicu, 2017; Perez-Hernández *et al.*, 2020). The evolution of rocky coasts is driven by the action of subaerial, biological and marine processes (Trenhaile, 2016; Pappalardo *et al.*, 2016; Rovere *et al.*, 2025). Major hazards related to coastal slopes are associated with two main geomorphological processes: mass movements and sea cliff retreat induced by gravity and wave action undercuts, respectively (Marques, 2008; Budetta, 2011).

In this context, we examined the Tigullio Gulf, in the eastern Liguria (Mediterranean Sea, NW Italy), focusing on the rocky coastal stretch 6 km long located between Zoagli and Chiavari (fig. 1a). This area is included within the proposed borders of the Portofino National Park and the Natura 2000 European Network, presenting remarkable geological and ecological heritage both on land and at sea (Ferrari *et al.*, 2025). It is characterized by steep coastal slopes bordered by sea cliffs interspersed by small fluvial valleys (fig. 1b). Agricultural terraces dominated the landscape for centuries. Since the 20th century, and especially after the 1960s, a urbanization process, known worldwide as "rapallizzazione" from the name of the city of Rapallo (fig. 1a) due to its widespread and scattered nature, has led to the encroachment of formerly natural environments, such as cliffs, beaches, and river mouths, increasing geomorphological hazard and risk scenarios, which are most likely further exacerbated by climate change (Acquaotta *et al.*, 2019; Brandolini *et al.*, 2021; fig. 1c). Thus, this is a scenic and meaningful example of a terraced coastal landscape that, rather than being abandoned, as commonly reported in previous studies (Mineo *et al.*, 2024; Pepe *et al.*, 2019), has partially maintained its agricultural function and has been partially transformed by urban expansion. The Tigullio Gulf was already investigated in some studies on geomorphology and geo-hydrological hazard focused on specific areas along the coast (Brandolini *et al.*, 2009), the Portofino area (Paliaga *et al.*, 2023, and references therein) and the cities of Rapallo (Brandolini *et al.*, 2021, and references therein) and Chiavari (Roccati *et al.*, 2021, and references therein). However, an overall assessment of the geomorphological features characterizing the whole rocky coastal stretch is still absent.

From this perspective, the research goal is to provide a geomorphological map of a highly sensitive morpho-climatic coastal environment with the aim of (i) defining and describing its landforms, (ii) improving the understanding of its geomorphological setting, and (iii) assessing both the evident and potential interactions between natural and anthropogenic processes. Thus, the output map at 1:5.000 scale aims to offer a fundamental knowledge base for further geomorphological research in the area and, within the frame of land planning and management, for future hazard assessment and zonation procedures, as well as for the development of effective strategies for geoheritage promotion and conservation.

STUDY AREA

The coastal stretch between Zoagli and Chiavari lies in the central part of the Tigullio Gulf within the Ligurian Sea (fig. 1). This physiographic unit, enclosed between the promontories of Sestri Levante, to the east, and Portofino, to the west, is predominantly bordered by steep, south-facing slopes (Regione Liguria, 2002a, 2002b). This research focuses on the area approximatively located slightly below sea level and up to 300-400 m a.s.l., which spread approximately over 6 km^2.

The geological setting is dominated by the Monte Antola Formation of Cretaceous-Paleocene age, which extends along all the coast between Chiavari and Genova (Giammarino *et al.*, 2002; Marroni *et al.*, 1992). It is a flysch mainly featured by marly limestone layers up to 2-3 m in thickness, interbedded with blackish grey shale, sometimes combined with clayey-arenaceous schist, generally occurring as thin layers 20-30 cm thick and occasionally as millimetric intercalations (Marini, 1981). These rocks are

Figure 1 - (a) Location of the study area (base map: DEM (Table 1)); (b) Google imagery of the coastal area between Zoagli and Chiavari; (c) Aerial view of the rocky coast between Chiavari and Zoagli; (d) Aerial view of the coastal sector of Marina di Bardi pocket beach (blue arrow) and the Castellaro cliff (pink arrows), fed by a minor watercourse; (e) Zoagli urban settlement and the railway infrastructure with the San Pietro agricultural terraced slope (orange arrows) and coastal slope (pink arrows) in the background. White arrows in b and c indicate the principal sites mentioned in the text. Photos by Liguria Region (c, d) and S. Pietrogrande (e).

affected by complex, polyphase brittle-ductile deformation events, resulting in fold structures at various scales, namely, from cleavage to metric size (Corsi *et al.*, 2001). Overall, the area is structurally conditioned by the presence of an anticline with a WNW- ESE trending axis, producing predominantly dip-slope stratification (Cortemiglia and Terranova, 1979). Bedding planes typically have dip between 55° and 65°, with azimuths ranging from 240° to 260° N. These structural characteristics strongly influence slope morphology and stability. The coastline itself is structurally aligned along fault-related escarpments trending WNW- ESE, which belong to a major system of tectonic lineaments parallel to the coast (fig. 2). A secondary system of NE-SW faults has conditioned the development of the drainage network (Fanucci and Nosengo, 1979; Fanucci *et al.*, 1980; Morelli *et al.*, 2022). This tectonic framework defines an extensive macro-fracturing of the rock mass, with frequent and persistent discontinuities isolating rock prisms of varying volumes, namely, from decimetric to metric size. These conditions contribute to widespread slope instability along the steep coastal slopes as revealed by previous geomechanical analyses (Brandolini *et al.*, 2009).

The climate of the area is typically Mediterranean, with an annual mean precipitation of 1150 mm and an average annual temperature slightly above 15°C. Summer temperatures (July - August) generally peak just below 25°C, while winter lows (December and January) average around 10°C. Prevailing winds blow from the south east (Scirocco), whereas the strongest winds originate from the southwest ("Libeccio" auct.), generating strong waves approaching the foot of the cliff. Strong south-westerly sea storms are characterized by wave trains up to 120 m in length, wave heights exceeding 5 m, and a wind speed reaching up to 30 knots (15.4 m/s), producing high-energy impacts on the rocky shoreline (ARPAL, 2024).

This area has long supported human settlement through maritime and harbour activities. Furthermore, the aforementioned mild climate fostered agricultural development on terraced slopes sustained by dry-stone walls over the last centuries and touristic settlements expansion after 1960s. Thus, agricultural activities initially, followed by urbanization, extensively transformed the landscape. Today urban settlements are surrounded by terraced slopes, which are partially cultivated with olive trees, and gradually blend into semi-natural reforested areas in the upper part of slopes (approximately at 350 m a.s.l.). Some of the main mass movements have historically and recently affected facilities and infrastructures. Similarly, flash floods and storm surges have severely hit the main valley floors and the shoreline.

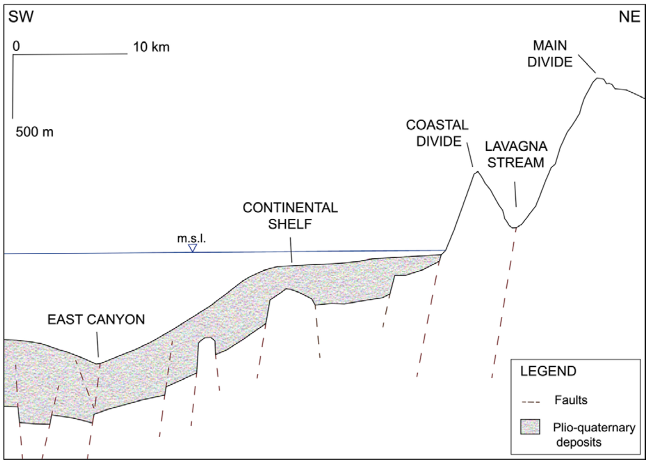

Figure 2 - Representative geological section showing the tectonic framework that conditions the overall coastal and inland settings (modified after Fanucci and Nosengo, 1978); m.s.l.: mean sea level.

MATERIALS AND METHODS

This research is based on geomorphological mapping. It was carried out using a consolidated methodology that integrates (i) remote sensing techniques, (ii) historical data collection and review, and (iii) field surveys for dataset acquisition and analysis (e.g., Azzoni *et al.*, 2017; Forti *et al.*, 2021). This approach allows for the analysis of geomorphological changes over time and, specifically, the interaction between (i) landforms and geomorphological processes and (ii) anthropogenic interventions. The geomorphological map of the investigated area was produced by using QGIS (QGIS.org, 2025).

Various spatial datasets, including aerial photographs, recent and historical maps, and digital terrain models (table 1), spanning the period 1936-2019, were collected from regional and national databases and imported in a GIS environment. DEM-based terrain analysis resulting in the definition of elevation, hillshade, and slope maps, along with 5-m interval contour lines was performed. The comparison and analysis of the aforementioned data, combined with the geomorphological data from previous studies (Brandolini *et al.*, 2009; Cortemiglia and Terranova, 1974; De Vita *et al.*, 2012) and field evidence from original surveys, allowed for the identification, interpretation and mapping of landforms.

The design of the geomorphological map followed the guidelines of the Italian Geomorphological Map (Campobasso *et al.*, 2018, 2021), developed by the Italian Institute for Environmental Protection and Research (ISPRA) along with the Italian Association of Physical Geography and Geomorphology (AIGeo), with some modifications in legend entries and symbols to better represent the anthropogenic features and the local setting. Five categories of landforms were hence distinguished according to genesis: (i) structural landforms, (ii) fluvial and runoff landforms, (iii) gravitational landforms, (iv) coastal landforms, and (v) anthropogenic landforms. Given the local geomorphological setting dominated by agricultural terraces, the analysis focused on the identification and mapping of terraced slopes based on DTM analysis and aerial imagery interpretation. Following the approach adopted in previous research (Cevasco *et al.*, 2012; 2013; Pepe *et al.*, 2019; Raso *et al.*, 2021), terraced areas were classified into three specific categories based on their current land use and land cover (LULC): (i) urbanized terraced area, (ii) cultivated terraced area, and (iii) terraced area covered by woods and shrubs. The present-day LULC was defined based on the LR LULC data dated back to 2024, aerial imagery interpretation, and field surveys. Data referred to the submerged sector of the study area were retrieved from the "Coastal-marine environment protection plan" (Regione Liguria, 2012). Information on bedrock lithology, bedding, and structural elements are from the geological map of the Recco - Chiavari area (Balbi *et al.*, 2005) and the LR geodatabase (https://geoportal.regione.liguria.it/). These elements were depicted in the geomorphological map and summarized in the geological

Table - 1 Summary of data sources considered in this research. Data marked with (i) * are freely-available from LR geoportal, (ii) ** are freely-available from the MATTM geoportal, and (iii) *** are freely-available from the INGV website (Tarquini *et al.*, 2007, 2023). IGMI: Italian Military Geographic Institute; INGV: National Institute of Geophysics and Volcanology; LR: Liguria Region; MATTM: Ministry for Environment, Land and Sea Protection of Italy; QMS: Quick Map Services QGIS Plugin (Plugin source: https://nextg is.com/blog/quickmapservices/). The scale referred to the Google Satellite Imagery represents the interval of visualization.

Data type	Year	Scale/Spatial resolution (m)	Source
Historical Map	1816-1827	1:9450	IGMI
Historical Map	1904	1:25000	IGMI
Historical Map	1936	1:25000	IGMI
Topographic map*	1977-1982	1:10000	LR
Topographic map*	1990-2006	1:5000	LR
Topographic map*	1994	1:25000	LR
Topographic map*	2007-2013	1:5000	LR
Topographic map*	2013	1:25000	LR
Aerial photo	1936	1:20000	IGMI
Aerial photo*	1973-1974	1:13000	LR
Orthophoto*	1986	1:10000	LR
Orthophoto*	2007	1:10000	LR
Orthophoto*	2016	1:10000	LR
Orthophoto*	2019	1:5000	LR
Google imagery	2023	1:1000-1:5000	QMS
DSM**	2008	1	MATTM
DEM (bathymetry)	2019	1	LR
DEM*	2023	5	LR
DEM***	2023	10	INGV

framework. The base layers illustrated in the map include vector data from the aforementioned LR geodatabase (https://geoportal.regione.liguria.it/) such as river, road, and rail networks, and building footprints.

Four geomorphological cross sections were outlined aiming to further illustrate the geomorphological setting of the investigated area. The LULC inset map shows the aforementioned regional data dated back to 2024, which were reclassified in nine classes according to the Corine Land Cover scheme (Copernicus Land Monitoring Service, 2019) to emphasise the contrast between anthropogenic and natural land use. Artificial areas include (i) discontinuous and (ii) continuous urban fabric, (iii) major road and railway networks, (iv) non-agricultural and artificial vegetated areas (i.e., green urban areas, sport and leisure facilities), and (v) agricultural areas. Natural and seminatural areas include (vi) seminatural forests (i.e., areas covered by shrubs and forest tree species), (vii) shore area (i.e., beaches and coastal protections), (viii) bare rock and (ix) watercourses. Moreover, the main fluvial stems were displayed in the land use map classifying them into culverted and non-culverted riverbed.

RESULTS

The geomorphological map attached to the present paper highlights the complex interplay between natural processes and landforms, on the one hand, and human activity, on the other hand, which characterizes the landscape of the study area. As depicted in fig. 3, most of the study area is cultivated (2.8 km^2). The areas covered by shrubs and forest tree species spread over 1.9 km^2, and the urban fabric class covers 0.7 km^2. The remaining 8% consists of road and railway network (0.2 km^2) and the other land use categories, each with an individual extent not exceeding 0.1 km^2.

The entire coastal sector exhibits active geomorphic processes essentially induced by gravity, wave action, running waters and human activities. Coastal morphology is mainly controlled by a NW-SE oriented anticlinal tectonic axis, which induces a prevalent dip toward the sea (fig. 4a). This tectonic setting results in a predominantly rocky coastline characterized by steep coastal slopes drained by short and low order streams and bordered by sea cliffs interspersed by very small fluvial coastal plain.

Structural landforms

The coastline and the drainage network appear to be structurally aligned along two main tectonic lineaments (faults and fractures) WNW-ESE and NE-SW oriented, which belong to major systems parallel and orthogonal to the coast, observable both inland and at sea (Fanucci and Nosengo, 1979; Fanucci *et al.*, 1980). High-angle intersections of these lineaments promote coastal retreat, resulting in the formation of triangular facets, notably along the cliffs of Castellaro and San Pietro in Rovereto (fig. 4b).

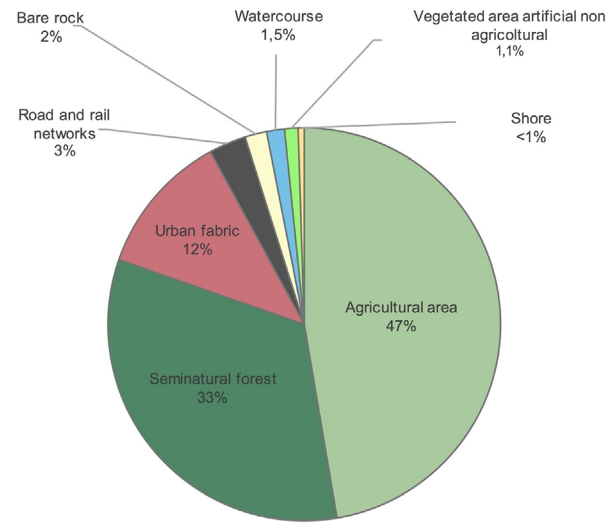

Figure 3 - Pie chart depicting the percentages of each land use class within the study area, with urban fabric including discontinuous and continuous urban fabric.

Fluvial and runoff landforms

The overall geomorphological setting of the study area highlights a clear prevalence of fluvial and surface-runoff-related landforms shaped by erosional processes. The study area mainly consists of very small catchments, typically a few tens of hectares in size, with the exception of the Semorile catchment, which covers 3.8 km^2. They are drained by steep and low-order streams, generally a few hundred meter long, with and overall orientation roughly perpendicular to the coastline (fig. 5a). These streams incise shallow eluvial and colluvial deposits on steep slopes and are largely characterized by bedrock channels. Furthermore, they exhibit an ephemeral flow regime that is closely controlled by rainfall events. The streams typically flow through V-shaped valleys, many of which are hanging valleys, with knickpoints near their mouths ranging from a few metres (e.g., beneath Zoagli railway station) to several tens of metres in height (e.g., close to San Pietro cliff) (fig. 5b). The lower part of the Semorile catchment hosts the most extensive alluvial deposits in the study area, forming a small alluvial plain that has been significantly altered by the urban development of Zoagli.

Slopes are predominantly mantled by eluvial-colluvial deposits, generally ranging from a few cm to 2 m in thickness, and rarely up to 3 m. Over the past centuries, these deposits have been extensively reworked by local people to create narrow agricultural terraces, supported by dry-stone retaining walls (figs 5a and 5c).

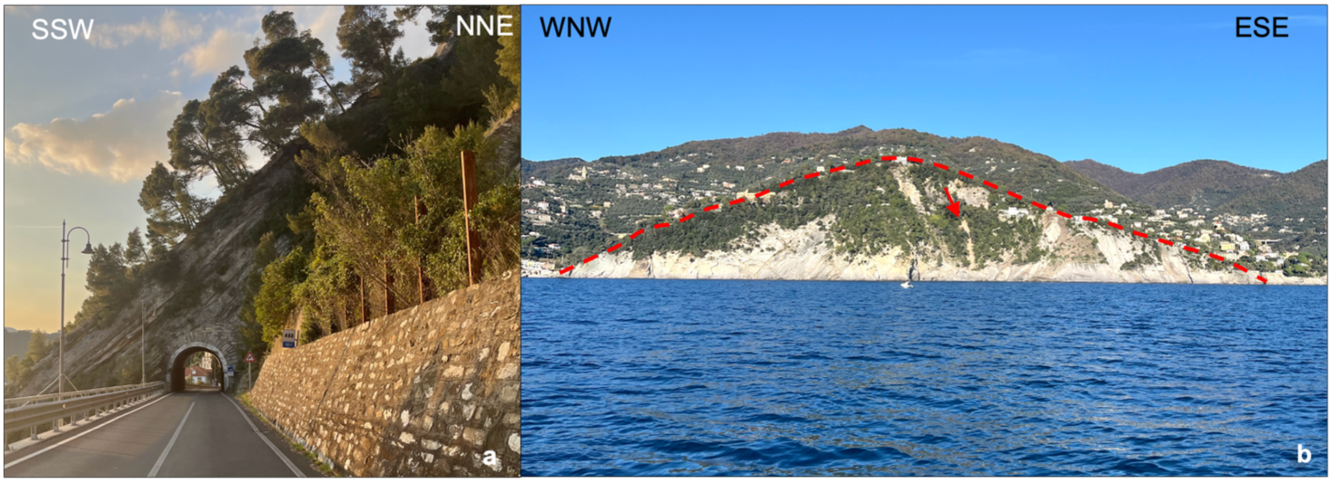

Figure 4 - (a) View from the Aurelia Road showing the tunnel excavated into the flysch strata dipping toward the sea; rockfall protection measures, including fences and nets, are visible along the roadside. (b) Triangular facet (red dashed line) with active landslide scarps and ancient quarry scarps at Castellaro cliff. A recent shallow landslide (red arrow) occurred in October 2024 and affecting former landslide deposits, is observable. Photos by P. Brandolini.

Figure 5 - (a) A typical V-shaped valley of the study area with slopes presenting agricultural terraces and scattered buildings, close to San Pietro di Rovereto hamlet; the red box indicates photo (b). (b) Example of hanging valley (red arrow); this is located at the outlet of the Rio Piscia V-shaped valley. (c) Overview of the agricultural terraced slopes, mainly presenting olive groves, around Zoagli hamlet. Photos by P. Brandolini.

Gravitational landforms

Widespread gravitational processes affect both the coastal slopes and the entire sea cliffs revealing their major role in landscape modelling. Landslides cover the 7.8% of the study area, corresponding to an overall extent of 0.45 km^2. The presence of (i) steeply dipping bedding planes toward the sea, all over the study area (fig. 4a), together with (ii) adversely oriented mass discontinuities affecting the flysch, (iii) sea wave undercutting, (iv) heavy rainfall episodes, and (vi) human-related interventions were identified as the causal factors of mass movement. These factors trigger i) large sliding gravitational movements, mostly translational, observable in particular at Castellaro and San Pietro hillslopes; ii) complex landslides including falls, topple and translational movements, as in the case of Liggia and Madonna delle Grazie (fig. 6a); iii) shallow landslides (soil slip) largely affecting former landslide deposits (fig. 6b); iv) debris and mud flow derived from the aforementioned shallow landslides. In numerous cases referred to i) and ii), mass movements affect both the subaerial and submerged portions of the slope, reaching depths of approximately 5-10 m. As for the state of activity of the major landslides, Brandolini *et al.* (2009) documented a cyclical pattern of alternating active and dormant phases.

The large area, located approximately between Liggia, to the west, and Mt. Bacezza, to the east, including the entire slope system from the sea level to the ridge, shows several geomorphological evidence linked to a deep-seated gravitational slope deformation (DSGSD) (fig. 6a). In fact, a significant counter slope close to the divide, which is well-evident on the geomorphological cross section DD' depicted in the geomorphological map (supplementary material), and deep fractures on which natural cavities were set, such as the two caves at 120-150 m a.s.l. (Delegazione Speleologica Ligure, 2025), were recognized. In addition, the presence of bulging morphologies at the slope toe in a context characterized by large coastal landslides, supports this interpretation.

Coastal landforms

The overall linear stretch of the coast under investigation presents at a major scale a continuous sequence of very small headlands and bays which makes it rather jagged. Almost the entire coastline is characterized by the presence of an active sea cliff, with elevations ranging from 5 to 50 m (figs 4b, 5 and 7). Cliff retreating is driven by sea wave undercutting along the above-mentioned structural weaknesses of the rock masses, where some sea caves and notches can be found. The cliff instability is also favoured by the contribution of selective erosion phenomena in the heterogeneous flysch lithology, causing recurring gravitational failures, mainly of translational and rockfall type (e.g. Castellaro, San Pietro in Rovereto and Tigullio Rocks). Moreover, sea stacks and submerged remnants of the cliff at sea (submerged stacks) testify the ongoing retreat. The continuity of the rocky coastline is just interrupted at the hamlets of Zoagli and Marina di Bardi by the presence of two very small beaches fed by alluvial coarse deposits of the Semorile and Bardi streams, respectively. Moreover, a small beach is also present at the foot of the slope affected by the Liggia landslide (fig. 6b); this is fed by the periodic reactivation of the landslide following high-intensity rainfall events. At the eastern boundary of the study area, where the high rocky coast terminates, lies the westernmost portion of the fluvial-coastal plain of the Entella Stream, upon which the city of Chiavari has developed.

Along the sea cliffs, some interbedded caves were mapped, formed through the combined action of gravitational and marine processes. These include haloclastism, locally enhanced by bioclastism, and the mechanical impact of wave action, which fracture the rock along pre-existing joints and promotes differential erosion of the schistose layers. Presumed marine terraces were identified according to morphological evidence at Castellaro (170-180 m a.s.l), Sant'Ambrogio (130 m) and close to the

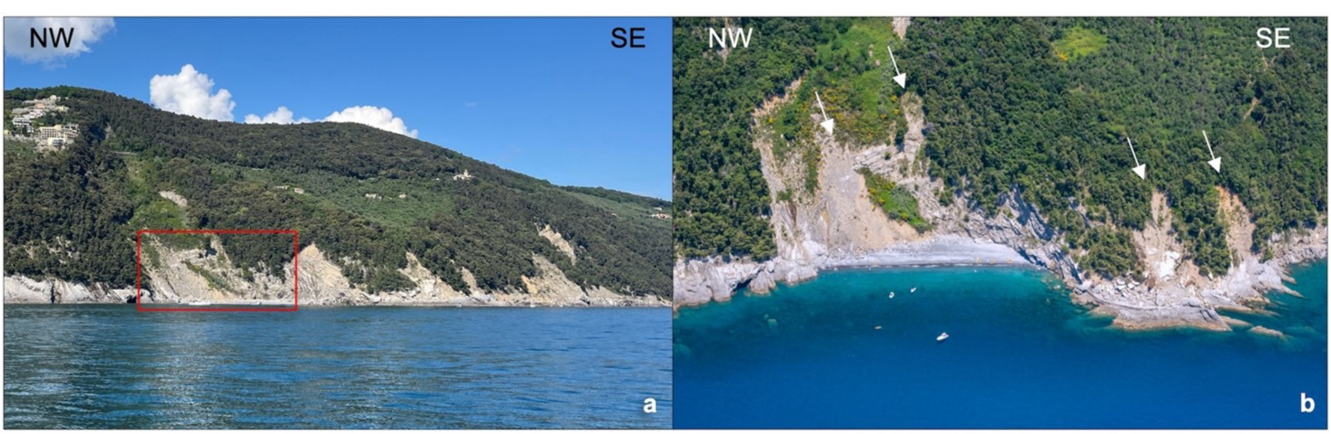

Figure 6 - The large area affected by DSGSD and presenting complex landslides including falls, topple and translational movements, at Le Grazie and Liggia coastal slope. The red box in (a) represents the location of (b). In (b) the Liggia landslide is depicted; the white arrows highlight the shallow landslides that have recently affected the overall ancient landslide deposit causing the formation of a beach at the slope toe. Photos by P. Brandolini (a), and Liguria Region (b).

Figure 7 - Typical coastal slope and cliff clearly showing flysch strata dipping toward the sea and affected by urbanization in the 1970s. In the Tigullio Rock (a) and San Pietro in Rovereto (b) areas touristic settlement were built down to the coastal slope up to the sea cliff edge. Furthermore, bathing settlements were built along and at the base of the sea cliff together with a cable car to reach them (a). Photos by P. Brandolini.

Tigullio Rock (105 m). However, the origin of these sub-flat surfaces located along the divide remains debated, and significant dislocation related to tectonic activity cannot be ruled out (Fanucci and Nosengo, 1979).

Nearshore deposits include (i) submerged landslide deposits, presenting metric to decametric blocks, located at the submerged slope toe of the major mass movements affecting the investigated coastal stretch at 5-10 m in depth, and (ii) coarse deposits constituting submerged beaches, approximately up to 5-7 m in depth. A seaward fining trend in grain size is observed, with sands prevailing up to 20 m depth and silts becoming dominant at depths greater than 20 m. Moreover, extensive areas of seagrass meadows are present west of San Pietro in Rovereto, interspersed with localized patches of dead seagrass matte (Regione Liguria, 2012; Robello *et al.*, 2024).

Anthropogenic landforms

Anthropogenic landforms are widespread along the investigated coastal area. Man-made terraced slopes with retaining dry-stone walls cover 64.6% (3.75 km^2) of the study area, constituting its main morphological element (fig. 8). Although historically used for agricultural purposes, the terraced slopes are now partially urbanized, exhibiting a discontinuous urban fabric over approximately 17% (0.63 km^2) of their extent (fig. 9a). The remaining terraced areas are cultivated for 71% (2.6 km^2), while about 12% (0.46 km^2) are covered by woodland and shrub vegetation. The former are primarily characterized by olive, and secondarily by vineyards and citrus groves; the latter can be assumed as abandoned since years or decades (Pappalardo, 2002; Raso *et al.*, 2021).

Extensive parts of the V-shaped valleys were modified through slope terracing (fig. 8), which established a new anthropogenic slope profile. Furthermore, local farmers constructed numerous channelization structures along streams together with a dense secondary drainage network connected to the main one. In addition, the downstream-most reaches of the main streams were channelized and culverted, especially near infrastructures and in urban areas (fig. 9b). The Semorile stream, for instance, is culverted for about 200 m beneath Zoagli (fig. 9c), and presents a concrete riverbed upstream of the culverted reach.

The coastal slopes host residential and tourist settlements (fig. 7), roads, and the railway line, which were often built through excavation and embankment. Furthermore, a few inactive quarries are located within the study area (fig. 9d). In the last decades several geo-hydrological risk mitigation works were built such as longshore defences, breakwaters groynes, slope stabilization nets and rockfall barriers.

DISCUSSION

The geomorphological map attached to the present paper highlights the landforms and processes characterizing the rocky coast in the Tigullio Gulf. Its development allowed to reconstruct both the historical and recent morphological evolution of the coastal sector between Zoagli and Chiavari, with particular emphasis on anthropogenic landforms and the geomorphological impact of human interventions on the landscape.

The landscape is controlled by tectonics and lithology, with two main lineaments: a WNW-ESE lineament, aligned along the coast and the main backward valleys, and a high-angle NNE-SSW lineament, along which the secondary valleys are oriented. The triangular facets, marked by landslide escarpments, manifest the rocky coastline retreat. This reflects the differential tectonic regime reported by seismic reflection studies of Fanucci and Nosengo (1979), with relative uplift of the emerged sector and subsidence of the submerged sector. Furthermore, the area presents multiple examples of selective sea-wave erosion driven by the various thickness, resistance, and dip direction of individual flysch strata, which has led to the formation of interbedded sea caves.

The study area has historically been known for its high susceptibility to slope instability processes, and mass movements are still widely distributed. Steep coastal slopes are bordered by sea cliffs generally extending up to approximately 50 m a.s.l. The geological and structural setting plays a key role in predisposing the study area to gravitational phenomena. In fact, coastal landslides initiation and evolution is severely conditioned by the intersection angle between flysch strata and the shoreline. Rock sliding prevails in case of dip direction of the strata perpendicular to the coastline with bedding planes inclined towards the sea. In contrast, more complex landslide mechanisms occur when the dip direction is oblique to the coastline (De Vita *et al.*, 2012). Wave action, further enhanced by the coastline's exposure to south-westerly winds (i.e., "Libeccio" auct.), causes sea cliff undercutting, leading to their retreat and potentially triggering additional regressive gravitational processes on the slope (e.g., rockfalls from steep cliffs and slope failures in colluvial deposits). These dynamics somewhere result in the erasure of the cliff edge, which is no more clearly recognizable along retreating cliffs that blend upwards into an unstable coastal slope. This combination of geomorphic processes has shaped high denudational scarps locally up to 170 m a.s.l. In addition, the evolution of the coastal slopes has been strongly impacted by historical quarrying activity mainly performed in the first decades of the 20th century for building construction. After exploitation the areas remained largely unstable and were affected by gravity-induced processes. The quarrying impact is clearly documented at the Castellaro cliff (fig. 10), where the shift of the Aurelia Road from the cliff edge to a newly-built tunnel allowed the quarrying activity to begin. Fig. 10a highlights the large volume of quarry-related and naturally-formed debris along the slope and at the slope toe along the shoreline. This setting resulted in a debris cone extending into the sea, which formed a beach currently totally removed by the sea.

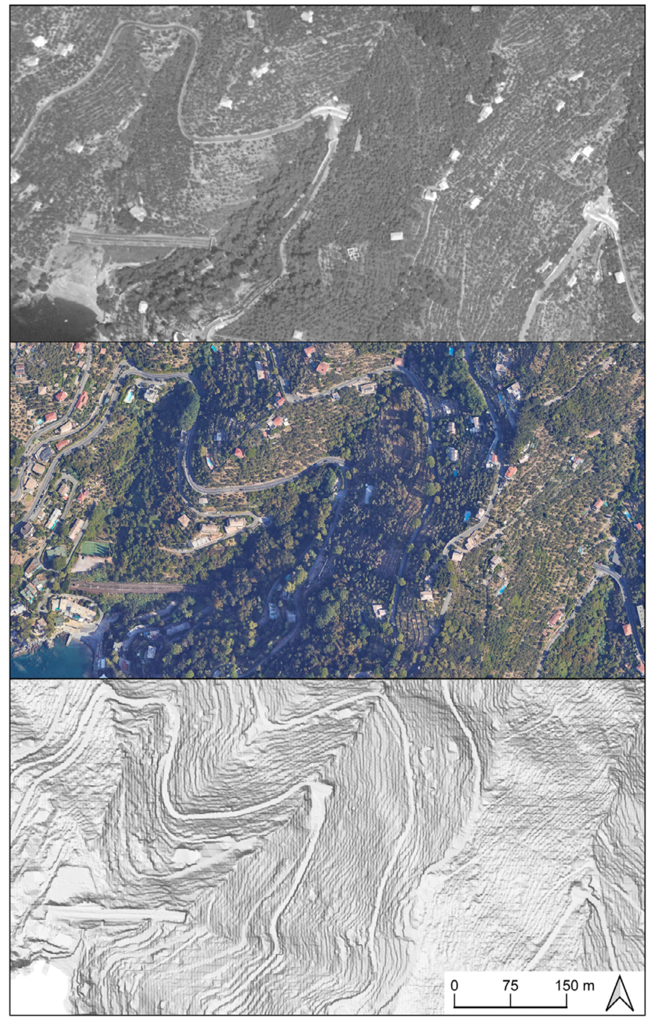

Figure 8 - A typical v-shaped valley affected by agricultural terracing of the slopes between Marina di Bardi and Castellaro in (a) 1936 and (b) 2019. The hillshade map (c) derived from the 2023 DEM (table 1) highlights the spatial distribution of terraces. Scale bar and north arrow in (c) are also referred to (a) and (b).

As illustrated in fig. 11a, in the early 19th century Zoagli was a small settlement located along the Semorile Stream, while the surrounding slopes were extensively terraced for agricultural purposes. The construction of terraces profoundly modified the original slope morphology, altering pre-existing geomorphological processes and requiring continuous maintenance to ensure slope stability (Brandolini *et al.*, 2015). From the early 20th century onwards, the area experienced progressive urban expansion, reaching its maximum extent during the 1960s and 1970s (fig. 11). To accommodate urban growth, the Semorile Stream was culverted within the urban sector, and former cultivated terraces were progressively occupied by scattered and discontinuous buildings (figs 9a and 11). These land-use changes and anthropogenic transformations reduced the effectiveness of traditional dry-stone retaining walls and increased the overall exposure to geomorphological hazards by pro-

Figure 9 - Anthropogenic landforms. (a) Urban landscape of Zoagli on the coast and the partially-urbanized terraces exhibiting a discontinuous urban fabric along the hillslopes; (b) the mouth of a small culverted stream; (c) the mouth of the Semorile Stream, downstream of the culverted reach beneath the Zoagli town centre; (d) the Castellaro ancient quarry scarp with protection structures. Photos by P. Brandolini (a, c, and d) and by S. Pietrogrande (b).

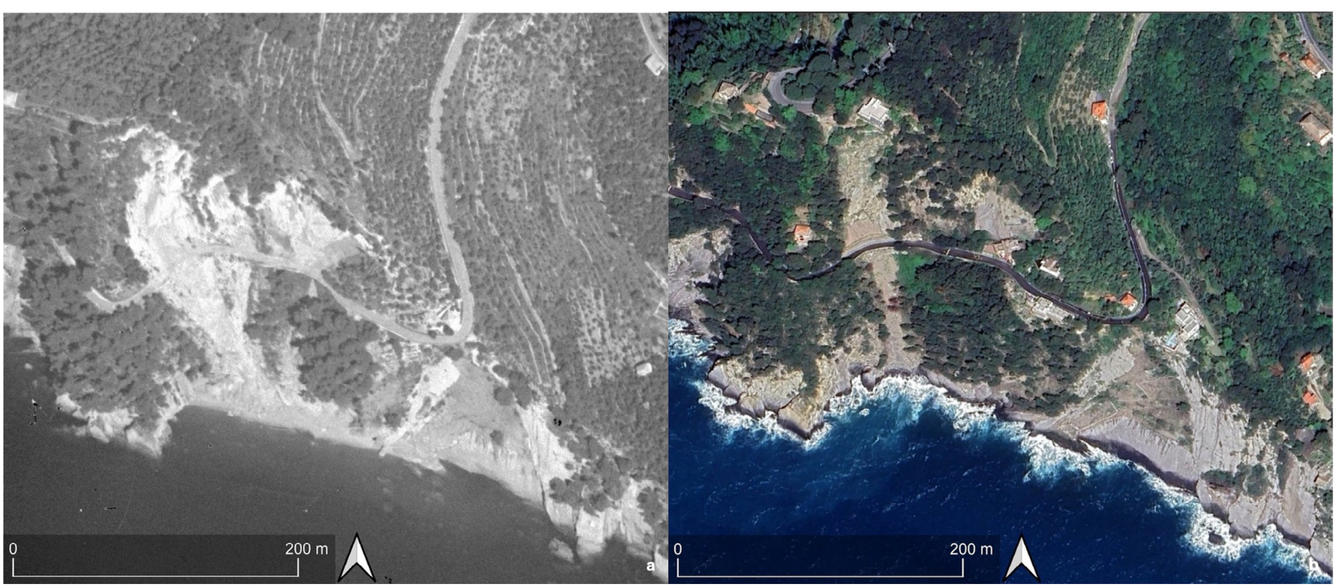

Figure 10 - Castellaro cliff: (a) 1936 Aerial photo; (b) 2023 google imagery. The large active scarps and debris cone on the slope and at the slope toe depicted in (a) are due to quarrying activity. After quarrying, namely, in the last decades, the slope evolution characterized by severe gravitational processes, erased the former anthropogenic imprint (b).

moting construction within zones prone to slope instability and alluvial processes. Today, large portions of the terraced slopes, historically used exclusively for agricultural purposes, are characterized by isolated buildings embedded within cultivated terraces or residential gardens (fig. 12). Urbanization has also been demonstrated through the construction of large tourist-residential complexes, which in some cases extend as far as the edge of the sea cliff (figs 5 and 7). In some cases, beach facilities associated with the complexes were built both along the cliffs and at their toe, as in the Tigullio Rock area (fig. 7a). Similarly, the valley floor at Marina di Bardi underwent excavation and reshaping of the original V-shaped profile, to accommodate tourist infrastructures.

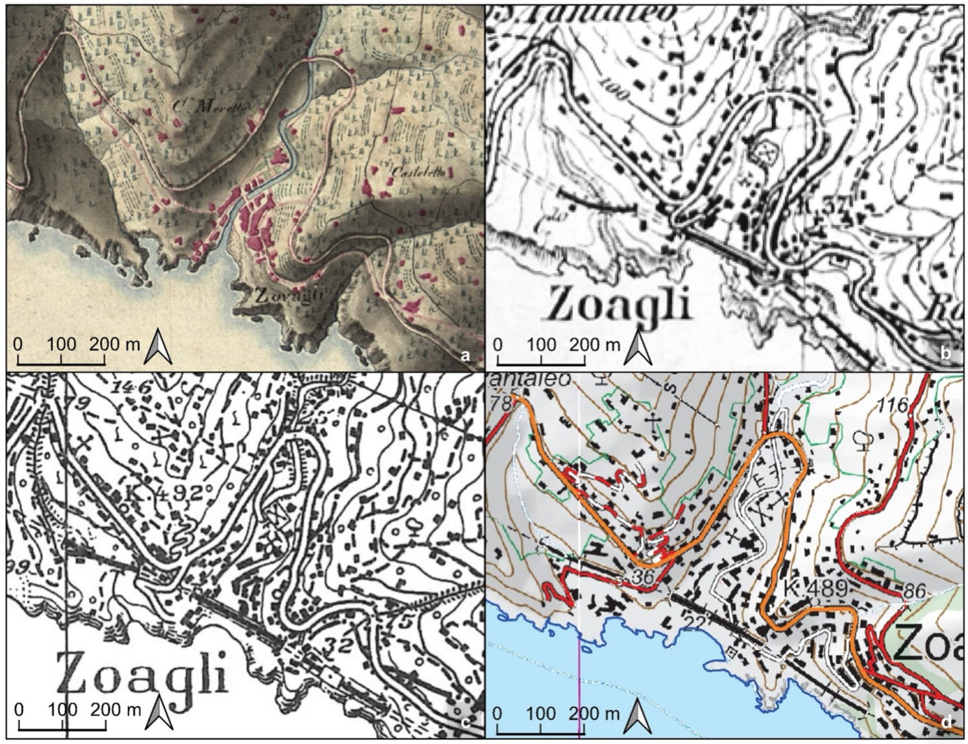

Figure 11 - Multitemporal comparison of maps referred to the Zoagli hamlet: (a) 1816-27; (b) 1904; (c) 1936; (d) 2013. This sequence documents the urban expansion occurred during the last 200 years over the Semorile valley floor, the shoreline, and the slopes. This process is highlighted by the increase in polygons (red in a and black in b, c, and d) and sinuous lines (black-bordered with white or coloured filling) representing buildings and roads, respectively.

These landscape changes resulted in the channelization and culverting of major streams, such as the Semorile (fig. 9c). In addition, the urban expansion was accompanied by the development and extension of the road network. Streams and drainage channels crossing the road network constitute a highly critical point, as they are often designed as narrow culverts, which act as bottlenecks and lack sufficient capacity to convey water and sediment (fig. 9b). In this area, the railway, which was constructed in 1868 connecting Chiavari and Genoa, appears at Zoagli, where it crosses the Semorile stream via a bridge and at the Chiavari fluvio-coastal plain limit. Fig. 13 shows the bridge at the beginning of the 20th century and nowadays, clearly illustrating the significant accretion of the shoreline. The major beaches are currently subject to periodic nourishment and are protected by coastal defence structures.

The documented anthropogenic imprint on the geomorphological landscape, associated with urbanization, resulted in a high exposure of built assets, infrastructure, and essential services to geo-hydrological hazards. As consequence, it generated new geo-hydrological risk scenarios and exacerbated the existing hazardous conditions (Brandolini *et al.*, 2021; Mandarino *et al.*, 2023, 2024; Roccati *et al.*, 2021). Recent storm surges, such as in 2018 (ARPAL, 2018), highlighted the longstanding critical issues related to cliff instability, which is furtherly exacerbated by the exposed assets located near the shoreline. The cliff and adjacent coastal slopes represent an area of high geo-hydrological hazard. In the last decades, along coastal areas it has been observed a marked increase in risk of bathing due to the advent of mass tourism, particularly during the summer season (Ferrari *et al.*, 2019). For this reason, navigation, swimming near the cliff, and access to the small beaches at the foot of the coastal slope have been recently forbidden by local authorities. Likewise, high-intensity rainfall events that induce landslide reactivation, debris flows, and fluvial activity have revealed the inherent vulnerability of the landscape which is heavily burdened by infrastructure and facilities poorly adapted to withstand morphogenetic processes (Brandolini *et al.*, 2021). In the future, climate change is most likely intensifying these issues by increasing the frequency and magnitude of extreme meteo-hydrological events, potentially leading to floods and landslides, thereby amplifying hydrogeomorphological risks along the coast (Cramer *et al.*, 2018; Acquaotta *et al.*, 2019).

As for agricultural terraces, this area displays a morphological and land-use evolution over the last century that diverges notably from that observed in many other Italian areas. Typically, the abandonment of terraced slopes that occurred throughout the 20th century in Liguria (Pepe *et al.* 2019) and beyond (Cerdà, 1997; MacDonald *et al.*, 2000) has led to the expansion of areas dominated by spontaneous vegetation (Pescini *et al.*, 2025) and, during the initial decades following abandonment, to widespread slope instability phenomena (Cevasco *et al.*, 2012; Moreno-de-las-Heras *et al.*, 2019). In contrast, in the study area only 12% of the cultivated land around the 1950s has been abandoned. The development of residential and tourism-related infrastructure has resulted in a transformation of former agricultural land into a fragmented pattern of buildings inter-

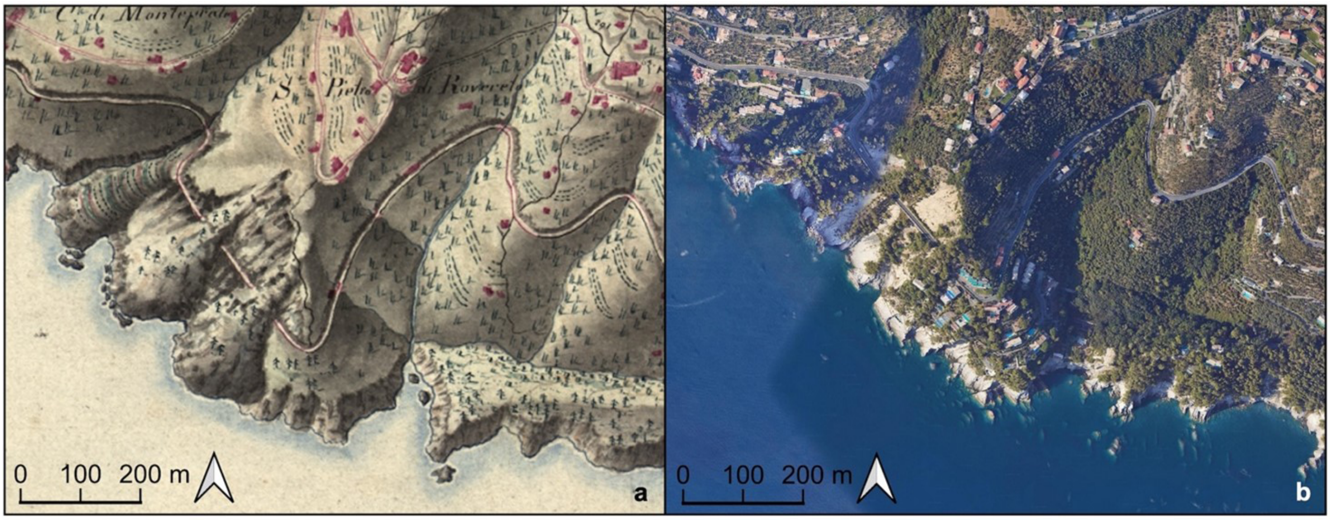

Figure 12 - San Pietro di Rovereto coastal slope in (a) 1816-27 and (b) 2019. The comparison highlights the significant land use change occurred in the last two centuries, from cultivated terraced slope with very few scattered buildings close to the San Pietro di Rovereto church (a) to the widespread scattered urbanization (b).

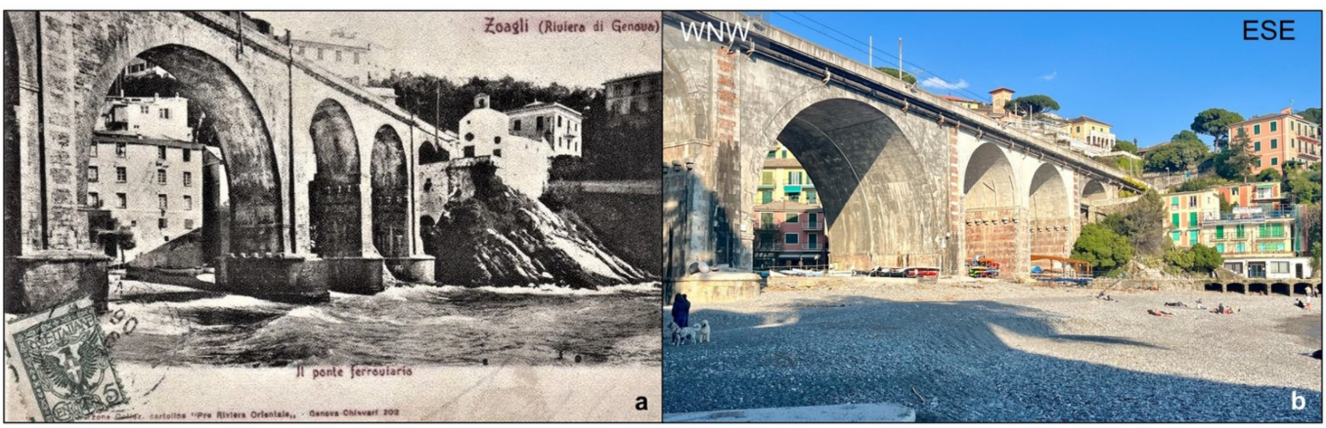

Figure 13 - The shoreline at Zoagli in the early 20th century (a) and today (b). The comparison shows the merked beach advancement essentially associated with seasonal nourishment carried out in the last decades. Images from ferrovie.it (a) and by P. Brandolini (b).

spersed with cultivated plots and gardens. This landscape transformation, along with a large conservation of agricultural areas, entail continuous maintenance of terraces over extensive areas (i.e., 88% of the terraced slopes). In many cases, these structures have been reconstructed either with the use of binder between the stones or entirely replaced with reinforced concrete, substantially altering the original material and structural characteristics of the dry-stone wall terracing system. Such modifications essentially define new anthropogenic works and generally reduce the permeability and drainage capacity of the structures, potentially triggering instability processes. However, the long-term geomorphological implications of these changes should be further investigated.

The identification of terraced slopes through remotely-sensed data, along with the challenges of conducting field surveys in the study area, characterized by both physical inaccessibility and restrictions related to property ownership, represented the main limitations of the analysis. The application of the guidelines of the Italian Geomorphological Map (Campobasso *et al.*, 2018, 2021) proved particularly effective in mapping the landforms characterizing the study area. However, the legend entries were integrated with a few specific elements to describe in detail the local context, especially with reference to terraced areas.

CONCLUSIONS

Geomorphological maps represent the landforms of a territory, emphasizing the local geomorphological processes, peculiarities, and evolution (Bosino *et al.*, 2024). The geomorphological map at 1:5.000 scale of the rocky coast between Zoagli and Chiavari in the Tigullio Gulf reveals a complex geomorphological setting resulting from the interaction between natural and anthropogenic factors. This map was developed through collection and review of archival data, geomorphological field surveys and indirect survey techniques based on the photointerpretation of aerial photographs, orthophotos, and satellite images, and the analysis of digital elevation models. The study area is characterized by (i) a geological setting markedly conditioning the geomorphological evolution, (ii) small valley bottoms that have been entirely artificialized, (iii) hillslopes that are almost completely terraced, (iv) a hydrographic network that is largely modified through channelization and culverting, and (v) widespread long-term slope instability processes. The investigated coastal slopes constitute a peculiar case of a terraced coastal landscape that has partially preserved its agricultural function and has been partially transformed by urban expansion. The urbanization process has been characterized by the construction of large settlements and discontinuous, scattered buildings associated with the development of residential and tourism infrastructure, which in some cases extends up to, and even beyond, the cliff edge. Therefore, the area represents an anthropogenic landscape, apart from most cliffs and the largest landslide bodies, which reflects ancient and recent human signatures associated with terracing and urbanization, respectively. Given the above, the outlined landscape setting makes the area highly exposed to geo-hydrological hazards, including mass movements, flash floods, and storm surges. In this context, anthropogenic elements represent both a vulnerability factor and a driver of increased hazard.

The outcomes from this research represent a solid base for developing further geomorphological research and supporting local authorities in sustainable land management and adaption planning, also under the perspective of geo-cultural heritage conservation and promotion. Moreover, they provide further insights to enhance both public awareness and risk perception about geomorphological processes.

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SUPPLEMENTARY MATERIAL

The geomorphological map associated to this article can be found in the online version at https://doi.org/10.4454/1pw9gw82

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