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ORIGINAL ARTICLE

A multi component approach to predict erosion susceptibility of rocky coasts: marine, terrestrial and climatic forcing—an application in Southern Italy

Maria Francesca Tursi[1] · Giorgio Anfuso[2] · Giorgio Manno[3] · Gaia Mattei[1] · Pietro P. C. Aucelli[1]

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Abstract

Rocky coasts are the most common type of coastal environment and are presently experiencing significant erosion as a consequence of accelerated sea-level rise and increase in coastal storms. This type of coastline, like all coastal environments, is subject to the effects of a huge number of marine and terrestrial processes that continually reshape them over time. This research suggests a new methodological approach for assessing the vulnerability of rocky coasts to forcing factors that may be emphasised by ongoing climate change. The proposed approach combines two matrices: the Physical Element Index (PEIx), which assesses the most relevant morphological and geotechnical features of the considered landform to evaluate its susceptibility to erosion, and the Cliff Forcing Index (CFIx), which accounts for the marine forces impacting the specific coastal form. In a first step, to construct the two matrices, several variables were selected from previous studies. In a second step, a specific weight factor (Wfi) was attributed to each variable, i.e. each one of the Physical Elements and Forcing Agents considered, according to their specific relevance/contribution to cliff erosion susceptibility. In a third step, the two matrices were combined through interpolation to generate the final Cliff Susceptibility Index (CSIx). The method was tested on different coastal areas sited along the southwest coast of Italy, differing in geological characteristics and marine conditions. The analysis demonstrated that most of the considered coastal sectors belonged to the “Low” (Cala Rossa, Cirella 1, Guardiola, Marechiaro, Punta del Corvo, Puolo, Torre di Mezzo), “Medium” (Capo Rama, Cirella 2, Seiano 1, Spiaggia del Poggio, Torrefumo 2) and “High” (Coroglio, Irminio, Punta Braccetto, Punta Pennata) classes of CSIx due to the interaction among morphological, geotechnical and forcing factors. This procedure allows the zonation of wide rocky coastal areas according to their grade of susceptibility and the identification of areas of criticism where specific studies and monitoring programs need to be developed to adopt sound management strategies.

Keywords Cliff · Rock platform · Lithology · Susceptibility index · Coastal erosion

Introduction

Historically, coastal regions were among the first settled areas due to their accessibility and abundance of resources (Erlandson et al. 2008; Bailey 2010). This continued in the last century and was especially true in Europe that experienced in such period significant economic, social and cultural changes (Halbac-Cotoara-Zamfir et al. 2020; Inglehart 2020; Paprotny et al. 2021) leading to the rapid growth of tourism, urban and industrial settlements along the coast (Salvati et al. 2015). In the Mediterranean basin, the majority of the population is concentrated in coastal areas (Mcgranahan et al. 2007) where housing services and tourism are the primary drivers of land occupation. The processes of littoralisation and over-exploitation of natural

✉ Gaia Mattei
gaia.mattei@uniparthenope.it

[1] Department of Science and Technology, University of Naples “Parthenope”, Centro Direzionale Isola C4, 80121 Naples, Italy

[2] Department of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, 11510 Puerto Real, Spain

[3] Department of Engineering, University of Palermo, Viale delle Scienze, Bd. 8, 90128 Palermo, Italy

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sources, which are expected to increase by ≈160% over the 2000–2030 period (Seto et al. 2011; Smiraglia et al. 2023), strongly affect the sensitivity of coastal areas that are prone to degradation due to natural process too (Salvati et al. 2015; Imbrenda et al. 2018). Despite the fact that land occupation is more widespread on low and flat coasts usually consisting of sandy beaches, numerous urban centres and anthropic facilities that require attention and protection measures are also often located on high and rocky coasts, i.e. steep coasts with possible narrow beaches at their foot. Italy has a coastline development of about 7900 km where important urban and industrial centres, road and railway infrastructures (Cinelli et al. 2021) and tourist activities are located (Ferretti et al. 2003). High and/or rocky coasts are about 59%, while beaches account for 41%. Geological hazards along rocky coasts are primarily related to the rapid detachment of material from the slope (Violante 2009). The erosion and transport of this material result in significant alterations to the physical landscape, posing hazards to coastal communities and human endeavours. This susceptibility potentially includes the risk of property and infrastructure damage, as well as the potential loss of lives (Violante 2009; Vanneschi et al. 2022).

The evaluation and assessment of coastal susceptibility is a subject of ongoing debate due to the wide range of factors and variables that influence coastal behaviour, e.g. natural phenomena and human activities. To implement effective protective measures, coastal managers need a complete understanding of the susceptibility of the considered coastal sector, as well as the future, potential socio-economic impacts (Cooper and McLaughlin 1998; Rangel-Buitrago and Anfuso 2015). Different authors have suggested a great number of methods for the characterisation of coastal environments based on susceptibility, vulnerability, and hazard criteria, along the Italian (Budetta et al. 2008; De Pippo et al. 2009; De Vita et al. 2012; Lucchetti et al. 2014; Matano et al. 2016; Caputo et al. 2018; Esposito et al. 2018a, b; Mattei et al. 2020; Anfuso et al. 2021; Di Luccio et al. 2023) other European (Del Río and Gracia 2009; Nunes et al. 2009; Furlani et al. 2011; Anfuso et al. 2013; Marques et al. 2013; Rangel-Buitrago and Anfuso 2015) and global coasts (Kennedy et al. 2013; Zhu et al. 2019; Rocha et al. 2020; Roukounis and Tsihrintzis 2022; Dada et al. 2024).

Cliff erosion is influenced by a large variety of marine and terrestrial processes depending on different factors, including the composition of cliff-forming materials and the interplay of physical forces such as local climatic conditions, tidal range, the frequency and strength of severe storm events and the action of chronic erosion processes (Hampton et al. 2004) that are at places reduced by the presence of beaches or other natural/artificial protective structures. These complex interactions may lead to accelerated erosion rates, which are typically manifested in the form of mass movements (Teixeira 2006). However, assessing cliff retreat poses significant challenges as it occurs intermittently and is often difficult to observe and measure.

The aim of this research is to apply a modified version of the method proposed by Tursi et al. (2023a) for the evaluation of the susceptibility of rocky coastal areas to erosion by using an index-based method. This method requests the careful choice and assessment of different geomorphological, geotechnical and dynamic variables that determine the degree of susceptibility of rocky coastal areas to land and marine-generated erosion processes. It allows defining different classes of susceptibility considering, for the first time, both physical elements and forcing characteristics affecting the cliff. The aim is to create an easy-to-use, general and non-site-specific tool consisting of a simple set of indicators applicable to different high coastal areas avoiding the requirement of exhaustive survey works. In addition, the index was developed to be applied to large coastal stretches to assess their susceptibility at a “regional” scale. The obtained data hold significant value for the development of appropriate land use organization and management approaches, particularly in less-developed coastal countries.

The approach was implemented in different coastal sectors positioned along the South-western coast of Italy, in the regions of Campania, Calabria and Sicilia. The study sectors were selected since they are different in geological, geomorphological and forcing/dynamic settings and levels of human activities. In particular, 62% of the considered coastal sectors are cut in sedimentary lithologies, 33% in igneous and 5% in metamorphic lithologies. The proposed index-based method was finally validated through the comparison of obtained results with recorded cliff erosion rates.

Methodology

Along the Southwestern Italian coast, 17 rocky coastal sectors were selected and their susceptibility to both land and marine-generated erosion processes was evaluated by using the Cliff Susceptibility Index (CSIx) (Tursi et al. 2023a). The key aspects of this methodology, as stated in Tursi et al. (2023a), comprise the following steps (Fig. 1):

(1) The first step was devoted to selecting different study areas, i.e. sites that differ in geological settings and marine characteristics. In particular, in order to consider a wide range of cases, three main types of rocky coasts were selected:

- Plunging cliffs (sensu Sunamura 1992), i.e. vertical or sub-vertical cliffs extending downward to a significant depth below the low-tide level without any formation of shore platform or ramp.

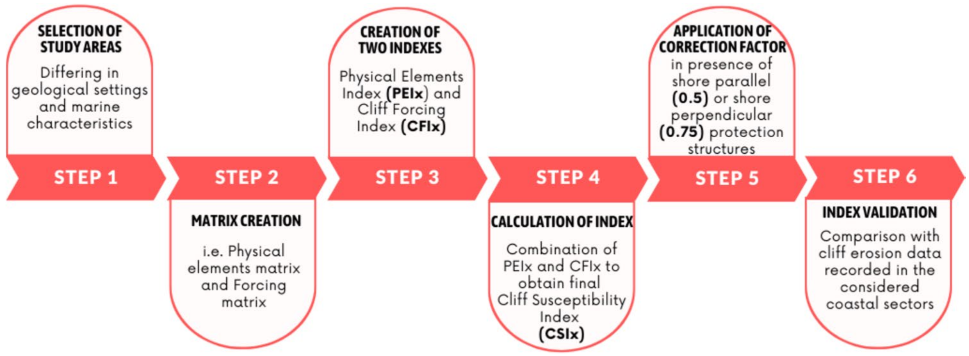


Fig. 1 Methodological step analysis used to calculate the CSIx

- Cliffs bordered by a narrow beach or shore platform. Following Sunamura (1992) and Trenhaile (1987), the shore platform is a horizontal to sub-horizontal (0–5 degrees) rocky surface transitioning formed in the intertidal zone due to the recession of a cliff because of marine processes such as wave erosion, dissolution due to biological activity and other weathering actions.
- Sloping coasts (sensu Biolchi et al. 2016). They consist of low-lying rocky coasts whose slope ranges between 5 and 45°.

(2) The second step was to propose: (i) a physical elements matrix (PEx) describing the proneness of different features of the rocky coast to erosion according to their distinctive geomorphological, geostructural and protective components and (ii) a forcing matrix that describes the forcing factors acting on the coast. The choice of the greater part of the variables used in the indexes was based on previous research (Sunamura 1992; Cooper and McLaughlin 1998; Benumof et al. 2000; Trenhaile 2002; McLaughlin and Cooper 2010; Di Paola et al. 2011; Rangel-Buitrago and Anfuso 2015) and the facility with which can be evaluated in any given area, avoiding the requirement of comprehensive survey work (Villa and McLeod 2002).

A detailed description of the parameters used in the two matrices is reported in Section "Description of indicators". The classes of each variable were rated from 1 to 5, from the lowest to the highest propensity to erosive processes and from the lowest to the highest exposure to marine agents. The variables were then weighted by different factors (Weight factor, Wfi), ranging from 0.5 to 1.0, according to their relevance in determining the general susceptibility of the cliff to erosion and forcing (Gornitz et al. 2022). Therefore, if the considered parameter described a process or aspect that was not considered decisive to cliff susceptibility (or was not a decisive forcing agent), its value was multiplied by 0.5 (lowest impact). On the other hand, when a parameter described an ordinary process/aspect, its value was multiplied by 0.8 (average impact) and, if the variable defined a process/aspect that significantly influenced cliff susceptibility (or forcing effects), its value was multiplied by 1 (highest impact).

(3) In the third step, two specific indexes were generated for each matrix, i.e., the Physical Elements Index (PEIx) and the Coastal Forcing Index (CFIx). Then each index was classified into five different classes (Rangel-Buitrago and Anfuso 2015; Rizzo et al. 2018).

(4) In the fourth step, the two indexes were combined and the Cliff Susceptibility Index (CSIx) was calculated. Section "Assessment of a correction factor for the CSIx" reports all the equations used to obtain the three indexes, and considering all the above, five susceptibility classes were obtained.

(5) Once the CSIx was obtained, a Correction Factor (CF) was applied where physical protection structures were observed (Section "Cross-validation of data obtained").

(6) In the final step, was tested the reliability of the results obtained by comparing them with cliff erosion rate evaluated between 1988 and 2023 for each considered coastal sector.

Description of indicators

Physical Elements Index

The physical elements index (PEIx) describes the cliff proneness to erosion processes by considering 14 factors including physical, geological and geomorphological variables and sub-variables (Rizzo et al. 2018). The factors were collected into six different groups according to Table 1 indicating the classes and criteria of classification used for each variable, with a score of 1 representing the lowest value and 5 representing the highest. The parameters used in the index were described as follows:

1. Morphology

Table 1 Physical element index classification from lowest—value 1 (green colour) tohighest—value 5 (red colour)

GROUP	No.	SUBVARIABLE	NULL/VERY LOW (1)	LOW (2)	MEDIUM (3)	HIGH (4)	VERY HIGH (5)	WEIGHT
MORPHOLOGY	1a	Height	$0 < h \leq 5$ m	$5 < h \leq 20$ m	$20 < h \leq 40$ m	$40 < h \leq 60$ m	$h > 60$ m	*0.5*
	1b	Slope	$S \leq 30°$	$30° < S \leq 40°$	$40° < S \leq 50°$	$50° < S \leq 60°$	$S > 60°$	*1*
LITHOLOGY	2a	Lithology (Uniaxal Compressive Strength)	Fresh basalt, chert, diabase, gneiss, granite, quartzite, limestone, marble (UCS ≥ 250 MPa)	Amphibolite, basalt, gabbro, granodiorite, rhyolite, phyllite, shale (250 < UCS ≤ 50 MPa)	Claystone, schist, very cemented siltstone, flysch, sandstone, tuff (50 < UCS ≤ 25 MPa)	Chalk, rocksalt (25 < UCS ≤ 5 MPa)	Volcanic ejecta (Highly weathered or altered rock) (UCS < 5 MPa)	*1*
EROSIONAL LANDFORM	3a	Marine erosional features	Free of erosional features	Presence of erosional features of centimetric dimensions	Dm	m	Several meters-caves (Usually observed in cliffs with horizontal strata)	*0.5*
	3b	Terrestrial erosional features	Free of erosional features	Rill	Minor gullies	Possible slump scars, weathering notch	Stepped and gullied, and slump scars	*0.5*
STRUCTURE DISCONTINUITIES	4a	Layer dip and strike	Landward dip	Transversal	Horizontal	Vertical	Seaward dip	*1*
	4b	Presence/ Abundance	Virtual absence of discontinuities, cracks, joints, faults (% ≤ 30%)	x	Some evidence of discontinuities cracks, faults (30 < % ≤ 60)	x	High density of discontinuities, cracks, fault (% > 60)	*0.4*
	4c	Persistence	Centimeter(cm)	x	Decimeter(dm)	x	Meter(m)	*0.2*
	4d	Aperture	Closed	x	Mixed (50% open/closed)	x	Open	*0.2*
	4e	Infilling	None	x	Hard Infilling	x	Soft infilling	*0.2*
COVER	5a	Vegetation cover	Mature, dense and undisturbed	Mature	Poor and ephemeral	Very poor	Bare	*0.5*
NATURAL PROTECTION	6a	Beach	Wide/high beach (waves reach the cliff at spring tides coinciding with storm surges)	x	Narrow/low beach (waves reach the cliff during daily high tide)	x	Absent (or unstable sediment)	*0.5*
	6b	Talus	Old large talus well vegetated	x	Fresh talus	x	Absent (or unstable sediment)	*0.8*
	6c	Platform	Presence of horizontal sloping shore platform (waves reach the cliff at spring tides coinciding with storm surges)	x	Presence of narrow horizontal/sloping shore platform (waves reach the cliff during daily high tide)	x	Absent	*1*

1a. Cliff height directly affects the potential instability, with higher cliffs being more prone to instability compared to lower ones. Consequently, as the class value increases, the chances of landslide occurrence also rise and vice versa (Montoya-Montes et al. 2012; Gerivani et al. 2020).

1b. Cliff Slope is closely associated with cliff instability, as higher slopes correspond to greater potential instability (De Pippo et al. 2009; Rangel-Buitrago and Anfuso 2015).

2. Lithology

2a. Cliff lithology (and compressive strength). These parameters are significant drivers of cliff erosion and instability. All potential types of rocks, from low to high sensible lithologies, were considered (Emery and Kuhn 1982; Hoek et al. 1998; Sunamura 2018).

3. Erosional landform

3a. Marine generated landforms. These characteristics are strictly associated with marine processes at the cliff foot (Trenhaile 2014). Primary agents include abrasion, bio-activity, dissolution exerted by ocean water and quarrying of blocks (Emery and Kuhn 1982). Rapid marine erosion often results in overstepping at the cliff base, triggering rock falls, slumps, and other types of ground instabilities.

3b. Terrestrial landforms. Cliff instability is also conditioned by subaerial processes such as the effects of wind, precipitation, marine spray, groundwater infiltration, freezing and thawing, etc. Rain and melting snow generate run-off processes that wash away soft sediments forming rills that may evolve into gullies (De Pippo et al. 2009; Trenhaile 2011; Bird 2016).

4. Structure discontinuities

4a. Strata dip and strike. The dip refers to the angle of inclination of rock layers in relation to the horizontal surface (Terzaghi 1962). Abrupt cliffs typically exhibit rocks that are either horizontally or vertically stratified, while intermediate angles often result in gentler slopes (Emery and Kuhn 1982; Hampton et al. 2004).

4b. Discontinuities presence/abundance considers the occurrence or abundance of discontinuities. Their presence often plays a significant role in cliff evolution as it reduces the overall resistance of the rocky massif (De Pippo et al. 2009).

4c. Discontinuities persistence is described to be the length of a discontinuity with respect to a reference line within the plane where the discontinuity is localised.

4d. Discontinuities aperture is the spacing between the sides of a discontinuity. They are closed (rock-to-rock contact), open (no contact), or mixed (approximately 50% open and 50% closed).

4e. Discontinuities filling is the existence of fill material in fractures that contributes to the instability of the cliff. Infilled discontinuities demonstrate a great variety of physical behaviours, especially in terms of permeability shear stress and deformability.

5. Cover

5a. Vegetation cover. Despite plant root systems are often limited to shallow soil layers in cliff environments and do not play a directly relevant role in cliff stabilization, the occurrence of vegetation on the top of the cliff is acknowledged for its protective role in regulating evapotranspiration, surface runoff and infiltration processes (Budetta et al. 2008; Hampton et al. 2004). Therefore, vegetation protects the cliff from the direct impact of rainfalls, favours water infiltration in the soil and also reduces run-off and associated rills' formation. Consequently, the vegetation cover is a natural stabilising parameter (Kogure et al. 2006, 2022; Coelho et al. 2009).

6. Natural protection

6a. Beach presence dissipates wave energy protecting the cliff from the action of waves (Del Río and Gracia 2009). The characteristics of the beach, i.e. its height and width, are crucial factors as a shallow beach enables waves to reach the cliff base and vice versa. Since waves carry sediments, their mechanical abrasion acts on the cliff foot (Sunamura 1992; Hoek et al. 1998) and their erosive power is determined by the recurrence with which waves reach the cliff base and by the characteristics of the beach.

6b. Presence of talus. Cliff retreat processes result in the release of deposits that sometimes accumulate at the cliff base offering a natural protection against sea agents (Quinn et al. 2010; Castedo et al. 2017). On the basis of their grain size, the formation of a talus underscores the effects of longshore currents and waves, i.e. fine sediments that are easily removed and vice versa.

6c. Shore platform, situated at the foreshore or shoreface, dissipates the energy of incoming waves (Sunamura 1992). The effectiveness of the shore platform's protection role is related to its width, continuity and location.

Cliff Forcing Index

The Cliff Forcing Index (CFIx) represents the potential level of stress exposure of a specific coastline (Rangel-Buitrago and Anfuso 2015; Mooser et al. 2020). The following forcing variables were considered: tidal range, degree of exposure of the coastline to wave fronts, and relative sea level trend.

7. Tidal range. It represents the periodic up-and-down motion of the sea surface associated with the gravitational attraction of astronomical objects. This parameter encompasses different scenarios as they determine the boundary for horizontal wave run-up (Benumof et al. 2000). Higher tidal ranges allow more effective dissipation of wave energy compared to lower tidal ranges, where the energy of waves is concentrated in a small area. Accordingly, in cliffed areas, higher tidal ranges are typically associated with a reduced erosion hazard (Gornitz 1991; Short 1999).
8. Degree of littoral exposure to wave fronts considers the susceptibility of the coast to storm impacts. It describes the angle between the shoreline and the approaching wavefronts during storm conditions (Garcia et al. 2000). Komar (1998) indicated that shore-parallel fronts present greater hazard levels compared to shore-oblique wavefronts.
9. Relative sea level trend. Considering the recent estimates of accelerating sea-level rise (Shukla et al. 2022), it is evident that the significance of relative sea-level change in a specific region will vary depending on the considered time span (Lee 2008). For this study, IPCC data from the SSP2-4.5 scenario presented by NASA (2023) were utilized, projecting sea-level rise aligned with the upper end of nationally determined contribution emission levels by 2030. This scenario slightly differs from a reference scenario with no additional climate policies, leading to an estimated warming of around 2.7 °C by the end of the twenty-first century. It is important to note that these databases provide data in absolute values, necessitating corrections to account for continent uplift values and local/regional subsidence (Vilardo et al. 2009; Matano 2019). The classes and the classification criteria used for each variable within the CFIx are presented in Table 2.

Cliff Susceptibility Index

The scores for each variable were calculated to obtain an absolute value for PEIx and CFIx by using Eqs. (1) and (2) in Table 3. Finally, a CSIx was established to represent the likelihood of a potentially damaging event occurring in a specific area. It is the result of the combination of the above-mentioned indexes, as shown in Eq. (3) reported in Table 4.

Considering all the above, five susceptibility classes were obtained and reported in Table 4.

Assessment of a correction factor for the CSIx

In the last step, a correction factor was applied when coastal protection structures were observed (e.g., groins, emerged and submerged breakwaters, etc.), as their influence can be very significant in certain areas (Ergin et al. 2004; Hartmann 2006). In fact, where coastal cliff recession undermines and destroys structures such as streets and constructions, or land of value for agriculture etc., the common approach is to protect the cliff foot with attached shore-parallel-type structures (King et al. 2022). In particular, such structures as seawalls (gabions, rock armours, concrete walls, etc.) and revetments (e.g. rip-rap revetments, etc.) avoid erosion at the cliff foot. Attached structures totally protect the backing cliff

Table 2 Cliff Forcing index elements rating from the lowest (1, green colour) to the highest value (3, red colour)

VARIABLE	No.	LOW/NULL (1)	MEDIUM (2)	HIGH (3)	WEIGHT
Tidal range	7	Macrotidal (Td ≥ 4 m)	Mesotidal (4 < Td ≤ 2 m)	Microtidal (Td < 2 m)	***0.5***
Degree of littoral exposition to wavefronts	8	45° ≤ α < 10° Oblique	10° ≤ α < 5° Subparallel	5° ≤ α < 0° Parallel	***1***
Relative sea level trend	9	Fall/Stable (rising lower than the average value at regional scale)	Rising (rising equal to average local trend at regional scale)	Highly rising (rising higher than average local trend at the regional scale)	***0.5***

Table 3 Equations regarding PEIx (1), CFIx (2) and CSIx (3)

Indexes	Equations	Parameters
Physical Elements Index (PEIx)	$PEI_x = \sum_{i=1}^{n} \frac{PE * WFi}{nPEI}$ (Eq. 1)	*PE*: physical elements value, *WFi*: weight factor *nPEI*: number of variables considered in the index assessment
Cliff Forcing Index (CFIx)	$CFI_x = \sum_{i=1}^{n} \frac{Ci * WFi}{nCFI}$ (Eq. 2)	*Ci*: forcing value *WFi*: weight factor *nCFI*: number of variables considered in the index assessment
Cliff Susceptibility Index (CSIx)	$CSI_x = \frac{(PEI*nPEI)+(CFI*nCFI)}{(nPEI+nCFI)}$ (Eq. 3)	–

Table 4 The five classes of CSIx obtained

CLASS	VALUE	COLOUR
Class I	$0.6 \leq CSIx \leq 1.0$	
Class II	$1.1 < CSIx \leq 1.5$	
Class III	$1.6 < CSIx \leq 1.9$	
Class IV	$2.0 < CSIx \leq 2.4$	
Class V	$2.5 < CSIx \leq 2.8$	

The colours indicate increasing susceptibility to erosion (from green to red)

from waves but transmit their energy to the cliff base and siphoning processes are observed in the case of porous structures (e.g. rip-rap revetments). Other parallel structures are detached breakwaters and exempla of shore-perpendicular structures are constituted by jetties and groins.

In this research, to evaluate the degree of armouring—defined as the ratio between the total extension of coastline protection structures and the length of the considered coastal area—the CSIx value was multiplied by using a Correction Factor (CFi) (Aybulatov and Artyukhin 1993; Manno et al. 2016). In particular, if the protection structure was shore-parallel (e.g. seawalls, etc.), a correction factor equal to 0.5 was used while if it was perpendicular to the shoreline (e.g. groins, jetties, etc.), a correction factor equal to 0.75 was applied.

Cross-validation of data obtained

The validity of the susceptibility was tested by the comparison with cliff erosion rates recorded for the coastal sectors considered (Cooper and McLaughlin 1998) obtained by means of 1:10,000 orthophotos, dating from 1988/1989, and Google Earth images (2023). Firstly, the cliff top was traced using orthophotos and Google Earth images, except for areas with very dense vegetation on the cliff top, where the cliff base was used (Moore and Griggs 2002; Pierre 2006). The coastlines were then compared in a GIS environment to speed up spatial analysis, interpolation and the merging of information derived from several sources.

After the acquisition of the two shorelines, cliff retreat values were evaluated employing the Area-Based Analysis (ABA) method (Smith and Cromley 2012; Anfuso et al. 2016; Manno et al. 2022). The ABA method employs two separate coastlines to construct a polygonal area representing the deviation between the two coastlines. ABA estimates the average shoreline changes in the considered coastal segment by dividing the area between the two coastlines, for the considered segment length (Aminti et al. 2004).

After the index evaluation, the Linear Multiple Regression (LMR) was employed for each investigated coastal sector in order to assess the existing relationship between the evaluated CSIx and the Cliff Retreat Rate (RR).

LMR is a statistical method that estimates the values of a dependent variable by using the observed values of multiple independent variables.

The correlation was estimated according to the following expression (Eq. 4) where "*f*" is the function symbol:

$$CSI = f \cdot (RR) \quad (4)$$

This model also provides the output information, like the coefficient of multiple determination R^2, to furnish details regarding the precision of the model estimation of the dependent variable. Little variations between the predicted and measured data suggest that the model accurately represents the real situation. Instead, considerable differences between predicted and measured data suggest that the model poorly represents data validity.

Study areas

The proposed method was applied to 17 coastal sectors located along the South-western part of Italy a semidiurnal microtidal environment. The selected areas differ from each other in geological and marine characteristics i.e. exposure of the coastal sector to major wave events, and relative sea level trends (Fig. 2). All the selected sites are located in the "Hot-summer Mediterranean climate" (*Csa*) following Köppen's classification (Köppen 1918).

The general description of each one of the considered sectors is reported as follows:

– Campi Flegrei coastal areas

The Campi Flegrei area is an active volcanic caldera situated in the central part of the Campania region (Southern Tyrrhenian Sea) (Esposito et al. 2018a) and is one of the areas with the highest volcanic and seismic hazard in the world (De Natale et al. 2006; Aucelli et al. 2022). Other natural and human-related hazards also exist in the area including landslides, soil erosion (Beneduce et al. 1988) as well as vertical ground movements—due to bradyseismic crises—which gave rise to uplift and subsidence episodes which affected the whole area in the past 15,000 years (Di Vito et al. 1999, 2016; Morhange et al. 2006; Isaia et al. 2019; Aucelli et al. 2020, 2021). The complex volcanic

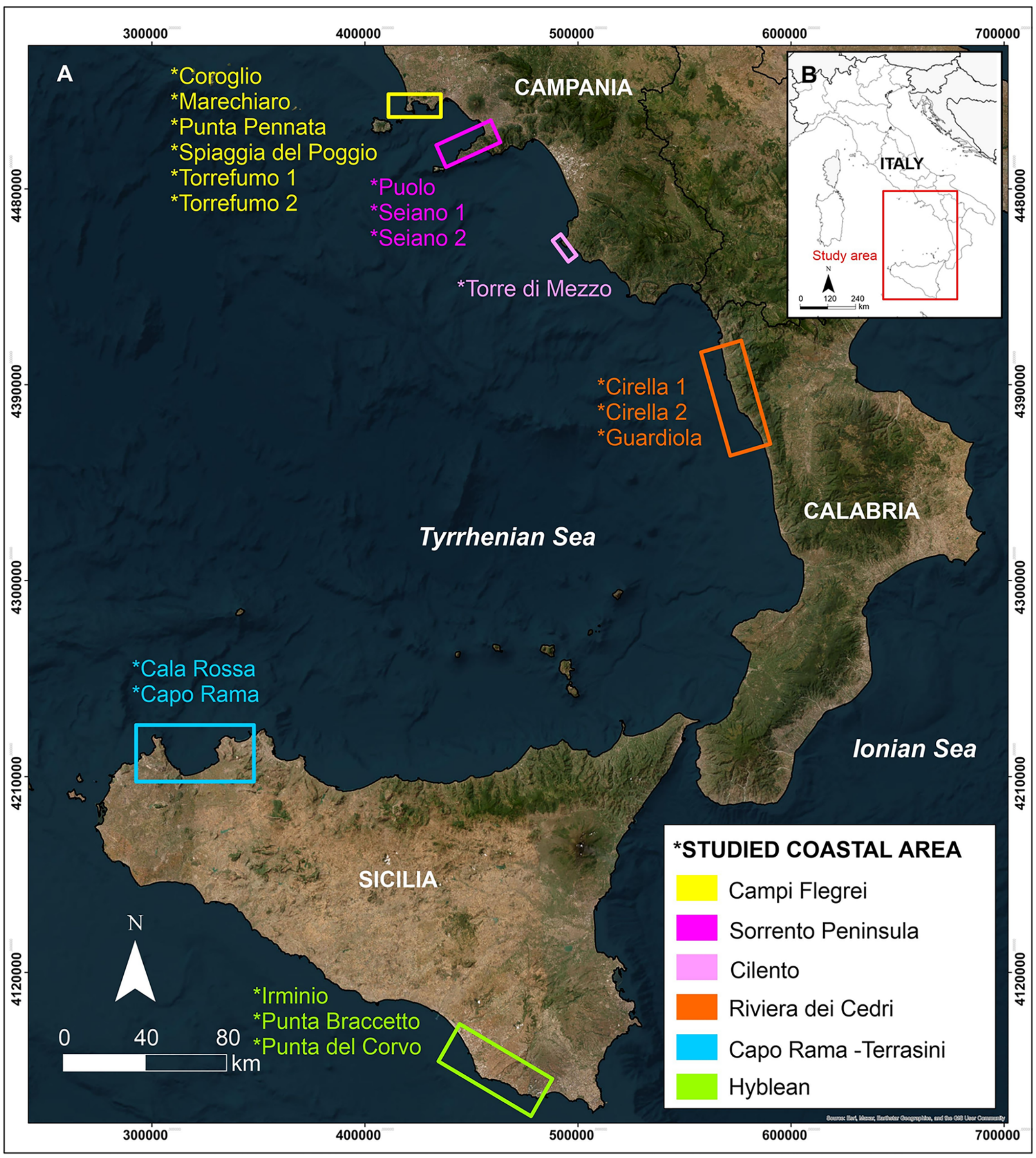


Fig. 2 Location of selected coastal sectors that fall in Campania, Calabria and Sicilia regions of Italy

history of the Phlegraean Fields modelled its morphology resulting in a hilly landscape shaped mainly by slope, volcanic and coastal processes (Mattei et al 2022, 2024).

The coast is subject to waves coming from the south and the southwest (from 180° N to 210° N) (Saviano et al. 2020), which can reach a significant height of more than 4.8 m during winter stormy events (Menna et al. 2007). In late spring and summer periods, the wind blows from the SSW direction (Menna et al. 2007), which produces wave height in the range of 0.4 to 0.6 m (Benassai et al. 1994; Saviano et al. 2020; Mattei et al. 2021). The rainfall regime shows a mean value of 700 mm/year (Esposito et al. 2018a).

Along the Campi Flegrei area, the coastal sectors selected are Coroglio, Marechiaro, Punta Pennata, Spiaggia del Poggio, and Torrefumo. It is important to underline that the Torrefumo coastal sector was considered twice in this work, that is before and after the emplacement in the early 1980s of a continuous seawall with a medium height of 4 m (a.s.l.) that protects the cliff toe from wave attack (Esposito et al. 2018a). In particular: Torrefumo 1 represents the condition of the coastal sector before the construction of the seawall, and Torrefumo 2 represents the present condition of the coastal sector, protected by the seawall, in order to consider how the construction of a protection structure may influence the CSIx value obtained. Most of the considered coastal sectors (Coroglio, Punta Pennata, Torrefumo 1, Torrefumo 2, Spiaggia del Poggio) are cliffs fronted by a narrow beach or shore platform while Marechiaro cliff is a sloping coast. Different volcanic units characterize the selected coastal sectors. In particular pyroclastic deposits, lithified ignimbrite deposits (Deino et al. 2004) and coarse-grained pumiceous fragments characterize the emerged part of Coroglio cliff while the seabed is characterized by fine to medium sands. The nearshore slope calculated from the shoreline to the 10 m water depth is about 3%. Marechiaro sector is mainly represented by yellowish pyroclastic deposits (tuff) divided into two different members, the lower formed by an alternation of cineritic level and the top member formed by thick massive ashy layers (Isaia et al. 2019). Both members characterize also the seabed, which shows a slope of about 6%. Punta Pennata is mainly characterised by pyroclastic deposits very rich in grey pumice and subordinate scoriae and lithic lava which also characterize the seabed (Isaia et al. 2018). The latter presents a nearshore' slope of about 8%. Spiaggia del Poggio is cut in stratified tuff composed of small pumice and lithic lava surrounded by an abundant ash matrix while the seabed, with a slope of about 5%, is represented by sandy gravel and well-sorted sands. Finally, the Torrefumo coastal area is characterised by pyroclastic rocks (Rosi and Sbrana 1987; Matano et al. 2016, 2020), pumices and ash beds, dark grey scoriae with intercalated grey ashes (Perrotta et al. 2010) and pumice lapilli beds in the emerged part (Deino et al. 2004) while the seabed is represented by sandy gravel and well-sorted sand and the nearshore' slope is about 5%.

– Sorrento Peninsula coastal areas

The Sorrento peninsula is situated in the central part of the Campania region and represents a rocky promontory elongated ENE—WSW and lowered toward the west. It has a complex topography which reflects the tectonic activity that affected this part of the Apennine chain during the Quaternary when extensive subsidence and uplift gave rise to a horst and graben structure (Brancaccio et al. 1991; Milia and Torrente 2015). In this area, a Mesozoic limestone-dolomitic carbonate platform succession is visible in the eastern sector of the southern flank of the ridge while a Miocene terrigenous succession outcrops in the west of Sorrento (De Vivo et al. 2001; Rolandi et al. 2020). Quaternary deposits of varying thickness cover the other units, mainly consisting of carbonate debris, unconsolidated volcano clastites and reduced gravelly-sandy deposits of ancient, recent and current beaches. The coastal area is represented by an alternation of promontories and bays, occasionally with little pebbly beaches at cliff base (De Pippo et al. 2007). Winds primarily blow from the north, even the incidence of southerly winds rises in spring and autumn. Significant wave heights typically range from 0.9 to 2.2 m but can reach up to 4.7 m, particularly during winter (De Pippo et al. 2009). The rainfall recorded is 1200 mm/year (De Pippo et al. 2009).

Selected sectors along the Penisola Sorrentina area are: Puolo, Seiano 1, and Seiano 2, where Puolo is a sloping coast, Seiano 1 sector is a plunging cliff-type coast and Seiano 2 is a cliff with a shore platform. The Puolo sector is represented by an alternation of grey crystalline dolostones, light brown limestones and conglomerates while the seabed is characterized by pelitic to medium-coarse sand showing a nearshore' slope of about 8%. The main geological units composing Seiano 1 are composed of an alternation of grey crystalline dolostones, light brown limestones and conglomerates (Iannace et al. 2015) while Seiano 2 is constituted by an alternation of grey crystalline dolostones, light brown limestones and conglomerates covered by thin layers of loose pyroclastic deposits (Iannace et al. 2015). Seiano 1 and Seiano 2 seabeds are both characterized by beach deposits formed by carbonate gravels and sands. Nearshore' slope is about 3% for Seiano 2, 6% for Puolo and 8% for Puolo.

– Cilento coastal areas

Cilento area is situated in the south of Campania region and is an NW- SE oriented area characterised by smooth ridges with regular and moderately steep slopes, alternating with concave-convex profiles (Guida and Valente 2019). The geological characteristics of the coastal sectors along this area consist mainly of stratified sandstones with marls and conglomerates that belong to the Cilento formation (Dramis et al. 2011). The main tectonic structures are N-S extensional faults showing vertical and transcurrent evidence of movement. Pocket beaches are observed at places. Waves mainly come from SW-NW directions with significant wave height (H_s > 3 m) and most energetic waves (H_s > 6 m) approach the coast from SW (Tursi et al. 2023b). The average annual temperature is 17 °C and the average annual rainfall is 760 mm/year (Guida and Valente 2019).

Torre di Mezzo coastal sector was selected as representative of the entire area, which is a sloping coast type. The geological units forming this coastal area are mainly represented by arenaceous-pelitic sandstones of thin/thick tabular layers, predominantly silicoclastics with medium to fine arenites (Martelli et al. 2016; Tursi et al. 2023b) continuing in the seabed that presents a slope of about 3%. Figure 3 reports the studied coastal sectors along Campi Flegrei, Sorrento Peninsula and Cilento areas. Figure 3 reports the studied coastal sectors along Campi Flegrei, Sorrento Peninsula and Cilento areas.

– Riviera dei Cedri coastal areas

Riviera dei Cedri area is situated in the Northern part of the Calabria Tyrrhenian coast. This part of the region is characterised by a coastal area that mainly extends along the footslope of a raised mountain belt (Ietto et al. 2023). It consists of rocky formations of dolostones, limestones and marbles, spanning from the Anisian to Langhian periods. Additionally, there are Cambrian to Upper Oligocene terrenes, comprising metamorphic assemblages of metapelitic, ophiolitic and carbonate origins, varying from high- to middle- to low-grade metamorphism (Morelli 1976; Carrara and Zuffa 1976; Boccaletti et al. 1984). The geological variability makes the considered coastal area a little irregular and mainly characterised by sandy beaches, alterned at places by rocky headlands (Ietto et al. 2023).

This coastal sector is exposed to winds predominantly blowing from the northwest, west and southwest. In particular, waves approaching from the northwest typically have a H_s between 2 and 3 m while waves from the west-southwest direction can reach wave heights exceeding 5 m (Ietto et al. 2023). Riviera dei Cedri is characterized by high-intensity rainfalls with values ranging between 600 and 1000 mm/year (Caloiero 1975).

In this area, three coastal sectors were selected: Cirella 1, Cirella 2 and Guardiola. The Cirella 1 and Cirella 2 sectors belong to the sloping coast type. The main geological unit composing Cirella 1 is a large bank of breccias with a decimetric clast size while Cirella 2 is composed by an alternation of grainstones, rudstones and mudstones (Ietto and Ietto 2011). The units that characterize these two coastal sectors in the emerged area continue in the seabed that presents

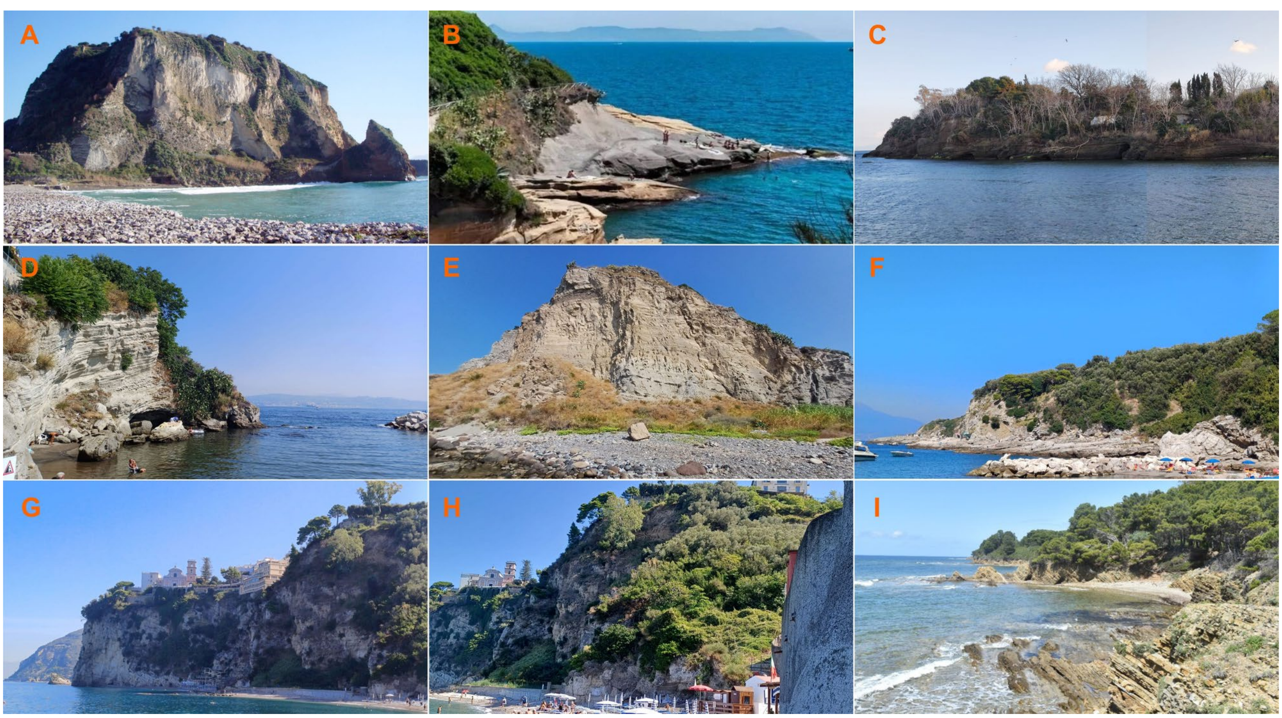


Fig. 3 Studied coastal sectors along the Campi Flegrei: Coroglio (**A**), Marechiaro (**B**), Punta Pennata (**C**) Spiaggia del Poggio (**D**), Torrefumo (**E**). Studied coastal along Sorrento Peninsula: Puolo (**F**), Seiano 1 (**G**) Seiano 2 (**H**). Studied coastal sector along Cilento area (**I**)

a slope of about 10% for Cirella 1 and 5% for Cirella 2. Guardiola is a sloping coast-type and consists of greenish phyllite gently sloping in the seabed. The nearshore' slope in this case is about 6%. Figure 4 reports the studied coastal sectors along Riviera dei Cedri area.

– Capo Rama-Terrasini coastal areas

The Capo Rama—Terrasini coasts are located on the northern coast of Sicilia, which is part of the inland sector of the Sicilian-Maghreb chain, a segment of the African continental crust composed of several tectonic units (Catalano and D'Argenio 1974; Basilone et al. 2016). The stratigraphic-structural units identified in this coastal area derive from the distortion of the shape of Mesozoic-Tertiary paleogeographic domains (Panormide and Imerese). The limestone coastline has been affected by the simultaneous action of the predominant marine abrasion and karst dissolution and, in places, caves have been formed. Other diffuse coastal forms are the rock stacks, stumps and wave-cut notches that are visible in correspondence with the mean sea level position. The coast is subject to waves coming from the west and the northwest (from 265° N to 305° N), which can reach a significant height of more than 5 m. Less frequent waves approach from the north, which have a H_s of about 3.5 m (National marine monitoring networks 2024). In this area, two coastal sectors were selected which are Cala Rossa and Capo Rama. An average temperature of 18 °C characterises these areas, with an average rainfall value of about 600 mm/year (Cannarozzo et al. 2006; Liuzzo et al. 2017).

Cala Rossa sector is a plunging cliff-type coast, composed by a Meso-Cenozoic stratigraphy that can be summarised as follows: grey and reddish radiolarites, crinoidal limestones, *calpionella* limestones, radiolarian mudstone and white marly limestones with planktonic foraminifera Capo Rama sector is a plunging cliff-type coast constituted by Upper Norian Triassic lithologies that consist of dolomites and dolomitic limestones with megalodontids, stromatolitic loferitic dolomites, and loferitic breccias (Catalano and D'argenio 1974). (Basilone et al. 2016). The seabed near the coast of Capo Cala Rossa and Capo Rama is mainly rocky with locally sandy areas above the rocky substratum near Cala Rossa. The nearshore' slope is 20% and 28% respectively at Capo Rama and Cala Rossa.

– Mediterranean Hyblean coastal areas

This area is part of the Hyblean Plateau that represents one of the emerged portions of the African foreland in southeastern Sicilia, linked to the post-Tortonian Africa-Europe convergence (Bonforte et al. 2015) and is essentially composed by a stratigraphic alternation of limestones and marls corresponding to the Ragusa Formation (Late Miocene). Along the coast are present Plio-Quaternary, sedimentary deposits showing different lithologies (Grasso et al. 2000). The Ragusa coastline belongs to the same physiographic unit and it is directly exposed to storms and winds coming from southeast, southwest and northwest. The most significant sea states are those coming from the northwest (from 210° to 310°), with wave heights exceeding 4 m (National marine monitoring networks 2024). These areas are characterized by a yearly average temperature of 18 °C and annual precipitation of 600 mm (Cannarozzo et al. 2006; Liuzzo et al. 2017). In this area, three coastal sectors have been selected: Irminio, Punta Braccetto and Punta del Corvo. In this area, three coastal sectors have been selected: Irminio, Punta Braccetto and Punta del Corvo.

The Irminio sector is a cliff fronted by a narrow beach and is composed by Quaternary, white calcareous silts, fine sands and pebbles corresponding to the paleo deposits of the Irminio River. The seabed, which shows a smooth slope (3%), is essentially sandy with rocky outcrops and *Posidonia oceanica* meadows. Punta Braccetto is a cliff fronted by a narrow beach and it is composed by Plio-Quaternary alternation of unconsolidated sands and silts at places, especially at the cliff top and base, cemented by vadose or marine waters. In this area the seabed is sandy with rocky outcrops and its slope is higher than in the previous case (10%). Punta del Corvo sector is a sloping coast type, mainly constituted by an alternation of limestones and marls while a reddish and

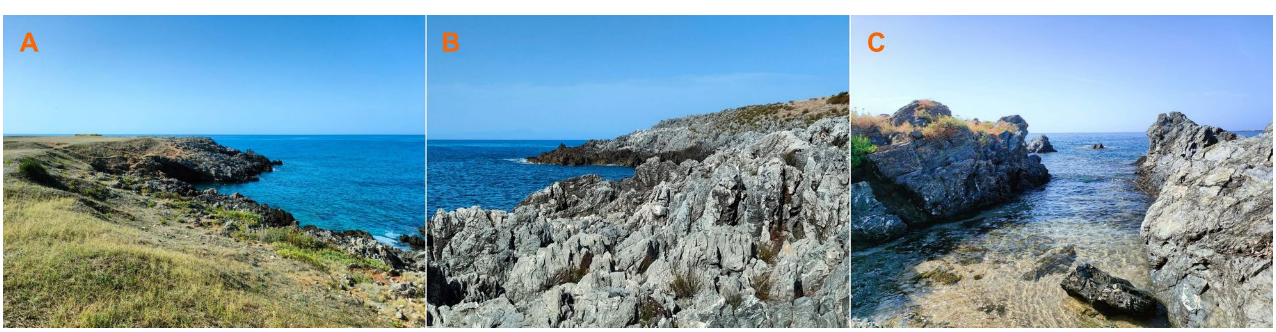


Fig. 4 Studied cliffs along the Riviera dei Cedri area: Cirella 1 (**A**), Cirella 2 (**B**), Guardiola (**C**)

cemented covering sedimentary deposit, composed by centimetric and decametric blocks merged by a silty matrix, is at places observed at the upper part (Anfuso and Martínez del Pozo 2005). The seabed fronting Punta del Corvo area is mainly rocky and shows a smooth slope (5%). Figure 5 reports the studied coastal sectors along the Sicilia coastal area.

Results and discussions

A total amount of 17 sites located along the Campi Flegrei (5), Penisola Sorrentina (3), Cilento (1), Riviera dei Cedri (3), Capo Rama-Terrasini (2), and Mediterranean Hyblean coastal areas (3) were field-tested during 2023. PEIx, CFIx and CSIx evaluation of the sites investigated is reported, in Section "Physical Elements Index (PEIx)", "Coastal Forcing Index (CFIx)" and "Cliff Susceptibility Index (CSIx)".

Physical Elements Index (PEIx)

The results showed that 39% of the sectors belong to the "Low" PEIx class (Class 2), 33% to the "Medium" class (Class 3), 22% to the "High" class (Class 4) and the remaining 6% to the "Very High" PEIx class (Class 5). Table 5 reports the main physical characteristics for each coastal sector.

High values of PEIx, i.e. classes 4 and 5, were mainly correlated with unconsolidated rocks such as very altered tuffs, e.g. at Torrefumo and Punta Pennata, and carbonatic sediments, e.g. at Irminio. At Seiano 1, cut in very resistant limestones, the high PEIx value was due to unfavourable scores such as the high value of cliff slope (> 60°) and height (h > 60 m) and the absence of natural/artificial protection at the cliff toe. Low PEIx values, i.e. classes 2 and 3, were related to very resistant lithologies such as limestones, e.g. at Cala Rossa, Punta del Corvo and Puolo, sandstones, e.g. at Torre di Mezzo and phyllites, e.g. at Guardiola. It is important to underline that the low value of PEIx recorded at Marechiaro, cut in tuff lithologies, was also linked to different favourable factors such as the low height and slope of the cliff and the very limited erosional features.

Cliff Forcing Index (CFIx)

The results show that 33% of the analyzed coastal sector falls into the "Very low" class of forcing, 17% in the "Low" class, 33% in the "Medium" and 17% in the "Very high" class. Table 6 reports the main forcing characteristics for each coastal sector.

Very high values of CFIx were observed in coastal sectors with littoral exposure parallel to the direction of major wavefronts, e.g. Torrefumo. High values were also influenced by an expected rise in sea level (according to the IPCC 2023) higher than the recent regional trend. Low CFIx values were obtained for coastal sectors oblique to the direction of wave fronts, e.g. Cirella 1 and Cirella 2, Puolo and Seiano and/or when the relative sea level trend is rising at a lower rate than the average regional value.

Cliff Susceptibility Index (CSIx)

The analysis demonstrated that 6% of the coastal sectors fell in the "Very Low" class of susceptibility (Class 1), 38% belonged to the "Low" class (Class 2), 28% to the "Medium" (Class 3), 22% to the "High" (Class 4) and the remaining 6% belonged to the "Very High" class (Class 5) of susceptibility. Figure 6 reports a graphical representation of PEIx

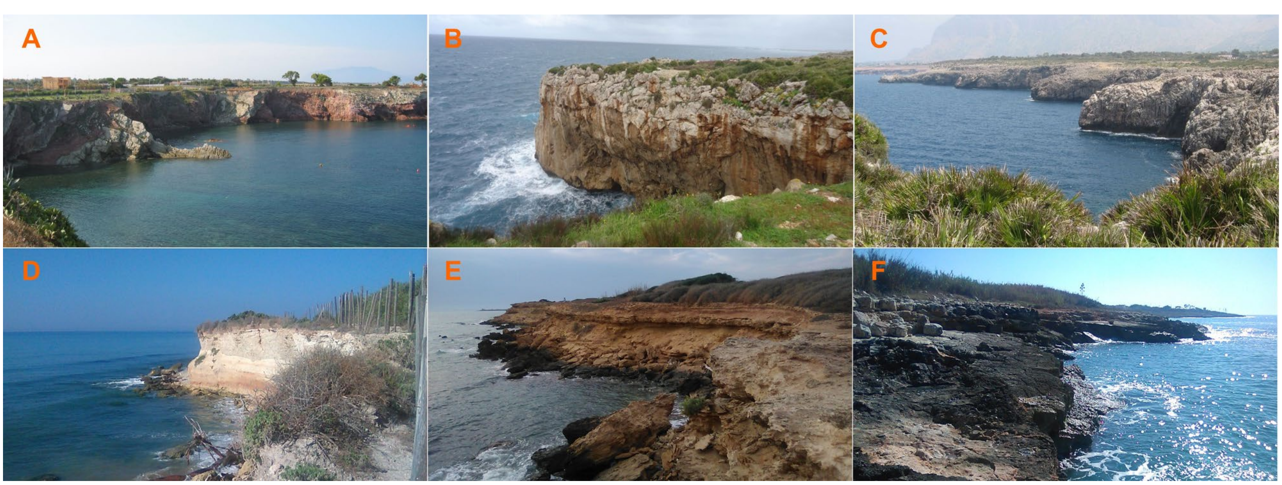


Fig. 5 Studied coastal sector along Capo Rama-Terrasini area: Cala Rossa (**A** and **B**), Capo Rama (**C**). Considered sector along the Hyblen area: Irminio (**D**) Punta Braccetto (**E**), Punta del Corvo (**F**)

Table 5 Physical characteristics of each coastal sector used to calculate its PEIx' score

Site	Height	Slope	Lithology	Marine erosional features	Land erosional features	Strata dip and strike	Structures	Persistence	Aperture	Infillig	Vegetation cover	Beach	Talus	Platform
Cala Rossa	$5 < h \leq 20$	$S > 60°$	Limestones	m	Rill	Transversal	$\% \leq 30$	dm	Closed	None	Mature, dense and undisturbed	Narrow/low beach[2]	Absent	Horizontal sloping shore platform[2]
Capo Rama	$5 < h \leq 20$	$S > 60°$	Limestones	m	Rill	Transversal	$30 < \% \leq 60$	dm	50% open/closed	None	Poor and ephemeral	Absent	Absent	Horizontal sloping shore platform[2]
Cirella 1	$0 < h \leq 5$	$30° < S \leq 40°$	Breccias	dm	Free of erosional features	Vertical	$30 < \% \leq 60$	dm	50% open/closed	None	Mature, dense and undisturbed	Absent	Fresh talus	Absent
Cirella 2	$5 < h \leq 20$	$40° < S \leq 50°$	Grainstones	Free of erosional features	Rill	Vertical	$\% > 60$	dm	Open	None	Mature, dense and undisturbed	Absent	Fresh talus	Absent
Coroglio	$h > 60$	$S > 60°$	Tuffs	m	Rill	Transversal	$30 < \% \leq 60$	m	Open	Soft infilling	Bare	Wide/high beach[1]	Old large talus well vegetated	Absent
Guardiola	$0 < h \leq 5$	$S \leq 30°$	Phyllites	cm	Free of erosional features	Landward dip	$30 < \% \leq 60$	dm	50% open/closed	Hard infilling	Bare	Absent	Fresh talus	Absent
Irminio	$0 < h \leq 5$	$S > 60°$	Sands and silts and pebbles	dm	Weathering notch	Horizontal	$30 < \% \leq 60$	dm	50% open/closed	None	Poor and ephemeral	Narrow/low beach[2]	Absent	Absent
Marechiaro	$0 < h \leq 5$	$S \leq 30°$	Tuffs	m	Free of erosional features	Seaward dip	$30 < \% \leq 60$	cm	Open	None	Bare	Absent	Fresh talus	Horizontal sloping shore platform[1]
Punta Braccetto	$0 < h \leq 5$	$S > 60°$	Sands and silts	dm	Possible slump scars	Horizontal	$\% \leq 30$	cm	Closed	None	Bare	Absent	Fresh talus	Absent
Punta del Corvo	$0 < h \leq 5$	$S \leq 30°$	Limestones	dm	Free of erosional features	Horizontal	$\% \leq 30$	cm	Closed	None	Poor and ephemeral	Absent	Absent	Absent

Table 5 (continued)

Site	Height	Slope	Lithology	Marine erosional features	Land erosional features	Strata dip and strike	Structures	Persistence	Aperture	Infillig	Vegetation cover	Beach	Talus	Platform
Punta Pennata	$5 < h \le 20$	$50° < S \le 60°$	Tuffs	m	Possible slump scars	Seaward dip	$30 < \% \le 60$	m	Open	Soft infilling	Mature, dense and undisturbed	Absent	Absent	Horizontal sloping shore platform[2]
Puolo	$5 < h \le 20$	$40° < S \le 50°$	Limestones	cm	Rill	Seaward dip	$30 < \% \le 60$	m	Open	None	Mature	Absent	Absent	Horizontal sloping shore platform[1]
Seiano 1	$h > 60$	$S > 60°$	Limestones	m	Possible slump scars	Landward dip	$30 < \% \le 60$	m	50% open/closed	Hard infilling	Poor and ephemeral	Absent	Absent	Absent
Seiano 2	$h > 60$	$S > 60°$	Limestones	cm	Stepped and gullied, and slump scars	Landward dip	$30 < \% \le 60$	m	50% open/closed	None	Mature, dense and undisturbed	Wide/high beach[1]	Old large talus well vegetated	Horizontal sloping shore platform[2]
Spiaggia del Poggio	$20 < h \le 40$	$50° < S \le 60°$	Tuffs	dm	Minor gullies	Seaward dip	$30 < \% \le 60$	dm	50% open/closed	Hard infilling	Mature	Narrow/low beach[2]	Fresh talus	Horizontal sloping shore platform[2]
Torre di Mezzo	$0 < h \le 5$	$S \le 30°$	Sandstones	cm	Possible slump scars	Landward dip	$30 < \% \le 60$	dm	50% open/closed	None	Mature, dense and undisturbed	Absent	Fresh talus	Horizontal sloping shore platform[1]
Torrefumo 1	$h > 60$	$S > 60°$	Tuffs	Several meters-caves	Stepped and gullied, and slump scars	Seaward dip	$\% > 60$	m	Open	Soft infilling	Bare	Absent	Absent	Absent
Torrefumo 2	$h > 60$	$S > 60°$	Tuffs	Free of erosional features	Stepped and gullied, and slump scars	Seaward dip	$\% > 60$	m	Open	Soft infilling	Poor and ephemeral	Wide/high beach[1]	old large talus well vegetated	Absent

[1]Waves reach the cliff at spring tides and storm surges

[2]Waves impact the cliff during daily high tide

Table 6 Forcing characteristics at each coastal sector used to calculate its CFIx' score

Site	Tidal range	Degree of littoral exposure to wave events	Relative sea level trend
Cala Rossa	Microtidal	Subparallel	Fall/stable
Capo Rama	Microtidal	Subparallel	Fall/stable
Cirella 1	Microtidal	Oblique	Fall/stable
Cirella 2	Microtidal	Oblique	Fall/stable
Coroglio	Microtidal	Oblique	Rising
Guardiola	Microtidal	Subparallel	Fall/stable
Irminio	Microtidal	Subparallel	Fall/stable
Marechiaro	Microtidal	Subparallel	Rising
Punta Braccetto	Microtidal	Parallel	Fall/stable
Punta del Corvo	Microtidal	Subparallel	Fall/stable
Punta Pennata	Microtidal	Oblique	Rising
Puolo	Microtidal	Oblique	Fall/stable
Seiano 1	Microtidal	Oblique	Fall/stable
Seiano 2	Microtidal	Oblique	Fall/stable
Spiaggia del Poggio	Microtidal	Oblique	Rising
Torre di Mezzo	Microtidal	Subparallel	Fall/stable
Torrefumo 1	Microtidal	Parallel	Rising
Torrefumo 2	Microtidal	Parallel	Rising

and CFIx for a few representative case studies and Fig. 7 is the graphical representation of CSIx values obtained at the considered coastal sectors.

According to the results obtained it is possible to observe:

Class 1 corresponded to areas of very low susceptibility, i.e. $0.6 \le$ CSIx ≤ 1. The only example was Seiano 2 which is cut into a very resistant lithology (limestones) and is fronted by a wide beach. On the upper part of the cliff, it is possible to observe the presence of a mature and undisturbed vegetation cover. Considering the forcing characteristics, good scores were obtained because the area is oblique to the direction of occurrence of predominant waves. Considering PEIx and CFIx values, the cliff fell into Class 2 of susceptibility but a correction factor (its score was multiplied by 25%) was applied due to the presence of a shore parallel protection structure at the cliff toe.

Class 2 corresponded with areas of low susceptibility, i.e. $1 <$ CSIx ≤ 1.5, and included 38% of the considered coastal sectors. Among the seven coastal areas that belonged to this class, five are cut in sedimentary (breccias, limestones and sandstones) lithologies, one in metamorphic (phyllites) rocks and one in igneous (tuff) rocks. Marechiaro (CSIx = 1.5) is a sloping coast type located in the Campi Flegrei coastal sector cut in volcanic lithologies that present good PEIx scores, e.g. for cliff' slope (30°) and height (5 m), absence of marine erosional features, bare vegetation cover and the presence of a wide horizontal shore platform at the cliff toe. Concerning forcing parameters, the good score obtained was linked to the subparallel exposition of the coast to wavefronts and the local rising sea level trend that is equal to the average regional trend.

Class 3 corresponded with areas with a medium level of susceptibility, (i.e. $1.5 <$ CSIx ≤ 1.9) and included 28% (or five sectors) of the considered sectors. Among them, two sectors are cut in volcanic and three in sedimentary lithologies. Capo Rama and Seiano 1 are both characterised by limestones showing respectively the highest (1.9) and the lowest (1.6) values recorded of Class 3 of CSIx. Torrefumo 2 belonged to this class of susceptibility despite showing a high value of PEIx and CFIx due to its morphological, geotechnical and meteo-marine characteristics resulting in a final CSIx score of 2.3. However, the medium value of susceptibility was especially due to the presence of a seawall that reduces by 25% the susceptibility value. Since the construction of the seawall, which was placed a few meters seaward of the cliff toe, the widespread retreat induced by wave action was dramatically reduced but landslides and weathering processes locally continued acting on the slope (Esposito et al. 2018b). The increase of beach elevation at the cliff toe is partially related to the emplacement of the protection structure. The area behind the structure is relatively sheltered and this allows the accumulation of collapsed material at the cliff toe that forms a talus. Furthermore, some of the positive changes observed at the cliff base are linked to an artificial sediment accumulation in order to fill the area back to the seawall (Esposito et al. 2018b).

Class 4 corresponded to the high class of susceptibility ($1.9 <$ CSIx ≤ 2.4) and included 22% of the considered sectors: 50% of them are cut in sedimentary (carbonatic sediments) and 50% in volcanic (tuffs) lithologies. Coroglio, in the Campi Flegrei area, with a CSIx = 2.0 was used as an example. Unfavourable scores were linked to tuff units that are characterised by an intricate system of planar discontinuities and fractures (Matano et al. 2016) and the high cliff slope and height. Favourable scores were related to the presence of a slope talus at the cliff base composed by breccias and caused by the frequent failures occurring along the cliff. The cliff instability is the result of several causes, like the complex volcano-tectonic evolution, the severe anthropic excavations of the cliffs since Roman times and significant erosion processes affecting a large part of the coastal area (Matano et al. 2020).

Class 5 corresponded to areas with a very high susceptibility, $2.4 <$ CSIx ≤ 2.8. Only one of the considered sectors fell in this class, i.e. Torrefumo 1 in Campania region. This cliff represents a particular case in the area since it experienced—before the construction of the sea-wall—very high retreat rates significantly higher than the ones recorded at nearby cliffs. In this case, the very high susceptibility is mainly due to the coexistence of different conditions such as the high cliff elevation and steep slope, the lithological

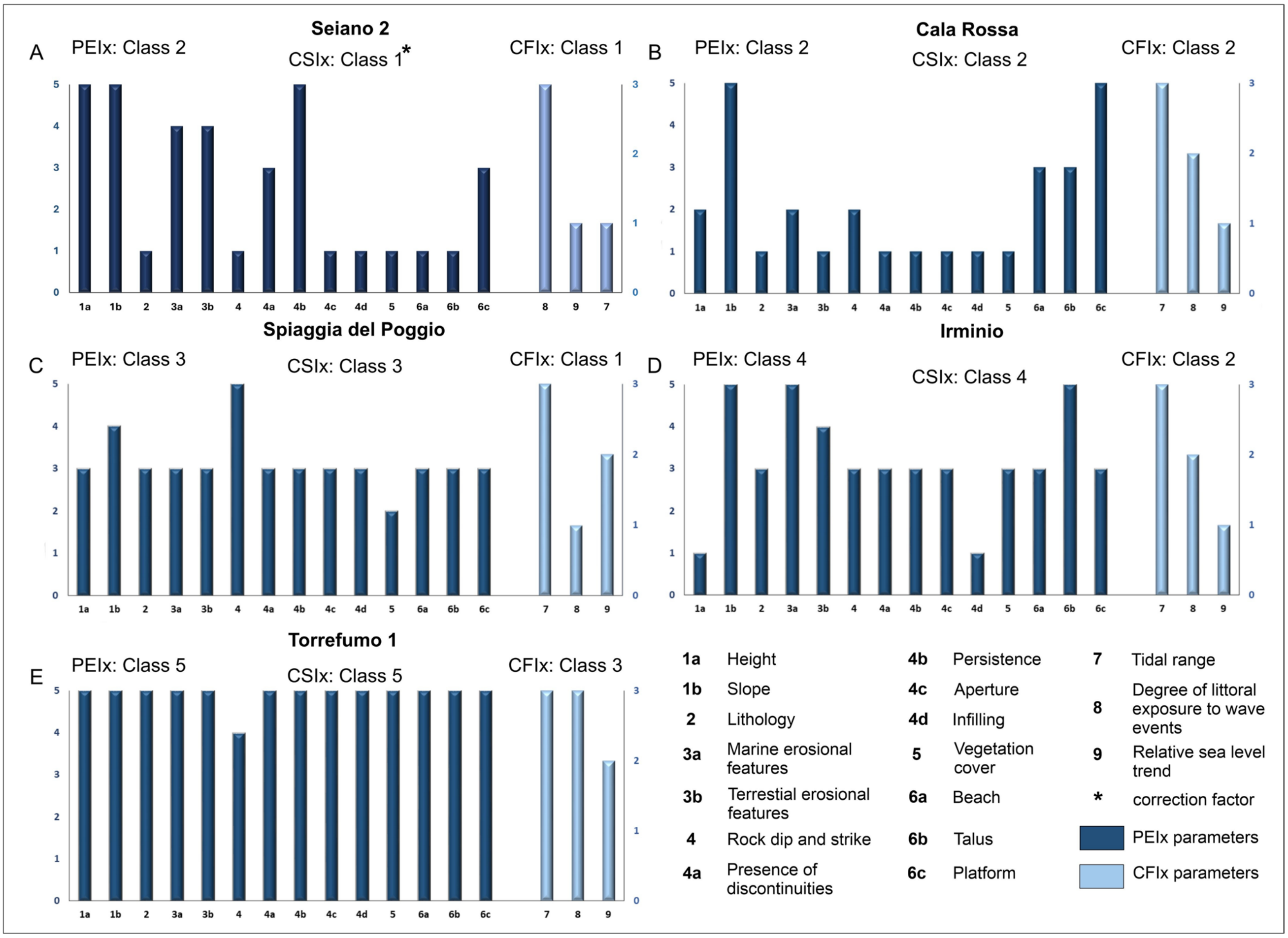
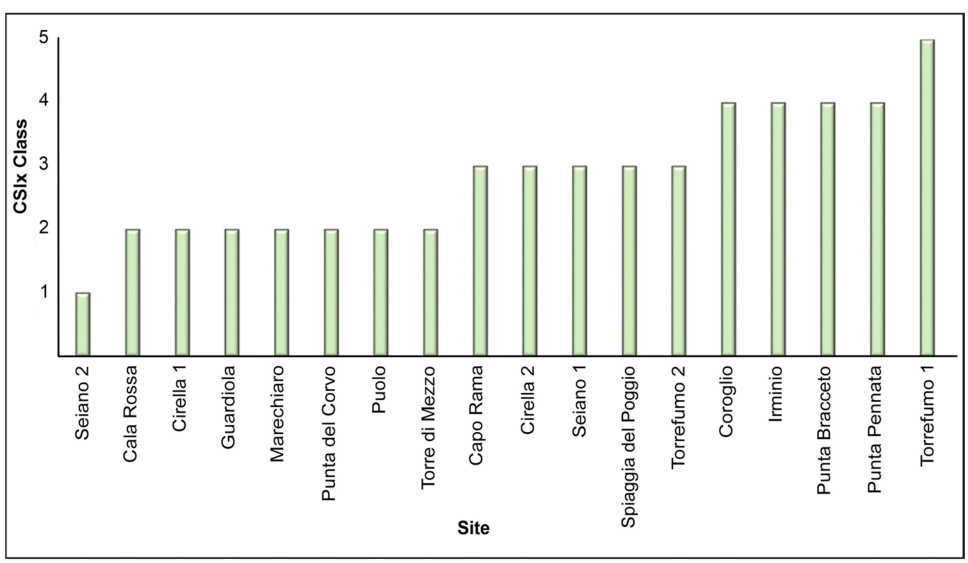


Fig. 6 Graphical representation of the collected data of PEIx (dark blue) and CFIx (light blue); **A** Seiano 2 (Class 1); **B** Cala Rossa (Class 2); **C** Spiaggia del Poggio (Class 3); **D** Irminio (Class 4) and **E** Torrefumo 1 (Class 5)

Fig. 7 Graphical representation of CSIx values obtained at the considered coastal sectors



characteristics, i.e. the presence of erodible lithologies as very altered tuff, the numerous families of discontinuities and the occurrence of gravity-related processes. This cliff has always been subject to attention since it is affected by significant landslides and a considerable retreat rate. In this regard, Esposito et al. (2018b) evaluated the values of cliff retreat from 1956 to 1974 and afterwards the building of an adherent wall to defend the cliff base in 1974. In the first period (1956–1974), the retreat rate was 1.20 m/y while in the second period (1974–2008) was 0.17 m/y, therefore, a significant reduction was achieved. The application of CSIx before and after the construction of the sea-wall showed that the susceptibility value changed from a very high value of 2.8 (Torrefumo 1) to a medium value of 1.7 (Torrefumo 2), confirming the improvement of its stability provided by the emplacement of the structure but highlighting also the presence of other phenomena that still threaten its stability, i.e. relevant retreat rates are still observed due to gravity. In Fig. 8 it is possible to observe the complex geomorphological situation of Torrefumo 2 cliff that, although protected at the base by a seawall, registers a high rate of retreat due to gravity-related processes.

By observing and comparing the different study sites is possible to observe that:

Cliffs cut in sedimentary rocks generally fall in classes 2 and 3 of susceptibility. Such cliffs share, besides their lithology (they are generally composed by limestones) and a UCS $\geq$ 250 MPa, several other physical factors. Within the group "Structure discontinuities" (Table 1) common scores at two sub-variables are usually observed, i.e. "Presence of structures", which usually present an abundance between 30 and 60% (at Capo Rama, Cirella 1, Irminio, Puolo, Seiano 1 and 2 and Torre di Mezzo) and"Infilling", being the absence of infilling material quite common.

Within the "Natural Protection" group (Table 1), the sub-variables "Beach" and "Talus" present "Very high" susceptibility values, i.e. absence of protection, e.g. at the cliff foot in Capo Rama, Cirella 1, Cirella 2, Punta Braccetto, Punta del Corvo Puolo, Seiano 1 and Torre di Mezzo.

Cliffs cut in igneous rocks generally belong to classes 3 and 4 of susceptibility. In this case, most relevant physical factors include within the group "Structure discontinuities" (Table 1), three sub-variables, i.e. "Presence of structures", which usually present an abundance between 30 and 60% at Coroglio, Marechiaro, Punta Pennata and Spiaggia del Poggio), "Aperture", with open discontinuities at Torrefumo 1 and 2 Punta Pennata and Coroglio and Marechiaro) and "Infilling", with the observation of soft infilling at Torrefumo 1 and 2 Punta Pennata and Coroglio. Last, the "Layer dip and strike" sub-variable appears to be an important factor at Marechiaro, Punta Pennata, Spiaggia del Poggio and Torrefumo 1 and 2 where strata dip seaward.

The only analysed cliff (Guardiola) cut in metamorphic rocks belongs to class 2 of susceptibility. In this case, besides the very resistant lithology (phyllite), the most relevant physical factors (Table 1) are the low height ($0 < h \leq 5$), the landward "strata dip and strike" and the absence of "terrestrial erosional features". However, it would be useful to have more case studies to identify further common trends.

Results of the used CSIx suggest that variables such as cliff lithology and the degree of exposure to waves' fronts determine the degree of susceptibility of rocky coastal sectors and such observations are confirmed by Walkden and Hall (2005), Trenhaile (2005), (2011) and Castedo et al. (2012). Furthermore, the relevance of the lithological composition to the sensitivity of rocky sectors is also in

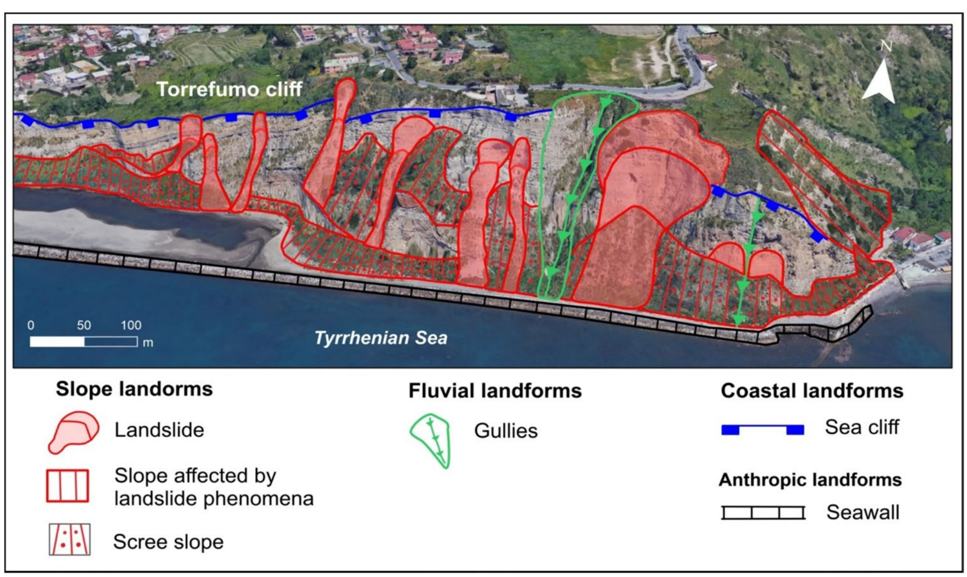


Fig. 8 Geomorphological sketch map of Torrefumo 2 evidencing the great number of gravity-induced landforms

Table 7 Results of the linear multiple regression analysis performed on cliff retreat rate and CSIx data

$f * RR$	
Multiple R	0.85
Multiple R^2	0.72
Adjusted R^2	0.70

Multiple R: multiple correlation coefficient. Multiple R^2: coefficient of multiple determination. Adjusted R^2: coefficient of determination adjusted by the number of independent variables

concordance with Hutchinson (1988), Benumof and Griggs (1999), Benumof et al. (2000), Budetta et al. (2008), Del Río and Gracia (2009); Gerivani et al. (2020). Those authors suggested that lithology is among the major factors influencing the stability of cliffs along with a wide range of attributes like grain size of composing materials (in the case of unconsolidated rocks), the existence of bedding planes, etc. The orientation of the coastline in relation to waves' fronts is another relevant aspect since wave action determines erosion processes acting at the cliff toe and at the beach (if any) in front of the cliff (Russell and Griggs 2012). Other relevant factors are the width of natural protective structures, i.e. beaches and shore platforms (Griggs2005; Russell and Griggs 2012), and vegetation cover that protects the cliff top from terrestrial processes (i.e. run-off) as suggested by Russell and Griggs (2012).

Finally, obtained CSIx values were verified by analysing the retreat rate between 1988 and 2023. The latter was evaluated following the ABA method reported in Sect. 2. Results of the analysis (Table 7) indicated that the multiple regression model had an acceptable correlation, as evidenced by the coefficient of multiple determination (R^2), with approximately 72–74% of the variation in the CSIx being explained by the model.

Last, some considerations can be carried out on the applicability to different climatic environments of the CSIx method that was tested in different geological settings, all of them belonging to the "Hot-summer Mediterranean climate" (Csa, Köppen 1918). In the case of tropical coastal regions (Group A, Köppen 1918) that are characterized by very high humidity and significant rainfalls, erosional landforms may be exacerbated with the formation of widespread rills and gullies, with water seeping into fractures and along discontinuity planes, this would probably affect points 3b and 4e of the used method (Table 1). However, such negative effects are partially counteracted by the fact that abundant rainfalls contribute to the development of a widespread and dense vegetation cover that reduces rain's erosion capacity and increases the protection of the cliff (point 5a, Table 1). In semi-arid coastal regions (Group B, Köppen 1918) characterized by extremely low rainfalls and high-temperature variations between day and night, such significant temperature variations will favour "freezing and thawing" processes leading to the opening of existing fractures and therefore influence the "aperture" parameter (point 4 d, Table 1). In polar coastal regions (Group E, Köppen 1918) cliff erosion is mainly due to weathering processes, essentially the "freezing and thawing" processes, and the subsequent removal of debris through mass movement. Here, weathering along joints, bedding planes and other natural fractures weakens the rock, making it more susceptible to dislodgment and removal by wave quarrying (Trenhaile 2011). This process further intensifies the impact of grounding ice blocks on the shore platform (Hansom 1983; Trenhaile 1987). Considering the previous assumptions, it is possible to state that, from one side, the proposed CSIx method is probably applicable for tropical and semi-arid climates but, on the other side, further studies should be conducted to adapt it to polar regions, it is probably necessary to reassign weighting factor to different parameters considered.

Conclusion

The scope of this paper was to test the validity of a novel method, based on existing approaches, to estimate the susceptibility to erosion processes of selected representative rocky coastal sectors chosen for their different lithologies and geological and structural characteristics along the South-western Italian coast. This constitutes a scientific planning instrument that considers a great number of components relevant to the evaluation of the susceptibility to erosion of rocky coasts. Furthermore, as it is mainly based on indirect analyses supported by photo-interpretation of orthophotographs and topographic maps, it does not require intensive fieldwork and can be applied to large coastal sectors. From a coastal management perspective, this procedure allows the zonation of wide rocky coastal areas according to their grade of susceptibility and the identification of areas of criticism where specific action strategies need to be adopted. In addition, the method allows getting useful information for appropriate spatial planning in areas that are not yet anthropised. In the case of anthropised sectors, the method leads to the identification of "hotspots" that require sound monitoring strategies and, at places, immediate protection. It is emblematic the case of Torrefumo that was evaluated before and after the construction of the seawall; the CSIx allowed to demonstrate the effectiveness of the emplacement of the structure that reduced its susceptibility to marine erosion processes.

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Declarations

Conflict of interest The authors declare no competing interests.

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