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Notes

Application of a method to assess coastal hazard: the cliffs of the Sorrento Peninsula and Capri (southern Italy)

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Abstract: A systematic method to quantify, rank and map the distribution of hazards is applied to the coastal cliffs of the Sorrento Peninsula and Capri (Campania, southern Italy). For such cliffs, which have previously been characterized in terms of types and processes, and therefore compartmentalized, the predisposition to a particular hazard (or indicator), based on its nature, magnitude and recurrence, is evaluated by assigning a code: the higher the predisposition, the higher the code for each compartment. Moreover, hazards can influence one another, and the number of such interactions indicates the seriousness of each hazard, to which a weighting is assigned. By comparing each code in a specific compartment using an interaction matrix, which takes the weighting into consideration, we have calculated a resultant, which is the overall hazard for the compartment. This resultant can also be expressed cartographically. In this application six primary hazards (parameters) are considered: cliff retreat, riverine flooding, storms, landslides, seismicity and volcanism, and man-made structures. The last is the most hazardous parameter, which is weighted highly, owing to its extensive influence on the other hazards. In contrast, riverine flooding and seismicity and volcanism are the least interactive.

Coastal areas are generally dynamic environments because continental and marine processes converge along them to produce a landscape that is subject to rapid changes. Such changes could be attributed to single catastrophic events, as well as to continual events and processes, which contribute to the modelling of the coastal landscape. The evolution of this landscape, in which waves, tides and marine currents interact, may modify the intensity of one of these processes by increasing or reducing the effects of another, in time and space. Moreover, some recent coastal changes are the result of human activity, which is able to heighten the effect of coastal processes.

In coastal areas, which vary greatly in topography, climate and vegetation as well as land use (tourism, industry, agriculture, etc.), the rate of coastline retreat has assumed significant proportions. This rate can represent a high degree of coastal hazard, especially in populated areas near the coast, because of frequent losses of money and property, and even of human life. In this case, knowledge of coastal hazards as well as their distribution becomes a basic tool for supporting planning and management decisions.

This paper proposes an application of a semi-quantitative method for assessing coastal hazard along a stretch of the Campania coast in southern Italy, where steep and rocky coasts are prevalent. This stretch, comprising a peninsula and its geologically related island, is known for its holiday resorts, such as Sorrento, Positano, Amalfi and Capri.

Coastal setting

The investigated coastal area is on the eastern side of the Tyrrhenian Sea in the region of Campania (Fig. 1) and has a very complex topography, which reflects the neotectonic activity affecting this portion of the Apennine chain during the Quaternary, when extensive subsidence and uplift resulted in a horst and graben structure (Brancaccio *et al.* 1991). Along this coast, the horst is represented by a narrow mountainous transverse ridge, oriented nearly east–west, with prevalent steep and rocky coastal cliffs, as observed along the Sorrento Peninsula and on Capri, whereas the graben consist of broad alluvial plains with sandy beaches, as seen on the Campania and Sele plains, respectively to the north and south of the Sorrento Peninsula (Fig. 1). In both plains the filling of the graben is mainly due to the contribution of alluvial sediments of the Volturno and Sele rivers, as well as to marine transgression. However, only on the

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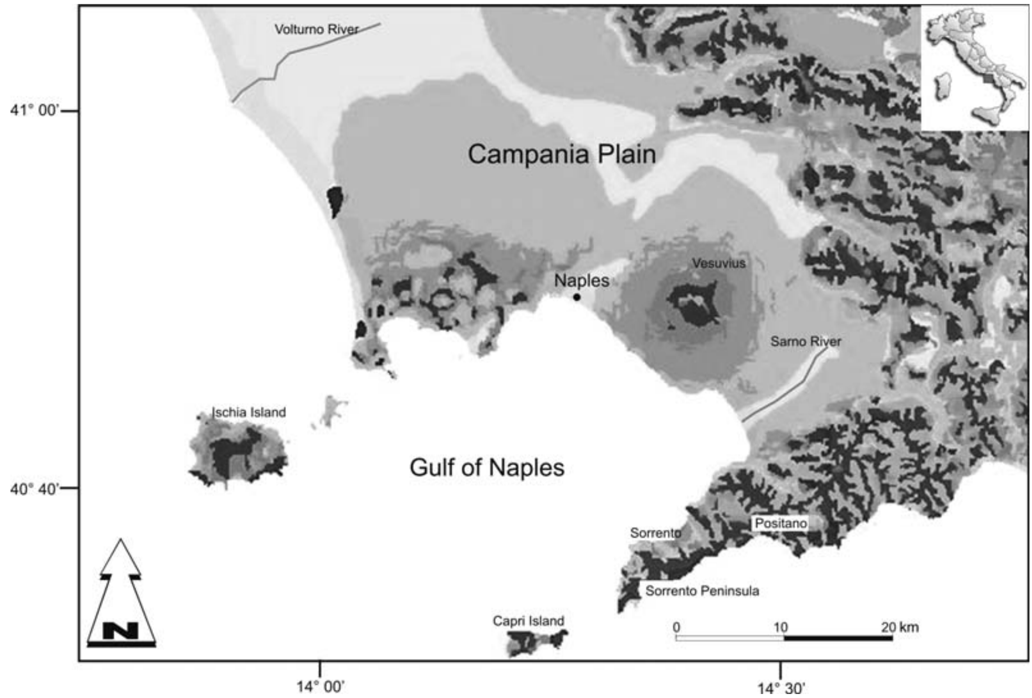


Fig. 1. Location of the study area. The Sele Plain and the Sele River are south of the area shown in the figure.

Campania Plain is there a major contribution in terms of thickness and distribution of deposits deriving from the volcanic centres of the Phlegrean Fields and Somma–Vesuvius, whose activity began in the Early–Middle Pleistocene (De Vivo *et al.* 2001). These products, in particular tuff and lava, reach the sea and characterize the rocks exposed in cliffs as well as part of the submarine floor in the Bay of Naples. Pyroclastic deposits are also found on hillslopes and in valleys bordering the Campania Plain as well as in the Sorrento Peninsula and on Capri.

Urbanization of the coastal area started in Classical times and has since expanded markedly, with the coast being used for several purposes (thermal bath complexes, fishing, shipping, tourism, etc.); thus some of the structures and infrastructure sited on the coast were protected from wave action. In time, these protected stretches have been extended because of the critical rate of coastal erosion and the greater occupation of the coastal zone for residential and industrial purposes. In most cases, the urbanized coastal stretches have lost the character of the natural environment as a result of engineering structures being built, at sea or on the coast, to protect the waterfront (‘technocoast’; De Pippo *et al.* 2008).

The rainfall and temperature recorded for the coast of Campania are typical for a Mediterranean climate, with a dry season between June and September and a wet season from October to May. For this coast the westernmost areas experience lower rainfall (Capri and the tip of the Sorrento Peninsula: <1000 mm a^{-1}) compared with the southeasternmost area (southern side of the Sorrento Peninsula: >1200 mm a^{-1}). The latter condition is due to a barrier effect to air masses from the south, especially in autumn, caused by the presence of high-altitude relief close to the coast (increasing eastward to 1440 m above sea level (a.s.l)).

Records from the Capri weather station (267 m a.s.l.) show a significant percentage of northerly winds, although the frequency of southerly winds, especially from the SE, increases in spring and in autumn, as already noted for rainfall. Probably related to the widest southern fetches, above all from the SW (>500 km), are the prevalent storm waves coming from the south; northwesterly storm waves are much less common.

Wave height generally ranges between 0.9 and 2.2 m, although heights of up to 4.7 m may be reached, especially in winter. Lower values occur in sheltered stretches, such as some areas in the Bay of Naples. Along the Campania coast the littoral drift is generally from NW to SE (Cocco *et al.* 1989, 1992).

Sea-cliff features

The morphological features and evolution of the rocky cliffs along the Sorrento Peninsula and Capri island have been defined through field observations, study of aerial photographs and satellite images, as well as single beam bathymetric surveys down to −20 or −30 m depth. Along this coastline, some rocky cliffs are characterized by a shore platform at their foot, whereas others continue vertically below sea level. On top of the cliff, a predominantly convex or almost uniform gradient (at times with crags) and occasionally a concave slope develops. There are also cases where the cliff represents the edge of a nearly horizontal or slightly inclined surface, such as Pleistocene marine terraces (Brancaccio *et al.* 1991).

The presence of the coastal platform (*sensu* Sunamura 1992) in most of the analysed morphologies indicates persistent erosion processes along the cliff, which have also occurred during sea-level stands other than the present. The physiography of the coastal platform is related both to the intensity of the erosional processes and to the time span in which they have acted, as well as to the structure and durability of the outcropping rocks (hard or soft). More specifically, cliffs with a platform up to 200 m wide, and occasionally up to 500 m, have been observed, with a bottom slope between 3% and 10%. Other cliffs with a platform, or rather a ramp, which extends for less than 100 m and with a slope exceeding 10% have been recognized. They are classified as sloping shore platforms (type A of Sunamura 1992), but our observations allow two categories to be discriminated within this type: A1, large coastal platforms with low gradient; A2, narrow coastal platforms with a significant gradient.

On the northern side of the Sorrento Peninsula, which is less subject to intense sea storms, coasts develop mainly with the type A1 profile, showing a large platform and reduced gradient (Fig. 2). The height of the cliffs varies greatly in relation to the lithology: between 25 and 70 m for carbonate formations; between 120 and 200 m for terrigenous (sandstone and pelite) units overlain by carbonate rocks; between 25 and 60 m for arenaceous–silty layers; less than 25 m for coastal slopes formed by pseudo-coherent talus deposits; up to 50 m for tuffs (Fig. 3) (De Pippo *et al.* 2007).

This variability is frequently associated with a geotechnical characterization of soft consistency rocks. Indeed, along the northern side of the Sorrento Peninsula the mechanical resistance tested on some rock masses, such as highly fractured limestones, proved mediocre (Budetta *et al.* 1991).

The profile classified as A2 develops frequently in the case of very high cliffs, essentially in carbonate rocks. The degradation materials usually accumulate at the cliff toe in the area of connection with the coastal platform, which is inclined at a few degrees. In some cases, the platform develops down to −7 or −8 m depth, with a 10° tilt. This situation is common along the Sorrento Peninsula, especially to the west of the village of Sorrento (Fig. 4). In some cases, a cliff can be located behind a fault offshore, as suggested by relict forms still anchored to the substratum (stacks to the south of Capri and Li Galli islets off Positano, on the southern side of the Sorrento Peninsula).

The initial lack of homogeneity in physico-mechanical characteristics of some lithotypes along the study cliffs is linked to marked tectonic movements and to the effects of intense degradation phenomena that are active along the slopes above them. Tectonics has acted on the massive rock formations leading to rock breakdown into blocks or, in some cases, to such a dense network of fractures that the rock resembles a cataclasite. On these rocks degradation phenomena, and thus the erosive action of the waves, are facilitated. Dissolution of carbonates with the development of microforms (rock pools and lapiés) and macroforms (caves) are among the most common weathering phenomena observed along the investigated coast. Moreover, detrital cover commonly develops along sea-cliffs, with characteristics suggesting that it is not due to present-day morphological conditions and degradation processes, but is inherited from the frost-wedging conditions existing during the latest Pleistocene glaciations.

Another cliff type has heights varying from 10 m to just over 100 m and is frequently characterized by slopes with medium gradients. At the foot of these coastal slopes, terraced surfaces are found, which may form exposed surfaces during low tide. On these surfaces, strips of well-cemented calcarenites with abundant mollusc fragments of a beach environment, probably of Tyrrhenian age (Brancaccio *et al.* 1991), are found. The surfaces are shaped by processes of chemical and physical weathering of the rocks, which are favoured by the frequent drying to which they are subjected. This morphotype can be observed along the northern sector of the Sorrento Peninsula and Capri, mainly on carbonate formations and secondarily on terrigenous deposits (De Pippo *et al.* 2007). The erosive action of waves has strongly shaped the coastal platform and therefore this type must be classified as a different form.

The extension of the emerged coastal profile in an underwater environment to −30 m, without significant erosive forms, highlights the role of tectonic movements that mainly occurred during the Pleistocene. The cliffs that develop along faults are usually steep, so the erosive action of waves vanishes or drastically decreases as a result of the well-known

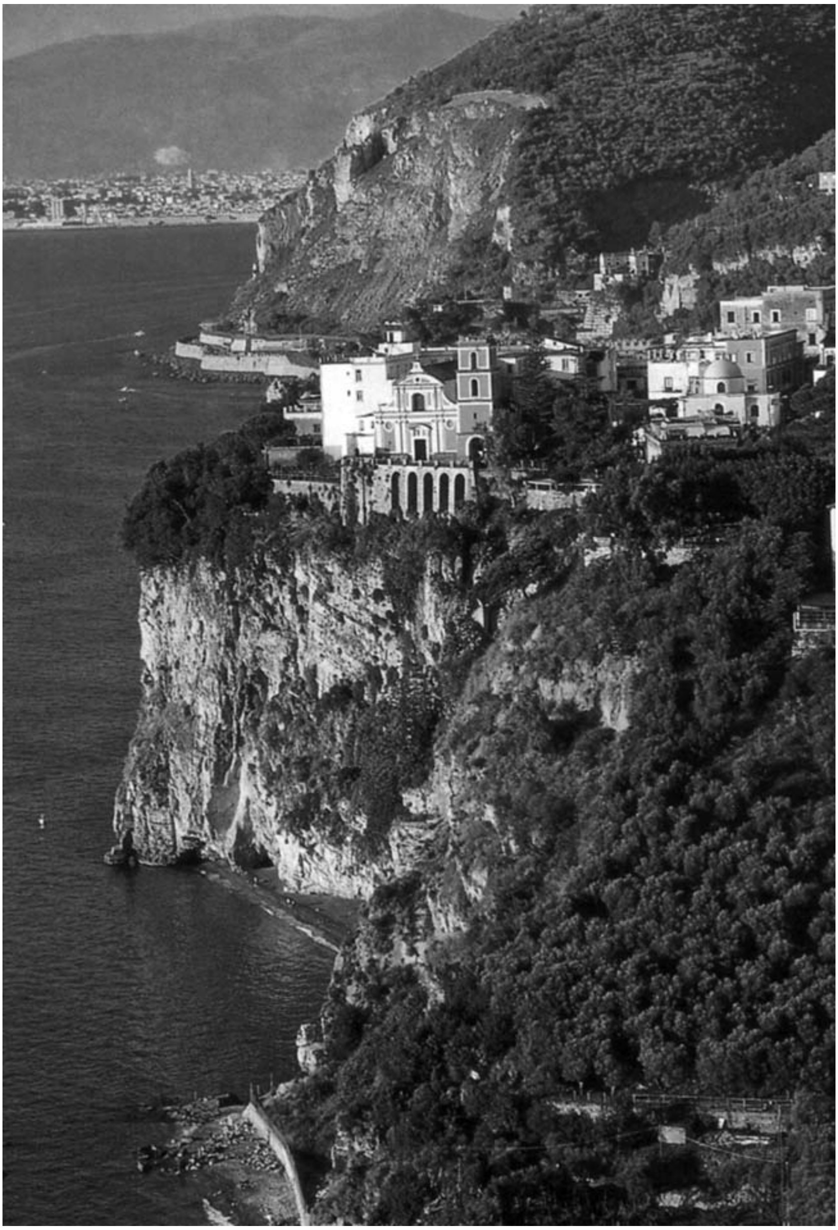


Fig. 2. Carbonate cliff with a pocket beach developed at its base. Bathymetric data reveal a wide and gently sloping shore platform offshore (Vico Equense village; northern side of the Sorrento Peninsula).

phenomena of reflection. These cliffs belong to the plunging cliff type of Sunamura (1992) and occur mainly in the carbonate formations at the tip of the Sorrento Peninsula (Punta Campanella) and in some segments of its southern side (Fig. 5; Brancaccio 1968; De Pippo *et al.* 1998, 2007), as well as in the west of Capri (Barattolo *et al.* 1992; De Pippo *et al.* 2007). These cliffs can be classified as hard rock cliffs. In particular, along their exposed surfaces palaeo sea-notches at different heights are found; the genesis of these is probably connected with recent sea-level highstands (Brancaccio *et al.* 1978; Pirazzoli 1993; Riccio *et al.* 2001), suggesting stability of the cliff and the persistence of the wave

Fig. 3. Cliff composed of volcanic tuff, about 50 m high. In this area a submerged shore platform reaches about 2 km width (S. Agnello on the northern side of the Sorrento Peninsula). (Note the large structures built on the top of the cliff.)

action. The formation of sea-notches on carbonate cliffs is mainly due to the dissolution of carbonate rocks and to organism grazing and perforation activity (biokarst). The role of chemical processes is also emphasized by the widespread presence of marine caves, especially along the southern cliffs of the Sorrento Peninsula, at sea level or slightly above or below it (De Pippo *et al.* 1998).

Fig. 4. Cliff composed of carbonate deposits, with a narrow and steep shore platform (Punta Gradelle on the northern side of the Sorrento Peninsula). (Note the cliff composed of tuff on the lower right.)

Fig. 5. Example of a plunging cliff. The photograph also shows truncated incisions (arrows indicate some of them). Seno di Ieranto near the western end of the Sorrento Peninsula.

Structural cliffs showing a continuity along the stream incisions orthogonal to the coast have great importance in the coastal landscape of Capri and the southern Sorrento Peninsula, thus defining a characteristic ria morphology. Such incisions partly extend underwater and often correspond to tectonic alignments (De Pippo *et al.* 2007). In other cases, they may be related to the degree of fracture of outcropping rocks or to varying resistance of rock formations along the slope. The latter case is observed, for example, along the southern side of the Sorrento Peninsula, where a structural slope is composed of Cretaceous limestone on Miocene arenaceous–pelitic deposits.

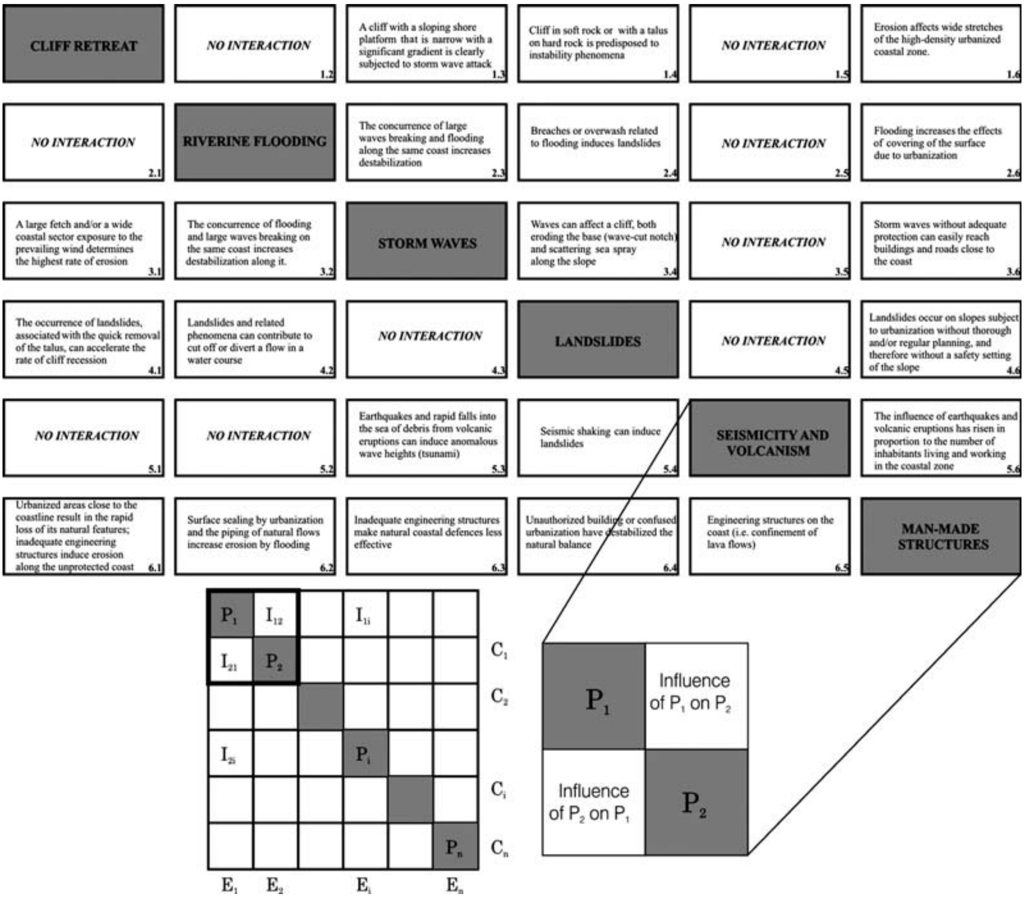
In conclusion, the morphology of the coast of the Sorrento Peninsula and Capri represents a dynamic result of past and long-term evolution and can be considered rather homogeneous, being mostly steep and rocky. Moreover, the stretch around Sorrento and Castellammare di Stabia in the Sorrento Peninsula, as well as the localities known as Marina Grande and Marina Piccola on Capri, are somewhat modified by anthropogenic action expressed by several manmade structures and by use of the waterfront, which have greatly interfered with the natural environment. The evolution of such cliffed coasts, which have lost most of their natural features, is less predictable than that of natural cliffs.

Method

In recent decades many attempts have been made to seek the elements that could be essential in assessing coastal hazard. At first, the erosion rate of a beach or along a cliff was measured to give the degree of hazard (e.g. in Italy, by Caputo *et al.* 1991). Later, other researchers recognized in the features of a coast (i.e. geological setting, coastal slope) as well as in the occurrence of some natural events (coastal erosion, wave damage from storm, rockfalls from the cliff) the potential hazard for an area (Berger 1997; Berger & Iams 1996; Bush *et al.* 1999). Recently, we proposed a method that followed the latter trend: the primary hazards were identified and ranked for a specific coastal area using an interaction matrix (De Pippo *et al.* 2008).

Here this method is applied to rocky coastal areas, which are characterized in terms of physical and anthropogenic features as well as morphological processes. An arrangement of these features as well as a high magnitude and a short recurrence interval of such processes could indicate the tendency to become a hazard. Therefore, a detailed knowledge of the coast is important to choose the most significant attribute to consider in ranking the matrix parameters. In other coastal studies (Bush *et al.* 2001; Richmond *et al.* 2001) the importance of the overall hazard has been given by a simple sum of the ranks, whereas in this study we opted to use a matrix in which primary hazards interact with each other in a given coastal area (Hudson 1992). This matrix, which has been tested in other environmental studies (e.g. Simeoni *et al.* 1999*a*, *b*), takes account of the impact of each parameter on the others.

In this application six parameters are considered: cliff retreat, riverine flooding, storm waves, landslides, seismicity and volcanism, and manmade structures; these are the most common hazards recognized along this coast. These parameters represent the basic components of the matrix, as they are plotted in the boxes of its diagonal. The other boxes in the matrix are filled by following a clockwise scheme of interaction. In particular, each element of the row that crosses one of the parameters on the mean diagonal shows the influence of this parameter on the system, thus indicating the cause of the phenomena, whereas each element of the column that crosses the same parameter shows the influence of the system on this parameter, thus focusing on the effect of the phenomena (Fig. 6). For instance, in the interaction between two diagonal terms such as cliff retreat and storm



CLIFF RETREAT	*NO INTERACTION* 1.2	A cliff with a sloping shore platform that is narrow with a significant gradient is clearly subjected to storm wave attack 1.3	Cliff in soft rock or with a talus on hard rock is predisposed to instability phenomena 1.4	*NO INTERACTION* 1.5	Erosion affects wide stretches of the high-density urbanized coastal zone. 1.6
NO INTERACTION 2.1	**RIVERINE FLOODING**	The concurrence of large waves breaking and flooding along the same coast increases destabilization 2.3	Breaches or overwash related to flooding induces landslides 2.4	*NO INTERACTION* 2.5	Flooding increases the effects of covering of the surface due to urbanization 2.6
A large fetch and/or a wide coastal sector exposure to the prevailing wind determines the highest rate of erosion 3.1	The concurrence of flooding and large waves breaking on the same coast increases destabilization along it. 3.2	**STORM WAVES**	Waves can affect a cliff, both eroding the base (wave-cut notch) and scattering sea spray along the slope 3.4	*NO INTERACTION* 3.5	Storm waves without adequate protection can easily reach buildings and roads close to the coast 3.6
The occurrence of landslides, associated with the quick removal of the talus, can accelerate the rate of cliff recession 4.1	Landslides and related phenomena can contribute to cut off or divert a flow in a water course 4.2	*NO INTERACTION* 4.3	**LANDSLIDES**	*NO INTERACTION* 4.5	Landslides occur on slopes subject to urbanization without thorough and/or regular planning, and therefore without a safety setting of the slope 4.6
NO INTERACTION 5.1	*NO INTERACTION* 5.2	Earthquakes and rapid falls into the sea of debris from volcanic eruptions can induce anomalous wave heights (tsunami) 5.3	Seismic shaking can induce landslides 5.4	**SEISMICITY AND VOLCANISM**	The influence of earthquakes and volcanic eruptions has risen in proportion to the number of inhabitants living and working in the coastal zone 5.6
Urbanized areas close to the coastline result in the rapid loss of its natural features; inadequate engineering structures induce erosion along the unprotected coast 6.1	Surface sealing by urbanization and the piping of natural flows increase erosion by flooding 6.2	Inadequate engineering structures make natural coastal defences less effective 6.3	Unauthorized building or confused urbanization have destabilized the natural balance 6.4	Engineering structures on the coast (i.e. confinement of lava flows) 6.5	**MAN-MADE STRUCTURES**

Fig. 6. Descriptive matrix showing the interactions of hazards. There are six major diagonal terms: cliff retreat, riverine flooding, storm waves, landslides, seismicity and volcanism, and manmade structures. This matrix indicates the influence of the morphological parameters on the system (the cause of the phenomena) or the influence of the system on each of the parameters (the effect of the phenomena) (lower-right scheme). The cause–effect diagram for *N* parameters (lower-left scheme) indicates how the interaction matrix is filled: the box I12 represents the influence of P1 on P2 (cause); conversely, the box I21 represents the influence of P2 on P1 (effect). This mechanism is repeated for each parameter recognized, shown as the diagonal terms in the interaction matrix.

waves, a cliff with a sloping shore platform, which is narrow with a significant gradient (cause), is clearly subject to storm wave attack, whereas a large fetch exposed to the prevailing wind, and therefore to the highest waves, results in the highest rate of erosion (effect).

Both causes and effects contribute at the same rate to coastal hazard assessment. However, in analysing the number of matches for the chosen parameter the most interactive parameters (which were subordinate in the study by Hudson 1992) are represented by the manmade structures and the landslides, whereas the least interactive are riverine flooding and seismicity and volcanism (which were dominant in the study by Hudson 1992). The most interactive factors account for the influence that the system has on them. In contrast, the least interactive, which are strictly related to the physical nature of the area, occur without affecting any changes from the surrounding context.

The importance of each parameter describing the cause–effect interaction is expressed through a semiquantitative score from zero to four (*Ip*), from nil to critical (Table 1). This score is attributed according to the features of a compartment of the coastal stretch examined, which differ from those of the adjacent ones. Such features (forms and processes) determine the score on this stretch, which reflects their predisposition to increase the hazard. Quantification of specific forms (indicators) could be fixed with a range of values or assigned a precise value for a particular stretch or left at the discretion of the operator. For instance, a slope with a low gradient ($<20^\circ$) free of erosional features has the minimum rank, a medium gradient (20–45°) with minor gullies or rills, and a steep gradient (45–70°) with several discontinuities are given respective scores of two and three, and lastly, an oversteepened to steep slope ($>70^\circ$) with slump scars has a score of four. Several indicators with high values give a final maximum score, but indicators of different signs could lower the final score. For instance, the presence of a toe protection of the cliff (beach or talus) lowers the score, notwithstanding other indicators able to increase erosion along the subaerial slope.

The score is also assigned on the basis of previously defined indicators of physical changes and/or events occurring in a suitable time range on a particular coastal stretch. Obviously, the probability of an event being repeated in a very short time range, of the order of a couple of years (high storm waves or landslides induced by heavy rainfall), makes the score significantly worse, whereas those events with a recurrence that is indefinable (volcanic eruption, seismicity, tsunami) or too long for the planning timetable (>10 years) weigh negligibly on the score. Lower recurrence times from 5 to 10 years and from 2 to 5 years respectively worsen the weight by scores of one and two.

For instance, a cliff exposed to a large fetch has a higher score than one exposed to a limited fetch, but this score could also change according to the presence or absence in the submerged profile of a sloping platform. Furthermore, if the recurrence of the storm waves is less than 5 years, the score of this stretch fixed at two (i.e. moderate fetch, cliff with a reduced and high-degree sloping shore platform, and so on) can be raised to four.

To avoid the excessive weighting of a single parameter, such as a locally induced retreat or a single exceptional event, this method considers the sum of the score both for the row and column. Such a sum, equal to the intensity of interaction as positive (cause) and negative (effects), does not yet correspond to the overall hazard, as the highest weight of parameters must be considered. We therefore established for the different geomorphological units the percentage of influence of each parameter (*Xp*) on the overall hazard (on a decreasing scale from a maximum of six to a minimum of zero). For instance, landslides are assigned a weight of five, as the number of causes and effects is lower than that of man-made structures; cliff retreat and storm waves are assigned a weight of four and three, respectively. The lowest weights are for riverine flooding and seismicity and volcanism (Table 2). The last factor has a reduced importance on the coast in question, although proximity to Vesuvius, an active volcano, or to the seismogenetic area of the Apennines, indicates some influence, which is why we decided to assign it the minimum weight. Although this consideration could emphasize the other weights and slightly increase the degree of overall hazard, we deem it none the less appropriate.

To define the overall hazard (*Ht*), the score (*Ip*), already defined for each coastal stretch and for each parameter, will be multiplied by the coefficient (*Xp*) related to the importance of one parameter over another, so that the weighted sum of the product of each parameter for this coefficient of hazard on the investigated coastal stretch is

$$Ht = \sum_{n=1-6} Ip_n Xp_n.$$

The degree of this hazard has been expressed cartographically from Low to Extreme (Stauble 2003): below the minimum value, that is absent or negligible, no map symbol is used (Table 3). This analysis could also be developed through a geographic information system (GIS), where each feature class has a relative database to which a weight could be attributed.

Table 1. *Rank of incidence of the most important indicators*

Indicators	Rank of incidence (*Ip*)			
	1	2	3	4
Erosion rate	Stable or low (near 0)	Moderate (<1 m a^{-1})	High (<5 m a^{-1})	Severe (>5 m a^{-1})
Nearshore and offshore topography	Natural protection (bars, reefs)	Coastal shelf of moderate width with discontinuous offshore bars	Wide shelf; shallow open water with steep slope without bars	Very narrow shelf; high wave energy; rapid deepening of nearshore; closeness to canyon heads offshore
Fetch	Limited (<50 n.m.)	Moderate (<150 n.m.)	Large (<300 n.m.)	Very large (>300 n.m.)
Geomorphological features	Upland (>6 m); very distant from a river mouth	Floodplain or low-elevation terraces (>3 m); within sight of an inlet or river mouth	Wide coastal plain (<3 m); near an inlet or river mouth	Wide coastal plain (<3 m); adjacent to an inlet or river mouth or close to a lagoon
Cliff topography	Low slope angle ($<20°$); free of erosional features	Medium slope (20–45°) angle; minor gullies or rill	Steep slope angle (45–70°); irregular and stepped; possible slump scars	Oversteepened to steep slope angle ($>70°$); stepped and gullied; slump scars
Mechanical condition of the rocks exposed on the cliff	No fractured or weathered 'hard' rocks	'Hard' rocks with a limited number of fractures or a little weathering with a seaward dip: no weathered 'soft' rocks	'Soft' rocks (clays, unconsolidated sands, volcanoclastic rocks) or moderately fractured or weathered 'hard' rocks	Saturated soft rocks (clays, unconsolidated sands, volcanoclastic rocks) or deeply fractured or weathered 'hard' rocks
Vegetation on the cliff	Mature, dense and undisturbed	Mature, undisturbed to minor rotation	Poor and ephemeral; toppled or rotated	Bare; burned or artificially removed
Toe protection of the cliff (beach or talus)	Wide beach or old large talus, well vegetated	Mainly wide beach or vegetated talus	Narrow beach, or eroded or fresh talus	Absent to narrow
Anthropogenic covered surface	$<25\%$	$>25\%$	$>50\%$	$>75\%$
Engineering structures	No structures	Few structures and fronted by beach	Structures grouped along the shoreline	Numerous structures on coast or offshore

n.m., nautical miles/1852 m.

Table 2. *Coding of hazard parameters for the steep and rocky shores*

Parameter number	Hazard parameters	Causes	Effects	Causes + effects	*Xp*
1	Cliff retreat	17	10	27	4
2	Riverine flooding	7	1	8	1
3	Storm	9	10	19	3
4	Landslide	8	24	32	5
5	Seismicity and volcanism	12	1	13	2
6	Manmade structures	19	26	45	6
Total		72	72	144	

Modified from De Pippo *et al.* (2008).

Table 3. *Overall hazard degree according to the weighted sum*

Overall hazard degree (*Ht*)	Weighted sum
Absent or negligible (N)	<21
Low (L)	>21
Medium (M)	>27
High (H)	>33
Extreme (E)	>39

Source: De Pippo *et al.* (2008).

Application

Six coastal hazards have been recognized in the study area, as follows.

(1) Cliff retreat resulting from erosion produced by wave action and weathering. One of the most important factors in cliff evolution is the lithology exposed: a mostly homogeneous hard rock, such as some limestones, will be modelled more slowly than a soft rock, such as tuff or alternating sandstone and shale. This first division produces a lower rank for hard rock ($Ip = 1$ or 2) and a higher rank for soft rock ($Ip = 3$ or 4). However, the presence of elements in hard rock such as fractures and faults, as well as notches and caves, may act as ‘catalysts’ in the rate of retreat, in which case the rank will be higher. Rock resistance tends to decrease with the increase in weathering phenomena. For instance, on the coastline studied, and especially on the carbonate outcrop, the climatic conditions allow karstic phenomena to develop. During periglacial conditions on the studied coast in the Pleistocene abundant detritus was produced, which now covers the coastal slopes. The great thickness of this talus, often with a significant contribution of pyroclastic elements, pushes the rank up to the maximum ($Ip = 4$).

The last element in cliff retreat is the replacement of rock and vegetation on the slope to construct buildings, roads or tourist facilities. This replacement yields greater dishomogeneity in the rock mass and leads to rainwater infiltration. The assigned rank, in this case, changes according to the type of lithology, the degree of weathering and the extent of the replaced surface.

(2) Riverine flooding occurring in conjunction with intense rainfall. Rapid rise in water level and flash-flooding along steep coastal streams have a series of hazardous implications, as reported for the 1954 catastrophic flood that occurred in the stream Bonea located at the southeastern stretch of the Sorrento Peninsula (the Amalfi coast; Esposito *et al.* 2004*a*, *b*; Violante *et al.* 2009), outside the study area. Indeed, in some steep streams along the northern side of the Sorrento Peninsula (Santo *et al.* 2002), as well as in the central portion of Capri, high-frequency events occur that affect the back area of the coast and could cause new open water to form. This could be a major hazard especially where the area has been urbanized (Rossi & Villani 1994), as in Castellammare di Stabia. Given its recurrence interval (<10 years) and intensity this hazard is ranked as medium close to the stream ($Ip = 2$). However, complete or partial removal of the detritus covering coastal slopes may increase the distance of the shoreface from the cliff, thus reducing the overall hazard.

(3) Storms are well known to those living along the coast, especially when high waves, usually produced by severe winter storms and consequent surges, cause severe property damage and are sometimes fatal.

Regardless of the exposure of the coast, some morphological traits of the shoreface area are important in assigning the rank. For instance, gravel beaches or debris cones lying at the foot of the cliff increase the distance between the shoreface and the cliff, thus averting the energy of the waves from the cliff and lowering the rank. Also, the presence of a sloping shore platform may lower the rank, especially when the platform is wide and has a low gradient (type A1 in this study), whereas a narrow coastal platform with a significant gradient (type A2 in this study) increases the rank, because of the short distance between the shoreline and the depth of breakers.

As regards coastal orientation, exposure of the coast to waves is related mainly to the distance the wave travels after leaving the generating area (the fetch) and secondarily to wave refraction. As mentioned above, the longest fetch and the direction of more frequent storms (40%) is from the SW. Hence swell strongly affects the southern side of the Sorrento Peninsula (*Ip* = 2–3). However, on this side of the peninsula the rank may differ depending on whether the cliff has a sloping shore platform or a plunging one. In contrast, on the northern side of the Sorrento Peninsula the fetches are shorter and affect only the westernmost area directly, especially Capri. Nevertheless, some local storms can come from the north in the Bay of Naples and generate waves that reach the coastal area of the port of Sorrento in approximately the same form as they are generated. In this case high waves strongly attack the cliffs, which are frequently of a sloping shore platform type (*Ip* = 2). In the Bay of Naples the phenomenon of refraction is also common, as a result of both the presence of several islands (i.e. Capri to the south, and Ischia and Procida to the north) and submarine topographic features. Indeed, volcanism in the Phlegrean Fields and on the Somma–Vesuvius edifice has created a very irregular sea floor with terraces and canyons (D'Argenio *et al.* 2004; Violante 2009), which may cause waves to converge or diverge.

(4) Landslides affecting the coastal slopes. The main parameters controlling the probability of rockfalls and mudflows relate to steepness and mechanical conditions of the exposed rocks (Hutchinson 1983; Sunamura 1983). The cliff profile is fundamental in attributing a rank of hazard, mainly on the basis of steepness and secondarily on height. The cliffs in soft rock are clearly less high and less steep, but the propensity to fail is high (*Ip* = 3–4), especially where there is undermining at the foot of the cliff, which is frequent on a narrow sloping shore platform. Steep and plunging cliff frequently occurs in hard rock (Fig. 7), where height and steepness generally reach the highest value, but the rank is low unless a significant intersection of fractures occurs. As noted above, discontinuities in the rock mass, such as overlapping of hard rock on soft rock and vice versa, interlayering of thick pelitic strata, and columnar structures, can be important predisposing factors leading to collapse of large blocks and debris (Budetta *et al.* 2000). In particular, the presence of sea-notches and tension cracks has been found to be responsible for the instability of even hard rock coastal cliffs (Kogure *et al.* 2006), whereas wide wave-cut terraces protect the

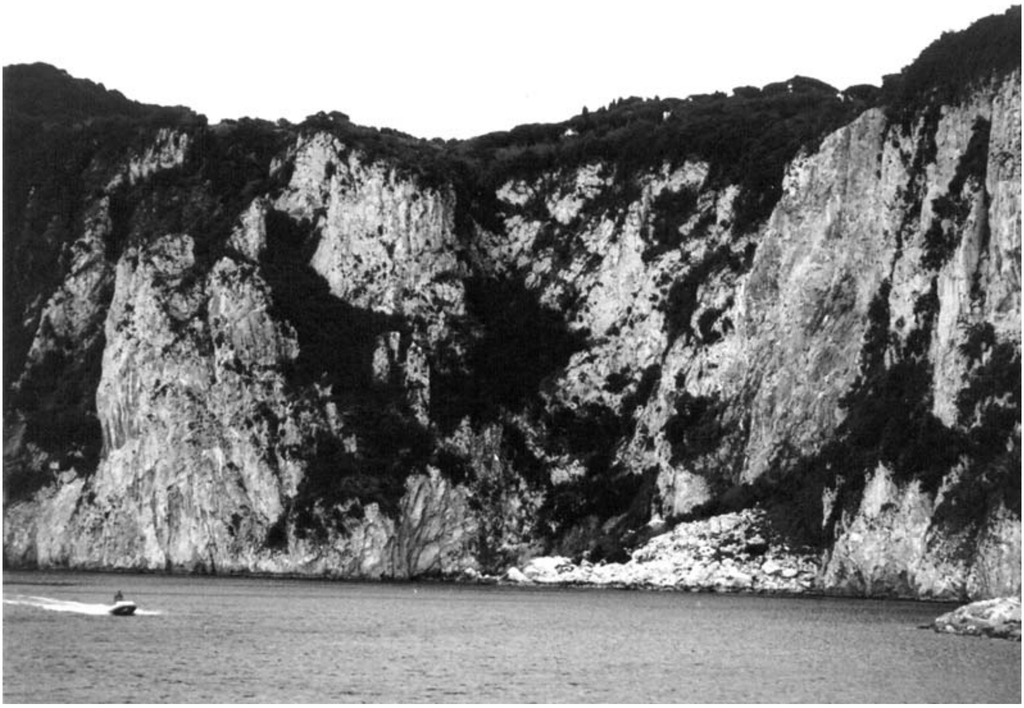


Fig. 7. Example of a carbonate cliff affected by slide phenomena (Marina Grande on the northern side of Capri).

cliff from mechanical erosion. The latter feature has controlled, for instance, the development of cliff profiles and hence their evolution generally towards a more stable condition (Sunamura 1983; Trenhaile 2002). Another characteristic that increases the rank is the existence of previous instability phenomena occurring along the cliff. According to recent data several landslides along the coastal cliffs both on the Sorrento Peninsula and on Capri have been reactivated. Indeed, significant damage and avoidable deaths occur both at the top of cliffs and at their base, often during autumn and winter. This may be explained by the greater intensity of the processes that affect the cliffs, such as wave action at the base, and the large amount of rain, which penetrates the weathered rocks at the top or along the cliff (Fiorillo & Wilson 2004). For these reasons the rocky cliffs of the Sorrento Peninsula are given a high score for this hazard, especially on the southern side (Budetta & Santo 1993; Budetta *et al.* 1994). A high score is also assigned to stretches affected by major forest fires, which reduce the vegetated area of the cliff (e.g. maquis), especially when the exposed lithology is unconsolidated sediment, which can easily slide seaward (Russo & Valletta 1995).

(5) The seismicity and volcanism hazard is concentrated in the area close to the volcanic edifice of Somma–Vesuvius, and is thus not so important for the Sorrento Peninsula and Capri. However, the volcanic activity of Vesuvius has strongly modified the topography in the easternmost part of the coast studied, so that a medium to low rank ($Ip = 1-2$) can be assigned. Examples of such modifications include lava flows reaching the sea (e.g. in 1805 on the Vesuvian coastline to the north of the study area) during eruptive phases, as well as pyroclastic products related to explosive phases covering the sea-cliffs and filling stream paths (Cinque & Robustelli 2009). The former change could lead to a rapid retreat of the slope over the cliff, as shown in some cases.

Seismic events related to both volcanism and tectonics (Campania is classified in Italy as a major seismogenetic region) must also be considered, but only in the easternmost area of the Sorrento Peninsula, and with a low degree ($Ip = 1$). For example, the village of Castellammare di Stabia was affected by the seismic waves produced by the earthquake that hit the Campania region on 23 November 1980 and the damage was classified as VIII on the MSC. However, the possibility of landslides and tsunamis being triggered should not be overlooked, as indicated by the National Catalogue of the INGV (Istituto Nazionale di Geofisica e Vulcanologia), which has reported at least two events that produced tsunamis, in 1631 and 1805, in the Bay of Naples. Other events, both ancient and recent, are considered unlikely to be related to such phenomena (Milia *et al.* 2003).

(6) Manmade structures. This primary hazard, which has a varying distribution throughout the study area, consists of buildings, roads, other infrastructure and services in proximity to the coastal area. In some cases, the impact comes from engineering structures close to the coastline designed to defend the coast against erosion and to protect infrastructure and services, to satisfy the growing demands of the tourist industry. For instance, the presence of a road along a coastal slope concentrates the infiltration of rainwater uphill and increases the possibility of a landslide, thereby raising the rank. Also, cliff lying on the lee shore of small harbours, or sea-walls, breakwaters and groynes can be affected by the channelling of energy from waves and currents. Here the score is greater than that for the adjacent cliff protected by construction.

Overall hazard assessment

The results obtained from the comparison of various hazards in each stretch of the studied coast were mapped, making the distribution of every hazard degree (from none (zero) to critical (IV)) easy to observe. In the area where this method was applied, these values were considered so that we could assign a degree (from negligible (N) to extreme (E)) to the overall coastal hazard (Ht).

Let us examine the cliffs of the Sorrento Peninsula in this regard (Fig. 8). This high rocky coast, formed both of limestones (varying from hard to soft rock) and clastic and tuffaceous deposits (soft rock) ($Ip = 1-2$ and $3-4$, respectively), is affected by landslides to different degrees: lower ($Ip < 2$) for the former, unfractured rocks and higher ($Ip > 2$) for the latter, especially when they contain significant discontinuities. The hazard is greater, for instance, in the stretch eastward from the village of Sorrento, which has thick detritus loosely cemented onto limestone, or in other cases weathered rock, as a result of the occurrence of remobilization along the steep streams after exceptional rainfall ($Ip = 2$).

Moreover, the presence of a particular cliff type can be decisive for the rate of retreat, as well as for its influence on other parameters: a cliff with a limited, strongly dipping shore platform will have an increased erosion rate in comparison with cliffs with broad, gently dipping shore platforms. Thus the score may be higher for the former and lower for the latter, under the same conditions. In applying this method, it is not possible to omit human impact, here consisting of residential and tourist facilities, which are often located above sheer drops to the sea, as well as the heavy traffic load on the only (winding) road cutting into the steep cliff ($Ip = 2$). Likewise, the effect on the

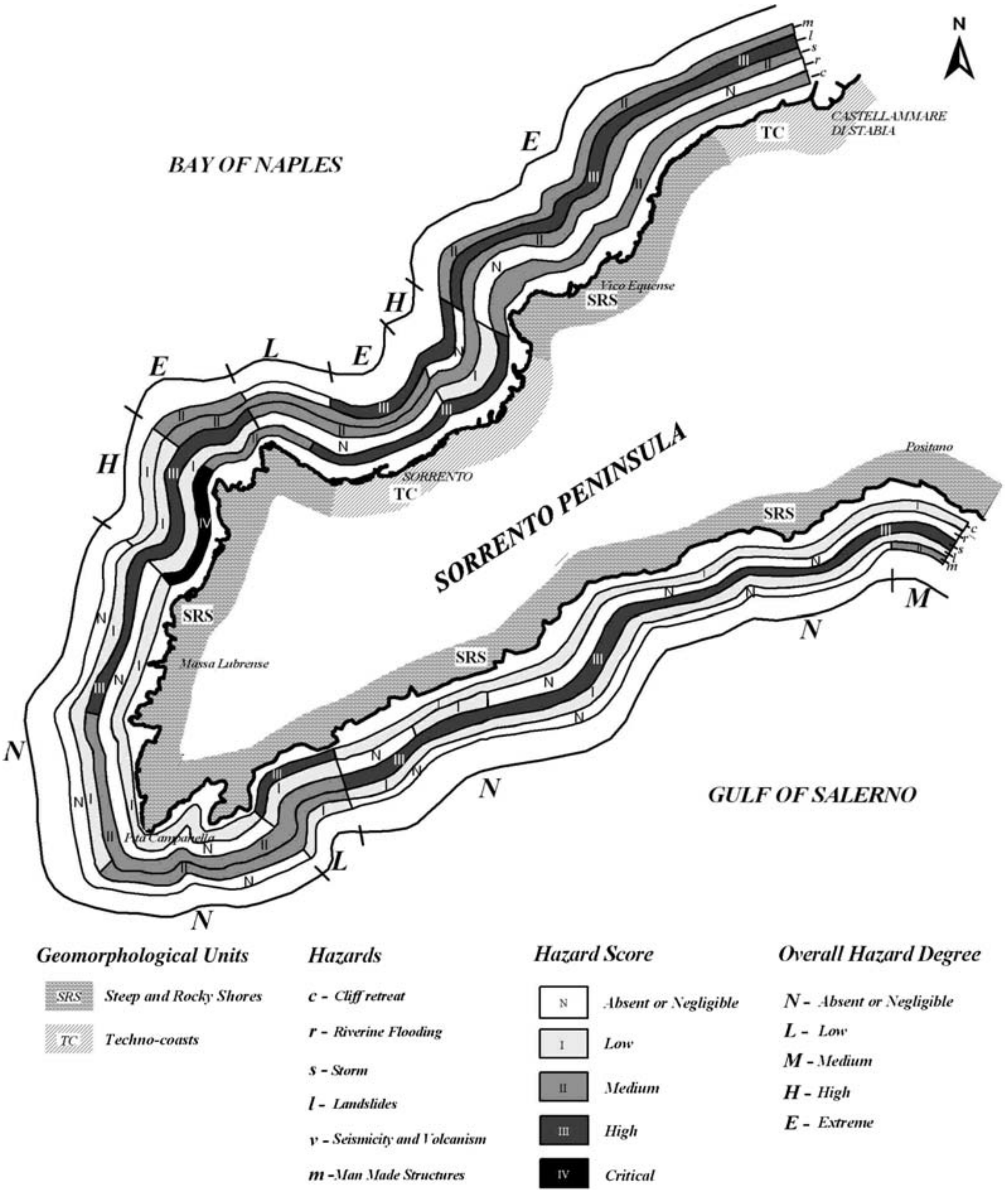


Fig. 8. Map of the Sorrento Peninsula coastline giving hazard scores for each parameter and overall hazard degree (slightly modified from De Pippo *et al.* 2008).

cliffs of strong wave action during winter storms is far from negligible, as a result of wave refraction, diffraction and reflection caused by the alternation of headlands and embayments, and at times by the absence of a shore platform ($Ip = 1$). As mentioned above, the interactive matrix shows that man-made structures and landslides have the highest scores ($Xp = 6$ and 5, respectively), whereas storm waves and riverine flooding are given medium ($Xp = 3$) and close to minimum scores ($Xp = 2$), respectively. Therefore the degree of overall hazard ranges from negligible ($Ht < 20$) on the southern side of the Sorrento Peninsula to extreme ($Ht = 41$–42) along the cliffs adjacent to the town of Vico Equense or in front of Sorrento.

Along the coastline on Capri the type of cliffs as well as the processes developing along the coastline vary depending on the side of the island (Fig. 9). For

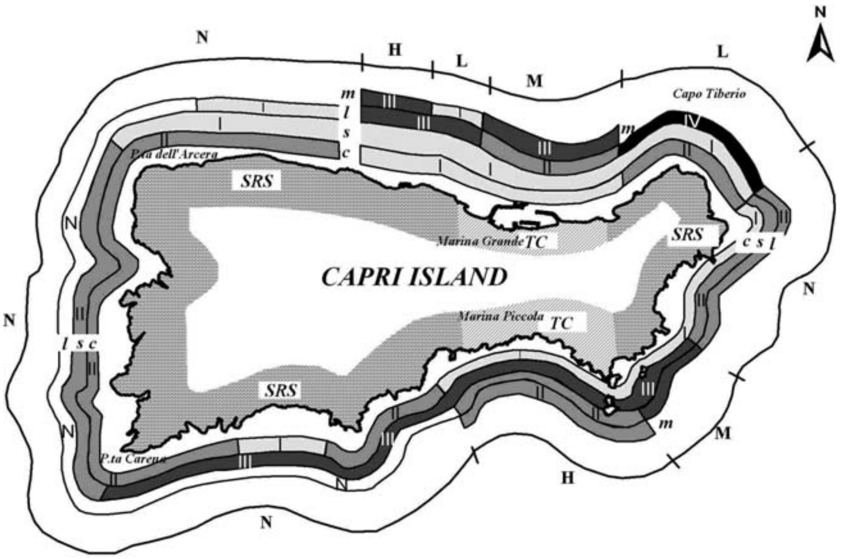


Fig. 9. Map of Capri coastline giving hazard scores for each parameter and overall hazard degree. (See the legend in Fig. 8.)

instance, plunging cliffs, mainly in limestone, are widespread on the western side ($Ip = 2$, as these cliffs are in a highly fractured condition), where retreat is much slower than on the eastern side, where cliffs with a subaerial face composed of soft rock (clastic deposits) occur, albeit with a gently sloping shore platform. Moreover, the superimposition of limestone on terrigenous deposits in turn covered by clastic rocks raised the score in the central portion of Capri, both on the north and south sides ($Ip = 2$). Importantly, a high or critical score may be assigned for landslides on the north-eastern side ($Ip = 3$–4), a high score for storm waves, also related to the widest fetch, is given to the southern side ($Ip = 3$), and a high or medium score for the development of buildings, roads and tourist facilities in the central portions ($Ip = 3$). After allowing for the weight of each hazard, the overall hazard is negligible on the western sides ($Ht < 14$) and extreme or high in the central portion ($40 < Ht < 35$).

Conclusions

The rocky coast of the Sorrento Peninsula and Capri forms very attractive scenery and, locally, a unique cultural landscape, which is one of the major economic factors in the region. However, in recent decades, the whole coast of Campania has experienced increasing human pressure as a result of residential and industrial construction as well as tourist infrastructure, resulting in a hazard for humans, damaged habitats and losses of landscape heritage. To establish best conservation practices and sustainable use of marine and coastal areas, integrated assessment, planning and management of marine and coastal areas are required. This is to prevent, control or mitigate adverse impacts from human activity in the marine and coastal environment, and to contribute to restoring degraded areas. Rocky coastal cliffs have so far aroused little attention relative to sandy beaches and dune systems, despite their regional importance as ecological systems, hazard areas and economic factors. Analysis of coastal evolution is often based exclusively upon the assessment of the rate of local and short-term hydrodynamic–geomorphological cliff modelling processes. In the proposed method we consider the various coastal hazards on a coastal stretch varying greatly in physical features and land use. This method is not limited to defining the rate of coastal retreat so as to assign a relative degree of coastal hazard, but is carried out in the knowledge that such characteristics and processes occur in the coastal zone and there may be interaction between them.

Along the studied coast six hazards are recognized: manmade structures, landslides, cliff retreat, storm waves, riverine flooding, and seismicity and volcanism. This list is given in descending order of influence derived from a dedicated interaction matrix, thus representing the significance of each parameter (its weight) along this kind of coast. Evaluation of each parameter is based on the frequency of particular events as well as the type and intensity of processes, which are inferred from historical, literature and archive data from several sources. The nature of some events, although not scientifically treated, is quantified according to a rating derived from analogous identifiable elements.

Evidently, the weight of each parameter related to hazard is strongly connected to the geology of the area, which includes sedimentary succession and tectonic structures (type and age of tectonic phase), as well as morphological features. This controls the development of current geomorphological processes, such as cliff retreat, and hence the degree of each hazard on a stretch of coast. Moreover, another parameter has to be considered in every analysis of the current landscape: that relating to manmade structures and human activity. This parameter usually has a negative influence on the system and sometimes is non-determinable, hence its weight is the highest.

The results obtained from several applications of the proposed interaction matrix along the Campania and Basilicata coastal zones, in a homogeneous geological context, encourage us to continue with further studies. Indeed, the occurrence of some events on the coast as well as preventive action in a planning project has confirmed the effectiveness of this method. Further applications to other geological contexts and other suggestions leading to the development of the matrix are welcome.

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