Landslide Hazard Assessment of the Cilento Rocky Coasts (Southern Italy)

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Abstract**—**This paper deals with natural and human causes giving rise to the erosion of the Cilento rocky coasts. It is predictable that, in 2100, along the coasts of the Mediterranean Sea a sea level rise varying between 9 and 30 cm will be attained. This increase will also cause a marked rise in the erosion of rocky coasts because a wide extension of highly erodible rock masses characterizes the studied area. Data regarding failure mechanisms, landslide mobility as well as run out distances of about 228 landslides directly or indirectly triggered by the wave motion were collected. Using these data and the IFFI Catalogue ("*Inventario Fenomeni Franosi Italiani*"), a Coastal Landslide Density Map was drawn that displays landslide density areas varying between 2 and 10 landslides per km^2. In addition to climatic, geomorphological and geological causes, coastal erosion is worsened by a poor supply of sediments providing beaches, coming from the nine main rivers of the area. Furthermore, these sediments show a granulometric sorting mainly towards fine sands and silts which are not suitable for the beach-nourishment. In order to obtain a relative estimate of net erosion and deposition along the bed rivers, the USPED (Unit Stream Power - based Erosion Deposition) model was applied that allowed to calculate a value of solid discharge, from the rivers of the area, of about 11 millions of T/year. An assessment of the potential degree of landslide hazard and rockfall mobility was performed by means of heuristic approaches based on the "Rock Engineering System" and "Reach Probability" methods. In spite of inevitable approximations, employed methods revealed that almost 56% of the coastal area displays high landslide hazard, 27% is characterized by medium landslide hazard, whereas only 17% is characterized by low landslide hazard.

Keywords**—** Cilento, hazard evaluation, rocky coasts, sea level rise.

I. Introduction

ALTHOUGH still controversial, the gradual increase in mean global warming, probably induced in part by human activities, will among other things lead to a rise in the sea level. In the last 2,000 years the sea level has risen about 1.30 meters, in tectonically stable areas of the central Mediterranean Sea. Due to a probable effect of the anthropic global warming, the sea level has risen about 12 cm during the last 100 years [1]. It is predictable that, in 2100, a world rise of about 0.18 ÷ 0.59 meters will be attained [2]. Due to weather conditions and heavy evaporations not compensated for river discharges characterizing an inland sea, a rise in the sea level of the Mediterranean Sea varying between 50% and 100% of the world scale value can be expected [1]. This increase also will cause a marked rise in the coastal erosion of rocky coasts.

The basic factors controlling marine erosion are well-known: the force of waves against the cliffs, as well as the lithology of exposed rock masses. Additional factors are reduction in rock strength owing to weathering by sea spray, rock mass removal, tidal action, and material fatigue caused by cyclic loading of waves [3]. Among geomorphological processes, undercutting by waves is undoubtedly the most important in causing coastal retreat. Waves erode the cliff toe, undercutting and over steepening it. This destabilizes the overlying slope, causing it to collapse. The resulting talus accumulation, which temporarily protects the cliff toe, is then attacked by waves and eroded away. So cliff undercutting resumes and the cycle repeats [4]. The notch development and its temporal widening cause increasing shear stress that leads to failure in rock masses. The failure models are not easily predictable owing to unknown shear stress and strain distributions [5], [6], [7].

This paper describes the current state of knowledge about landslide hazard affecting the Cilento rocky coasts (Fig. 1). Several scientific and technical documents regarding geological aspects, landslide triggering causes, solid discharges from river beds, landslide hazard as well potential mobility of landslide debris have been collected and summarized. In such a way, a global outline directs towards coastal planning and engineering mitigation has been proposed.

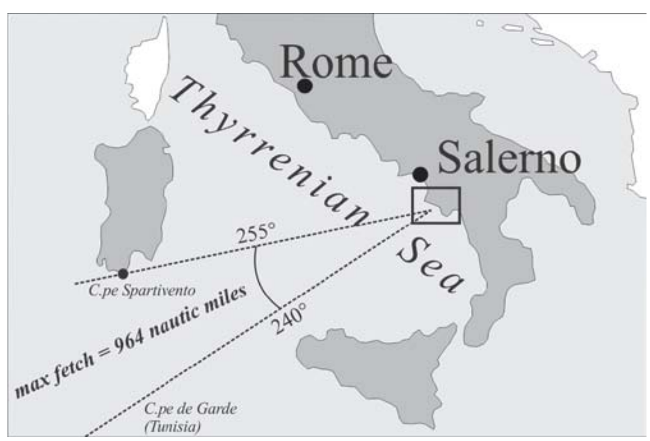

Fig 1 The study area

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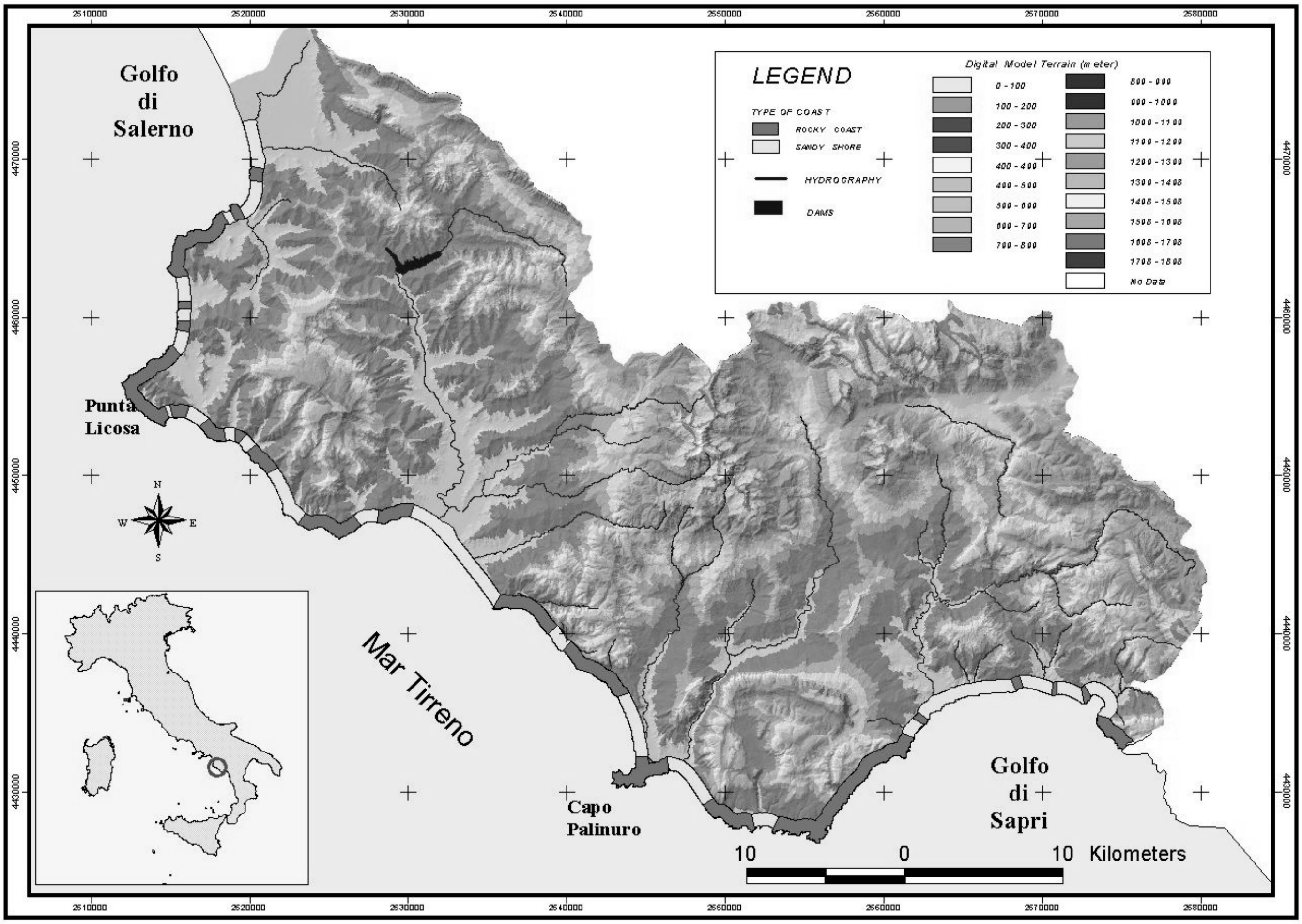

Fig. 2 Types of coasts affecting the studied shoreline

The resident population, in the 15 coastal Municipalities, totals about 76,500 inhabitants, with a mean density of 179 inhabitants per km^2. The shoreline is crossed by some important transportation corridors (state roads and the Tyrrhenian railway) linking famous tourist resorts such as Agropoli, Casalvelino, Palinuro, and Sapri. Furthermore, during the summer the whole coastal stretch is intensely inhabited and exploited for bathing purposes. As a result, more and more new human settlements and infrastructures will be exposed to a high landslide risk.

II. Geomorphological and Geological Setting

The shoreline extends for about 118 km between Agropoli and Sapri, being included in the physiographic unit of the Cilento Coast as well as partly in the Gulf of Salerno and in the Gulf of Sapri units (Fig. 2).

The shoreline between Punta Licosa and Capo Palinuro is affected by a maximum fetch of about 964 nautical miles, on average coming from the strike N245° (Fig. 1). According to wave motion data recorded by the Italian Ondametric Network (time span July 1989 - December 2003), the most frequent provenance of wave motion is included in the sector comprised between N210° and N330°. The maximum recorded wave height (*Hs*) is about 7 m, coming from the strike N270° [8]. The Italian Ondametric Network recorded 52 sea storms which lengths of time were between approximately seven days (Ponza 24/12/1999) and a few hours, during the time span March 1999 - December 2003. Very often the wave motion is in the west sector with prevailing strike N270°. These waves cause a long shore drift from NW towards SE, whereas the prevailing drift is in the direction W – E in the Gulf of Sapri.

In order to protect the shoreline, several sea works (such as artificial reefs, and shelters) are present, whereas quay walls and jetties constitute the main harbor works located between Agropoli and Sapri. In total, the anthropized shoreline extends for about 14 km.

The shoreline is exposed to the tsunami hazard caused by earthquakes or submerged volcanic eruptions. For this area, the hazard exposure is lower than that affecting Southern Calabria, the Straits of Messina and Eastern Sicily [9], [10]. With reference to the Lower Tyrrhenian sea between the Campania region and Sicily, the Italian Tsunami Catalogue edited by INGV (*Istituto Nazionale di Geofisica e Vulcanologia*) reports 72 tsunami events during the time span 79 ad - 2004 [11]. Furthermore, the coast is more exposed to anomalous waves caused by submerged volcanic eruptions from the Aeolian or Marsili seamounts. Waves coming from the Stromboli Island (caused by the 30th December 2002 tsunami) reached the shoreline in the Sapri Bay causing slight damages.

With reference to sea level changes caused by recent tectonic movements, stationary conditions or only a slight uplift (lower than 0.07 mm per year) were established [12]. This was stated on the basis of several geologic and biological leading indicators dating back to the Tyrrhenian period (about 125,000 years ago). A maximum ground lowering of about 0.03 mm per year only for the shoreline belonging to the Mount Bulgheria sector has been recorded [12].

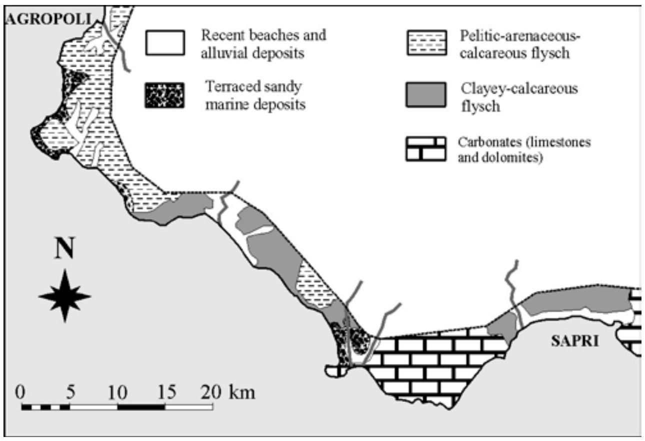

Fig. 3 Schematic geological map of the study area

The coastal stretch consists of sandy and pebbled beaches (sometimes pocket beaches), alternating with high cliffs and steep slopes. Sandy shorelines have considerable lengths just to the north of Agropoli, Santa Maria di Castellabate, between Casalvelino Marina and Ascea, north and south of Capo Palinuro and between Policastro Bussentino and Villammare.

These beaches are nourished by weathering and landform erosion processes affecting sandstones and pelitic limestones belonging to flysch formations cropping out in the inner part of the Cilento region. Almost all of these shorelines are eroded beaches with a mean withdrawal of about 8 - 10 m (in the last 50 years). It should be noted that the widest withdrawal was near harbor works, mostly built in the 60s and 70s of the last century. This confirms the strong influence of human causes.

Quaternary tectonics and the lithological characteristics of the meso-cenozoic bedrock strongly influence the geomorphic evolution of the coast, which is structure-controlled and is highly indented owing to differential erosion. The headlands generally occur at the intersections of plio-quaternary faults or reflect the presence of more resistant rock masses. In contrast, the bays have developed where the rock masses have a greater pelitic content. The coastline is also typified by Pleistocene marine terraces, the highest and oldest of which occur 150 and 70 m above sea level.

The rocky coast extends for about 62 km (Fig. 3). This coastal type is mainly made of steep slopes and cliffs with outcropping arenaceous-conglomeratic strata alternating with silty-marly or calcilutitic ones belonging to the Cilento Flysch Units [13]. These flysch formations are made up of material with different lithological properties. The heterogeneity of the strata is indicated by: (i) the fine grained (pelitic) matrix which is both interbedded and contains rock layers/fragments; (ii) the presence of strong and weak bands; (iii) the presence of clay mineral horizons and sheared discontinuities all of which reduce the flysch to a soil-like material. This material, referred to as "block-in-matrix" or intensely fissured clay shales [14], [15], has an intricate network of millimetre to centrimetre-spaced fissures which divide it into very small fragments. On a larger (macroscopic) scale, a chaotic deposit can be seen, with intercalations of blocks or layers of calcarenites, sandstones or calcareous marls and a pelitic fraction of locally oriented clayey fragments varying in thickness from one to a few millimetres. These Units are a succession of 4,500 m thick turbiditic layers of distal facies at the base, changing into proximal units towards the top that was deformed, uplifted and folded during the Tertiary.

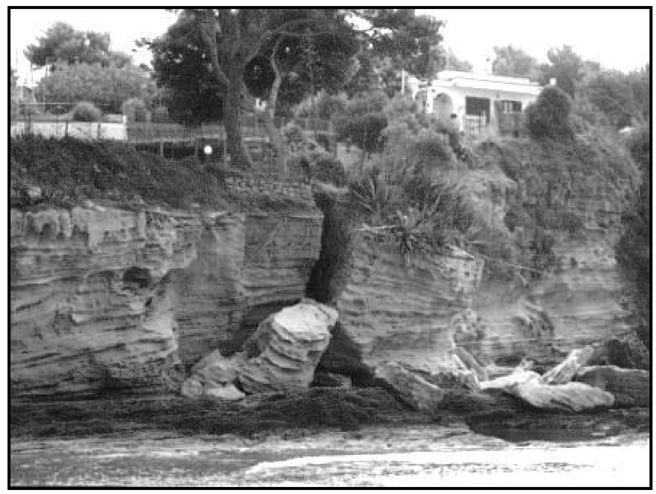
Fig. 4 Complex toppling affecting a sea cliff

Along the shoreline, limestones, cherty-limestones and dolomites belonging to the Alburno-Cervati and Mount Bulgheria Units subordinately crop out. These rock masses mainly consist of Upper Trias – Eocene carbonate rocks belonging to the Campania - Lucania - Calabrian Platform [13]. The Mount Bulgheria (Fig. 3) is a horst transversally oriented towards the Apennine chain, and characterized by a monoclinal inclined towards NE which, along the coast, is faulted by major NE-SW-oriented faults and is affected by numerous strike-slip faults. The present-day orographic setting of the coastal stretch is the result of several tectonic uplifting phases during the Pliocene and the lower Pleistocene. Several normal faults caused different lifting rates in the carbonatic platform, giving rise to formation of embayments and headlands. Due to the very active tectonic disturbance, several carbonate rock masses heavily fractured or intensely cataclastic crop out. Consequently, the continuity of bedding planes and other tectonic discontinuities is disrupted and sometimes rocks may behave as isotropic masses.

Overlying the above-mentioned flysch formations and carbonate rock masses are quaternary marine and continental deposits several meters thick which are mainly represented by Quaternary polygenic conglomerates and cemented Aeolian sands. These deposits at intervals crop out, mainly concentrated along the northern sector between Agropoli and Punta Licosa.

III. Coastal landslides

Along the rocky coast, many landslides have been identified. They are mainly represented by rotational slides evolving into flows and local falls. Many among the slides were clearly triggered by undercutting due to waves (Fig. 4). Sometimes, irregularities due to selective erosion processes affecting horizontal bedding planes, where less cemented materials outcrop, favour the cliff undercutting and cause overhanging rocks to fall. Major complex topples occur along sub vertical joints, the orientations of which are nearly parallel to the cliff. These failures apparently develop when increasing shear stresses exceed material strength and lead to the formation of shear planes along which the rock mass slides and then topple [16]. Sand removal by waves also causes over steepening of the overlying slope promoting minor rocky slab detachments along strata. These failures are testified by the presence of several collapsed boulders lying at cliff toes.

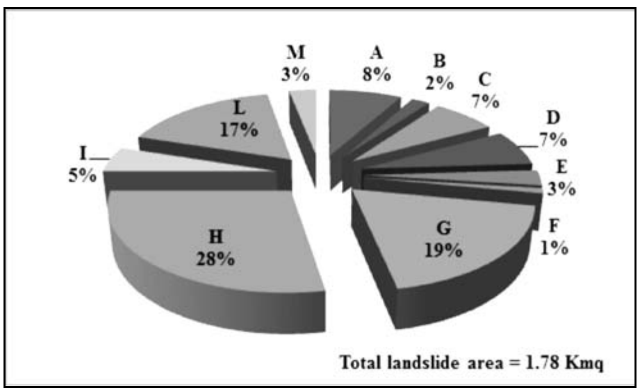

Fig 5 Frequency of typologies and areas of the landslides affecting the studied coast. Key: A = active debris flows; B = inactive slow earth flows; C = active slow earth flows; D = dormant slow earth flows; E = rock-falls; F = active rotational slides; G = suspended rotational slides; H = dormant rotational slides; I = active complex slide-flows; L = dormant complex slide-flows; M = active translational slides

With reference to rotational slides, these mainly affect flysch formations and are promoted by the high lithological heterogeneity and geostructural layout of these intensely sheared and fissured materials. Furthermore, evidences of reactivation are given by landslide debris covering the pebbly beach.

About 228 landslides directly or indirectly triggered by the wave motion were classified (Fig. 5). The whole unstable area is about 1.78 Km^2 and the dormant rotational slides occupy about 28% of the coastal area, followed by the inactive rotational slides that, instead, occupy about 19% of the coastal area, and by the complex landslides.

Falls, rather than representing a high proportion, only occupy 3% of the total unstable area. Such events, numerous, but of limited overall extent, are very frequent on active cliffs as well as on fossil cliffs, and are, very often, triggered directly or indirectly by waves. On account of the sudden

Fig. 6 The rock fall which affected in 2007 the Palinuro sea arch

detachment of various shaped rock blocks, falls take place on near-vertical or very steep slopes (Fig. 6). The critical rupture surfaces are usually identified by the intersection of 2-4 main joint sets corresponding to bedding planes, faults (at times with obvious strike-slip lines) and tectonic joints. These landslides are sudden phenomena, occasionally causing casualties or heavy damage to bathing establishments and other structures located at cliff or slope foots. A greater risk level is attained in summer when beaches are more crowded.

Using landslide data by the IFFI Catalogue ("*Inventario Fenomeni Franosi Italiani"*) [17], a Coastal Landslide Density Map was drawn (Fig. 7). The map displays landslide density areas varying between 2 and 10 landslides per km^2. The greater landslide concentration is found along the coastal stretches between Agropoli and Punta Licosa, Montecorice and Pioppi, Ascea and Pisciotta, as well Scario and Ispani. In these areas arenaceous-pelitic and marly-calcareous strata which are ascribed to the so-called "structurally complex formations" crop out. This confirms the important role in the landslide triggering played by lithology and geotechnical properties of rocks, compared to wave energy and climate.

In addition to geomorphological and geological causes, coastal landslides are also due to the reduction in solid discharges coming from the rivers of the region. Beach erosion at the cliff toe, not counterbalanced by sediment transport to the beach environment, more and more exposes rock masses to direct wave attack, favouring slope failures. Solid discharges coming from the nine main river basins of the whole Cilento region were calculated applying the USPED (Unit Stream Power - based Erosion Deposition) model [18], [19], [20]. A global value of about 11 millions of T/year was estimated by means of this approach (Table 1).

As is known, USPED is a simple model which predicts the spatial distribution of erosion and deposition rates for a steady state overland flow with uniform rainfall excess conditions for transport capacity limited case of erosion process [19]. For the transport capacity limited case, we assume that the sediment flow rate $q_s(r)$ at the sediment transport capacity $T(r)$, with $r=(x,y)$, is given by:

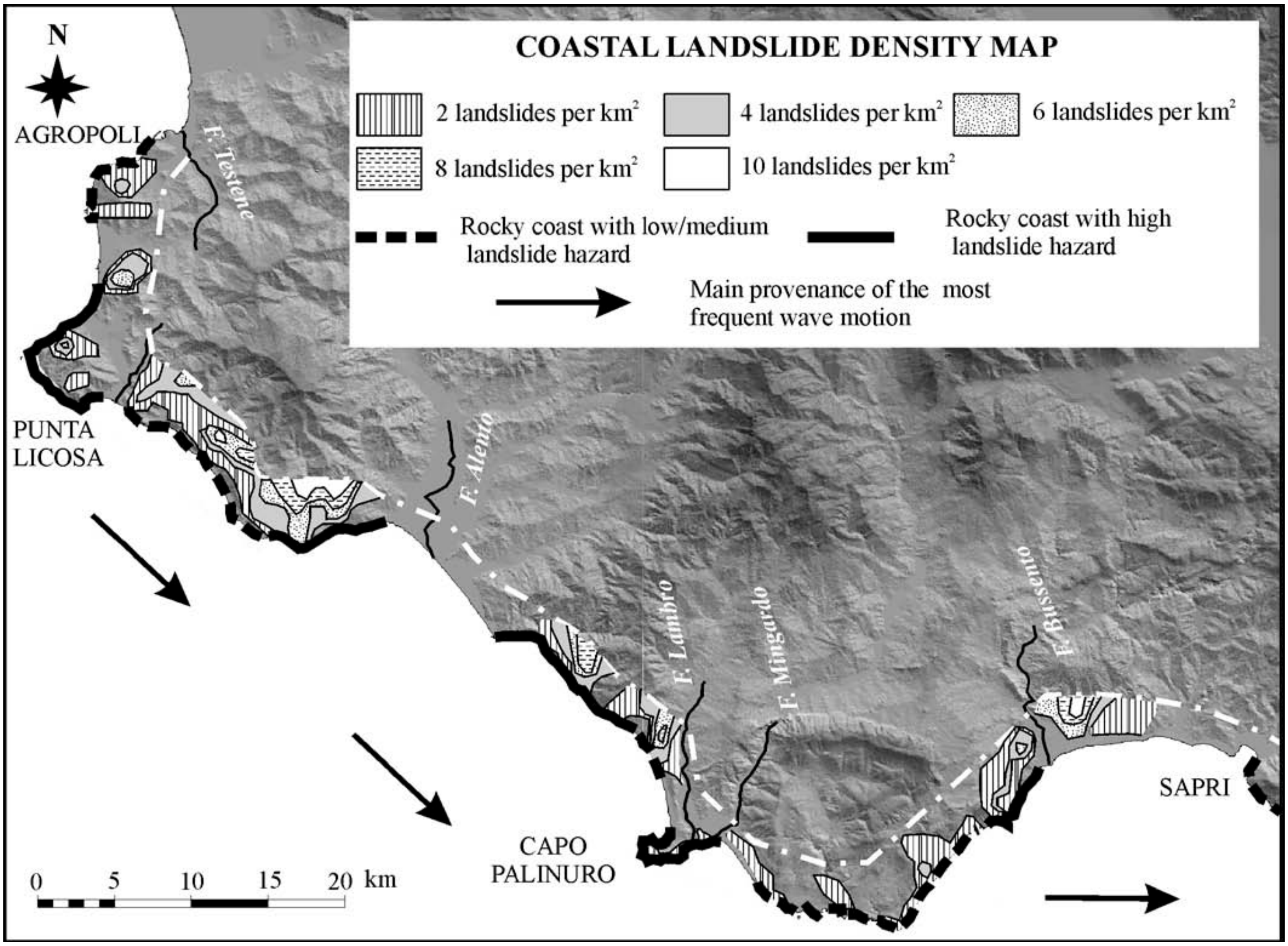

Fig. 7 Landslide density map of the Cilento shoreline

$$|q_s(r)| = T(r) = K_t(r)\,|q(r)|^m\,sinb(r)^n \qquad (1)$$

where: *b(r)[deg]* is slope, *q(r)* is water flow rate, $K_t(r)$ is transportability coefficient dependent on soil and cover, *m, n* are constants depending on the type of flow and soil properties. Steady state water flow can be expressed as a function of upslope contributing area per unit contour width *A*(r)*[m]*.

Table 1 Mean annual solid discharge (T/km^2) coming from the following rivers

Solofrone	2,307
Testene	1,906
Alento	12,926
Lambro	2,660
Mingardo	3,410
Bussento	5,418

In order to obtain a relative estimate of net erosion and deposition, USPED incorporates the USLE parameters R (the rainfall factor), K (the soil erodibility factor), L and S (the slope length and steepness) as well C and P (the vegetation and support practice factors) [21]. For the whole studied region, modeling of erosion and deposition processes within a GIS required a DEM (with resolution of 20 x 20 m), aerial photos, rainfall and land-use (agricultural) data, as well geological and hydrogeological maps. These data were then modeled using the approach based on the Unit Stream Power within the framework reported in the Figure 8.

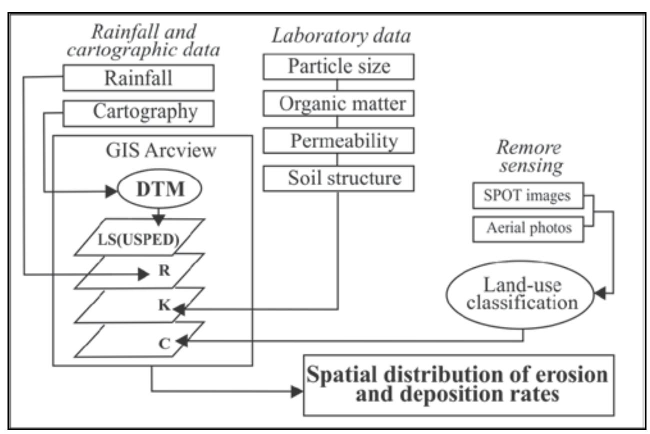

Fig 8 Conceptual flow diagram used in order to apply USPED

Due to the wide outcropping of clayey or clayey-marly flysch in all river basins of the Cilento region, the eroded material coming from slopes are predominantly fine-grained. These sediments accumulate in the final portions of river beds having a very low gradient, and only during more severe floods they reach the coastline. In the last decades (at least since the 1990s) was also observed a decrease of rainfalls in this region, and therefore a smaller number of river floods able to transport eroded sediments to the sea. Furthermore, these sediments show a granulometric sorting mainly towards fine sands and silts; consequently they are not suitable for the beach-nourishment.

The beach erosion is also worsened by the sand and gravel drawing from river beds and sediment trapping in reservoirs. With reference to this matter, an amount of allowed withdrawals of about 13,400 m^3 per year, during the time span 1979 – 1999, was calculated. As this amount does not take into account illegal withdrawals it is a rounded down value. The Piano della Rocca dam and other reservoirs located in the Alento river basin detain about 19,600 m^3 per year of sediments. It was calculated that the total amount of sediments that don't reach the shoreline (due to the sediment drawing from river beds and trapping in reservoirs) is about 4.5% of the total theoretical solid discharge [20].

IV. Coastal landslide hazard

In order to evaluate the variable degree of the landslide hazard, an in-depth study was carried out [3]. Data regarding failure mechanisms, landslide mobility as well as run out distances of the landslide debris also were collected. The major geomorphological, geological and structural features of about 154 slopes and cliffs in carbonatic rocks and flysch have been analyzed, measuring several topographical, geological, geomechanical, and wave hydraulic parameters.

A heuristic approach was used to evaluate the triggering hazard of landslides, using the "Rock Engineering System" (RES) method [22], [23]. RES involves a series of steps including: (1) the choice of parameters relevant to the triggering landslide assessment, (2) the analysis of binary interaction between parameters, (3) the weighting of interaction importance, (4) the rating assignment to different classes of parameter values and (5) the final computation of an "Instability Index" (*I.I.*) expressed in percentage varying from 1 to 100 and calculated by:

$$I.I._j = \sum_i = (a_i \ x \ P_{ij}) \qquad (2)$$

where: i refers to the parameters; j to the examined cliffs or slopes (from 1 to n); a_i is the deducted value C+E for each parameter; P_{ij} is the code allocated to different classes of values of the parameters and it is different for different cliffs (i^{th} cliff or slope).

For each cliff or slope, twelve topographical, geological, environmental and climatic parameters were analyzed, which were: height, cliff slope, orientation, attitude of bedding planes, clay fraction, jointing, vegetation, rainfall intensity, groundwater, wave-motion, pre-existent instability, man-made structures. C+E is the sum of the "causes" and the "effects" parameters describing the tendency of the system to instability. C describes the influence of the parameter on the system, whereas F describes the influence of the system on the parameter. Causes and effects can be evaluated using an asymmetric matrix display where the parameters are listed along the main diagonal of a square matrix and the interactions considered in the off-diagonal boxes of the matrix. The interactions are to be read in a clockwise sense, as they might be path dependent. For instance, the influence of the rainfall on jointing is different from the influence of discontinuity mechanical properties on rainfalls. Of course, in the latter there is not interaction between parameters. Differently, between rainfalls and slope instabilities there is a heavy interaction; the reverse is not true. Some parameters are described qualitatively (for example: jointing, vegetation, man-made structures etc.); others are described quantitatively (for example: cliff height, cliff slope, rainfall intensity, etc.). For this reason, it is not possible to utilize the actual parameter values directly to compute the instability index, but a rating is assigned to different classes of parameter descriptions and values.

Three classes of parameter values were set, with ratings of 0 for "neutral", 1 for "contributory" and 2 for "essential" to instability. Thus, higher ratings are always assigned to classes of parameter values associated with higher instability. Lastly, the value C+E of each parameter is expressed as a rate on the total amount and deducted so that, when all the codes have 2 as their highest value, the highest instability index will be 100; the higher is the index, the greater is the potential instability. Through this mode of presentation, the components of the slope instability problem were studied within a total framework and in parallel, rather than separately [23], [24].

Values of the I.I. were grouped into 3 classes marking low, medium and high triggering landslide hazard (Table 2). High triggering landslide hazard affects about 33% of carbonate cliffs and about 54% of slopes in arenaceous-marly flysch.

Table 2 Distribution of cliffs and slopes with different triggering landslide hazard classes.

Rocky cliffs			
Hazard class	I.I. ranges	No. of cliffs	Cliff percentage
Low	26 – 40%	40	41%
Medium	41 – 60%	25	26%
High	61 – 83%	32	33%
Flysch slopes			
Hazard class	I.I. ranges	No. of slopes	Slope percentage
Low	32 – 40%	5	9%
Medium	41 – 60%	21	37%
High	61 – 79%	31	54%

In order to evaluate the potential mobility of landslide debris an empirical approach was adopted based on the estimation of travel distances. This approach only was employed for rock falls because they are usually sudden and happen without any apparent warning signs. Furthermore, the stopping points of boulders affect areas located at cliff bases, sometimes exploited for bathing purposes. To estimate potential rockfall travel distances, the “Reach Probability” method was adopted [25]. The reach probability is the frequency of falling boulders that could reach a point of the exposed area located at the cliff base. “Reach boundary” lines are obtained by joining points with the same value of reach probability. On the basis of univariable statistical analysis of reach angles in Solà d’Andorra (Central Pyrenees) on a total number of 110 individual boulders with volumes ranging from 0.1 to 14 m^3, reach probabilities of 10%, 1%, and 0.1% were calculated corresponding to reach boundaries of 0.1, 0.01, and 0.001 [25] . Values of reach probability range from 0 to 1: the closer a point is to the cliff base, the higher is the reach probability. The value 1 represents points reached by all individual boulders, usually located at the foot of the cliff. Any individual block may reach points with a value of 0. The 90^{th}, 99^{th}, and 99.9^{th} percentile correspond to the percentage of boulders stopping before reaching the 0.1, 0.01, and 0.001 reach boundaries, respectively. The above percentiles coincide with reach angle values of 41.3°, 39.5°, and 36.9°, respectively [26]. In the study area, the above-mentioned approach was adopted in order to draw three reach boundary lines representing the assigned probabilities. An example of the applied methodology is shown in the Figure 9.

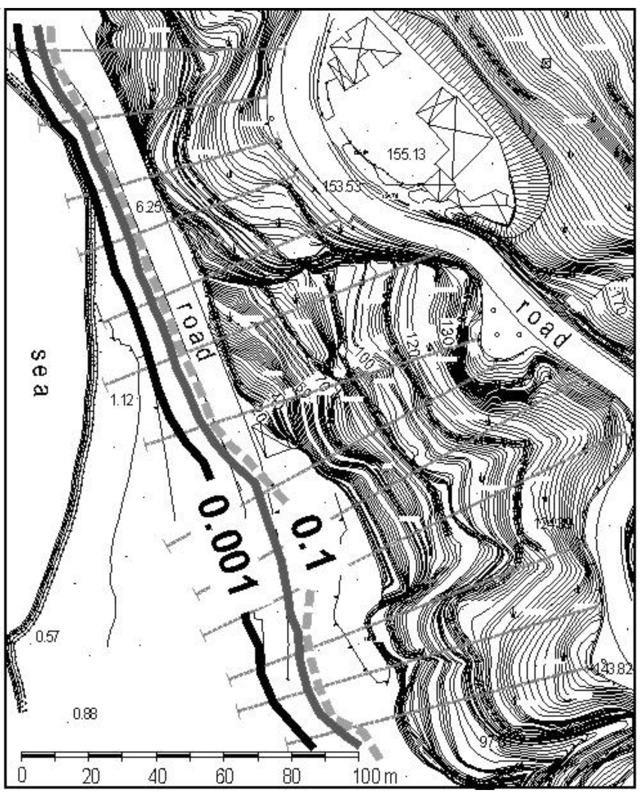

Fig 9 Map of reach boundary probability lines of 0.1 (41.3°), 0.01 (39.5°), and 0.001 (36.9°) for a coastal slope

Thirteen topographical cross sections of the entire cliff, between the upper cliff edge and the flat area below, were reconstructed. Considering the cliff edge as the upper envelope of potential rockfall sources, energy lines were drawn from the top of the cliff, and dipping downslope 41.3°, 39.5°, and 36.9° respectively. As the cross section spacing is low, reach probabilities along the analyzed cross sections were interpolated in order to obtain the reach boundary lines (Fig. 9).

V. Discussion and Conclusion

The used approaches for the triggering landslide hazard and rockfall mobility evaluations are simple tools because the extent of the examined rocky coast (about 62 km in length) does not allow more detailed analyses.

The RES methodology contains some elements of subjectivity, mainly in the choice of the numerical codes given to the different parameters of instability. In spite of the inevitable approximations and simplifications, RES allows a rapid and useful delimitation of the most significant areas in which it is necessary to take preventive action from landslides and to make appropriate territorial planning. Of course, its application in many cliffs must be considered as preliminary to more detailed geotechnical and geomechanical researches.

As far as the results for the “reach probability” method are concerned, we can highlight that this empirical approach disregards major variables such as: slope topography, height of fall, rockfall size, block velocity, and impact energy restitution coefficients. Furthermore, run-out values are calculated by ignoring the stopping action due to possible obstacles which can interfere with the trajectories. Consequently, this approach can be used as a preliminary assessment of the travel distance in extensive areas, in anticipation of more realistic models.

In spite of the above-mentioned lacks, employed methods revealed that almost 56% of the coastal area displays high landslide hazard, 27% is characterized by medium landslide hazard, whereas only 17% is characterized by low landslide hazard.

In conclusion, the Cilento shoreline shows an environmental setting produced by combination and interaction of many complex, natural causes. Some are "long-term" causes, as they are related to geological phenomena the effects of which, are appreciated over time (e.g., Neotectonics) or located away from the area most directly affected (e.g., tidal waves generated by a tsunami). Other causes are structural as they are linked to the geomechanical properties of outcropping rock-masses. There are also occasional factors which originate from the offshore wave motion and that, in turn, determine the magnitude of the wave energy transfer to the shoreline, the sediment drift, as well as cliff erosion.

In recent decades, man-made actions have added to natural factors. Their effects propagate both at the global scale (e.g., the global warming and consequent sea level rise) and local one (e.g., the human settlement, poorly designed coastal defenses, reduced solid discharges coming from rivers). Unfortunately, the emerging overall negative outline is no different from that characterizing other Mediterranean coastal areas. This outline is characterized by increasing erosion processes that give rise to serious environmental and economic consequences.

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