

Assessment of Coastal Vulnerability Through the Use of GIS Tools in South Sicily (Italy)

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Abstract This study assessed coastal erosion vulnerability along a 90-km sector, which included both erosional and accretionary beaches, and different levels of human occupation. Two aerial photogrammetric flights were used to reconstruct coastal evolution between 1977 and 1999. During this period, extensive accretion was recorded up-drift of human structures at harbors and ports, e.g., Scoglitti (105.6 m), Donnalucata (52.8 m), and Pozzallo (94.6 m). Conversely, erosion was recorded in downdrift areas, with maximum values at Modica Stream mouth (63.8 m) and Point Castellazzo (35.2 m). Assessments were subsequently divided into four categories ranging from “high erosion” to “accretion.” Several sources were examined to assess human activities and land use. The latter was mapped and divided into four categories, ranging from “very high” to “no capital” land use. Subsequently, coastal erosion vulnerability was assessed by combining land use categories with recorded coastline behavior. Results showed “very high” to “high” vulnerability along 5.8% and 16.6%, respectively, of the littoral, while 20.9% and 56.7%, respectively, was found to exhibit “medium” and “low/very low” vulnerability. A very good agreement between predicted coastal vulnerability and coastal trend had been observed over recent years. Furthermore, several human structures and activities are located within the

“imminent collapse zone (ICZ)” which reached maximum values of 17.5 m at Modica Stream and 13.5 m at Point Braccetto.

Keywords Aerial photograph · Beach erosion · Vulnerability · Land use · Sicily

Introduction

The shoreline is highly dynamic and changes temporally and spatially in response to variations in coastal processes (Bird 1993; Carter 1988; Forbes and others 2004). Over time frames of less than a year, the major factor influencing shoreline change is seasonal wave climate (Masselink and Pattiaratchi 2001). Considering decadal time frames, the important factors influencing shoreline change includes the impacts of large storms and tsunamis (Cooper and others 2004, Donnelly and others 2001; Scheffers and others 2005; Stone and others 1997). For time frames longer than a decade, the main factors causing shoreline change are sea level rise, coastal storm climatology and variations in sediment supply (Orford and others 2002; Pethick 2001; Shand and others 2001; Thom and Hall 1991).

Despite causes and/or reasons for coastal erosion, littoral retreat is always reflected by overwash and/or beach and dune erosion (Bird 1993). When natural processes affect or threaten human activities or infrastructure, they become a natural hazard (Short 1999). In order to prevent natural hazard impact and associated economic and human losses, coastal managers need to know the intrinsic littoral vulnerability. This is determined using information on the physical and ecological coastal features, human occupation, and present and future shoreline trends. Predictions of the future coastline position can be based on coastal changes

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which have occurred over recent decades (Crowell and others 1999). In detail, according to Douglas and others (1998) and Galgano and Douglas (2000), shoreline position records >60 years are needed to derive a reliable trend.

Vertical aerial photographs, satellite imagery and maps are very useful data sources to reconstruct coastline change at long (>60 years) and medium (between 10 and 60 years) temporal and spatial scales (Crowell and others 1993). They also display coastal type distribution and dune field evolution (Dolan and others 1980; Fisher and Overton 1994; Forbes and others 2004; Jiménez and others 1997; Leatherman 1983). Over the last two decades, airborne laser surveys “LIDAR” (“Light Detection and Ranging”) have been greatly developed and used in coastal morphological studies (Brock and others 2002; Woolard and Colby 2002; Robertson and others 2007). This remote sensing technique, usually carried out from a small aeroplane, allows detailed 3D surveys to be undertaken, but its application is limited by rather expensive costs.

Furthermore, vertical aerial photographs, satellite imagery and maps give pertinent information for environmental mapping and classification, examination of storms effects, characteristics of wave shoaling, land use, etc. (Anfuso and Martínez 2005; Berlanga and Ruiz 2002; Crowell and others 1991; Dickson 1990; El-Asmar 2002; Gorman and others 1998). Vulnerability maps have been obtained for several coastal sectors around the world through the use of Geographical Information Systems (GIS), computer-assisted multivariate analysis and numerical models (Cooper and McLaughlin 1998; Kelly 2000; LOICZ 1995). In the USA, “Flood Insurance Rate Maps” have been created by the government (Kelly 2000) and “Coastal Zone Hazard Maps” have been prepared for coastlines affected by hurricane Hugo (Bush and others 1996).

In Spain, Sánchez-Arcilla and others (1998) evaluated the Ebro delta vulnerability over different time scales and Domínguez and others (2005) presented an assessment of coastal vulnerability for an Andalusian coastal sector. McLaughlin and others (2002) developed a GIS based coastal vulnerability index for Northern Ireland (UK) that took into account socio-economic activities, resistance to erosion and coastal energy characteristics (Gornitz 1990). Lizárraga and others (2001) combined beach reduction at Rosario (Mexico) with the probability of damage to landward structures and obtained a vulnerability matrix. Furthermore, Pethick (2001) and Hansom (2001) introduced new concepts of coastal management: coastal planners must be prepared for medium and long-term changes in land use, such as replacement of a beach by a salt marsh.

In this study, a coastal vulnerability map was created by comparing data on coastal erosion/accretion and land use along the 90-km littoral between the Dirillo River mouth

and Point Castellazzo, Sicily (Italy). Beach erosion and accretion rates were derived by comparing multitemporal and multiscale aerial photographs (Martínez and Anfuso 2008). Land use types have been estimated from field observations, aerial photographs and maps. The data obtained may be used to predict future coastal trends and hence determine safe construction locations, and land use plans which are a principal requirement for the study area.

Study Area

The area investigated is part of the Ragusa Province, South Sicily (Italy; Fig. 1) administrative region. The northern part, i.e., the sector between the Dirillo River mouth and the Point Secca promontory, runs NW-SE while the southern part, extending from the Point Secca to the Point Castellazzo promontories, runs approximately E-W (Fig. 1).

The littoral is composed of sandy beaches of different widths, rich in quartz ($\cong 65\%$), carbonates ($\cong 30\%$), feldspars, and heavy minerals (Amore and Randazzo 1993; Anfuso 1999). The beach face has a low gradient (approximately $1\text{--}2^\circ$) and consists of fine sand. Nearshore areas present smooth slopes with bathymetric contours running parallel to the coastline (Fig. 1) and at the shoreline, there are no observed areas of wave energy divergence or convergence. Diffraction and refraction processes correspond to locations of anthropogenic structures. One or more longshore bars are frequently observed. These control breaking wave processes and usually take place far from the shoreline, giving rise to large surf zones with spilling breakers that are typical of dissipative beach states (Short 1999). Beaches are backed by dune ridges and cliffs while promontories in the study area, divide the littoral zone into morphological cells (Carter 1988).

Hard cemented limestone and sandstone of the Miocene Ragusa Formation (Grasso 1997) give rise to hard cliffs at several coastal sectors, i.e., between Casuzze and Marina di Ragusa, Cava d’Aliga and Sampieri, and at Marina di Modica and Pozzallo. At P. Braccetto, consolidated Plio-Quaternary sandstones produce hard cliffs that are very resistant to erosion. The aforementioned cliffs account for 18.7% of the total coastline (Anfuso and Martínez 2005) with no evidence of erosion during last century (Anfuso 1993).

Late Miocene clays belonging to the Tellaro Formation (Grasso 1997) give rise to a bluff at Camarina while cliffs at Scoglitti and Caucana, are formed by Plio-Quaternary unconsolidated marls. At the Irminio River mouth, the cliff is composed of Quaternary unconsolidated marls with very fine calcareous sands and pebbles representing fluvial and marine deposits. These cliffs account for 15.6% of the

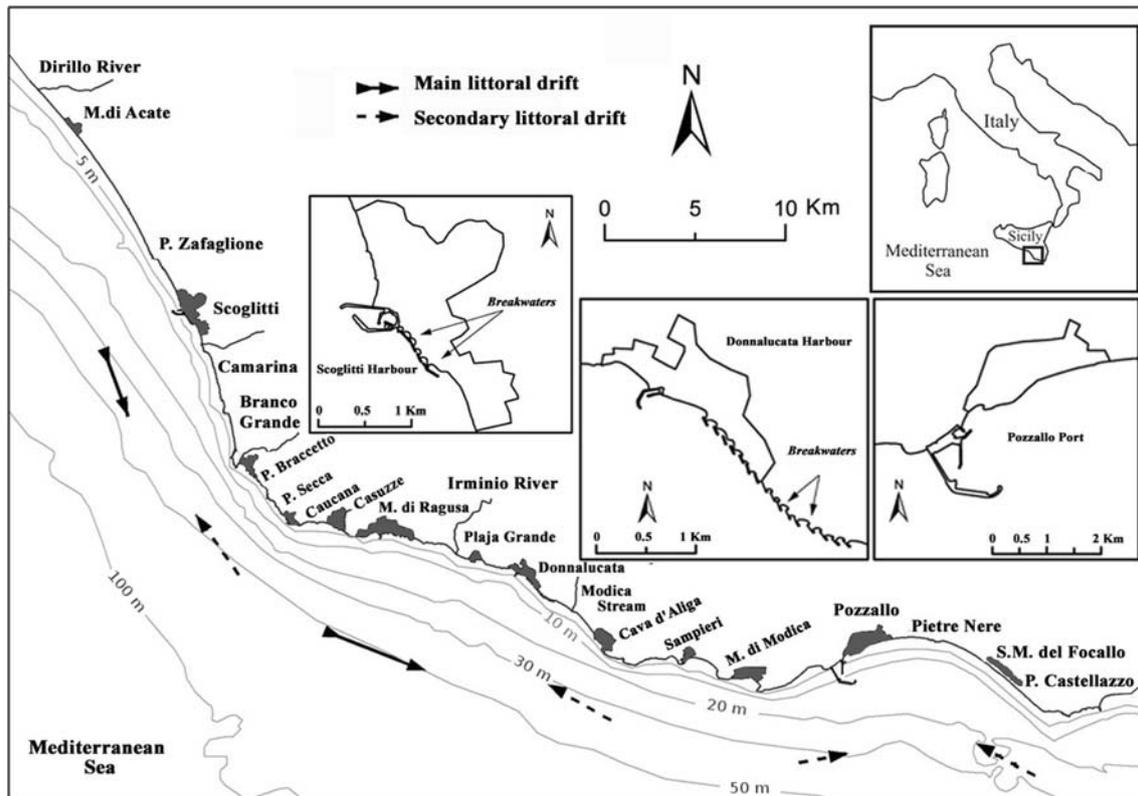


Fig. 1 Location map of the studied zone showing bathymetric contours and most important coastal villages, ports, harbors, and breakwaters (modified from Anfuso and Martínez 2005)

coastal length (Anfuso and Martínez 2005). At these locations, consolidated blocks fall from the upper cemented part and accumulate at the cliff toe, forming a natural defence against coastal erosion. Most of the studied coastal sectors recorded a small retreat during the last century and appear more or less stable in the long and medium-term (Anfuso 1993). Consequently, retreat rates are too small to be characterized within the time frame of this study. Despite small quantities of pebbles accumulating at the Irminio River mouth cliff, little of the very fine sediments has eroded at other locations and these are rapidly winnowed by waves. According to Amore and Randazzo (1993) and Anfuso (1999), no significant sedimentary inputs to the littoral budget are derived from fluvial inputs or cliff retreat (Anfuso and Martínez 2005).

The study area is microtidal (astronomical spring tidal range 20 cm), with prevailing winds blowing from the West, SW, and SSW. Winds from the East and ESE are particularly significant during autumn and spring (Anfuso 1999). According to the “Littoral Environment Observation” (LEO) measurement system, based on visual deep water wave observations, most severe storms strike the coast from the West with ESE being the next most frequent direction. Data from the nearest offshore buoy confirmed LEO observations. Most frequent and severe storms

approach from W and WNW with significant wave heights greater than 5 m, less severe storms approach from SE, with maximum significant wave heights of 3 m (Fig. 2).

Because of its coastal orientation, the northern sector is essentially affected by storms from a westerly direction and the southern sector is influenced by storms approaching from east and west, which give rise to important longshore currents. The main littoral drift in this area is southeast, evidenced by decreases in sediment grain size (Amore and Randazzo 1993; Anfuso 1999). An opposite transport is also recorded, especially during the spring and autumn (Anfuso 1999). As a result of coastline orientation, the westward directed transport is significant, especially in the sector between Cava d’Aliga and P. Castellazzo (Fig. 1).

In terms of land occupation, since the 1960s and 1970s, the study area has seen a significant increase in human pressure, mainly due to increasing tourism and agricultural activities which provide important economic resources for the hinterland (Fig. 3). The lack of a management policy and the huge and rapid increase of human occupation, resulted in urban sprawl and considerable coastal stress. A management response is now required to protect coastal and, specifically, beach resources upon which the local economy is based.

Fig. 2 Significant wave height and frequencies for the 1989–2007 period. Values recorded by the directional buoy located at Mazzara del Vallo, in the Sicilian Channel. The buoy belongs to the Italian wave climate service

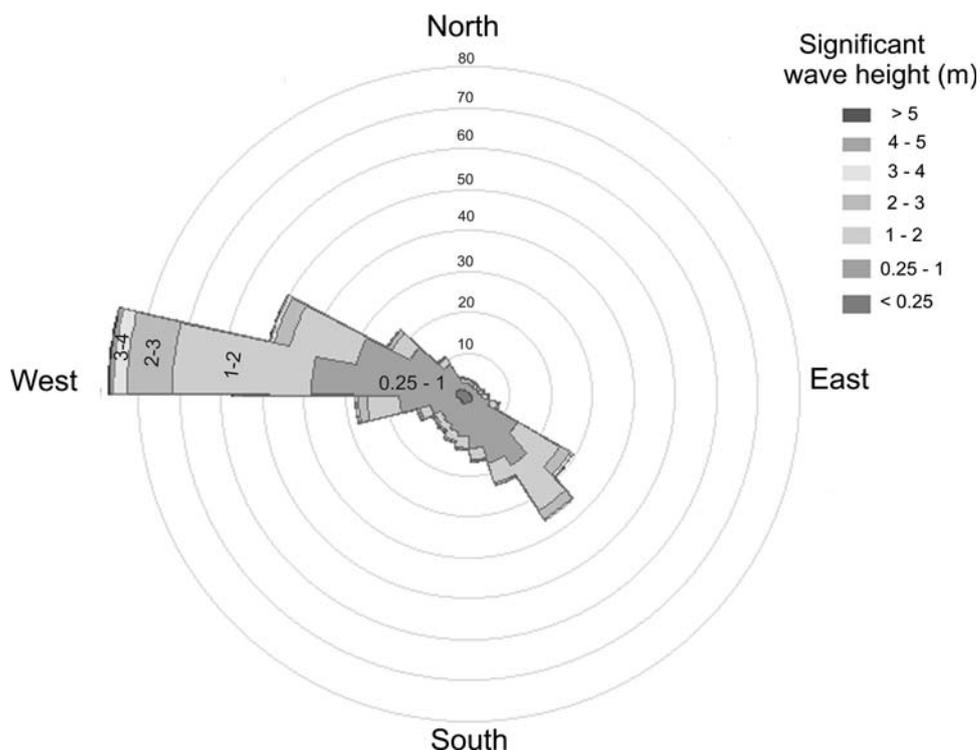


Fig. 3 Human occupation along the studied littoral. Greenhouses between P. Zafaglione and Marina di Acate (a), very dense occupation because of summerhouses at Marina di Ragusa (b), Donnalucata harbor and downdrift breakwaters (c), and scattered occupation, consisting of summerhouses and a littoral road, in the southern part of Santa Maria del Focallo beach (d)



It is important to note that most human activities and construction have been developed within the “protection” and “influence” zones defined by the Italian Coastal Act (2004). Within the protection zone, extending 150 m landward, any kind of construction is effectively prohibited, and within the influence zone, which is 150 m landward extended, any construction needs to be approved by the local Planning Office.

Methods

Offshore significant wave height data between 1989–2007 was obtained from the offshore directional wave buoy, located at Mazzara del Vallo in the Sicilian Channel. This buoy is located west of the study area, over a depth of 20 m, and data is provided as part of the Italian wave climate service.

The coastal erosion susceptibility map was based on result interpretation and combination from the medium-term littoral evolution in conjunction with the distribution of land use activities. In order to assess the land use map, data from the 1999 orthophotographs and the Land Use Map (Celeste 1997) was utilized. Because of the Land Use Map inaccuracies, land uses were interpreted and mapped on the 1999 aerial orthophotographs. These were provided by the Sicilian Regional Administration and constitute an official cartographical product with 1 m spatial resolution. The 1999 aerial orthophotographs also define the basic cartography used for GIS projects within this study.

Land use information was further complemented by accurate field observations regarding the type and percentage of land occupation (following from Malvárez and Domínguez 2000). In this work, land use and human activities were mapped within the littoral zone, extending from the shoreline to a landward distance of 500 m.

Analysis of coastal evolution was carried out for a 22-year period (medium-term, according to Crowell and others 1993) using two photogrammetric flights (following the “end point rate” method, Jiménez and others 1997), the 1977 photographs (in B&W at 1:17,000 scale), and the 1999 geo-referenced orthophotographs (in color at 1:12,500 scale). Following the methods described by Jiménez and others (1997), Leatherman (1983), and Pajak and Leatherman (2002), the 1977 photos were scanned, geo-referenced, and computer rectified to eliminate scale and distortion problems (Chuvieco 2000; Crowell and others 1991; Lillesand and Kiefer 1987; Moore 2000). Ground Control Points (GCP^s) for photo registration have been obtained from the geo-referenced 1999 orthophotographs and all the information is presented in Gauss-Boaga Coordinates (zone 2). Taking into account the smooth topography of the studied area, a polynomial transformation was applied in the registration process (Chuvieco 2000). The number of GCP^s used varied from one photograph to another (from 9 to 15 units) and their position was located in unequivocal places (Thieler and Danforth 1994).

Distortion related photographic error (Dolan and others 1980; Crowell and others 1991; Anders and Byrnes 1991; Moore 2000) was resolved and controlled in the geo-referenced documents by visual observation, achieved by comparing the registered photograph with the base map and deriving the root mean square error (RMSE). This was calculated using all GCP^s of each photogram as reference points, allowing the photographs a geometrical accuracy of approximately 5 m.

Usually, in a microtidal environment, the shoreline position has been defined as the water line at the time of the photo (Dolan and others 1979; 1980, Douglas and Crowell 2000; Leatherman 1983; Pajak and Leatherman 2002; Zhang and others 2002). In this case the shoreline was considered as the

instantaneous water line position (Boak and Turner 2005). Moreover, because it was not possible to reconstruct tidal conditions at the moment the photograph was taken, it was assumed that the daily water line position is subject to a maximum uncertainty of 4 m, taking into account the intertidal slope of the studied beaches (Dolan and others 1980; Anonymous 2005). Wave height effects were not considered because no storm conditions were observed in any of the photographs. Furthermore, aerial photographs were taken each year at the end of the summer, thus damping seasonal fluctuations (Morton 1979; Crowell and others 1993). In addition, the effects of seasonal variation and the influence of individual storms on shoreline evolution have limited importance because of the time span considered (Dolan and others 1991). An additional positional shoreline error was determined with an accuracy of 1 m because of photographic spatial resolution limitations. Consequently, the total shoreline mapping error was assumed to be 10 m.

The “Spatial Analyst” extension of the ArcGIS 9.1TM software (CA, USA) was used for all spatial analysis. Differences between the 1977 and 1999 coastlines were established in correspondence with 121 transects, regularly spaced along the sandy littoral sectors. The methods used included “union” and “intersection” operations (ArcGIS ESRI[®] terminology) between geographical layers containing different kinds of information. In detail, the “union” operation allowed joining the two studied coastlines. As a result, with the tools provided by programmed scripts, a new layer with area variations (square meters) between the two coastlines was determined in a new database layer. The newly created layer was built up with polygons formed by the intersection of the two coastlines. The “intersection” operation was carried out between the layer containing transects and the new layer containing the surface variations. The result was a new polyline layer where transects had been cut by the polygons. Considering the segments located within the polygons, their length and erosion/accretion rates were calculated. Those segments obtained by coastline intersections and clipped transect layers, where the length was lower than 10 m, were discarded as they were within the methodological error. Consequently, discarded segments were not displayed in the final cartography.

The vulnerability “matrix” resulted from the spatial union between retreat rates and land uses layers. Due to the different geometric data type structure of each layer, i.e. polylines for the retreat rate layer and polygons for the land use layer, the resultant layer contained small segments (almost point) indicated where transects (retreat rates layer) intersected polygon boundaries (land use layer). As a result, the new layer contained fields of original layers, containing information of coastline behavior and land use in each record. That layer allowed the evaluation of vulnerability along the littoral.

Results and Discussion

Wave Climate

Significant wave height (H_s) presented important seasonal variations during the 1989–1999 period (Fig. 4): higher values ($H_s > 2$ m) characterized winter months from September to May, and most importantly storms ($H_s > 4$ m) approaching from W and WNW, essentially took place during November to March. These datasets coincided with the wave climate trend presented in Fig. 2 which is referenced to the 1989–2007 period, this way it is possible to state that wave climate during the investigated period was representative for the study area.

Littoral Evolution

Using GIS tools, retreat and accretion rates for the 1977–1999 period were determined and grouped into four categories; “high erosion” (>-1 m/yr), “erosion” (between -0.2 and -1 m/yr), “stability” (between -0.2 and $+0.2$ m/yr), and “accretion” ($>+0.2$ m/yr; Fig. 5).

Data obtained was useful in demonstrating shoreline variability at different beach locations and enabled erosion and accretion patterns along the littoral to be discerned. The obtained data, based on the use of two sets of aerial photographs, confirmed results presented by Anfuso and Martínez (2005) and Martínez and Anfuso (2008) which reconstructed the evolution of the investigated coastal sector using several documents, i.e., the 1967 topographic map and aerial photographs from 1977, 1987, and 1999. Along the analyzed intervals, accretion processes were always evident updrift of human structures while erosion was always recorded downdrift. In fact, significant areas of accretion had been observed close to harbors and ports, usually on the western sides of the aforementioned structures, with erosion processes prevailing downdrift (Anfuso and Martínez 2005; Martínez and Anfuso 2008; Fig. 5).

A similar situation was observed by Bray and others (1995), Bray (1997), Jayappa and others (2003), Runyan and Griggs (2003), Zviely and Klein (2003), and Phillips (2007). The coastal units described were greatly impacted because human structures and sediment circulation diminished as shorelines became more heavily protected and

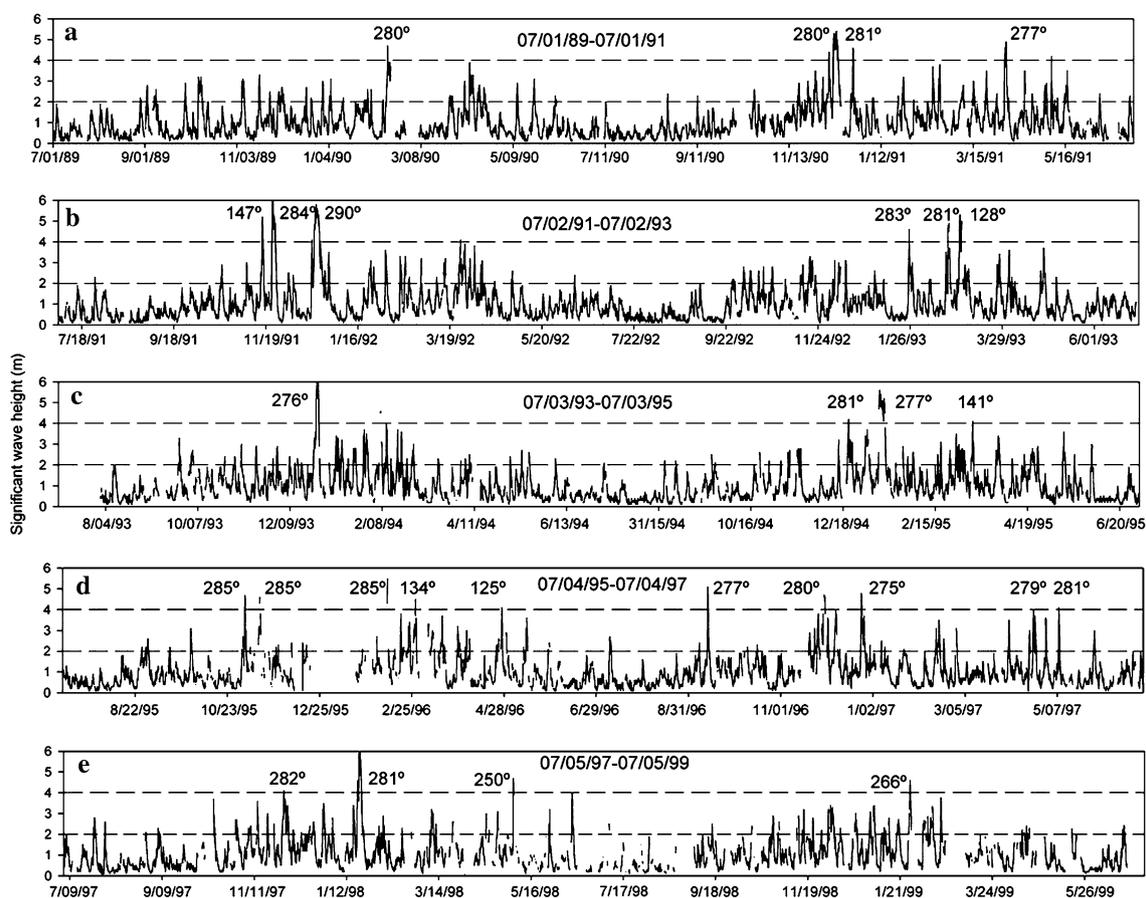


Fig. 4 Significant wave heights, with direction of approximation for most important storms, recorded during the 1989–1999 period by the offshore buoy located at Mazzara del Vallo, over a water depth of about 20 m. The buoy belongs to the Italian wave climate service

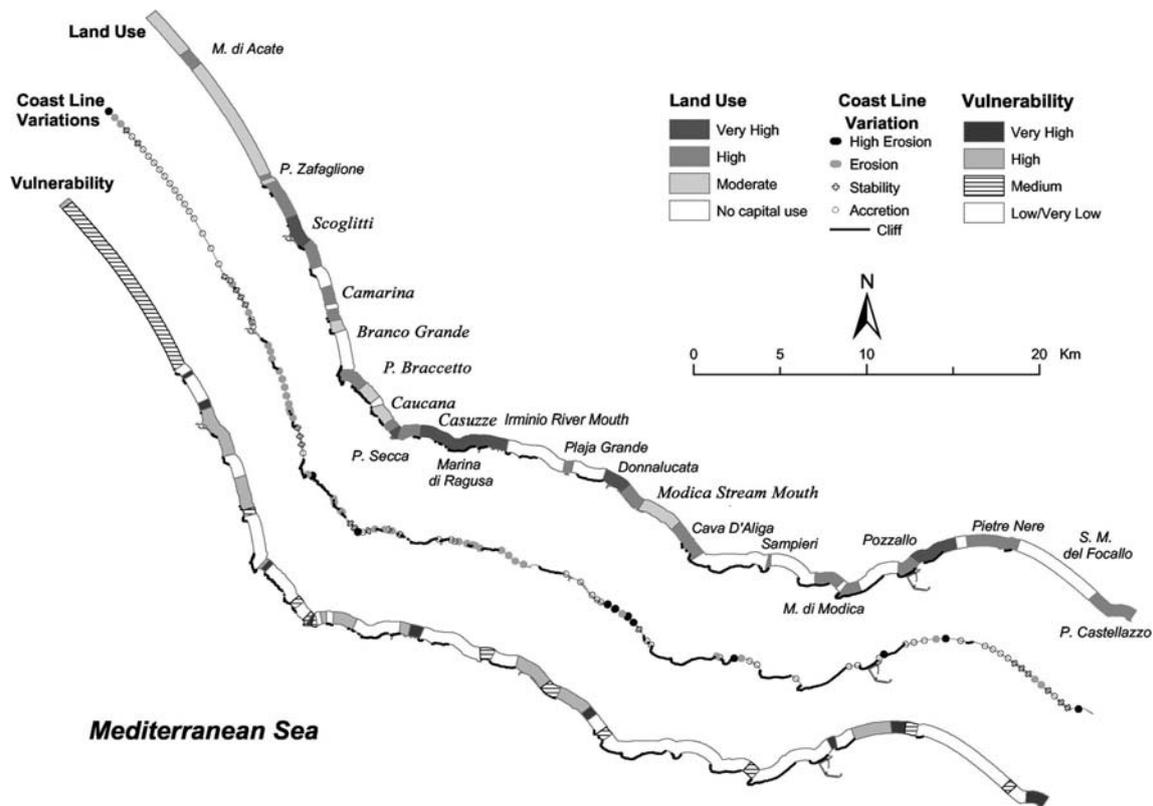


Fig. 5 Land use, coastline variations, and vulnerability along the studied zone

erosion yields were reduced. In this article, the most important accretion was observed updrift of Scoglitti (105.6 m; Fig. 6a) and Donnalucata (52 m) harbors (Fig. 5). In Pozzallo, the port structures had a significant influence on the adjacent eastern and western beaches (respectively 94.6 and 50.4 m of accretion, Fig. 6b), as beaches readjusted their dynamic equilibrium (Martínez and Anfuso 2008). Erosion of approximately 35 m was observed at P. Castellazzo and was related to the Pozzallo port construction.

Secondly, accretion has been observed on a number of beaches not affected by human structures, i.e., Cava d'Aliga, Sampieri and Marina di Modica (Fig. 5). These beaches experienced significant enlargement, as well as dune growth and landward migration. Dune erosion (and landward migration) had also been observed in the Natural Park of Branco Grande (Figs. 5, 6c, and 6d).

Significant erosion has generally been observed close to the eastern side (i.e., downdrift) of harbors and ports. At these locations, the coastline has been artificially stabilized through the construction of several breakwaters but erosion problems shifted downdrift, with more breakwaters progressively put in place. Examples include south of Scoglitti harbor (Fig. 7a and 7b) and east of Marina di Ragusa, where the breakwaters induced a progressive formation of

tombolos, with average accretion rates of 2.5 m/yr and 2 m/yr, respectively.

East of Donnalucata harbor (Fig. 3c), an important and rapid gain was observed (approximately 99 m) and extensive erosion (approximately 63 m) was experienced downdrift of the easternmost breakwater, i.e., at the mouth of Modica Stream. Locally, retreat processes have been counteracted with seawalls and rip-rap revetments where shorefront property was at risk. Seawalls progressively reduced beach width and in other areas, rip-rap produced accretion, as observed by Pilkey and Dixon (1996) at other littoral locations. In other places there was erosion problems related to the impact of anthropogenic structures, although these were relatively far from the construction.

At the Natural Park of the Irmínio River mouth, the beach has been eroded (Fig. 5). This erosion accelerated during recent years, reducing beach width, eroding dunes and exposing an ancient deposit of fluvial pebbles along the whole beach. This resulted in a high beach face slope which strongly contrasted with the previous smooth slopes observed by Amore and Randazzo (1993) and Anfuso (1999). Erosion at the Irmínio River mouth is related to the loss of sand trapped by structures (Martínez and Anfuso 2008): at Marina di Ragusa, 13,400 m² of the beach accumulated during the period 1977–1999 and behind the Playa

Fig. 6 Beach accretion north of Scoglitti harbor (a) and east of Pozzallo port where palm trees have been planted and bars and beach facilities constructed in the formed beach (b; photo courtesy of G. Pisana). It is possible to note the Pozzallo port structure at the horizon. Dune erosion (c) and landward migration (d) on the Mediterranean bushes at Branco Grande Natural Park area



Grande breakwater, 60,000 m² and 21,000 m² of new beach were respectively formed in the 1967–1977 and 1977–1987 periods. At Santa Maria del Focallo, the beach eroded and this was evidenced by undermining processes at the littoral road (which was protected by concrete blocks, Fig. 7c), dune escarpments and vegetal dune cover degradation.

Finally, it should be noted that the most significant cause of coastal erosion over the studied time frame was longshore transport, which favored updrift sediment accumulation corresponding to human structure location (thus subtracting sediments from the littoral budget), and decreased sedimentary supply from weirs and dams (Martínez and Anfuso 2008). Secondly, erosive processes were also related to shore-normal transport which only achieved notable importance during storms. Conversely, overwash processes are not common due to coastal morphology, i.e., the non-existence of low-lying areas (“accommodation space”) behind beach ridges and dunes.

Land Use

Land use includes tourist, agricultural, fishing, conservation and recreational activities, which have been grouped into four different categories according to economic values (Fig. 5). Tourist activities consist of summerhouses, hotels and other recreational structures devoted to local tourist demand, e.g., people who move from the hinterland to coast at summer time. The most important tourist coastal

villages, originally devoted to agricultural and fishing activities, are Scoglitti, P. Secca, Casuzze, Marina di Ragusa, Donnalucata and Pozzallo (Figs. 1 and 5). These villages have a total population of 26,000 inhabitants during wintertime and 175,000 inhabitants during the summer, with the maximum population being recorded in July and August (Anfuso and Martínez 2005). Coastal villages have been grouped according to the methodology of Malvárez and Domínguez (2000), within the “very high capital” land use category, because of high urbanization (Fig. 3b and 3c). Harbors and ports, essentially devoted to recreational and fishing boats and cargo ships, have been included within this category.

Coastal villages characterized by scatter settlements have been included within the “high capital land use” category (Malvárez and Domínguez 2000; Figs. 1 and 5). These settlements generally comprise one or two storey summerhouses surrounded by gardens (Fig. 3d). Agriculturally devoted areas and farms have been mapped within the “moderate capital land use” category (Figs. 3a and 5). Agricultural activities are carried out along the coastal plain and consist of traditional and intensive use, i.e., wheat, irrigated crops, and greenhouses. These activities represented an important economic source during the 1970s and 1980s but are now very much in decline. Finally, unpopulated and natural protected areas, namely the Irmínio River mouth and Branco Grande, were mapped within the “no capital” land use class (Fig. 5).



Fig. 7 Erosive processes southward of Scoglitti breakwaters, undermining the littoral road (a), where a rip-rap revetment was created to stop cliff retreat, and a bar constructed on the dry beach (b). Concrete blocks implemented at Santa Maria del Focallo to protect the littoral road (c; photo courtesy of G. Pisana). It is possible to note wave reflection processes on the concrete blocks which produced the deepening of the nearshore zone close to the structure

Coastal Vulnerability

Information on coastal erosion/accretion and land use has been combined in order to obtain several classes of coastal susceptibility (Table 1).

A value of “4” was attributed to high erosion (>1 m/yr) which represents the maximum hazard; “3” was attributed to erosion processes producing retreat rates lower than

1 m/yr, which represent a medium hazard; “2” was attributed to accretion which represents a low hazard. This is because sand accumulation in the backshore forms foredunes, which migrate landward and affect human structures, as observed at P. Secca, Donnalucata, etc. or cover littoral roads which need periodic maintenance. Lastly, “1” was for no beach change, i.e., no hazard (Table 1).

With land use (Table 1), the classification ranged from “4” (very high capital use) to “1” (no capital use, i.e., no economic value). According to the combination of the erosion/accretion and land use attributed values, different classes of coastal vulnerability have been obtained, ranging from “very high” (>12), “high” (>8 and 12), “medium” (>4 and 8), to “low/very low” (≤ 4).

“Very high vulnerability” was found in 5.8% of the littoral (Table 1, Fig. 5) and was recorded at Scoglitti, P. Braccetto, Marina di Ragusa, Modica Stream mouth, Pietre Nere, and P. Castellazzo. This usually resulted from a combination of “high erosion” rates and “very high” and “high” capital land use. “High vulnerability” was recorded in 16.6% of the littoral (Table 1, Fig. 5). In general, it was a combination of “very high” and “high” capital land use with “high erosion,” “erosion,” and “accretion” classes.

Lastly, “medium” and “low/very low” vulnerability values were observed along 20.9% and 56.7% of the littoral, respectively. These values were related to the combination of the “no capital” land use class and “stability” and “accretion” classes. It is also important to note that all cliffed coastal sectors were classified within the “low/very low” vulnerability class because they have been stable during last century (Anfuso 1993).

Coastal retreat rates were used to calculate the imminent collapse zone (ICZ, Crowell and others 1999), i.e., the littoral zone threatened by imminent erosion, extending from shoreline landward with a width equivalent to five times the site erosion rate plus approximately 3.0 m (10 ft). Considering the maximum retreat rates, the ICZ is located 7.5 m and 13.5 m landward respectively at Scoglitti and P. Braccetto; 10.5 m at P. Secca, 4 m at Caucana and 6 m at Marina di Ragusa. At the Modica Stream mouth, the ICZ is projected 17.5 m landward, at Pietre Nere it is 8 m landward and at Santa Maria del Focallo and P. Castellazzo it is 6.5 m and 11 m landward, respectively.

Table 1 Vulnerability matrix

Coastal evolution	Very high capital use (4)	High capital use (3)	Moderate capital use (2)	No capital use (1)
High erosion (4)	16	12	8	4
Erosion (3)	12	9	6	3
Accretion (2)	8	6	4	2
Stability (1)	4	3	2	1

It is particularly interesting to underline the high agreement between the predicted coastal vulnerability (Fig. 5) and the ICZ extension on one hand, and the actual coastal trend from field observations. In fact, over recent years (from 1999 to present), strong erosion has been affecting several coastal structures which fall within the predicted ICZ (with the 1977–1999 retreat rates) and “very high” and “high” vulnerability classes (Fig. 5). During 2005, wave processes increasingly eroded beaches and produced slumps in the cliffs, north and south of Scoglitti harbor (Figs. 5, 7a, and 7b), which threatened the littoral road. It is important to note that these sectors were not considered in the vulnerability map as cliffed sectors (i.e., stable; Fig. 5). The cliff, comprising sandstone and marl was not active until few years ago and had been protected by a sandy beach, as shown in the 1999 photographs. Now however, the beach is almost totally eroded and wave processes attack the cliff which is eroding, especially south of the harbor (Fig. 7a).

In response to the high degree of vulnerability predicted for Caucana, it is important to note that significant erosive processes affected this beach between 1999 and 2004. Then beach nourishment was undertaken along an 800 m coastal sector to halt retreat and protect the littoral road and archaeological remains. Other areas at Caucana are presently experiencing severe erosion (Fig. 8a). Further protective works, essentially rip-rap revetments, have recently been put in place to protect summerhouses and development situated within the ICZ at P. Braccetto and Modica Stream area (Fig. 8b) and Pietre Nere (Fig. 8c).

Considerations for Coastal Zone Management

In Italy there are several laws and provisions dealing directly and indirectly with coasts, nature conservation, activity regulation and land/urban planning. Responsibilities are vertically distributed between the National and the Regional Governments, the Provinces and the local Municipalities, as well as between several branches of different ministries, essentially the Ministry of Environment and the Ministry of Public Works and Transport.

Over the last decade, the importance of Regional Government in coastal planning, protection and management has been significantly enhanced in order to strengthen the link between the local population and their representatives. Despite this, stakeholders are currently only active at a very local scale, when there is a direct tangible benefit and assets to defend (i.e., summerhouses, restaurants, etc.). Consequently, governance of coastal hazards is at present administrated on a reactive basis. Protective measures are always introduced under remedial rather than preventative conditions, in response to local stakeholder pressure when

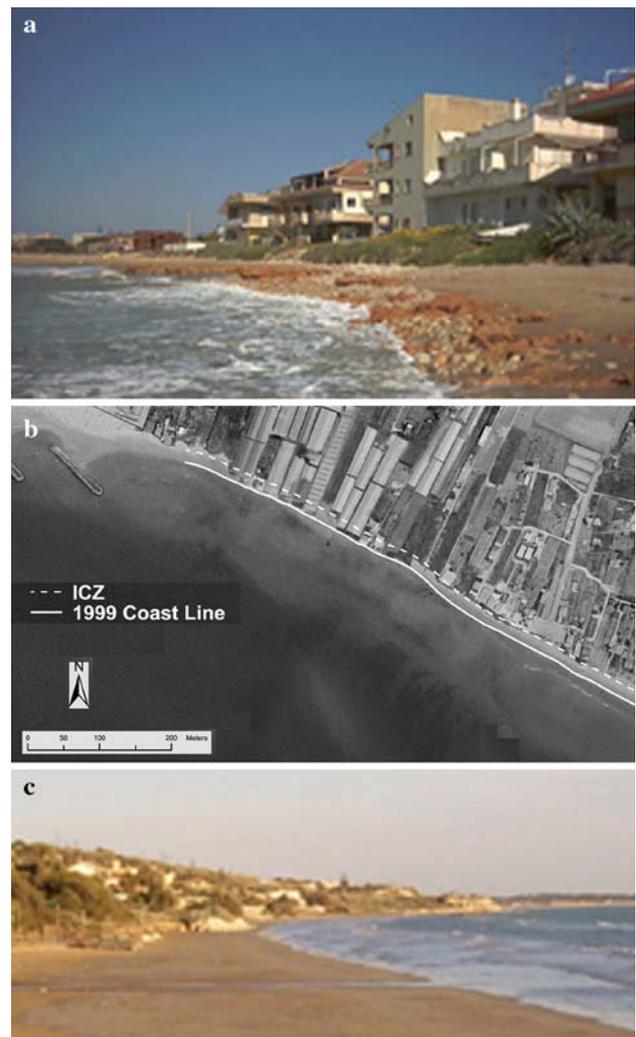


Fig. 8 Beach erosion at Caucana outcrops a rocky-shore platform (a; photo courtesy of M. Florida), probably in future years the backing human constructions will be suffer erosion problems. Human structures within the ICZ at Modica Stream area (b) and rip-rap revetments at Pietre Nere (c) to protect summerhouses

property destruction is imminent. In the study area, storm mitigation structures, e.g., breakwaters and rip-rap revetments constructed by the Regional Government and Province, have been specifically located to protect not only very high capital land use zones but also low density or even non-urbanized areas. The value of the areas protected in the past, varied considerably, from €20/m² for moderate capital use areas, €100 to €300/m² for currently vacant areas which will undergo development and €2,500 to €4,000/m² for high and very high capital land use areas. The cost of a standard breakwater structure comprised of stone blocks (i.e., about 50 m long), was approximately €200,000 and the cost of revetments or coastal structures composed of concrete blocks varied, the unit cost of a concrete block being €92/m³. It is therefore evident that

these costs, especially those associated with the construction of numerous breakwaters, are much greater than the value of the eroded areas.

The local planning staff must identify coastal problems and mitigation strategies from a regional, long-term perspective. In this sense, the construction of port and harbor by-pass systems would provide a real foundation for cost-effective, coordinated coastal zone management. An example is observed at Pozzallo and S.M. del Focallo municipalities: sediments eroded at S.M. del Focallo were accumulated in the shadow area of Pozzallo port, this way generating economic losses at S.M. del Focallo municipality and gains at Pozzallo municipality where a wide beach formed. Furthermore, to slow down erosion associated with hard engineering, authorities should support beach nourishment projects and consider a policy of managed retreat, in response to increased sea levels and associated storms. Relocation is probably the most appropriate solution for the littoral roads at Santa Maria del Focallo and P. Castellazzo. Abandonment could be a solution for summerhouses threatened by erosive processes in Modica Stream mouth and Pietre Nere.

It is also important to regulate future development by restricting certain activities in specific eroding zones, as well as to protect other vulnerable coastal areas which, in near future, will probably experience severe erosion. Prevention is of great importance at Camarina, Casuzze, Marina di Ragusa, and Pozzallo where beaches suffer periodic erosion during severe storms, even though until recently, no damage has been recorded by the back beach structures. In these areas, rather than hard engineering, nourishment projects may be implemented to prevent future coastal damage. Lastly, future efforts must be carried out to lower nourishment costs, which at present range from €12 to €16 per m³ of filled sand, because it is obtained from land deposits. To this end, the Province Administration developed a program of marine geophysical investigations devoted to locating suitable marine sand deposits for nourishment purposes.

Conclusions

With the coastline coming under rapidly increasing pressure from tourism and economic development, there is a pressing need to present environmentally acceptable solutions for both current and future shoreline problems. Results of the present study showed that through the use of aerial images and GIS, a useful and appropriate tool for quantifying coastal evolution can be developed. Consequently, complex and difficult-to-calculate indices are not necessary to evaluate coastal erosion resilience. In addition, spatial analysis by GIS tools proved useful in

generating and cross-examining land use and coastal evolution information, in order to obtain a vulnerability matrix. The vulnerability assessment procedure allowed easy preparation and representation, and will be very useful for future hazard prevention and the development of coastal management strategies and plans. Information can be periodically updated and thus may be considered a dynamic process.

For Sicilian coastal environment protection and careful use of natural littoral resources, it appears too difficult to turn existing public opinion and general approval of political environmental aims, into concrete sustainable actions. The main causes are lack of information, knowledge and understanding of specific environmental issues among local actors, especially administrators. Economic and environmental goals appear hard to reconcile with priority always being given to economic aspects. Previously, littoral urbanization prevailed over natural and environmental considerations. Consensus and collaboration between the public, administration and economic actors is still a crucial prerequisite for achievement of long-term environmental goals. In the study area, there is no permanent constructive relationship between stakeholders and local administrators, the occasional interactions being related to solving specific, erosion problems at a very local scale.

The majority of important erosion problems, closely related to the construction of ports, harbors, and breakwaters and which represent a high risk for about the twenty percent of the littoral, have always been solved by remedial actions, i.e., the use of hard structures, which shifted erosion processes down drift. A general management plan should be based on extensive beach nourishment works and construction of sand by-pass systems for more important harbors and ports.

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