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ORIGINAL ARTICLE

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Towards management of coastal erosion problems and human structure impacts using GIS tools: case study in Ragusa Province, Southern Sicily, Italy

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Abstract A geomorphologic approach, combined with GIS spatial analysis, was used to investigate a 90-km long coastal sector in Southern Sicily, Italy, affected by important erosive processes. Applied methodology allowed the creation of a database involving a range of coastal characteristics thereby providing helpful information on coastal processes and general sediment circulation patterns. Coastal erosion, mainly linked to the construction of ports and harbours, has been locally mitigated by the construction of solid structures which themselves generate significant environmental stress in downdrift areas. In recent times, several nourishment projects have been planned to solve existing erosive problems, yet there is still a lack of a general erosion management plan based on the installation of port and harbour bypassing systems and including the phasing out of current beach cleaning and port maintenance procedures that produce a great quantity of sediments.

Keywords Erosion · Port · Management · Sicily

Introduction

Coastal retreat is the landward displacement of shoreline due to marine erosion or flooding (Bird 1993). Usually, this process is mitigated by protection works constructed on specific sites, to solve concrete and urgent problems. Most of these works constitute temporary remedial action that does not form part of a general erosion management plan (Hooke 1998; Pethick 2001). According to Fischer (1985), Carter (1988), Bray et al. (1995), coastal erosion management should be organized on a broad scale (i.e. at a large, regional scale) so that the dynamics of the whole coastal system are considered, including the influence of human-made structures on littoral drift (Jayappa et al. 2003 and Zviely and Klein 2003). In this sense, Bray and Hooke (1995), Bray et al. (1995), Komar (1998) and Short (1999), affirm that for a better understanding of coastal erosion problems, it is important to identify the areas of inputs, transfers, storage and outputs of sediments through the identification of different and interrelated coastal units or cells and, within each unit, of the various dynamic landforms (Bray and Hooke 1995, Bray et al. 1995 and Runyan and Griggs 2003). In order to assess the impact of human activities on the coastal zone and sea level rise, it is important to comprehend these transfer processes, which operate between different units at diverse temporal and spatial scales (Bray et al. 1995, Orviku et al. 2003 and Woodworth and Player 2003). Unfortunately, very few projects of this type exist: in U.K., Fleming (1989), Bray et al. (1991), Bry and Hooke (1995) and Bry (1997); in the Netherlands, De Ruig and Louisse (1991) and in the USA, Rosenfield et al. (1991) and Runyan and Griggs (2003), among others. A general analysis of coastal zone management has been published by Dal Cin and Simeoni (1994), Lizárraga and Fischer (1998), Suanez and Bruzzi (1999), Fischer and Arredondo (1999), Malvárez and Domínguez (2000), Snoussi and Tabet-Aoul (2000), Lizárraga et al. (2001) and Healy et al. (2002).

The area investigated in this paper is a 90-km long costal sector in Ragusa Province (South of Sicily, Italy), where beach-houses, roads, and other human activities and construction which have appeared over the last 30–40 years, are exceedingly close to the shoreline. Most of these structures are threatened by important, natural erosive processes that have been accentuated by the construction of harbours and ports. These structures have halted littoral transport and have generated significant erosion problems in downdrift areas, partially counteracted by the emplacement of seawalls and breakwaters that have shifted erosion processes further downdrift.

This work constitutes a first, partially empirical study aimed to improve the general knowledge of morphological characteristics, erosion problems, broad sediment circulation patterns and the distribution of cells in the studied littoral, to highlight past errors and mismanagement, evident in the management of erosion problems.

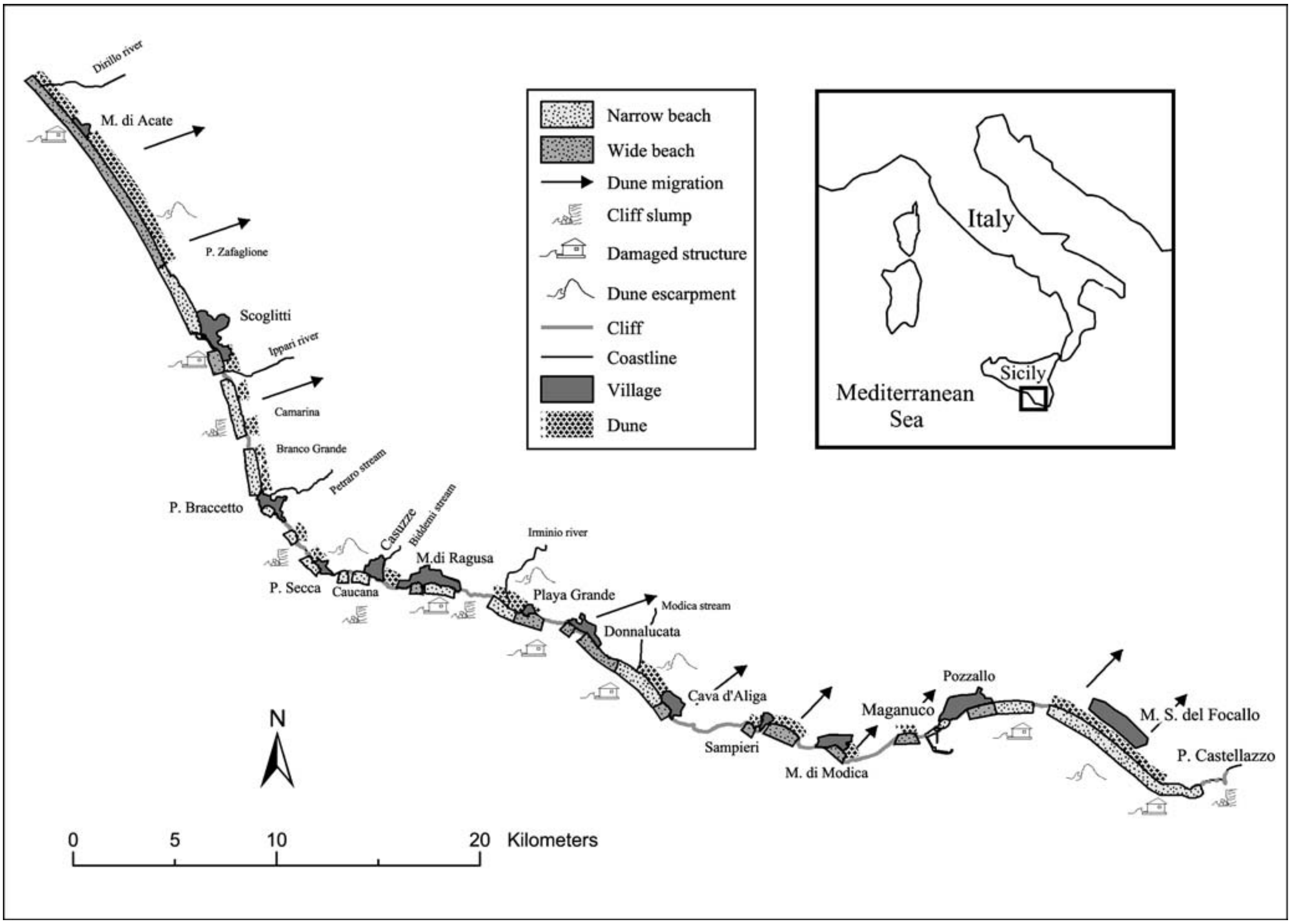
To this end, GIS tools were used to map the main natural landforms and human constructions along the littoral zone, thereby quantifying the shoreline variations related to the impact of human structures.

Obtained results constitute basic, useful information concerning an area characterized by a great lack of data, and they are intended to be employed by local government planning staff as a preliminary guide to the integrated coastal erosion management of the littoral zone in question. In addition, the results found here can be applied by managers in similar environmental scenarios, in order to prevent or solve similar erosion problems since they constitute a study case that can be used by researchers to broaden the general data base and the knowledge of littoral zone behaviour and evolution, within European and Mediterranean projects.

Study Zone

Administratively, the littoral zone studied belongs to the Ragusa Province, South of Sicily, Italy (Fig. 1). Coastal orientation varies from NW–SE in the northern sector,

Fig. 1 Landforms distribution along the study area



between the Dirillo river mouth and Point Secca promontory, to E–W in the southern sector, from Point Secca to Point Castellazzo (Fig. 1). The sandy beaches are of varying width, rich in quartz (≅65%), carbonates (≅30%), containing feldspars and heavy minerals, (G. Randazzo 1985, unpublished; Amore and Randazzo 1993 and Anfuso 1999).

The beaches are backed by dune ridges and cliffs cut in sandstones, marls and limestones. Following Ben-Havraham and Grasso (1990) and Grasso (1997), cliffs are related to a NE–SW oriented normal fault system that forms promontories, i.e. uplifted rocky blocks, dividing the littoral zone in morphological cells (in the sense of those described by Carter 1988). Significant sedimentary inputs are not derived from cliff retreat because eroded sediments are generally too fine, being rapidly winnowed by waves and currents. In a few places, small quantities of pebbly sediments from cliff retreat, have generated small gravel beaches.

Fluvial inputs, according to Amore and Randazzo (1997) and Anfuso (1999), are not significant, since many rivers are from predominantly chalk catchments, with consequent high solute, but low sediment loads. Additionally, sediment supply, significant at an historical scale, was greatly restricted owing to weirs and dams[1] that favour the silting up of rivers during summer periods and, in the last decade, because of the artificial canalization of rivers and streams in order to avoid flooding of urban areas.

As for the marine climate, the zone is a "microtidal environment" (Davies 1964), principally affected by winds blowing from the third quadrant. Winds from the second quadrant are also present and are of greater import in autumn and spring. According to the KNMI data (Leo observations), the largest storms hit the coast preferentially from the third and fourth quadrants, with deep water values of significant wave height (H_s) of 8 m and 11 s. associated period (T). Lesser storms approach from the second quadrant with H_s = 5.5 m and T = 10.5 s. Due to the coastal orientation, the northern sector is essentially affected by storms from the west, with a consequent coupling of a south-eastward littoral drift, while the southern sector is struck by storms approaching from the east and the west giving rise to significant longshore currents, as well as from the south, forming predominantly cross-shore transport. Additionally, the decrease in sediment grain sizes seen from north to south, helps to confirm the general predominance in the area of a south-eastward littoral drift, even though transport in the opposite direction is occasionally recorded (Anfuso 1999).

Over the past 30–40 years, the study area has seen a great increase in human activities, constituting an important economic resource for the hinterland. Many man-made structures and recreational activities are threatened by coastal retreat. In order to counteract this process, seawalls, breakwaters and rip-rap revetments have been built whenever destruction of property was imminent, without any adequate planning or proper consideration of their long term side-effects.

Methods

Landforms characteristics and land use activities were obtained according to Dickson (1990), Crowell et al. (1991, 1993) and Gorman et al. (1998), through several field observations and the analysis of recent aerial photographs and topographic maps.

Qualitative information on the recent coastline evolution was obtained by detailed field observations, qualitatively consulting aerial photographs of different years and unpublished reports (e.g. those carried out for the nourishment projects at Caucana and S. M. del Focallo, among others), old postcards and oblique photos and previous studies (G. Anfuso 1993, unpublished; Amore and Randazzo 1993; Anfuso 1999 and Liguori et al. 2005). The information gathered allowed the general determination of major erosion and accretion areas along the littoral zone.The information obtained was incorporated into a GIS project in conjunction with the distribution of natural and human coastal structures, in order to give a preliminary approximation of the sediment circulation patterns and, hence, of the coastal compartmentalisation (i.e. littoral cells' distributions).

In this way, structures that divided adjacent zones of similar or opposing characteristics, (i.e. "divergent", "meeting" or "pulse" zones, Lowry and Carter 1982), were chosen as cell limits, corresponding to discontinuities in the rate or the direction of sediment transport. Limits were be classified as "fixed", if they are stable, "transient" or "free", if their position changes with time (Carter 1988 and Bray et al. 1995).

To confirm obtained results, coastline changes were quantified with respect to Scoglitti harbour by means of aerial photographs and maps from various years and on differing scales (according to Stafford 1971; Dolan et al. 1980; 1991; Leatherman 1983; Jiménez et al. 1997 and Pajak and Leatherman 2002). Aerial photographs were taken at the end of summer period each year, in order to keep to a minimum the possible effects of coastal seasonal variability. The documents presented in Table 1, were geo-referenced and geometrically rectified

[1]Since 1983, Santa Rosalia dam, on the Irminio river (the largest in the region), retains a water volume of 1,536×10^6 m^3, greatly diminishing potential suspended and bed loads, nowadays composed only by very fine sands, silts and clays, unstable in beach environment.

Table 1 Topographic maps and aerial photographs analysed

Document	Year	Scale
Topographic map	1967	1:25,000
Aerial photographs	1977	1:17,000
Aerial photographs	1987	1:12,500
Orthophotographs	1994	1:12,500
Topographic map	1999	1:2,000

Table 2 Main coastal features lengths

Landforms	Length (m)	Percentage (%)
Beaches	59,922	65.7
Dunes	31,430	34.4
Hard cliffs	17,085	18.7
Weak cliffs	14,227	15.6
Transformed coastline	14,129	15.5
Total coastline length[a]	91,234	100

[a]it is the sum of beaches and hard and weak cliffs lengths

to eliminate effects of scale and distortion (Lillesand and Kiefer 1987; Crowell et al. 1991; More 2000).

The ENVI 3.6 software was used for geo-referencing and document registration processes. These were later transferred to ArcGIS 8.1 for their integration, digitalization and finally for the analysis of information.

Ground Control Points (GCP[s]) for photo registration were obtained from the topographic maps of 1999, at a scale of 1:2,000, edited by the local municipality. All the information was presented as Gauss-Boaga Coordinates (zone 2), with the Roma 1940 datum.

Taking into account the smooth topography of the studied area, a polynomial transformation (second and third orders) was applied in the registration process (Chuvieco 2000). The number of GCP[s] used varied from one photograph to another, ranging from 9 U to 15 U. Their position was located in unequivocal places such as groins and building corners according to Thieler and Danforth (1994). The error in the geo-referenced photographs was controlled with the root mean square error (RMSE) and with visual estimations, comparing the registered photo with the base map. Since the studied area is a littoral zone, a homogeneous distribution of the GCP[s] was not always possible over the entire photograph. This was cause of a certain variation in the obtained RMSE, occasionally reaching a relatively high value. The final photograph nevertheless, correctly matched the base map in all cases.

In a further step, registered photographs were integrated in a GIS in order to digitalize the coastline, defined at the water line at the time of the photo, corresponding to each studied year.

Beach dimensions were measured for the time span from 1977 to 1997 with GIS tools and utilising the spacilly referenced information generated form aerial photographs, distances and surfaces among the different coastlines were calculated.

Results

Landform units

Figure 1 is a schematic representation of the distribution of villages, dunes (with associated directions of migration), beaches, and cliffs, as well as of the locations of dune escarpments, cliff slumps and damaged structures.

Different landforms are described in the following sections and their length is presented in Table 2.

Beaches

The littoral zone is mainly composed of open and pocket fine-sand beaches of varying dimensions, from hundreds of meters to several kilometres. The longer beaches are Santa Maria del Focallo, in the South, and the Dirillo River—Point Zafaglione beach, being 7.7 km and 11.2 km long respectively. Long beaches are also observed at the mouth of the Irminio River and Modica stream (Fig. 1).

The mean dry beach width is about 30 m, with wider beaches (from 60 km to 120 m) being observed in the southern sector, updrift of most prominent headlands that form southwest facing coastal entrances. Wider beaches are also present along the entire littoral updrift, or in response to human structures (Fig. 1). Morphological seasonal changes are on the scale of tens of meters, with wider beaches observed during summer time, i.e. from June to August (G. Anfuso, 1993 unpublished).

Furthermore, significant morphological changes can be recorded also at a smaller temporal scale, due to the significant effect of longshore transport that, over a period of days, can accumulate or erode large volumes of sediments. Lastly, sedimentological seasonal variations are very small, with coarser sediments observed during winter time, i.e. more energetic conditions.

Beach face slopes are usually of a low gradient (about 1–2°) and consist of fine sands. Steeper gradients are observed between the Dirillo river mouth and Point Zafaglione, and are associated with medium sands (G. Anfuso 1993 unpublished) and beach cusps, reflecting intermediate beach states (Wright and Short 1984; Short 1999).

Nearshore areas are generally not steep (1–2%), being characterized by large surf zones with spilling breakers, typical of dissipative beach states (Wright and Short 1984; Short 1999). One or more longshore bars (Type V of Greenwood and Davidson-Arnott 1979) are often observed and control breaking wave processes that usually take place a significant distance from the shore line.

Dunes

The morphodynamic characteristics of local dunes are related to the action of predominant winds that blow from western directions that give rise to generally small W–E elongated incipient foredunes and single dune ridges, parallel to the shoreline. The Dunes' altitude ranges from 2 m to 6 m, with the highest values measured in the dunes of the pocket beaches in the southern sector, where the linear ridges are higher in their eastern parts owing to sand accumulation. Ridges are also well developed at the Dirillo river mouth, at Santa Maria del Focallo beach and in protected areas such as the Irminio river mouth and Branco Grande area (Fig. 1), which are covered by a vigorous layer of vegetation composed of Mediterranean bushes (lentisk, juniper and tamarisk) and pioneer plants (especially beach grass, sea eryngium and sand lily).

Sand supply availability represents the most important factor controlling dune formation (Hesp 2002). In the northern sector, there are very few sedimentary supplies and the foredunes have almost disappeared with dune ridges suffering periodic erosion during winter (Fig. 1). Large sediment sinks are related to the landward transport of sand that, in places, threatens summer houses (Fig. 2) or covers coastal roads warranting periodic maintenance. Examples of these processes are quite common at north of Scoglitti harbour, in Camarina beach, west of P. Secca and Donnalucata harbours, as well as in Sampieri and Santa Maria del Focallo beaches. Sediment collected is not re-injected in beach system, and is commonly accumulated in city dumps.

Cliffs

Uplifted rocky blocks are shaped by marine processes, forming cliffs and promontories, quite common along the littoral zone (Fig. 1). Their height above sea level is generally 3–5 m, with maximum values of 16 m at the Ippari river mouth, where a high bluff is eroded on soft Miocene marls. In the southern sector, cliffed coastline is also well developed, having a maximum altitude of about 6–7 m.

According to Trenhaile (2002), rock resistance to sea related processes depends on various factors such as chemical composition, angle of dip, strike, bed thickness, joint density and pattern, degree of weathering, etc. All these characteristics vary to a great degree along the littoral zone. Rocks with a low degree of resistance are the sandstones of the Pleistocene marine terraces and the Low Miocene marls that forms outcrops from P. Zafaglione to Casuzze, close to the Irminio river mouth and at Point Castellazzo (Fig. 1). These "weak" rocks are susceptible to landslides and rock fall, which occur due to wave erosion at the foot of the cliff. The presence of blocks of rock at the foot of the cliff, remnants from previous falls, should reduce cliff erosion; but, during heavy storms, sea waves pass over them reactivating the erosive processes. The bluff at Ippari river mouth, formed on clay and marls, is predominantly affected by mudslide erosive process. Most parts of the cliffs between Casuzze and Pozzallo are composed of horizontal dipping beds of an Upper Miocene limestone, very resistant to wave action.

Lastly, it is important to stress that the headlands and cliffs between Casuzze and Pozzallo are active, while the remnant cliffs are protected by narrow sandy or (rarely) conglomeratic beaches, easily reached during winter storms.

Fig. 2 Landward migration of a sand dune that threats a summer house westward of Point Secca harbour

Human constructions and interventions

Figure 3 shows areas with low levels of urbanisation (“transformed areas”), highly urbanised areas (“highly transformed areas”), as well as representing the main zones of beach erosion, accretion and stability. The distribution of antropic structures (seawalls, rip-rap revetments, breakwaters, ports and harbours), the main and secondary littoral drift directions and the locations of the main cell’s limits can also been seen in the figure.

Coastal occupation

Urban development in the studied littoral zone has seen a great increase in recent decades, as has been the case in other Mediterranean areas (Malvárez and Domínguez 2000). Small, pre-existing villages, with fishing or agricultural activities as their staple occupations, have recorded a great expansion, essentially linked to the construction of summer houses related to the local tourist demand. Table 3 (ISTAT 2001), shows the approximate winter and summer populations for the main villages.

As can be observed, population peak is recorded in summer time, July and August, when people move to the coast from the hinterland, generating a significant environmental pressure, i.e. increase in demand for water, incrementing sewage pollution, etc.

Ports and harbours

Scoglitti harbour is host to intensive and traditional fishing activities. The port consists of a main E–W oriented, 400 m long breakwater and has a maximum depth of about 4 m (Fig. 3).

A small harbour exists at Point Secca and a larger one in Donnalucata (Fig. 3), both being devoted to recreational and small fishing boats.

To the South (Fig. 3), Pozzallo port, the largest of the province, was constructed in the seventies to support the

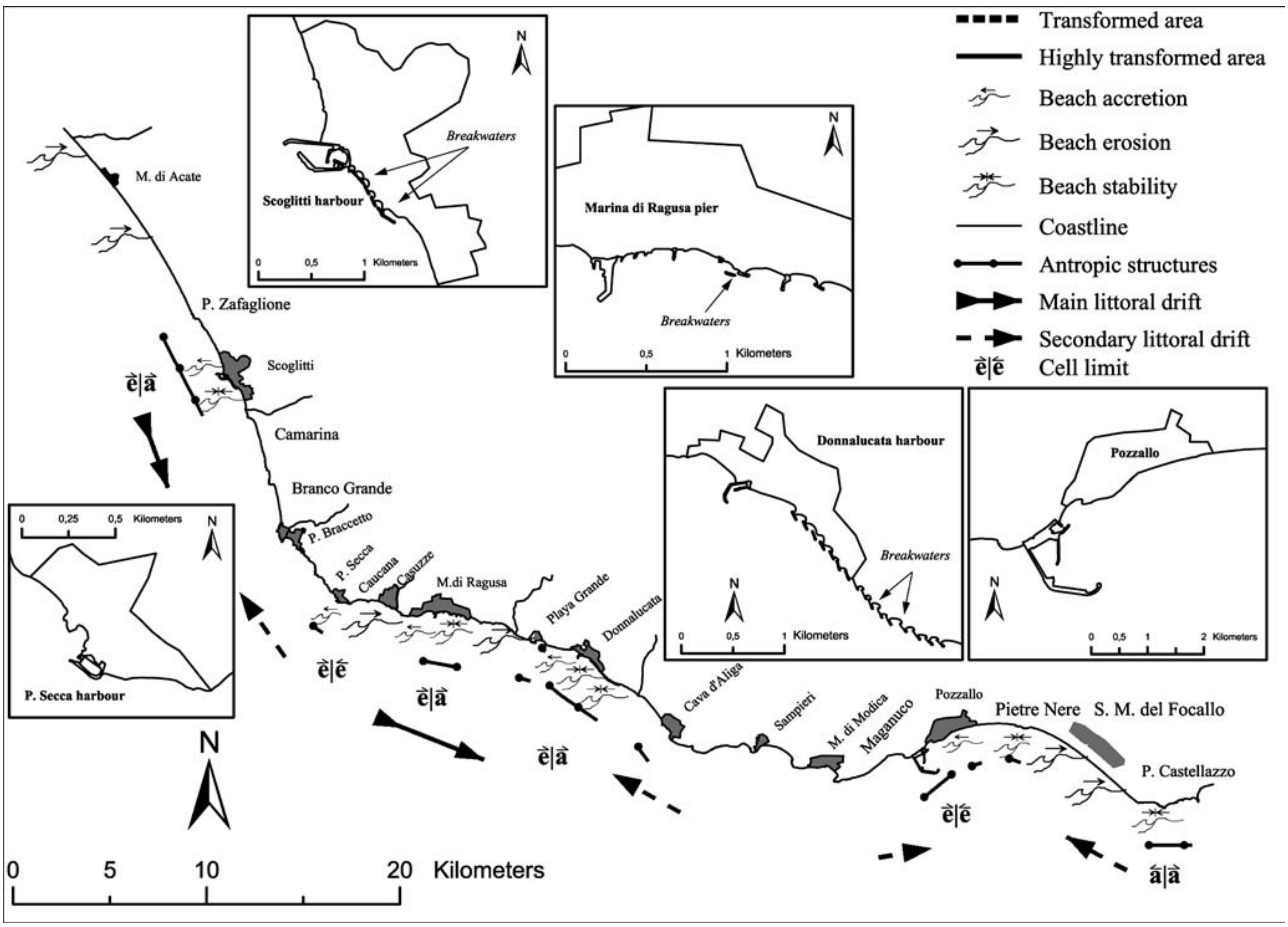


Fig. 3 Location and characteristics of human activities and engineering structures, and main zones of coastal erosion, accretion and stability in the studied littoral. Principal cell limits are also presented

Table 3 Approximate population of most important villages along the littoral

Village	Winter population	Increment during summer time	Total population in summer time
Marina di Acate	0	16,000	16,000
Scoglitti	3,000	63,000	66,000
Point Braccetto	0	3,000	3,000
Point Secca	500	7,000	7,500
Casuzze	0	23,000	23,000
Marina di Ragusa	3,000	43,000	46,000
Playa Grande	0	2,000	2,000
Donnalucata	2,000	8,000	10,000
Cava d'Aliga	1,000	8,000	9,000
Sampieri	1,000	18,000	19,000
Marina di Modica	3,000	25,000	28,000
Pozzallo	17,500	5,000	22,500
Santa Maria del Focallo	0	8,000	8,000

industrial activities carried out in the hinterland. It was originally composed of an offshore dock joined to the mainland by a pier, which did not greatly affect littoral drift. In the Eighties, it was modified by the construction of a new east pier in order to protect the port from the waves coming from the third quadrant. Currently, there is a 1864 m long, N–S oriented, main breakwater, and a maximum depth of 15 m. This structure, still underused, is now devoted to recreational and fishing boats as well as cargo ships.

Additionally, pier rope haulages can be found at Casuzze, Marina di Ragusa, Sampieri, Marina di Modica and Pozzallo. These areas, initially used for traditional fishing purposes, now house small recreational boats.

In order to quantify accretion and erosion in areas around Scoglitti harbour, aerial photographs and maps of different years and scales were analysed (Fig. 4).

In 1977, the original structure was modified by the construction of a south pier in order to avoid periodic accumulations of sand and algae transported by waves coming from the third quadrant. The aerial photos dated 1987, show a small accretion on the north and south sides, where erosive processes abated by the construction of six breakwaters. It is important to note that the coastline observed in the 1987 photographs is probably displaced landward, owing to storms around the time the photograph was taken. As can be observed in the photograph from 1994, the process of accretion (0.014 km^2) continued, the pier under construction was completed and a large new one was built to the north of the existing structure. Shoreline advancement (0.01 km^2) also continued in successive years (Fig. 4, 1997 coastline). Despite these interventions, sedimentation problems persisted and periodical dredging was undertaken. Surprisingly, the notion of creating a sand by-pass was never taken in to consideration by the local Administration which is currently elongating the existing piers once more, in order to solve silting problems.

Protective structures

Defensive structures, consisting mainly of detached breakwaters made from calcareous blocks, were constructed along the littoral zone in order to locally block coastal retreat rather than prevente it on a larger scale. These defensive structures were often close to engineering structures, resulting in the downdrift shifting of erosive problems (Fig. 3). The great majority of them are now connected to the shoreline by tombolos, while others have been partially or heavily damaged by storm waves (at Scoglitti) or are partially buried (at Donnalucata).

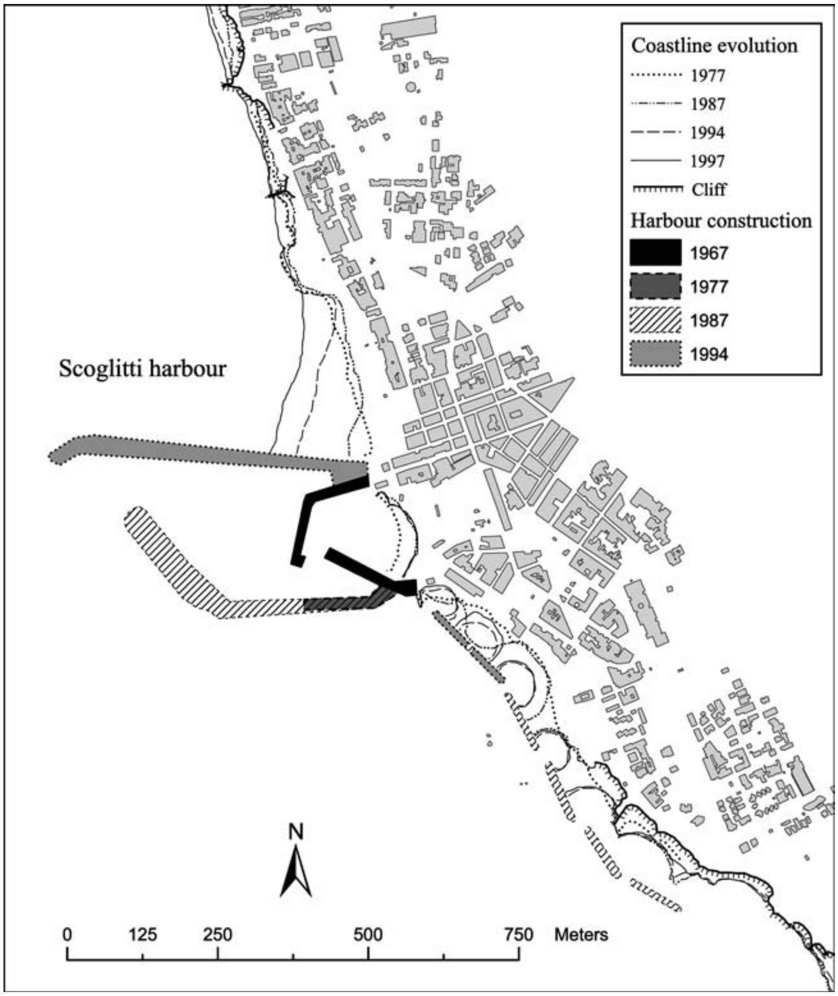
Sea walls and rip-rap revetments are present in very narrow coastal sectors, usually to preserve coastal roads (between P. Zafaglione and Scoglitti, at Marina di Ragusa, west of Playa Grande, and at S.M. del Focallo beach) or summer houses (at Modica stream mouth, Fig. 5, and at Pietre Nere beach).

Location and characteristics of protective works are presented in Table 4.

Finally, a beach nourishment program was carried out in Caucana beach from spring to autumn 2004, along an 800 m long coastal stretch, where a littoral coastal road and Byzantine archaeological remains have been damaged by coastal recession. About 71,000 m^3 of gravel (especially) and smaller pebbles along with 4,000 m^3 of sand (Porcino et al. 1997) were pumped in to build up the beach. Furthermore, submerged rocky shoals were constructed perpendicular to the shore, to create small, morphological cells and to block littoral transport. A major impediment to the execution of the project was the elevated cost of the material used to nourish the area (13 €/m^3), owing to the fact that they were being obtained from land deposits. Usually locally dredged sand is more economical (Muñoz et al. 2001 reported costs of around 3 US $/m^3 for replenishment projects carried out in the Cadiz Gulf in Spain 1998).

A nourishment project was also designed for Santa Maria del Focallo beach in order to stop erosive

Fig. 4 Coastline evolution around Scoglitti area from 1977 to 1997 and phases of harbour construction



processes. The proposed engineering works currently have no financial backing since they are considered excessively expensive (11,000,000 €), owing to the escalation in the cost of sand. Several preliminary nourishment projects have been designed for the Dirillo river mouth—P. Zafaglione, P. Zafaglione-Scoglitti, Caucana-Casuzze and Modica river mouth sectors. These projects consist of the pumping of artificial sand

Fig. 5 Summer houses located downdrift of the sixteen breakwaters constructed in Donnalucata to stop erosive processes related to the harbour

Table 4 Characteristics of most important protective structures

Location	Type	Material	Number	Unitary length (m)
Point Zafaglione -Scoglitti	Seawall	Concrete	1	3,000
Scoglitti	Breakwater	Rocky blocks	6	40
M. di Ragusa	Seawall	Concrete	1	300
M. di Ragusa	Breakwater	Rocky blocks	3	60
Playa Grande	Breakwater	Rocky blocks	1	200
Playa Grande	Rip-rap revet.	Concrete blocks	1	100
Donnalucata	Breakwater	Rocky blocks	16	80
Spinasanta beach	Rip-rap revet.	Rocky blocks	1	100
Pietre Nere beach	Breakwater	Rocky blocks	1	140
St M. Focallo beach	Rip-rap revet.	Concrete blocks	1	100
Point Castellazzo	Breakwater	Rocky blocks	4	75

(about 300,000 m^3) accompanied by the construction of small engineering structures, for a total amount of 9,200,000 €.

Harbours and littoral maintenance politics

In the littoral zone studied, significant sediment sinks are related to remediations works undertaken by the local Administration in the maintenance of ports or harbours or during beach cleaning processes. Great quantities of sediments and algae are periodically dredged in ports and harbours (Fig. 6) with these works typically being carried out as urgent remedial action (stop-gap activities) and not periodically, according to a management plan.

In addition, according to data of Table 5, dredged sediments were habitually accumulated in dumps or pumped offshore, to deeper waters (Pozzallo), eliminating them from the sedimentary budget.

Furthermore, beach cleaning methods and maintenance, based on the removal of large quantities of *posidonia oceanica* seaweed or other marine phanerogams usually accumulated on beaches during summer and autumn periods, represents the elimination of large quantities of sediment, therefore, favouring beach erosion.

Discussion

Coastal compartmentalisation

Despite the localized accretions corresponding to the breakwaters at Scoglitti, Marina di Ragusa, Playa Grande, Donnalucata, Pietre Nere and Punta Castellazzo, the distribution of the main accretion and erosion areas (shown in the legend of Fig. 3 and marked with an "e" or an "a", representing accumulation or erosion zone limits, respectively following the nomenclature of Lowry and Carter 1982), bore a strict relationship with the location of human structures. This allowed a first approximation of the division of the coast in littoral cells (Carter 1988). The most important limits are Scoglitti, Punta Secca and Donnalucata harbours, Pozzallo port, Marina di Ragusa haulage zone, and the headland (fronted by breakwaters) at P. Castellazzo, Fig. 3). These structures constitute artificial, fixed limits, that allow little or no transport in a given direction (see Bray et al. 1995), depending on their dimensions and wave characteristics. Headlands and cliffed coastal sectors constitute less important limits that require further study leading to their complete characterisation. Nevertheless, they allow periodic bi-directional transport that,

Fig. 6 Algae and sediments accumulated in Donnalucata harbour due to waves and currents from the second quadrant

Table 5 Volumes of dredged sediments

Location	Period	Dredged volumes (m^3)	Destination of dredged sand
Scoglitti harbour[a]	2004	35,000	Downdrift
Point Secca harbour	1985–1995	12,000	City dump [b]
Donnalucata harbour[a]	1990–2000	9,000	City dump
Pozzallo port[c]	1982–1995	1,150,000	3,700 Km offshore

[a]Underestimate because no data exist for previous years, when dredged sediments were accumulated in city dumps
[b]Probably, 4,000 m^3 will be rescued and used for the Caucana ongoing nourishment project
[c]During the 2000 an unknown volume of sand was dredged and pumped east of Pozzallo

according to field observations, takes place along narrow zones parallel to the shoreline, extending to a variable depth (maximum 6–10 m), depending on wave conditions and bottom morphology. Furthermore, bypassing of headlands takes place locally as a consequence of bed load sand transport onto longshore bars.

According to previous observations, the littoral zone studied, was divided by human (mostly) and natural structures in cells of different dimensions and characteristics, a fact that has not been taken into account by the local coastal managers while designing the protective structures or the nourishment projects.

In fact, the effects of coastal embaymentisation in the littoral zone on beach plan form and surf zone circulation are quite evident. As observed during field observations, beach plan form within a cell exhibits extreme variability. Waves produce longshore movement of sand that is the result of erosion in the updrift cell side and accumulation in the downdrift limit: an opposite transport mechanism produces a beach plan form rotation.

The degree of impact of headlands or other structures on the surf zone circulation in pocket beaches depends on wave and beach characteristics (Martens et al. 1999). According to field observations and to Short (1999), when a pocket beach is limited by headlands or human structures widely spaced and/or subjected to fair weathar conditions, cell limits do not affect the surf circulation at all. When the beach receives energetic waves, the cell limits control surf circulation through the formation of rip currents. The beaches studied generally displayed normal surf zone conditions during fair weather but, during storms, rips, with extended sediment plumes, are observed close to the cell boundaries. These processes produce significant offshore sediment transport and favour sediment by-pass between adjacent beaches.

It is interesting to note that the coastal circulation system varies along the studied littoral zone. In the northern sector, they are partially protected (because of its orientation) from swell approaching from the second quadrant. The littoral zone belongs to a lengthy cell which most likely extends to a northern limit at Gela port (out beyond the studied zone) and, to a southern limit at Scoglitti harbour. Within this cell, the longshore current transports sediments south-eastward, producing erosion at Marina di Acate and P. Zafaglione and accretion updrift (to the north) of Scoglitti harbour (Figs. 3 and 4). Sediment accumulated in that area is not removed by the second and third quadrants' approaching waves and associated currents because of the lee side harbour. To solve downdrift erosion problems, six breakwaters were constructed. Despite this, the ongoing shoreline retreat is threatening a coastal road. Scoglitti harbour, therefore, constitutes an almost absolute, pulse limit that impedes transport in both directions: the north dock is quite extended and almost impermeable, while the harbour entrance is a sediment sink area with swell and currents from the second and third quadrants.

The large littoral cell between Scoglitti and P. Secca, is made up of sub-cells composed by several relatively stable pocket beaches between headlands.

In the southern sector, the situation is somewhat different. While waves attacking from the west are still dominant, an opposing transport mechanism is also present in places as a result of the of coastal orientation. Distinct transport mechanisms can be observed, e.g. accretion at one or both sides of a limit, depending on the limit characteristics and on the interaction between it and the littoral transport.

In this way, on occasions, sediments are accumulated at both extremities of a cell, entering in the lee sides of the cell boundaries. Eastward or westward longshore transports do not remobilise them, so these volumes are then lost to the system, and erosion is consequently generated in the central part of the cell, probably characterised by the existence of migrating, free limit.

An example of this process can be seen in the large cell, which includes several sub-cells, bordered to the west by the small harbour at Point Secca and, eastward, by the Marina di Ragusa pier rope haulage (Fig. 3). Sediments are accumulated predominantly at the east side of P. Secca harbour and, to a lesser extent, west of the harbour, caused by wind processes (Fig. 2), with the harbour acting as a partial e/e limit (i.e. a converging limit, Fig. 3). On the other side of the cell, accretion takes place adjacently (westward) up to the pier rope haulage, that acts as a partial, pulse limit (i.e. e/a in Fig. 3), since erosion is recorded downdrift.

In the morphological cell between Marina di Ragusa and Donnalucata (Fig. 3), both structures constitute partial, pulse limits that allow a unidirectional (eastward) transport since their entrances, south-westward oriented, act as sedimentary traps for the westward directed transport (Fig. 6). A large accretion can be seen updrift (west) of Donnalucata harbour, and erosion is present of the beach west of the Marina di Ragusa limit, where three breakwaters were constructed, as well as downdrift of Donnalucata harbour (Fig. 3). Erosion was also found in the central part of the cell: at Playa Grande. A breakwater was constructed, causing downdrift erosion corresponding to a coastal road protected by a rip-rap revetment (Table 4).

The zone between Donnalucata and Pozzallo is quite extensive and contains several sub-cells containing pocket beaches between headlands (i.e. at Cava d' Aliga, Sampieri, M. di Modica and Maganuco, Figs. 1 and 3). Further studies are required for a better approximation of the sediment circulation patterns in this area. Nevertheless, the following outcomes were reached: significant erosion is present downdrift of Donnalucata, where sixteen breakwaters have been placed in succession to prevent erosion processes that have been shifting downdrift and currently threaten summer houses protected by rip-rap revetments (Fig. 5). It is probable that minor accretion takes place in the pocket beaches delimited by headlands at Cava d' Aliga, Sampieri, M. di Modica and Maganuco, but that sediment supplies to these beaches are transported inland by wind processes, forming extended landward-migrating dunes, implying or indicating that no important changes in shoreline positions are perceived. The aforementioned hypotheses were confirmed for the Maganuco pocket beach by a study carried out, comparing 1977 and 1999 aerial photographs (Liguori et al. 2005): central and eastern parts of the beach showed an accretion of 0.02 km^2, attributable to an eastward transport mechanism.

Finally, the cell between Pozzallo and P. Castellazzo is bordered by Pozzallo port constitutes an absolute, converging limit, and by the breakwaters and cliffed coast at P. Castellazzo acting as a partial, divergent limit.

Pozzallo port displays accretion on both sides (Liguori et al. 2005): at Maganuco (as previously observed) and eastward, at an old, small, filled-in pier where in the 1977–1999 period, 0.08 km^2 of accretion occurred. This was due to the prevalence of waves and associated currents from the second quadrant that accumulated sediment close on the protected east side of the port where their removal by third quadrant waves was not possible. Consequent erosion was recorded at the east end of the port, at Pietre Nere, where summer houses or edification were protected by rip-rap revetments and a breakwater, as well as at Santa Maria del Focallo beach, where a road, greatly damaged by erosive processes, was protected by concrete blocks.

Utility of the GIS approach

The incorporation and implementation into a GIS project of data from several sources and the generation of new ones by means of spatial analysis, allowed the creation of an initial data base containing coastal landform characteristics, buildings of concern, existence of various types of erosion and the division of the Ragusa Province coastline into cells. Such information can be used in its entirety or at different levels and scales by local planning staff or other end-users according to the specific objectives, e.g. coastal zone management, tourism, environmental training programmes, or other activities.

The main advantage of the GIS system is the ability to add new sets of information. This way, the degree and types of human occupations, natural environments, morphological evolution at different temporal scales, distribution of beach facilities, environmental and water quality, etc., can be easily integrated and spatially analysed in GIS applications in order to provide an Integrated Coastal Zone Management plan, and/or the generation of coastal vulnerability maps based on coastal land uses and shoreline retreat rates or beach characteristics (Fischer 1985; Fischer and Arredondo 1999).

A further advantage is that the collected and produced information presented in this paper along with GIS tools constitute a basic, initial open data base on the studied zone that can be combined with other GIS studies carried out for the European or Mediterranean area, in order to enlarge existing data bases on coastal behaviour and tendencies at different spatial and temporal scales.

Errors in shoreline mapping

The sources of error in shoreline mapping, can be divided into two categories, errors introduced by data sources and errors introduced by the measurement methods (Moore 2000).

In this study, the former errors were related to the image space distortion and the object space displacement. To resolve these problems, aerial photos were georeferenced and geometrically rectified. According to the RMSE values obtained, the photographs' geometrical error was ± 5 m.

The latter error is related to the interpretation of the studied documents; the foot of the dune usually representing the high water line (Crowell et al. 1993; Fisher and Overton 1994; etc.). In this case the 'water/sand contact point' was designated as such and tidal variation (about 0.2 m), or meteorological effects were considered negligible. Nevertheless, it is important to stress that the latter effects may be significant under storm conditions owing to the shallow gradient of the beach. For example the 1987 shoreline position in Fig. 4 may have been positioned excessively landward due to storm conditions at the time the photograph was taken; in the littoral zone studied, with beach slopes of 1–2°, a storm surge of 0.50 m would produce a shoreline landward migration of approximately 15–25 m. Further, the fact that shoreline suffers both seasonal as well as daily/weekly variations must be taken into account in the investigation of long-term charges (Moore 2000). Both these effects can produce quite a significant error, ranging from centimetres to meters.

In addition, some error is also introduced by the operator because of the quality of the scanned image, i.e. the difficulty in the identification of the precise position of the water/sand contact related to the spatial resolution of the photograph. In this study, this error was approximately ± 1 m.

Cumulatively, for the coastal zone in question, and in similar areas typified by smooth gradient, microtidal beaches, the error involved in the mapping process is less significant than the natural shoreline variations related to seasonal or short-term fluctuations such as sea level increases associated with storm surges. Following these assumptions, shoreline changes lower than about 10 m cannot be seen as representative in long-term studies.

Considerations

Applied methodology permitted an approximation of the distribution of the littoral cells which controlled sediment circulation patterns. Cell limits were essentially represented by man-made structures that constituted fixed, partial or total impermeable limits that worked as pulse, converging or divergent zones of sediment transport.

Main areas of erosion were always located downdrift of partially permeable or impermeable limits, essentially harbours and ports, and in the central part of cells characterised by accretion at both ends, i.e. the P. Secca-Marina di Ragusa and the Pozzallo—P. Castellazzo cells. The local government planning staff have not take into account coastal compartmentalisation and sedimentary transport pathways and, in order to solve coastal retreat, they have constructed solid structures downdrift of cell limits, shifting erosion problems to other areas located downdrift.

The information obtained in this study, will be of use in the correct design of long-term, general, erosion management plan that should be based mainly on the installation of ports and harbours by-pass systems, in order to restore the natural sediment circulation patterns. This way, sediments would be transported by the updrift currents, accumulating in areas located close to cell limits, to the downdrift, erosive areas, or from the accumulative extremities of a cell to its central, eroding part.

Further, a general erosion management plan should also reduce the sediment losses related to artificial and natural causes. This way, sediments dredged in ports and harbours, in past years essentially accumulated in city dumps, must be pumped in a downdrift direction to erosive areas or used in nourishment projects.

Current beach cleaning maintenance procedures must be modified: collected sediments and algae, traditionally accumulated in city dumps, should preferably be amassed in the backbeach forming a store of sediments available during storms. Additionally, wind processes that generate inland migrating dunes and foredunes, often threatening human constructions, must be prevented by positioning fences or by the stabilising with vegetation.

Finally, further studies are required to quantify sediment transport and sedimentary interchanges between coastal landforms and beaches as well as within the large, cells and sub-cells described here.

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