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SCIENCE

Morpho-sedimentary features and sediment transport model of the submerged beach of the 'Pineta della foce del Garigliano' SCI Site (Caserta, southern Italy)

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ABSTRACT
In this paper, we present the results of a detailed geomorphological and sedimentological study of a coastal sector of southern Italy, the Pineta della foce del Garigliano SCI (i.e. Site of Community Importance), which is largely affected by shoreline retreat and the degradation of dune habitat. The analysis of shoreline evolution demonstrates that severe erosion processes have occurred over the last 50 years. They caused the complete dismantling of the foredune, whereas the anomalous and advanced position of the secondary dune promoted a progressive loss of vegetation habitat of high environmental value such as juniper (*Juniperus oxycedrus* ssp. *macrocarpa*). Morpho-sedimentary data and hydrodynamic models suggest that the main climate events promoted a net longshore transport toward the South. Our analyses confirm that erosion processes are linked to natural factors but several negative human practices have contributed to the acceleration of shoreline retreat and degradation of the dune habitat. In addition to its scientific value, the map and data here presented represent an important tool for beach management purposes.

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KEYWORDS
Coastal geomorphology; wave and hydrodynamic models; beach management; sedimentology; coastal landforms; Garigliano river

1. Introduction

This paper describes the results of an integrated geomorphological and sedimentological study of the Pineta della Foce del Garigliano SCI (i.e. Site of Community Importance) area, carried out within the European LIFE + Nature & Biodiversity Project PROVIDUNE (LIFE07NAT/IT/000519) multi-disciplinary research project. The main objective of the Providune project is a detailed reconstruction of the environmental features of some Italian SCI areas (see De Muro, Ibba, & Kalb, 2015; Sabato, Longhitano, Gioia, Cilumbriello, & Spalluto, 2012, for the results of the morpho-sedimentary studies carried out in other coastal sectors of the Providune project) in order to acquire basic information useful for the preservation and safeguarding of coastal dune habitats. Similar to other coastal sectors of southern Italy, shoreline retreat represents a current problem for the study area due both to natural and anthropic factors. Actually, human activities and urbanization have promoted and accelerated coastal erosion as well as the degradation of the dune habitat (Di Stefano, De Pietro, Monaco, & Zanini, 2013; Manca, Pascucci, Deluca, Cossu, & Andreucci, 2013; Sabato et al., 2012).

Several researchers have demonstrated that a mature and well-developed dune system assumes an important role in coastal defence plans, since it contributes to the coastal sediment budget and represents a physical barrier able to prevent shoreline retreat (Di Stefano et al., 2013; El Banna, 2008; Keijsers et al., 2015). Moreover, dune ridges host a significant habitat of natural and landscape value (Munoz-Valles & Cambrolle, 2014). Therefore, actions aimed at the protection of dunes are particularly important for the coastal environment: they can be planned only after gaining a detailed knowledge of morpho-sedimentary features and sediment transport of the coastal system. This analysis underpins the identification of good practices for coastal management.

The map here presented and the results of the detailed analyses of geomorphological, sedimentological and hydrodynamic features of the Pineta della Foce del Garigliano SCI area represent a significant contribution to the planning of erosion mitigation actions.

The SCI area is located to the left side (SE) of the Garigliano River mouth, northern Campania, Italy (Figure 1), and is included in wider wave-dominated coastal sectors affected by a severe morphological evolution and anthropic pressure (De Pippo et al., 2008).

2. Materials and methods

2.1. Study area

The Pineta della Foce del Garigliano SCI area is located in the northern sector of the Campania region and its

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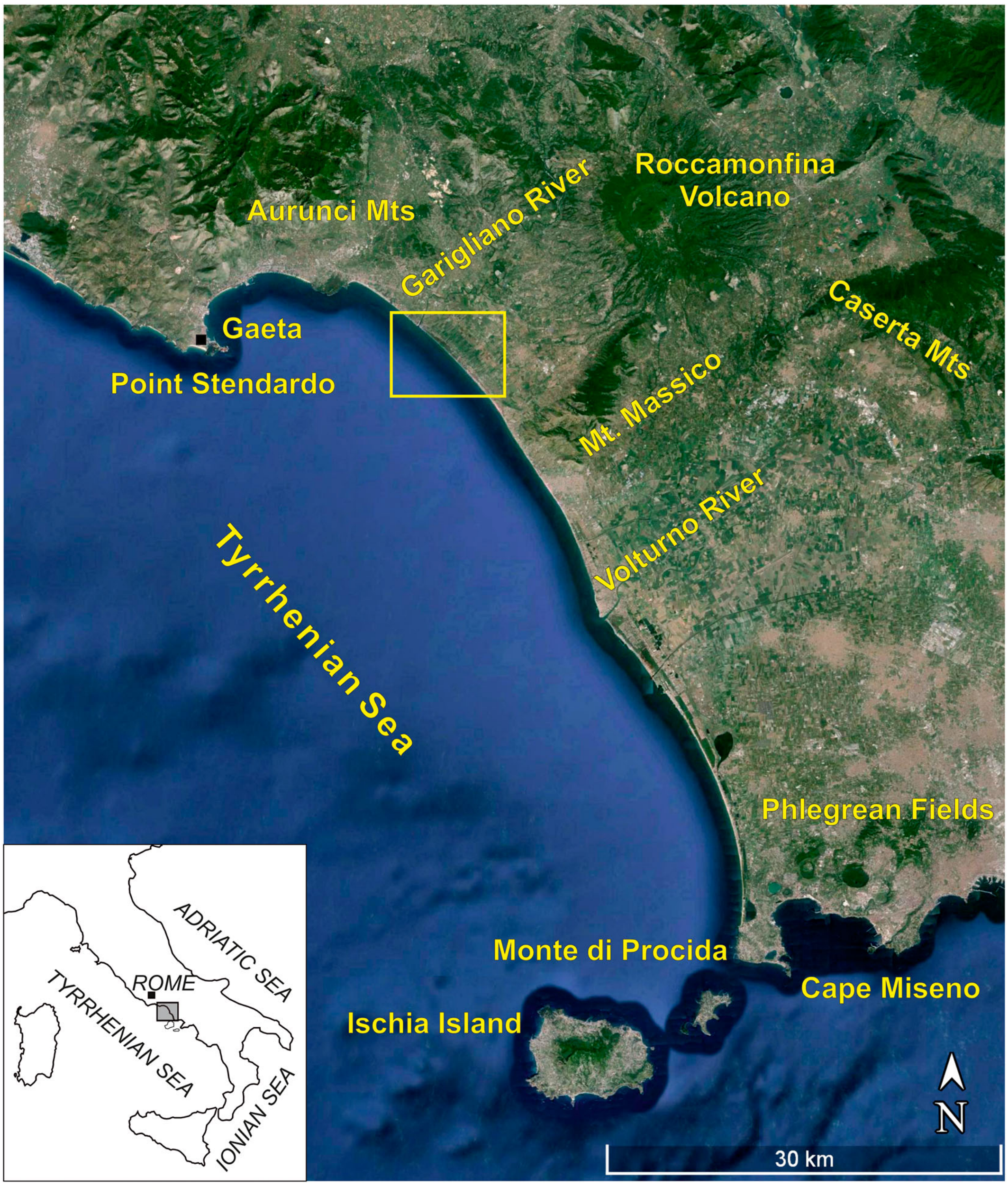

Figure 1. Location map and main toponyms of the Gaeta Gulf and surrounds. The study area is represented by the gray box. The inset shows a geographical sketch of the southern Italy (study area is shown in the rectangle).

coastal physiographic units are bounded by the Point Stendardo (near to Gaeta town), to the Northwest, and Monte di Procida, to the Southeast (Figure 1). The maximum geographical fetch is 700 km long, N200°E direction.

The study area extends for 2.7 km and the emerged beach features, in its inner part, several generations (at least six) of alternating dune ridges and depressions, Holocene in age (Abate, De Pippo, Ilardi, & Pennetta, 1998). The present-day beach is narrower in the northern sectors (about 10 m) than in the southern ones (35 m). Currently the dune system is mainly composed of remnants of embryonic dunes, which are partly covered by vegetated and more mature dune ridges; this secondary dune features vegetation species such as the juniper (*Juniperus oxycedrus* ssp. *macrocarpa*).

The Garigliano River flows within a low-elevation flat-bottomed valley of tectonic origin, bounded by the carbonate massifs of Mts. Aurunci to the North, and Mt. Massico to the South (Billi, Bosi, & De Meo, 1997). Towards the Northeast, the Garigliano River coastal plain is delimited by the Roccamonfina volcano (Figure 2). High-angle and/or listric faults affecting the carbonate ridges are responsible for the structuring of a coastal graben, which is filled by up to a 1000 m of Plio-cene-Pleistocene clastic deposits (Ippolito, Ortolani, & Russo, 1973). These deposits are covered by dune sediments dating from the Upper Pleistocene (i.e. about 125 kyr, Tyrrhenian high-stand) to the Holocene (Abate et al., 1998).

The lower reach of the Garigliano River is a meandering channel with a suspended and coarse load

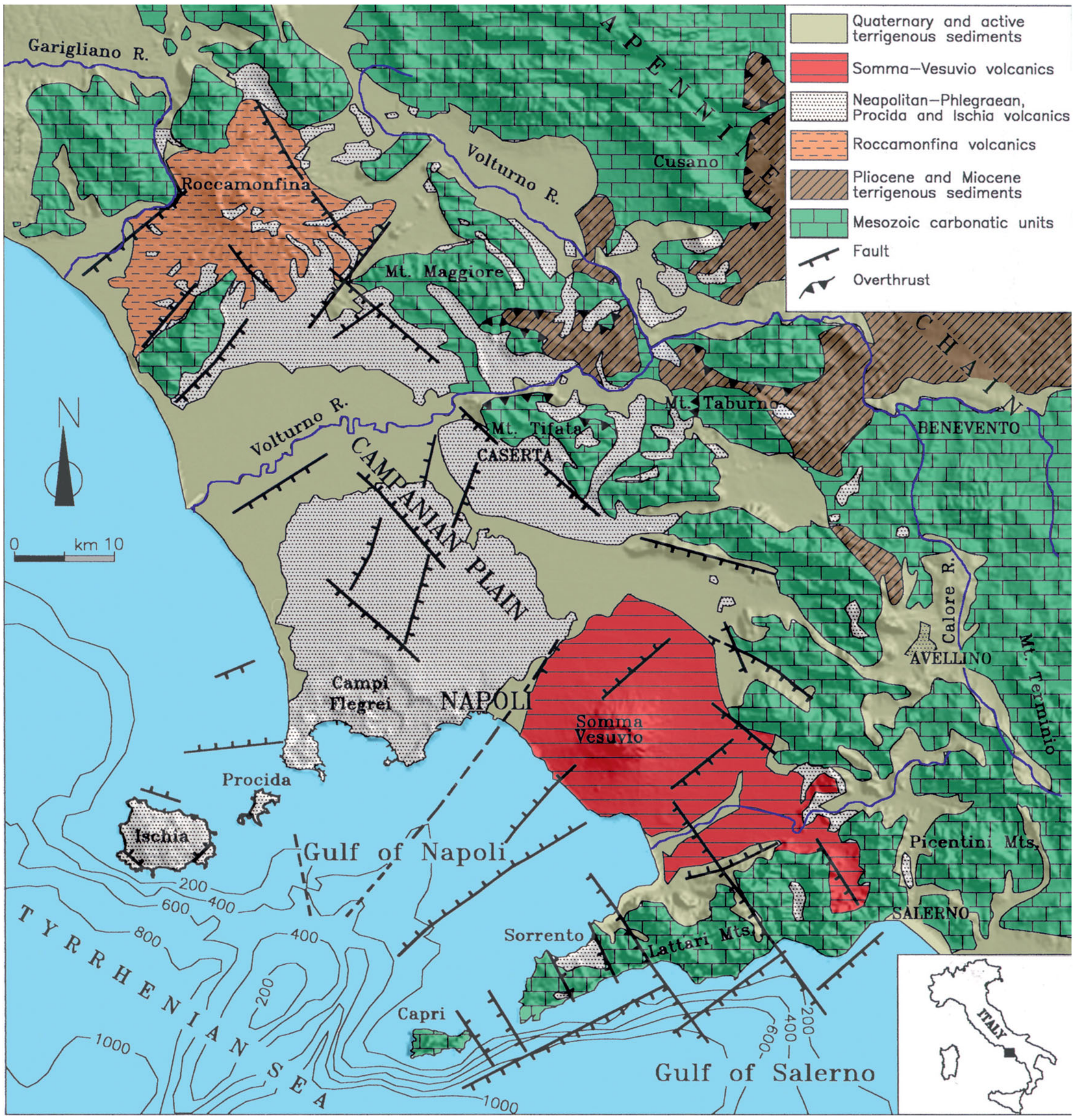

Figure 2. Geological sketch of the study area (after Orsi, de Vita, & Di Vito, 1996).

mainly related to the Roccamonfina volcano as well as the carbonate morphological high of Mt. Aurunci.

Several authors have provided contrasting interpretations of the longshore sediment transport; petrographic (Gandolfi & Paganelli, 1984) and morpho-sedimentary (Pennetta, Corbelli, Esposito, Gattullo, & Nappi, 2011) analyses and the use of artificial tracers (Cocco, De Pippo, & Massari, 1988) suggest net longshore transport of Garigliano River sediments from Northwest to Southeast, whereas recent technical reports (AdBN, 2007) based on sediment transport modeling suggest net transport (difference between southward and northward drift) toward the northern sector over the last 20 years. Historical analyses of coastal evolution indicate that the study area was affected by some generalized progradational processes of approximately 3 m/yr from 1883 to 1909 (Cocco, De Pippo, & Giulivo, 1986); more recently, the morphodynamic evolution has a prevailing erosional trend (Pennetta et al., 2011).

2.2. Methodology

The historical (i.e. about 100 years) evolution of the coastline has been reconstructed using multi-temporal analysis of topographic maps (Istituto Geografico Militare IGMI, years: 1883, 1954 and 1991; Carta Tecnica Regionale, scale 1:5000, year: 2004) and aerial orthophotos ('Aima CGR colore', scale 1:5000 year: 1998; ORCA project, scale 1:5000, year: 2005), stored in a geographic information system (GIS). Present-day coastline results from data acquired in real time with a kinematic global positioning system (GPS) survey, which allowed the reconstruction of the emerged beach topography.

Three bathymetric surveys (May 2010, June 2010 and December 2010) were performed using a Hydrobox 21 single beam echo sounder; the data were interpolated using geostatistical techniques to draw a bathymetric map for each survey.

During topographic and bathymetric surveys, a significant number of sediment samples were collected, both on the emerged (foreshore and backshore sub-environments) and submerged beach (shoreface environments up to offshore transition) of the relatively small SCI area in order to characterize their textural and sedimentological parameters. The sampling strategy has provided a regular and dense distribution of sediment samples within the main morphological units of the emerged and submerged sectors of the study area. In the coastal zone, 152 sediment samples, 100 of which on the emerged beach near the foreshore and 52 along the seabed, were collected. The sediment samples were subjected to grain size and texture analysis and morphoscopic features of the quartz grains were studied. The particle size analysis was performed according to common sedimentology techniques. After preparation and washing with a vacuum pump, the samples were dried in an oven at 110°C for 24 h, weighed with an analytical balance and dry sieved through a series of stacked sieves, with 1/4 φ class intervals up to 63 μm, in a mechanical sieve shaker for 15 min. For each sample, histograms and cumulative curves were plotted and a statistical summary calculated (Folk & Ward, 1957). For the grain size fractions between 125 and 500 μm, the samples were observed through an optical microscope to identify the morphoscopic characteristics of the quartz grains. All these features are summarized on the map of mean grain size distribution, encompassing both emerged and submerged beach sectors (Main Map). The grain size contour map was constructed using the kriging spatial interpolation method. The hydrodynamic model was reconstructed using acquired bathymetric and sedimentological data together with an analysis of the main wind direction using data from the Ponza Island oceanographic buoy (Figure 3). This analysis allowed us to infer that the main climate events of this sector of the Gaeta Gulf are related to winds blowing from 255°N and 270°N. Therefore, we reconstructed the sediment transport model on the basis of these hydrodynamic scenarios. Such models have been constrained using the bathymetric and geomorphological data of the emerged and submerged coastal area. According to the main climate features observed at the Ponza buoy, models were built using the following

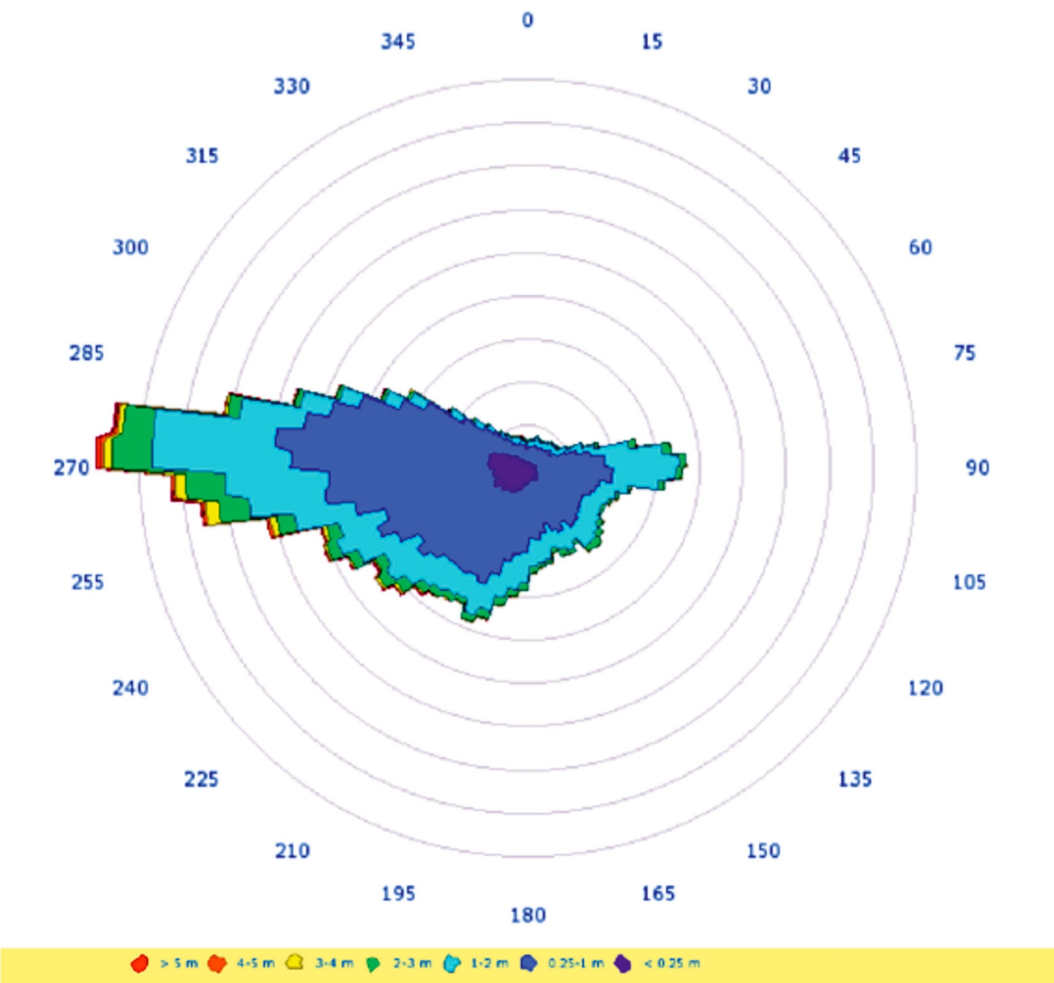

Figure 3. Wind data acquired by Ponza Island oceanographic buoy; period: 1 July 1989–31 December 2001. Absolute (N270) and relative (N255) maxima of the wind data and its magnitude have been used to infer the hydrodynamic scenarios of the DELFT-3D models.

parameters: wind velocity, 10 m/s; event duration, 24 h; wave height (Hs), 2 m; and peak period (Tp), 7.5 s.

The hydrodynamic models allowed us to infer the main direction of waves and reconstruct the direction and magnitude of hydrodynamic flow during extreme events with winds blowing from 255°N and 270°N. Finally, a geomorphological survey was performed, aimed at identifying the main landforms and geomorphic elements of the emerged sectors of the study area.

3. Results

3.1. Morpho-sedimentary analyses

The submerged sandy beach is characterized, in its inner zone and within −4 m depth, by a hummocky longshore belt of bars and troughs, which are located at 120–150 m from the coast. These marine forms pass seaward to a more regular morphology, sloping offshore with a low gradient, down to −11 m.

The arrangement of sediment along transversal transects observed reveals the normal coast-to-sea transition, varying from the shoreline, where gravel and coarse sand ($-1.9 < Mz$, mean grain size < -2.8) are present, and the surf zone, characterized by medium ($2 < Mz < 1$) to fine ($3 < Mz < 2$) sand which are generally well sorted ($0.5 < \sigma_I < 1$). Skewness values (Sk_I) of sediments are negative or close to 0, suggesting asymmetry of frequency curves toward coarser grain size fractions. This observation links the sedimentological features to a high hydrodynamic energy and wave-dominated environment.

Grain size analysis reveals that the bar and trough system in the northern sector of the submerged beach generally features medium sand ($1\ \varphi < Mz < 2\ \varphi$), although a local and anomalous presence of fine sand ($2\ \varphi < Mz < 3\ \varphi$) in some central and southern proximal sectors of the study area (Main Map) was recorded. This anomaly alternates with medium sand in the submerged beach together with the occurrence of several depressions ('depression area', Main Map) which can be attributed to both natural and human factors: the anomaly in grain size zonation is partly related to the erosion processes affecting the dune ridge made by fine and very fine sand, which promoted the deposition of these sediments in the submerged beach. Moreover, the occurrence of a depressed area in the submerged beach suggests that dredging for beach nourishment is a common practice in the study area.

The emerged sandy beach is bounded inland by multiple dune ridges, passing landward to a depression. The investigated coastal system is affected by a strong driving forces, which have resulted in a general shoreline retreat. Historical analysis of the coastline reveals that the sandy beach has been affected by severe erosional processes over the last 50 years (Figure 4). From 1954 to 2009, it is possible to detect a coastline retreat of about 80–90 m in the northern sector, whereas the rate of coastline retreat is lower in the southernmost sectors of the study area (i.e. about 35–45 m, Figure 4). This observation is also confirmed by the absence of a foredune or primary dune, which is generally related to a negative sediment budget of the beach. This unstable system shows considerable evidence of erosion related to wave attack at the base of the dunes and sometimes due to anthropogenic factors (cleaning and widening of the beach by mechanical vehicles), with steeper windward slopes (30°) than those downwind. Many access ways and paths to the sea as well as cup-shaped or trough-shaped depressions (blowouts) fragment the dunes, accelerating the dismantling process. Blowouts are common forms in coastal dune environments affected by erosion processes (Bird, 2012), promoted by climatically controlled factors or human impact.

The sediment distribution of the emerged sector is generally regular, with a gradual decrease of average grain size from the beach to the dune area (Figure 5). Sediments of the second order dunes, (with the foredunes absent 25–50 m from the shoreline) are classified as fine sand ($Mz = 2.5–3$) and moderately well sorted ($0.5 < \sigma_I < 1.0$) along the slope. The dune crests are characterized by very fine sands ($3 < Mz < 3.5$), moderately well sorted or poorly sorted. The trend of frequency curves of these samples gradually migrates from asymmetrical toward the coarse fraction to nearly symmetrical. Fine sands are also present on the back of the second order dunes, into the interdunal depression, and on the third order dune ridges ($3 < Mz < 3.5$).

Even the thinner sandy sediments of the dune environment have textural features compatible with the sorting ability of deflation processes that are present in this morpho-climatic context. However, it was observed that the dry beach sediments show textural and granulometric characteristics similar to those of the dunes, except for the crests areas. This observation suggests that the second order dunes, which were stable in the past, have now been reactivated by erosional processes (Main Map). Currently, the second order dunes provide sediments to the dry beach. Normally, the dry beach is sustained by a foredune, however this has been completely eroded.

All the sedimentary features appear to be affected by reworking due to human activities. One of the most noticeable is beach cleaning using mechanical equipment, which affects the whole emerged beach and the dune system. In fact, field surveys carried out during the project verified that this practice occurs daily in the summer.

4.2. Hydrodynamic models

The reconstructed bathymetry and sedimentology, together with the analysis of main climate events,

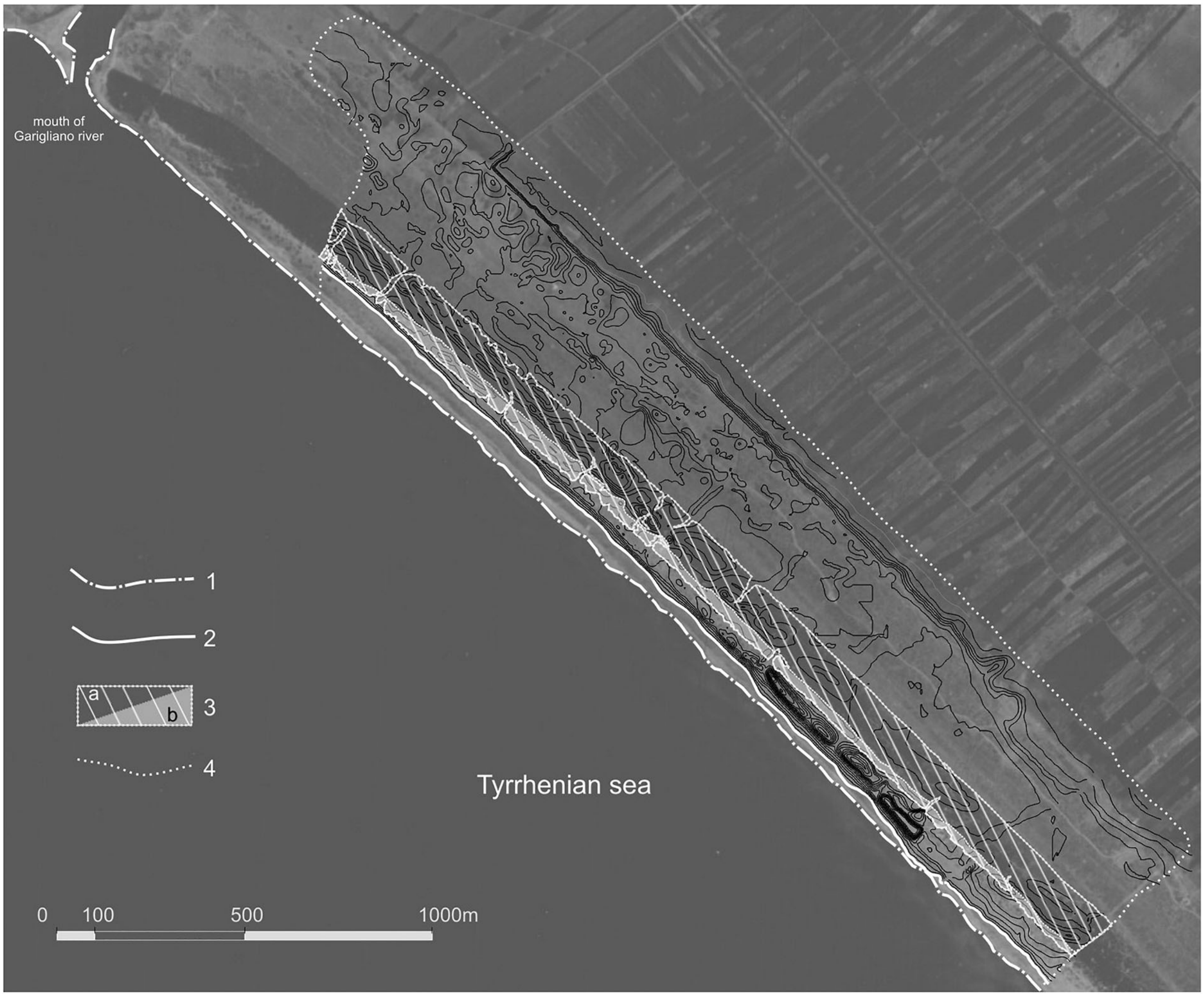

Figure 4. Coastline evolution of the SCI area (after Pennetta et al., 2011). Legend: 1 – 1954 shoreline; 2 – 2009 shoreline; 3 – extent of anthropogenic pine forest in 1954; 3a – extent of the same forest in 2009; 3b – retreating forest area due to erosion processes, later colonized by scrubland (including, commonly, juniper), where not impacted by human activity; 4 – SCI area.

were used to produce wave and hydrodynamic models of the study area. Analysis of wind and current data from the Ponza Island oceanographic buoy allowed us to produce two main hydrodynamic scenarios, corresponding to N255°- and N270°-trending marine extreme events. Hydrodynamic models provided some additional information about sediment transport and the erosion/deposition sectors during these main climate events.

4.2.1 N255° Model

This model depicts waves that turn to the NNE. The speed values of hydrodynamic flow are low in the distal sector while for the first meters of the submerged beach, the velocity reaches its maximum. As with the previous model, the direction of flow generates a longshore current towards the Southeast with associated rip currents in the southern sector (see Main Map). Sediment dynamics during this event, indicate that the areas with the greatest excavation coincide with the bar and trough system (surf zone), which characterizes the first few meters of the submerged beach, with limited accumulation zones particularly near the shore line.

4.2.2 N270° Model

This model depicts waves that tend to turn to the NNE. This scenario creates a main NW–SE longshore current (see Main Map). The effect on sea bottom sediment shows that the most important excavation coincides with the bar and trough system (surf zone), characterizing the first few meters of the submerged beach. These accumulation zones are limited in the southern sector and particularly near the shoreline.

5. Conclusions

A morpho-sedimentary map of an SCI area located to the left side (SE) of the Garigliano River mouth is presented. The results allow us to infer that the analyzed coastland is diffusely affected by erosion processes linked to natural factors, as well as to various anthropogenic activities. Shoreline retreat and dune erosion have occurred over the last 50 years, as demonstrated

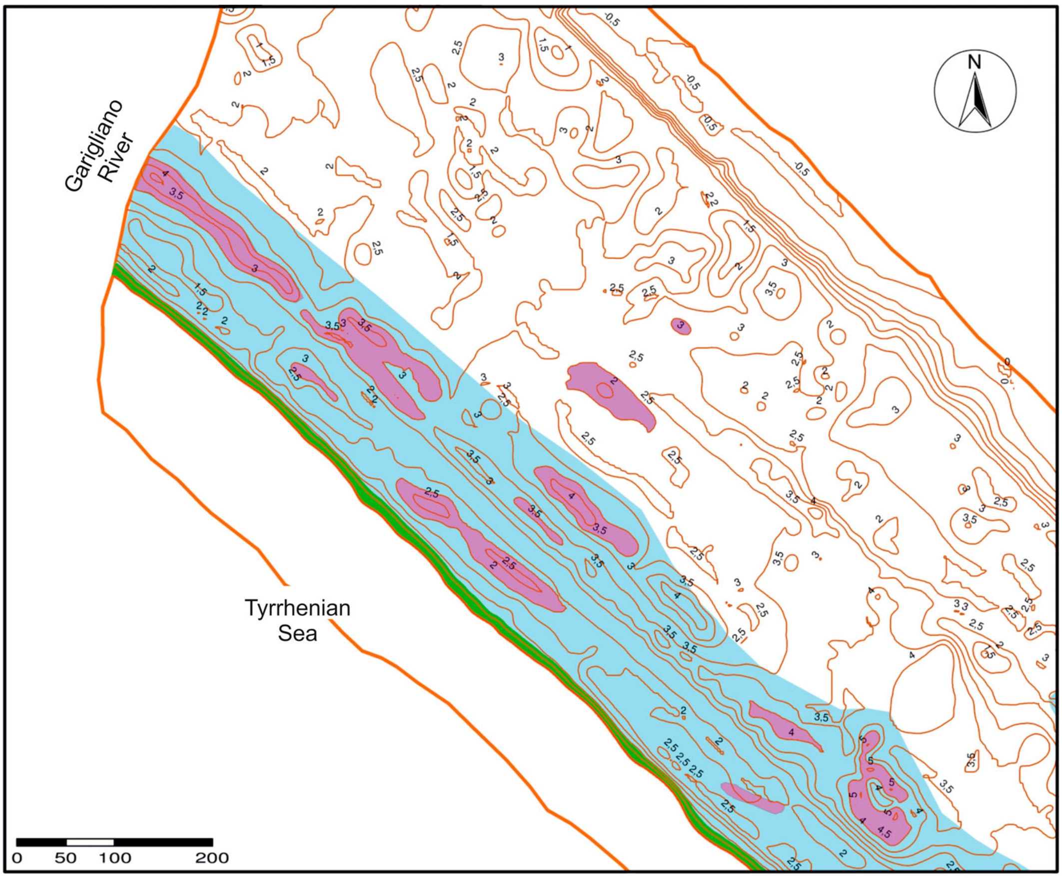

Figure 5. Detail of the grain size map in the northern sector of the SCI area, located to the left (SE) of the Garigliano River mouth. The grain size of sediment is indicated by different colors: violet, very fine sand; sky-blue, fine sand; green, medium sand; brown line, SCI area.

by the comparison between historic maps and present-day topographic surveys. As a consequence, erosional processes have caused the complete dismantling of the foredune, whilst the anomalous and advanced position of the secondary dune has promoted a progressive loss of vegetation habitat of high environmental value. Hydrodynamic models and the mapping of forms of the submerged beach provided additional information about sediment transport processes and the evolution of the SCI area. Main climate events generated currents from W and WNW directions, which should be able to re-mobilize sediments from the surf zone of the northernmost sectors. Prevailing erosion phenomena in the northern area could explain the higher rates of shoreline retreat in this sector. Modeling also suggests a moderate accumulation in the southern sector, which is frequently affected by dredging for beach nourishment. This negative practice together with other inland human activities such as the reduction of sediment river supply caused by the construction of river protection structures, the creation of high-impact beach access by dune cutting or paths are all factors that have contributed to modification of the sediment balance and to worsening erosion phenomena. Finally, an important role can be played at a regional scale by the potential sediment trap of some human structures to the northwest of the SCI area, such as the Gaeta and Formia harbors and, southward, some coastal protection break waters, which could represent an obstacle to longshore transport.

Software

The data were processed using QCAD (www.qcad.org) and QGIS (www.qgis.org) in order to create a georeferenced topographic-bathymetric base. The coordinate system of the GPS survey (i.e. UTM-WGS84) has been selected as the spatial reference. This software was also used to map the grain size distribution of sediments. Global Mapper 15 was used to produce a Digital Terrain Model (DTM) of the study area.The WAVE and FLOW modules of Deltares Delft3D were implemented (Kalb, 2008). The final map was produced using the Adobe Illustrator CS5 software.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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MORPHO-SEDIMENTARY FEATURES AND SEDIMENT TRANSPORT MODEL OF THE SUBMERGED BEACH OF THE "*PINETA DELLA FOCE DEL GARIGLIANO*" SCI SITE (CASERTA, SOUTHERN ITALY)

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1 : 5000 scale

0 100 200 300 400 500m

PROJECTION: UTM 33N WGS84 datum

The geomorphological map of the submerged beach of the area of *"Pineta della foce del Garigliano"* IT8010019 SCI sites (European NATURA2000 network) is made up with the results of a detailed geomorphological and sedimentological study of a coastal sector of southern Italy, the Garigliano River area, which is largely affected by shoreline retreat and degradation of dune habitat. Analysis of shoreline evolution demonstrated that severe erosion processes occurred in the last 50 years. They caused the complete dismantling of the foredune, whereas the anomalous and advanced position of the secondary dune promoted a progressive loss of vegetation habitat of high environment value such as the juniper. Morpho-sedimentary data and hydrodynamic models suggest that the main climate events promoted a net longshore transport toward the South. Our analyses confirms that erosion processes are certainly linked to natural factors but several negative human practises contribute to accelerate the shoreline retreat and the degradation of dune habitat. In addition to its scientific value, this map represents an important tool for beach management purposes.

Keywords: Coastal geomorphology, Wave and hydrodynamic models, Beach management, Sedimentology, Coastal landforms, Garigliano River.

Morphological features

- Dune ridge
- Trough axis
- Bar axis
- Channel
- Depression area
- Accumulation area
- Shore line

Grain size features

- Gravel
- Very coarse sand
- Coarse sand
- Medium sand
- Fine sand
- Very fine sand

Topographic and bathymetric features

- Contour line (1m interval)
- Depth line (5m interval)
- Depth line (1m interval)

Hydrographic features

- Stream, river or artificial channel
- Pond

Man-made forms

- Motorway and asphalt road (A); Path (B)
- Buildings and houses built between 1975 and 1985
- Buildings and houses built between 1985 and 1998
- Buildings and houses built between 1998 and 2010
- Camping area
- Parking area

Other features

- Site of Community Importance (SCI) area boundary European Commission Habitats Directive (92/43/EEC)
- Area not studied

The Map is based on Orthophotos produced by Regione Campania (ORCA Project) during the years 2004-2005.
Projection UTM 33N WGS84 datum.

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