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# An integrated sea-land approach for mapping geomorphological and sedimentological features in an urban microtidal wave-dominated beach: a case study from S Sardinia, western Mediterranean

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## ABSTRACT

An integrated cartographic approach has been used to summarize different data (geomorphological, sedimentological, hydrodynamic, ecological and anthropic) from an urban microtidal, wave-dominated beach and adjacent inner shelf in a comprehensive and easily readable mapping output. The study area is located in S Sardinia (Italy, Mediterranean Sea) and focuses on Poetto beach. All the data in this study were processed to produce a **Main Map** (1:6400 scale) showing the key characteristics of the entire area and three detailed secondary maps (1:56,000 and 1:59,000 scale) that include topographic and eco-graphic profiles, the distribution of sedimentary facies and the main anthropic impact. This map, providing detailed information on the beach dynamics, human impact and the marine ecological status of the Poetto urban beach, represents a useful new tool to facilitate environmental conservation and beach management.

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## KEYWORDS

Geomorphology; sedimentology; *Posidonia oceanica* meadow; beach management; Mediterranean sea; Poetto beach

## 1. Introduction

Urban beaches are dynamic sedimentary environments, highly impacted by human activities. They provide important functions for human recreation, economy of coastal cities and support the protection of coastal development from storms and flooding, acting as a barrier in respect to physical forcing (Jimenez, Euan Avila, Villatoro Lacouture, & Silva Casarin, 2016). However, coastal management practices often alter urban beach morphology and dynamics using inappropriate procedures for routine maintenance (Nordstrom, Jackson, Freestone, Koroty, & Puleo, 2012; Simeone & De Falco, 2012, 2013). For example, the removal of seagrass banquettes through mechanical cleaning impacts the backshore section of the beach system (Buosi et al., 2017; De Falco, Simeone, & Baroli, 2008), and the trucks, transiting on the beach to allow its removal, flatten the berms and reduce sand permeability, with subsequent coastal erosion (De Muro & De Falco, 2015).

Understanding of the interactions between beach dynamics (sediment origin and transport pathways, classification and distribution of morpho-sedimentological features, identification of sediment facies in relation to wind, waves and hydrodynamic-induced processes, etc.), human impact (e.g. nourishment works, fragmentation of dune habitats) and infrastructure, marine biota (distribution of *Posidonia oceanica*

meadow) and climate forcing can be crucial for coastal managers to provide benefits for beach management, risk prevention and coastal planning (De Muro & De Falco, 2015). When combined these data in a unique cartographic product, they can be easily used by decision-makers to assess territorial and marine features and locate vulnerable areas in need of conservation and protection. Recently, significant efforts were made to synthesize the outputs of research studies in a useful format for coastal managers (De Muro, Batzella, De Falco, & Porta, 2010; De Muro, Ibba, & Kalb, 2016; Rovere et al., 2015; Stojanovic & Ballinger, 2009). From this effort, several maps were realized by the scientific community to identify coastal hazards and/or coastal vulnerability (De Muro, Batzella, Kalb, & Pusceddu, 2008; De Muro, Pusceddu, & Kalb, 2010; Mendoza & Jimenez, 2008; Olita et al., 2012; Rovere et al., 2013). However, only a limited number of maps have the capacity to integrate coastal geomorphology information (onshore and offshore), geological background, sediment data, benthic habitat mapping, hydrodynamic modeling (longshore and rip currents) and human impact as shown in Buosi et al. (2017). The **Main Map** presented herein is the first map summarizing anthropogenic impact (e.g. nourishment activities, grooves due to pedestrian and vehicle impact) on a beach system as well as geomorphological, ecological quality status of seabed, hydrodynamic and

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sedimentological data. Therefore, the aim of this paper is to synthesize, using a digital map, the results of several studies conducted in an urban Mediterranean beach, located in the south of Sardinia (Figure 1). More specific goals are: (i) to identify the main human impacts and pressures; (ii) to assess the relationship between coastal processes and sediment input from nourishment activities; (iii) to evaluate the environmental status and (iv) to describe the overall beach system from backbeach to inner shelf.

Furthermore, the map provides a multidisciplinary baseline product to support the future assessment of anthropogenic impacts and monitoring of environmental changes related to sea level rise and increased extreme events linked to global warming.

This work is part of a more extended study aiming to provide a large cartographic archive of the Sardinian coasts (Buosi et al., 2017; De Muro et al., 2016; De Muro, Porta, Passarella, & Ibba, 2017; De Muro, Pusceddu, Buosi, & Ibba, 2017).

## 2. Study site

### 2.1. Regional setting

The Cagliari Gulf is located in the south of Sardinia between two Paleozoic tectonic blocks (western Mediterranean Sea; Appendix 1). The gulf shows both the extreme eastern edge of Cenozoic structures related to the Oligo-Miocene graben-system (Casula, Cherchi, Montadert, Murru, & Sarria, 2001; Cherchi & Montadert, 1982) and the NW-SE Plio-Quaternary Campidano graben. The calcareous Capo S. Elia promontory divides two Pleistocene-Holocene beach systems (Giorino – La Maddalena on the W and Poetto on the E).

Before the urban development of Cagliari (1900), these beach systems were connected and characterized by a sedimentary eolian interchange (blue and light blue arrows, Appendix 1). This flux of sediments was interrupted as a consequence of the expansion of Cagliari.

### 2.2. Poetto: urban beach

Poetto beach is an urban beach (*sensu* Jimenez, Gracia, Valdemoro, Mendoza, & Sanchez-Arcilla, 2011), because in the eastern sector of the Gulf (Appendix 1) it fronts the city of Cagliari.

Cagliari and its neighbors have more than 500,000 inhabitants, and the Poetto beach is the most frequented beach in Sardinia (about 100,000 people per day; Strazzera, Cherchi, & Ferrini, 2008).

Poetto is a Mediterranean microtidal wave-dominated sandy beach with a length of 8 km and a maximum width of about 100 m. Residual embryo dunes and foredunes are mainly located on the backbeach of the easternmost sector. Foredunes have been completely eroded due to the construction of a

pedestrian/cycling road along the shoreline. Embryo dunes are highly impacted by pedestrian transit for beach access that causes cross-shore fragmentation. Additionally, the seaward side of these dunes is eroded on a daily basis due to beach cleaning and bulldozing.

Damage to infrastructure located closer to the shoreline and caused by storms was recorded on the western side of Poetto beach. For this reason, a nourishment project was carried out in 2002 on the western side of the study area, using mainly bioclastic/biogenic sediments. The nourishment has significantly modified the textural, compositional and morphological features of the backshore, shoreline and shoreface, which were originally composed of medium-fine siliciclastic sand.

Increasing residential users and tourists, urbanization and sediment nourishment are the main human interferences occurring on Poetto beach. Moreover, beach cleaning operations (e.g. removal of *P. oceanica* banquettes or seagrass berm) and other maintenance procedures (e.g. bulldozing) could affect beach morphology.

### 2.3. Wave climate and hydrodynamics

The Gulf of Cagliari is characterized by low energy waves with a significant wave height ( $H_s$ ) lower than 1 m (80% of cases). The studied area is mainly exposed to wind and waves coming from S (Figure 1).

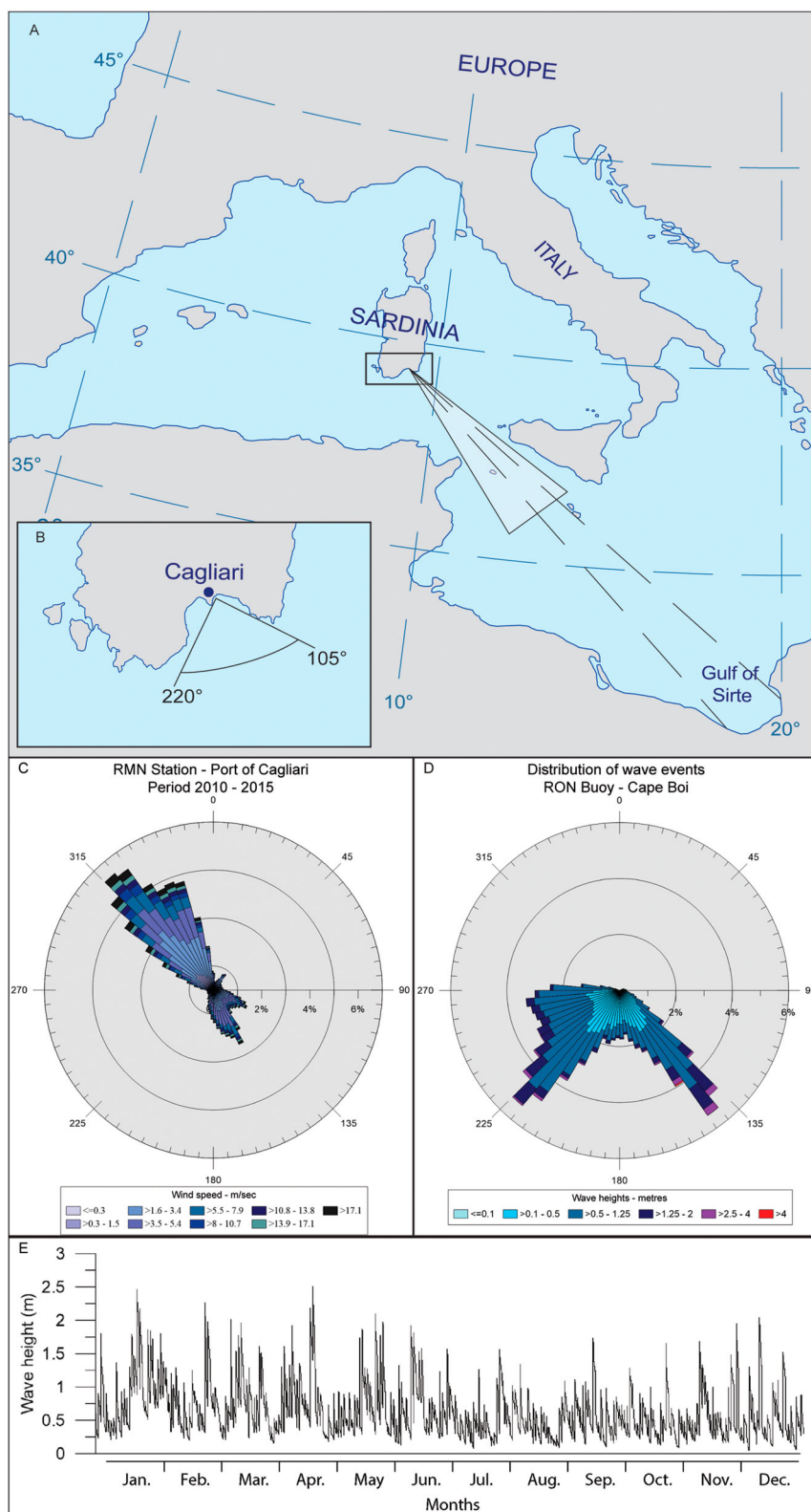
Highest wave heights on Poetto beach occurred from October to April (Figure 1(E)). Waves coming from SE were ~66% of total wave events, maximum wave height for this sector was 4.3 m, peak period 11 s. Waves coming from SW were ~34% of total wave events, maximum wave height for this sector was 3.4 m, peak period 7 s. Tidal range is low (less than 20 cm), with a maximum tidal range of about 40 cm (Brambilla, van Rooijen, Simeone, Ibba, & De Muro, 2016).

## 3. Methods

Morpho-sedimentological data were used to create the map of Poetto beach (referred to as *Main Map*). These data were acquired following the Coastal and Marine Geomorphology Group methodological protocols (CMGG, University of Cagliari; Batzella et al., 2011; De Muro, Kalb, Ibba, Ferraro, & Ferrara, 2010; Pennetta et al., 2016; Pusceddu et al., 2011).

Data collection and analysis included topographic and bathymetric surveys, sediment sampling, video images, aerial photographs, acoustic profiles (Side Scan Sonar, single beam), wind, wave and tide information, numerical modeling and ecological elements (like distribution of seagrass meadow).

The anthropogenic impact was identified in the long term through an analysis of historical cartography, satellite and aerial images. Short-term impacts were documented during field surveys and using video data.



**Figure 1.** Geographical setting of the study area. (A) The geographical fetch and the effective fetch of 500 km in relation to Poetto beach. (B) Exposure field of wave motion. (C) Wind data (RMN Station – Port of Cagliari). (D) Distribution of wave events (Rete Ondametrica Nazionale – RON Buoy Cape Boi). (E) Hydrodynamics data: offshore significant wave height ( $H_s$ ) acquired during 2014.

The map of Poetto beach (Main Map) includes one detailed map (1:6400 scale) and three inset maps: (Map 1) morpho-sedimentological map; (Map 2) sedimentary facies (1:56,000 scale); (Map 3) sediment sampling grid, topographic and acoustic profiles (1:59,000 scale); and (Map 4) human impact and use (1:59,000 scale).

### 3.1. Topographic and bathymetric surveys

To estimate the beach morphological variability and the shoreline position, a series of cross-shore profiles (spaced about 400 m, repeated 6 times from October 2012 up to December 2013) were acquired using a Differential Global Positioning System (DGPS) for

the backshore. Along shoreface, the DGPS was coupled with a single beam Echosounder (*Reson Navisound 215*) (Haxel & Holman, 2004; Morton, Leach, Paine, & Cardoza, 1993). The profiles were measured from the landward limit of the beach (man-made limit constituted by a pedestrian/cycling road) up to a depth of 18 m (Map 3). During acquisition of topographic profiles, the extent of seagrass berms was mapped using a DGPS. The areas interested by this features were then reported in the map. According to Gómez-Pujol, Orfila, Álvarez-Ellacuría, Terrados, and Tintoré (2013), the position of seagrass berm is quite variable and dynamic in time and space. Therefore, its position in a static map is just indicative of a possible zone for seagrass berm deposition.

### 3.2. Sediments analysis

Seventy-one sediment samples were collected on the backshore, the shoreface and the inner shelf using a bailer, a Van Veen grab (5 L) and scuba divers, respectively (Map 3).

Grain-size analyses were performed following the ASTM international standard methodology. The <6700  $\mu\text{m}$  and >63  $\mu\text{m}$  fraction was dry sieved through sieves spaced at  $\frac{1}{4}$  phi ( $\phi$ ) per unit (Wentworth, 1922). The statistical parameters (Folk & Ward, 1957) were obtained using the Gradistat software (Blott & Pye, 2001). The sediment mineralogical composition was established in a semi-quantitative way under an optical microscope in order to distinguish quartz, feldspars, other minerals, litho- and bioclasts. The volume percentage of each mineralogical class was recognized using the areal comparison method (the areal percentage of each mineral estimated using visual comparison tables; Lewis & McConchie, 1994).

Sedimentary facies (Map 2) were identified based on the grain-size and mineralogical/petrographical composition of the sediment, Side Scan Sonar, satellite images, scuba diving and underwater video data (De Falco, De Muro, Batzella, & Cucco, 2011; De Muro et al., 2016; Lecca, De Muro, Cossellu, & Pau, 2005; VV.AA., 2013, 2016).

For each sample, the sediment density was determined using a pycnometer and the sediment fall velocity was determined using mean diameter ( $M_z$ ) and density ( $\rho_s$ ) as input values for the Le Roux (1997) formula.

### 3.3. Video monitoring

A video monitoring station was installed on the top of the hill on the headland that bounds the beach on the southwestern side (Capo Sant'Elia, Main Map).

Snapshot images were collected twice a day. In total, 180 snapshots were captured during each interval. The interval between two consecutive images was 30 s. The

snapshot images were processed to obtain Timex images, which were georectified. The georectification of the Timex images was achieved using the package 'g\_rect' for Matlab (Pawlowicz, 2003). The method considers the geometric characteristics of the field of view of the digital camera. Twenty-two ground control points, acquired using a DGPS, were used to implement the georectification.

Video monitoring was used for (1) assessment of human impact (beach cleaning, bulldozing, placement and removal of café and restaurant kiosks at the beginning and end of each tourist season, etc.) and (2) measurement and evaluation of water mass movements (wave refraction angles, cross- and long-shore sediment dispersion, swash, run up, flooding areas, timing of flooding and the return to the state of equilibrium).

In addition, georectified timex images were used to define the morphodynamic states (following the classification of Short, 1999). The position of bars was manually determined on the georectified images and included in the Main Map.

### 3.4. Wave data

The wave data measured by the offshore buoy located in the Gulf of Cagliari (39°6'52''–9°24'20'') were obtained from the database ISPRA-R.O.N. (Rete Ondametrica Nazionale) (Bencivenga, Nardone, Ruggiero, & Calore, 2012).

Breaking wave height ( $H_b$ ) was determined using the formula by Kamphuis (1991, Equation 1), and used to determine the  $\Omega$  parameter for each of the studied profiles:

$$H_b = 0.56 \exp(3.5m)h. \quad (1)$$

In the formula,  $m$  is the average profile slope measured from beachface to inner bar;  $h$  is the depth where the waves break, generally located on the seaward side of the inner bar, 0.56 and 3.5 are constants.

The classification is based on the dimensionless fall velocity  $\Omega$  (Dean, 1973; Short, 1999) (Equation 2):

$$\Omega = H_b / (W_s T), \quad (2)$$

where  $H_b$  was breaking wave,  $T$  was the mean wave period recorded by buoy during the monitoring period and  $W_s$  is the fall velocity (Brambilla et al., 2016). The landward limit of the maximum run-up was estimated from timex images along the beachface or the backshore. The run-up limit was tracked manually along the area visible on the georectified timex images. Furthermore, run-up elevation was calculated along four profiles using the formula of Hunt (1959) for the most extreme storm events. This value was used to draw the run-up limits on the map in areas where no imagery was available.

### 3.5. Ecological data

The distribution of *P. oceanica* meadow and the ecological status (based on benthic foraminiferal assemblages) were evaluated to provide baseline environmental data for the studied area.

The distribution of seagrass meadow (mainly *P. oceanica*) was assessed using aerial photographs, scuba diving and eco-graphic profiles.

To evaluate the ecological status, we used the classification scheme proposed by Bouchet, Alve, Rygg, and Telford (2012) based on benthic foraminiferal diversity, expressed as the exponential of the bias-corrected version of the Shannon–Wiener index (Shannon & Weaver, 1963). Assessment of the ecological status is based on the deviation of population characteristics from reference conditions and the outcome of the analysis feeds into five status classes (high, good, moderate, poor and bad). High status is considered as unimpacted reference or background conditions. Good status corresponds to environmental alterations or contaminant levels that have no ecosystem impact. Alterations or contaminant levels corresponding to moderate, poor and bad status if they have chronic, acute and severe acute ecosystem impacts, respectively (WFD, 2000/60/EC). For this purpose, ten sediment samples were collected with a Van Veen grab. Each sediment was preserved in ethyl alcohol and treated with Rose Bengal (2 g of Rose Bengal in 1000 mL of ethyl alcohol) to distinguish living and dead specimens. In the laboratory, a constant volume of about 50 cm<sup>3</sup> of sediment for each sample was treated following the procedure reported by Buosi et al. (2013a, 2013b) and Schintu et al. (2016).

### 3.6. Numerical models

The Delft-3D software (Deltares, The Netherlands) was used to provide hydrodynamic scenarios of the study area during typical wave events. The WAVE and FLOW modules were used for the study of wave motion and hydrodynamics. The set-up of the model was described in Brambilla et al. (2016).

The use of numerical modeling allowed us in to visualize several features in different hydrodynamic and climatic conditions, such as shoreface width, cross- and long-shore current directions, and position of bars and trough. The main goal of this application is to draw dynamic features on a static platform such as a map.

## 4. Results

### 4.1. Sedimentary facies

Seven sedimentary facies were identified in the area (Map 2, Appendix 2).

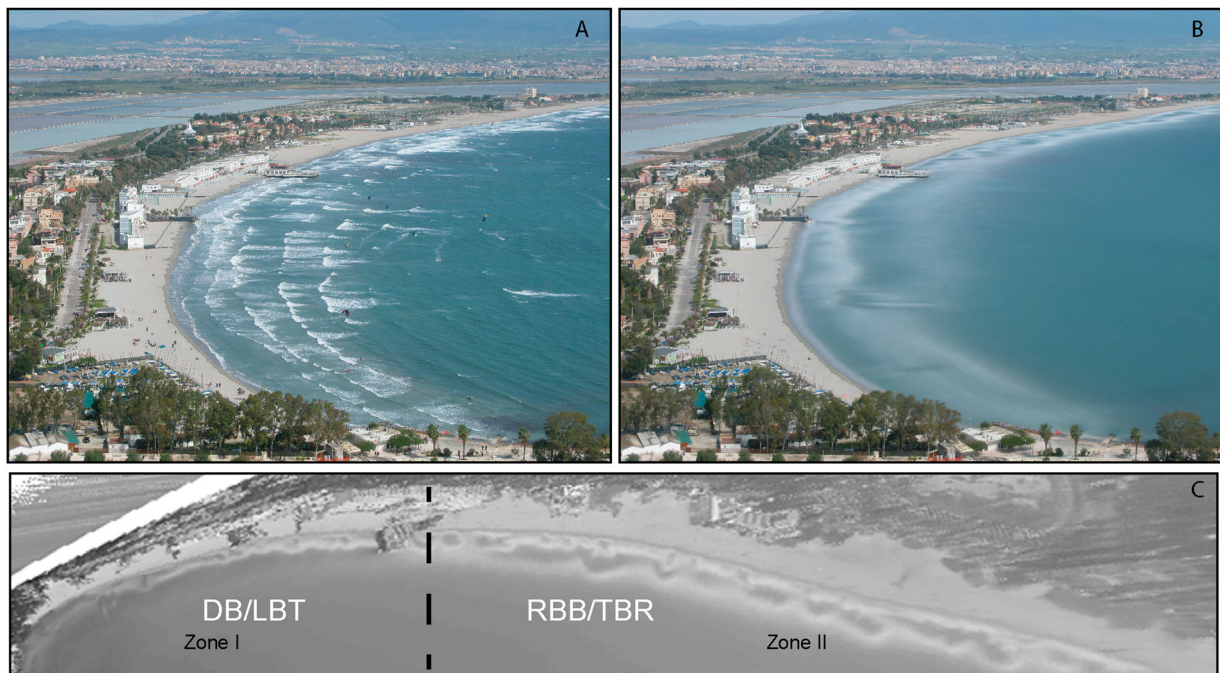
Facies A (backshore/beachface) is mainly composed of mixed siliciclastic-bioclastic sand (75%) with 20.5% of bioclasts. Facies B (shoreface) includes mainly siliciclastic sand (79.6% quartz + feldspar) with a low percentage of mud and gravel. Facies C (beachface/shoreface) is composed of sand and gravelly sand with calci-lithic and terrigenous components (Appendix 2). This facies is found on the bottom of the cliffs of Capo S. Elia promontory in parallel strips between the shoreline and the upper limit of the *P. oceanica* meadow (Map 2). Facies D is a mixed bioclastic and siliciclastic sediment mapped between 1 and 5 m depth that characterize the area close to the upper limit of the *P. oceanica* meadow. Facies E (backshore/shoreface, nourishment) is characterized by a relevant fraction of bioclastic grains (Appendix 2). This facies could be a mixing between the original siliciclastic sediment (Facies A and B) and the new anthropogenic materials. Facies F was sampled in the intermattes occurring within the *P. oceanica* meadow (5–30 m depth; Map 2). This facies is characterized by mixed siliciclastic-bioclastic gravel and sand with a 33% bioclastic component. Facies G consists of detritic gravelly sand (84.2% bioclasts; Appendix 2) and was mapped below the lower limit of the *P. oceanica* meadow (at 30–50 m depth).

### 4.2. Morphodynamic classification

Poetto beach can be subdivided into four areas with different morphodynamic states (*sensu* Short, 1999). The first and second areas were also detected in the Timex images (Figure 2). In Figure 3, the averaged beach profiles acquired along each zone were reported. Along each averaged profile, the morphological and sedimentary features, the run-up levels and the  $\Omega$  parameter are described. The value of  $\Omega$  calculated along Poetto beach's profiles is in agreement with the value previously described for other Mediterranean semi-enclosed beaches (Gomez-Pujol et al., 2007).

The first area, located on the westernmost side of the beach, was characterized by a dissipative state (Figure 3). This was corroborated by the beach profile morphology and by the estimation of the  $\Omega$  (about 6.2). A berm separates the beachface and the backshore areas.

From the second to the fourth areas, the beach assumes a more intermediate state. The second area was characterized by an LBT/TBR (Longshore Bar and Tough/Transverse Bar and Rip) morphologies. Two bars can be identified from the beach profile (Figure 3), the  $\Omega$  value (3.7) was in agreement with this morphodynamic state. A well-pronounced berm, between the beachface and the backshore, was found. This morphological feature can favor the long-term flooding of this area.



**Figure 2.** (A) Snapshot image. (B) Respective timex image. (C) Corresponding timex image rectified.

Along the third zone, the beach shows an intermediate state, but the number of bars decreases and only one can be identified in the profile (Figure 3). The  $\Omega$  value (4.2) is in agreement with the observed morphology.

In the fourth area, the beach morphology along the profile is influenced by several rocky outcrops that occur in the shoreface close to the shoreline. In this area, as well as in the third zone, the berm is not well pronounced and the beachface results in continuity with the backshore.

The level of run-up was reported in Figure 3 and Appendix 3. Zone 2 shows the maximum run-up, whereas the minimum was recognized in Zone 1.

Numerical models show that during the SE events opposite longshore currents develop on the beach (Figure 4(A)). The convergence of these currents produce a main rip current flowing offshore for about 400 m and located about 1 km eastward of the western limit of the beach (Figure 4(B)). During the SW events, several cells are active on the shoreface. These cells produce several longshore currents running from SW to SE and several rip currents, mainly evident in the central and eastern sectors (Figure 4(C,D)).

### 4.3. Ecological data

The *P. oceanica* meadow grows on a muddy-sandy substrate. The meadow upper limit occurs at ~15 m depth along the western sector, at 7 m depth in the central part of beach and at ~3 m depth along the eastern side. Intermatte channels are common in the entire area down to 20 m depth (Map 2), while rocky outcrops are located near Capo Sant'Elia promontory (at W) and Torre Foxi (at E, Map 1).

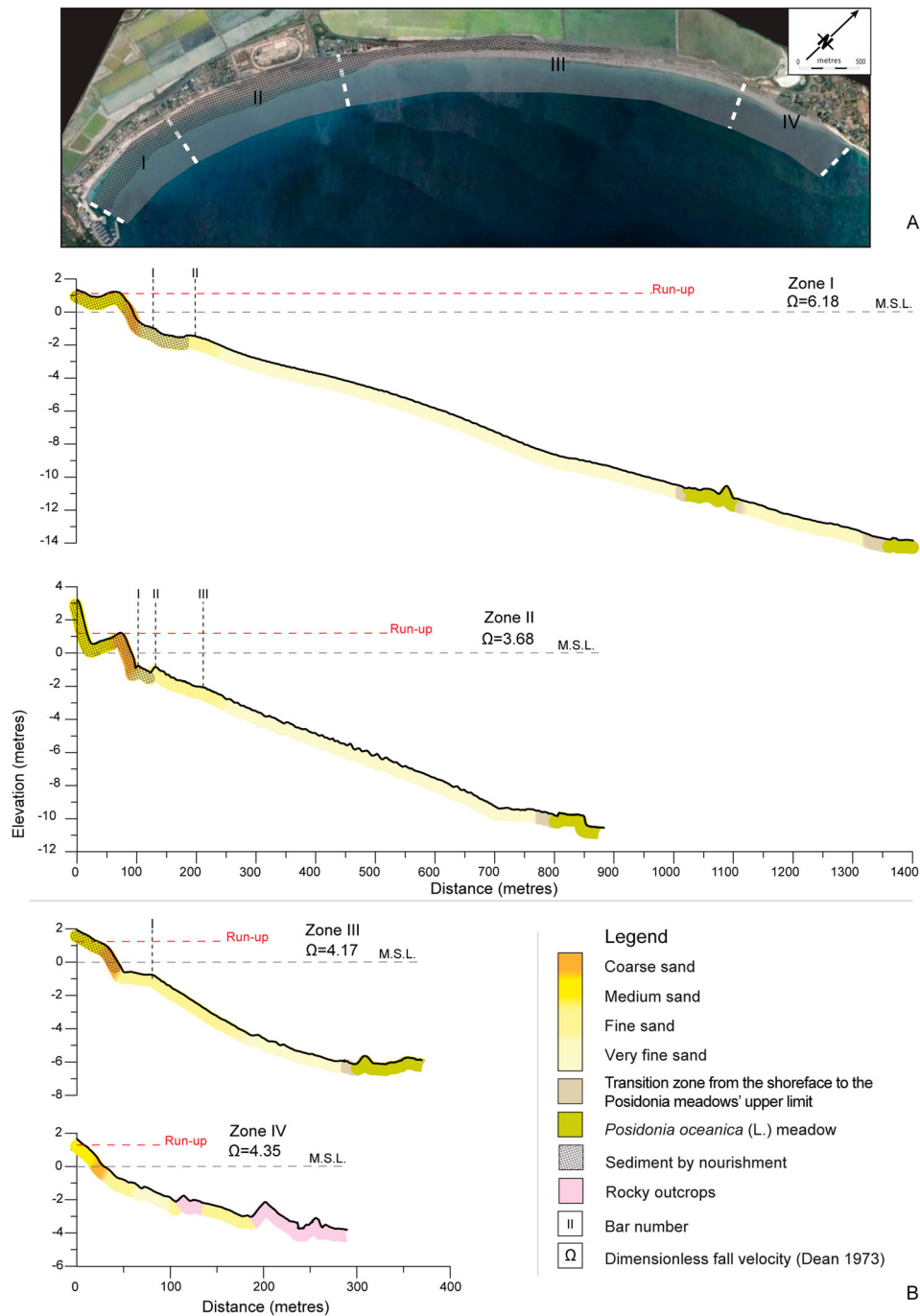
The environmental status of the inner shelf of Poetto beach, based on benthic foraminiferal assemblages, is reported in Figure 5 and Appendix 4. A moderate ecological status is found on the eastern side of the beach close to the Rio Foxi mouth and in the central part of the inner shelf. The benthic foraminiferal assemblages show a good ecological status in the western area and a high value only in one sample (Figure 5). All the investigated assemblages comprised no less than 90% of epiphytic foraminifers (Appendix 4), which indicate a low impacted status of *P. oceanica* meadow.

### 4.4. Anthropogenic impact

Map 4 shows sectors where human impact may influence the beach morphology and dynamics.

A road (pedestrian/cycling) limits the beach amplitude landward. This road is parallel to the beach for its whole longshore development. A further road runs seaward of the barrier that separates Poetto beach from the Molentargius lagoon.

In the westernmost area (sector 1, Map 4), a tourist port and coastal defense structures were identified. Beach cleaning operations were performed along the whole extension of the backshore (sector 2), often with heavy machinery, and repeated several times during the year. The western side of the beach (sector 3) is characterized by residential and recreational urbanization. Along this sector, nourishment works were performed (about 300,000 m<sup>3</sup> of sand) in 2002 (Valloni & Barsanti, 2007). In sector 4 (Map 4), the backshore is occupied by roads, woody kiosks (~3800 m<sup>2</sup>) and masonry structures (~32,800 m<sup>2</sup>). The eastern side of the beach (sector 5) includes an urban area, where the



**Figure 3.** (A) The four main zones identified in Poetto beach. (B) The four profiles of the beach with the bottom features, run-up and ohm values for each identified beach zone.

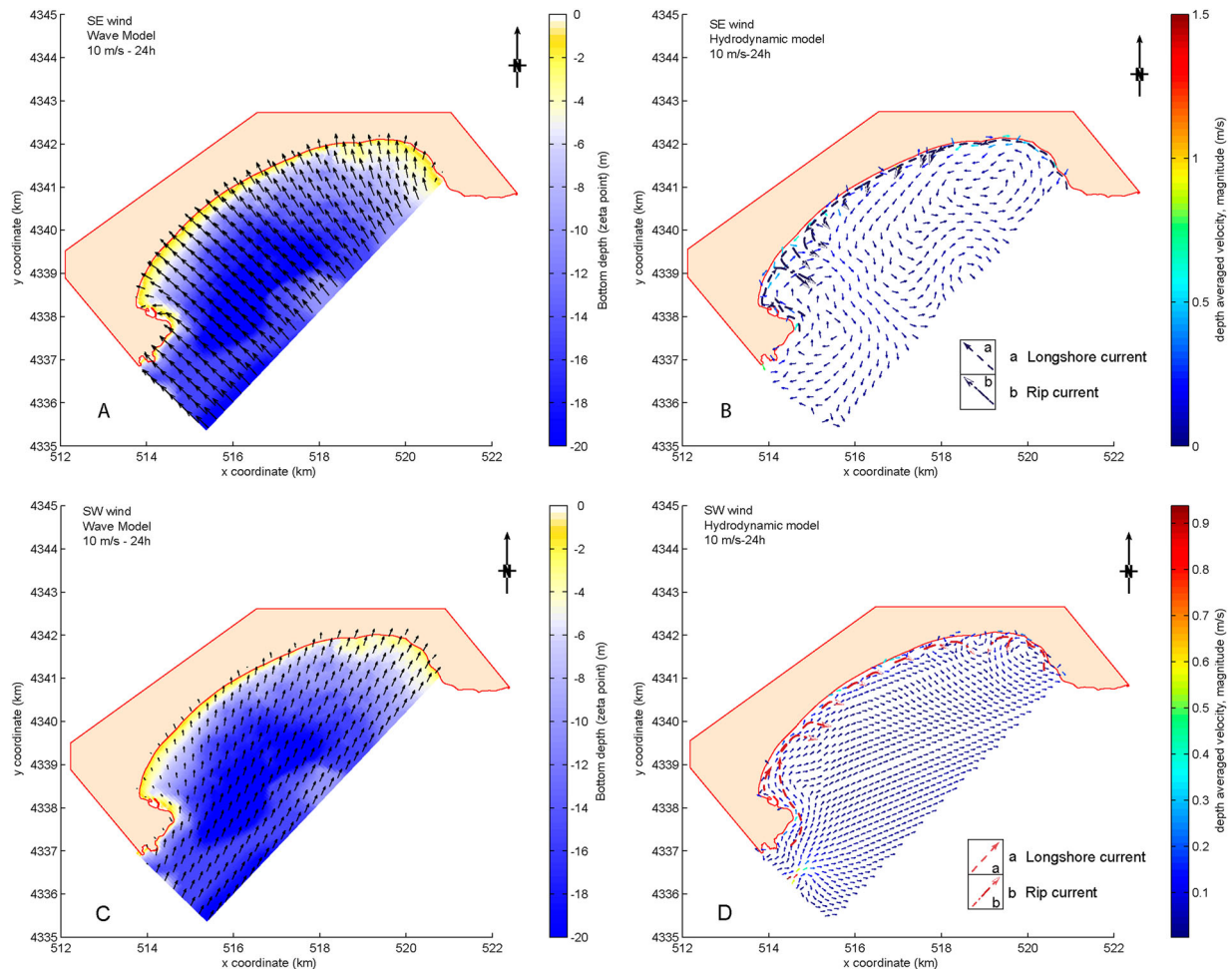
backshore is impacted by the presence of woody kiosks. In sectors 2, 3, 4 and 5, woody kiosks and masonry structures are built in dynamic zones that are usually affected by coastal flooding from storm surges with more than 2 m wave height. In these areas, after storm events, standing water can occur up to some weeks later. On the entire inner shelf, the anchorage of small boats can affect the seagrass meadow (sector 6, Map 4).

## 5. Discussion and conclusions

In the Main Map, the sediment distribution shows a clear distinction between the original siliciclastic

sediment and the new anthropogenic input of bioclastic/biogenic materials that is the consequence of nourishment. Previous studies (Ferrara & Palmerini, 1974), conducted on Poetto beach before the nourishment project (2002), showed that the sediment of the backshore/beachface was composed of fine and very fine siliciclastic sand with a very low content of carbonate particles. Comparing these data with our results, the grain size of Poetto, as well as the bioclastic content in the sediment, shows an increase. The material used for the nourishment was coarser with a higher carbonate content (Lai, 2008) than the natural siliciclastic sediment. Thus, the coarsening of sediment





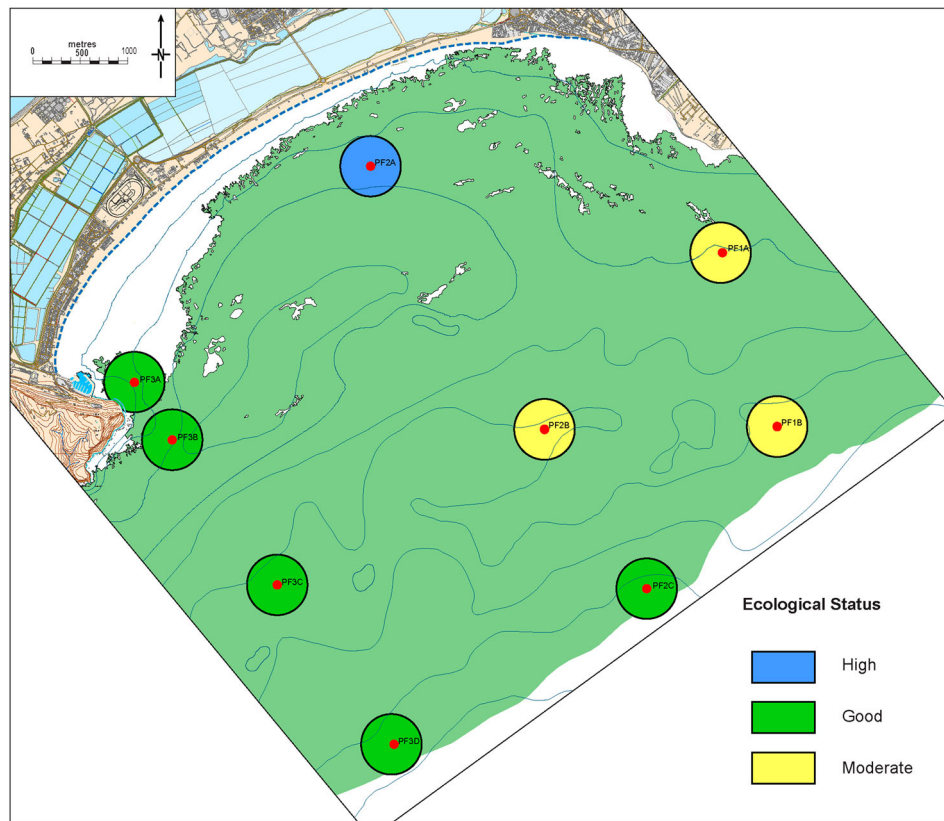
**Figure 4.** Wave (A) and hydrodynamic (B) model induced by winds blowing from the SE. Wave (C) and hydrodynamic (D) model induced by winds blowing from the SW.

and the increasing bioclastic content can be considered as a direct consequence of the nourishment. Furthermore, the [Main Map](#) shows that the grain size and the bioclastic contents are increasing not only in the area of nourishment but also towards E for about ~2 km ([Maps 1 and 2](#)). This could be related to the main sediment transport path that promotes a drift of sediment along beachface from W to E.

Morphodynamic states of the beach could be influenced by the sediment features. Notably, along the central area (Zones 2 and 3, [Figure 3](#)) the morphodynamic states were intermediate, with some morphological characteristics (e.g. the steeper beachface), that can be interpreted as reflective features. These differences in morphodynamic behavior are reflected in the run-up incidence along Poetto beach. Higher run-ups were found along the central area (Zone 2 and eastern part of Zone 3). The morphology of this area, maximum beach level of about 2 m and width of backshore of about 100 m, controls the run-up effect. In fact, along this area, the run-up may cause a flooding of the backshore, which in some cases can remain for several days due to the high berm developed during storms that is produced by the impermeability of the bioclastic mud from nourishment. On the other hand, the lower

beach height (1.3 m) and the limited width of the beach (<20 m) allow a collision of the run-up/up-rush with the human infrastructure in the eastern sector of Zone 1. In regards to the human infrastructure, the easternmost area of the beach is more vulnerable to direct damage due to wave collision, whereas the central area is more vulnerable to long-term flooding. The infrastructure could interfere with the maximum run-up causing erosion of the scarp and scours on the areas where a collision between run-up/up-rush and man-made structures occurs. Furthermore, the beach cleaning operations, that are carried out mainly in spring and summer, could flatten and lower the backshore level, compacting sediments ([Simeone, De Falco, Como, Olita, & De Muro, 2008](#); [Simeone, De Muro, & De Falco, 2013](#)). This operation could increase the effect of the run-up, shifting the run-up regime from collision to overwash (*sensu* [Sallenger, 2000](#)).

The nearshore circulation ([Figure 4](#)) highlighted that a main rip current characterizes the western side of the beach ([Map 1](#)). Rip currents can lead to a seabed disturbance, producing scours or other erosive forms ([Short, 1999](#)), this could influence the development of sea bed vegetation. In fact, the seagrass *P. oceanica* is sensitive to sediment mobility ([Vacchi et al., 2017](#))



**Figure 5.** Map showing the ecological status of the seabed based on benthic foraminiferal analysis.

that, on Poetto beach, could happen in correspondence to the rip location where the upper limit of *P. oceanica* moves away from the shoreline.

The ecological status, evaluated using living benthic foraminifera as environmental bioindicators (e.g. Alve, 1991; Bouchet et al., 2012; Scott et al., 2005), suggests that the seabed is of a moderate to high quality (Figure 5). This is also confirmed by the dominant abundance of epiphytic foraminifera. In fact, in coastal areas that are characterized by degraded vegetation cover, epiphytic species are absent (Vidović, Čosović, Juračić, & Petricoli, 2009). Thus, even if the studied urban beach appears affected by high human pressure, the seabed, the *P. oceanica* meadow and the benthic foraminiferal assemblages do not seem impacted (Buosi et al., 2013a; Schintu et al., 2016). *Posidonia oceanica* meadow plays a crucial role in the physical equilibrium of the Mediterranean coasts protecting the coastline from erosion. It is known that seagrass meadow may attenuate hydrodynamic forces, may increase the sediment retention and may reduce sediment resuspension (De Falco, Molinaroli, Baroli, & Bellacicco, 2003; De Falco, Molinaroli, Conforti, Simeone, & Tonielli, 2017; De Muro et al., 2016). These factors contribute to beach stability, further enhanced by biogenic sediment supply from the meadow (De Muro & De Falco, 2015; De Muro, Porta, et al., 2017; Tecchiato, Buosi, Ibba, Ryan, & De Muro, 2016).

This cartographic product, providing data on the complex interaction of a variety of sedimentological,

geomorphological, ecological, hydrodynamic and anthropogenic processes, represents the most comprehensive spatial benchmark available to date for this urban beach. The present study may represent a starting point for monitoring of future changes, using the following parameters as indicators of changes: shoreline position, reduced/increased embryo dunes fragmentation, tide measurement to monitor the sea level rise, sediment dispersion following nourishment activities, changes to *P. oceanica* upper limit and meadow density in response to increasing turbidity that may be related to the composition of carbonate sediments used for nourishments, and changes in ecological conditions.

### Software

Reson PDS2000 was used for the acquisition of the bathymetric data. ESRI ArcGIS 10.0 was used to create a georeferenced topographic–bathymetric base map and to depict the granulometric distribution of the sediment. A land–sea DTM was produced by Global Mapper 14. The WAVE and FLOW modules of Deltares Delft-3D were applied and verified using measurements and land studies. The final map was produced using Adobe Illustrator CS5.

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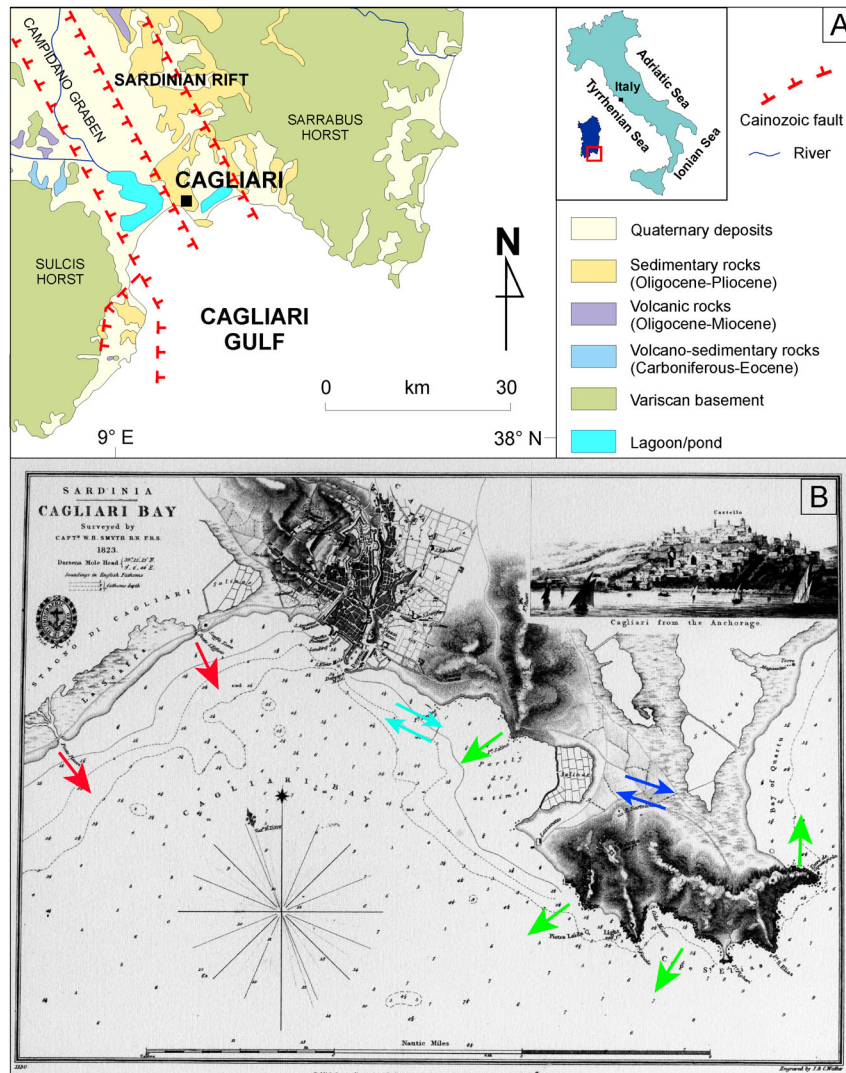
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## Appendices

Appendix 1. (A) Geological map of the study area. (B) Map showing the Gulf of Cagliari during 1823 (from Hydrographic Office – Royal Navy R:N: F.R.S; modified). Sediment input from Capo Sant’Elia (mainly carbonate and siliciclastic) and Santa Gilla lagoon (siliclastic) is indicated by green and red arrows, respectively. Before the urban development of Cagliari (1900), the Pleistocene-Holocene beach systems (Giorgino – La Maddalena at W and Poetto at E) were connected and were characterized by a sedimentary eolian interchange (blue and light blue arrows).



## Appendix 2. Characteristics of the sediment facies of Poetto.

Sediment facies	Gravel %	Sand %	Mud %	Quartz + Feldspar %	Other minerals %	Lithoclasts %	Bioclasts %	Depositional Environments
(A) Mixed siliciclastic-bioclastic sand	7.2 ±9.6	92.7 ±9.6	0.1 ±0.1	75.0 ±6.1	1.3 ±0.5	3.2 ±1.0	20.5 ±5.0	Backshore and beachface sand
(B) Mainly siliciclastic sands	0.3 ±0.5	97.6 ±3.9	2.1 ±4.0	79.6 ±3.2	0.8 ±0.4	0.9 ±0.7	18.6 ±2.7	Shoreface sands (0–5 m)
(C) Calci-lithic	2.8 ±3.2	96.0 ±2.6	0.8 ±1.5	32.3 ±14.2	23.8 ±27.0	20.5 ±39.7	23.0 ±32.4	Beachface/shoreface (0–5 m)
(D) Mixed siliciclastic-bioclastic sands	0.2 ±0.2	97.7 ±2.8	2.0 ±2.8	71.6 ±4.1	1.1 ±0.4	1.1 ±0.8	26.1 ±4.5	Transition from shoreface to the upper limit of meadow (5–7 m)
(E) Mixed siliciclastic-bioclastic sands	2.1 ±3.6	97.9 ±3.6	0.1 ±0.1	65.1 ±8.8	0.9 ±0.5	2.0 ±1.7	32.1 ±8.5	Backshore and shoreface sediment by nourishment (up to 5 m depth)
(F) Biogenic gravelly sands	12.2 ±22.3	87.8 ±5.9	0.1 ±0.1	63.5 ±31.8	1.0 ±1.4	2.5 ±3.5	33.0 ±36.8	Intermattes (5–30 m)
(G) Detritic gravelly sands	11.3 ±7.8	88.2 ±7.5	0.8 ±1.2	14.5 ±13.2	0.2 ±0.4	1.7 ±1.6	84.2 ±14.9	Posidonia meadow’s lower limit (30–50 m)

**Appendix 3.** Run-up level, calculated by using Hunt's formula along the four representative profiles.  $\Omega$  is the dimensionless fall parameter, MBH is the maximum beach height measured by DGPS along each profile.

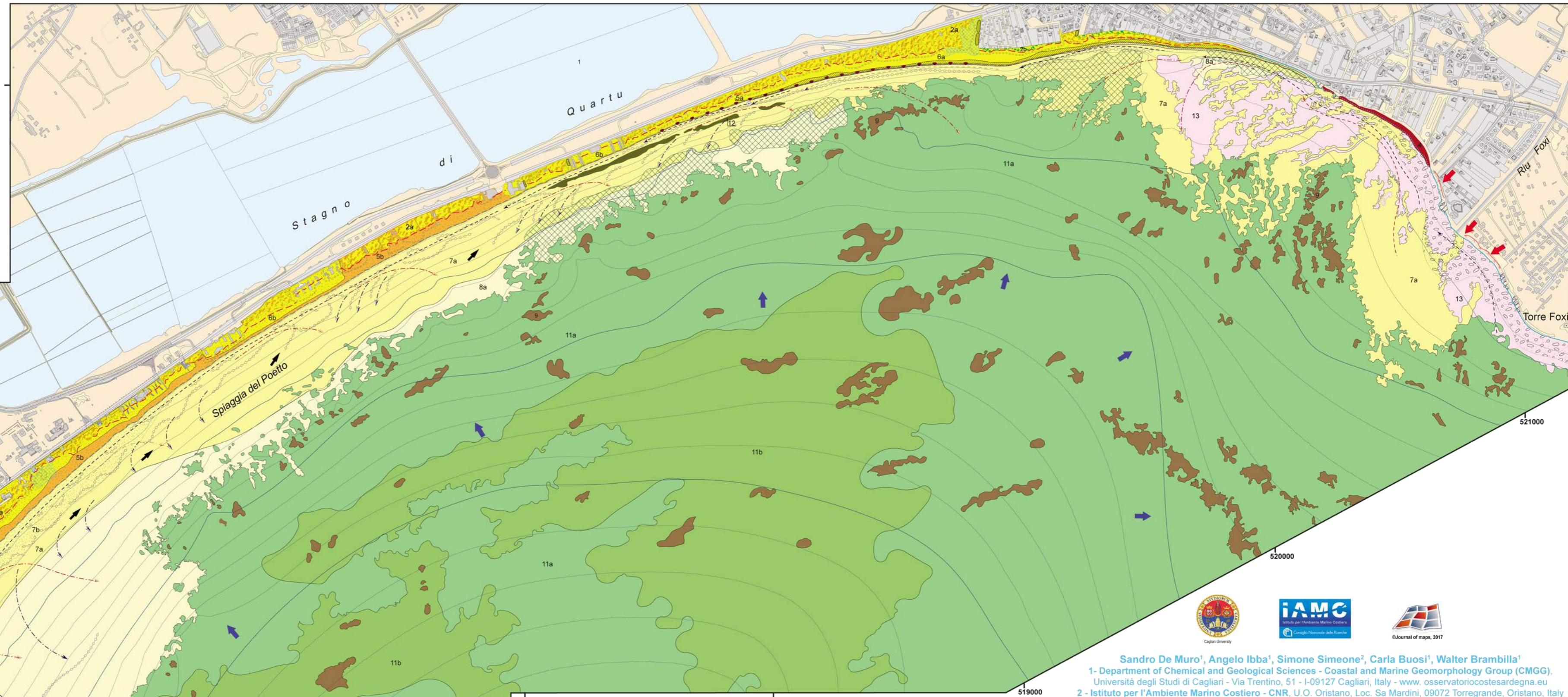
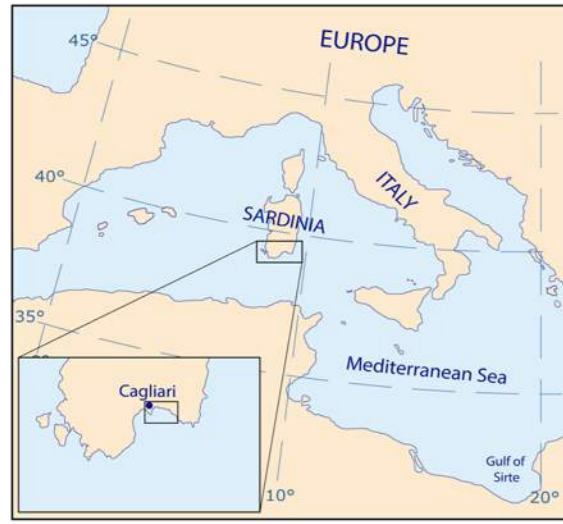
Beach area	Run up (m)	$\Omega$	MBH (m)
Zone 1	1.1	6.2	1.3
Zone 2	1.3	3.7	3.2
Zone 3	1.2	4.2	1.7
Zone 4	1.2	4.4	1.4

**Appendix 4.** Foraminiferal composition of living faunas, Shannon index and ecological status in the different samples of the study area. Only species with the highest abundance are shown.

Sample	Benthic assemblages	Shannon index	Ecological status
PF1A	<i>Rosalina floridana</i> 16.8%; <i>Cibicides refulgens</i> 12.2%; <i>Rosalina bradyi</i> 10.6%	3.7	Moderate
PF1B	<i>Rosalina floridana</i> 19.4%; <i>Cibicides refulgens</i> 10.2%; <i>Trentomphalus bulloides</i> 9.2%	3.6	Moderate
PF2A	<i>Rosalina floridana</i> 18.6%; <i>Asterigerinata mamilla</i> 6.7%; <i>Ammonia papillosa</i> 5.1%	4.4	High
PF2B	<i>Rosalina floridana</i> 19.6%; <i>Asterigerinata mamilla</i> 9.0%; <i>Cibicides refulgens</i> 11.7%	3.6	Moderate
PF2C	<i>Asterigerinata mamilla</i> 20.8%; <i>Rosalina floridana</i> 15.3%; <i>Cibicides refulgens</i> 11.7%	4.2	Good
PF3A	<i>Rosalina floridana</i> 19.7%; <i>Elphidium gerthi</i> 9.9%; <i>Bolivina spathulata</i> 6.0%	4.0	Good
PF3B	<i>Rosalina floridana</i> 16.2%; <i>Asterigerinata mamilla</i> 12.6%; <i>Cibicides refulgens</i> 9.7%	3.9	Good
PF3C	<i>Asterigerinata mamilla</i> 18.9%; <i>Rosalina floridana</i> 17.0%; <i>Cibicides refulgens</i> 9.6%	3.9	Good
PF3D	<i>Asterigerinata mamilla</i> 16.9%; <i>Cibicides refulgens</i> 14.0%; <i>Rosalina floridana</i> 11.6%	4.0	Good

# AN INTEGRATED SEA-LAND APPROACH FOR MAPPING GEOMORPHOLOGICAL AND SEDIMENTOLOGICAL FEATURES IN AN URBAN MICROTIDAL WAVE-DOMINATED BEACH: A CASE STUDY FROM S SARDINIA, WESTERN MEDITERRANEAN

Scale 1:6400  
Metres  
PROJECTION: UTM 32N WGS84 Datum

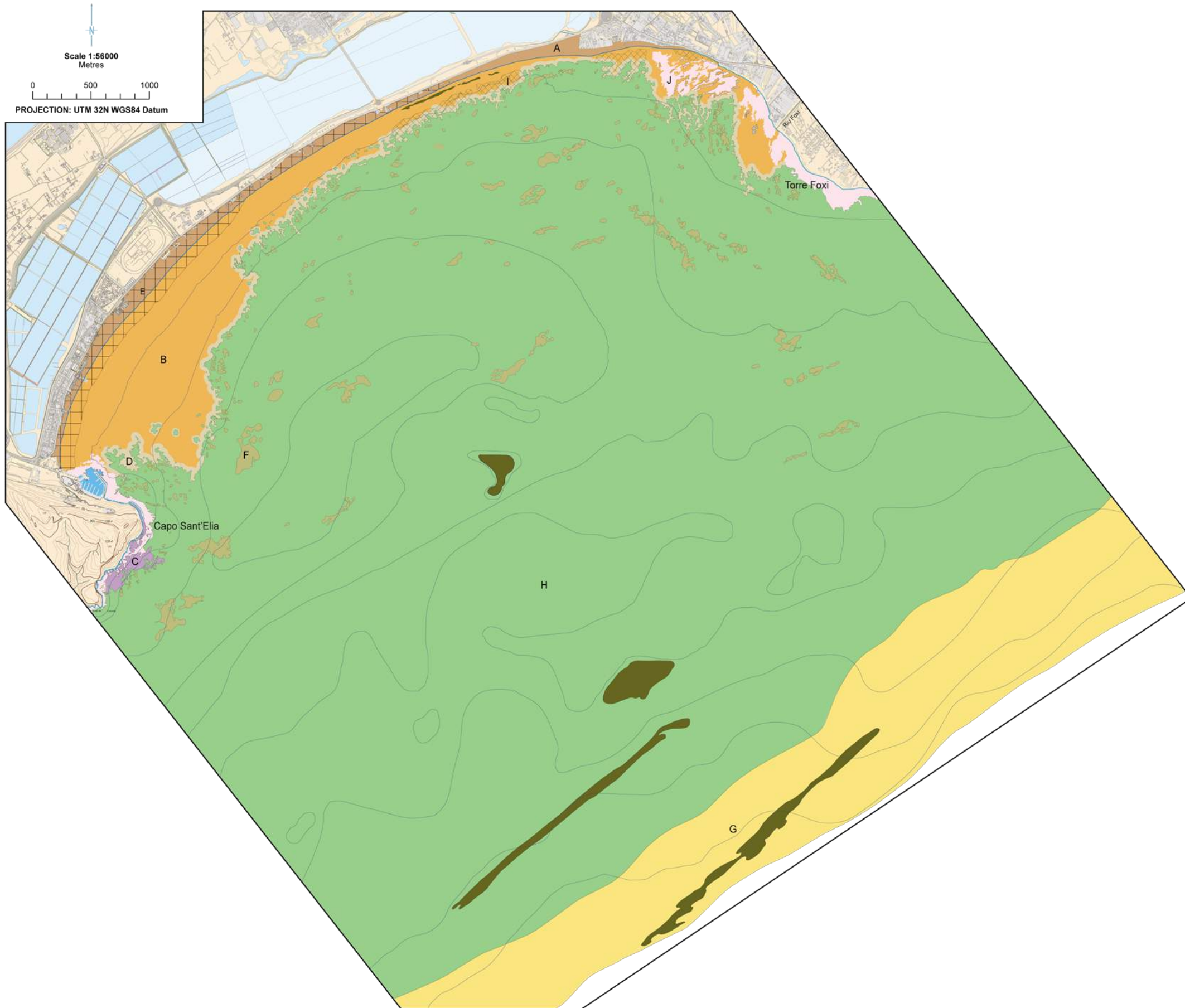


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Forms, processes and deposits of backbeach		Forms, processes and deposits of shoreface and inner shelf		Hydrographic features	
Natural	Human-induced	Natural	Human-induced	A	B
	1 Saltworks	Bar axis		Stream (A); River (B)	
2a, 2b	Embryo dune (2a); Fore dune (2b);	Biogenic input (A); Siliclastic input (B); Calc-lithic input (C)		Topographic and bathymetric features	
	Artificial dune	Bioclastic sediments (nourishment) drift		50 Contour line (50m interval)	
	Cliff	Hydrodynamic features connected to main flow energy		Contour line (10m interval)	
	Erosion scarp		A Longshore current, due to 135° wave direction B Rip current, due to 135° wave direction	Depth line (-5m interval)	
	Washover fan	A Longshore current, due to 225° wave direction B Rip current, due to 225° wave direction		Depth line (-1m interval)	
	A Grooves due to pedestrian impact B Grooves due to vehicle impact	<b>Sediment features</b>		<b>Man-made forms</b>	
<b>Forms, processes and deposits of the backshore</b>		Natural	Human-induced	Artificial storage of the "seagrass berm", mainly <i>Posidonia oceanica</i> (L.) Delile with sand, gravel and cobble	
	Cobble	Mainly Siliclastic		Artificial reefs and coastal defense structures	
	Cobbly gravel	7a	7b	Artificial submerged reef (pebble and cobble)	
	Coarse sand (5a); Coarse sand by nourishment (5b)	8a	8b	Artificial boulders	
	Medium sand (6a); Medium sand by nourishment (6b)	9		Building, house	
	Cusps of cobble	Mainly Bioclastic		Tower (A); Bridge (B)	
	Landward limit of run-up			Motorway and asphalt road	
	Standing water after flooding			Path, track	
	A Shoreline: cliff-rock (A); sandy beach (B); cobble beach (C)	<b>Other seabottom features</b>			
	Preferential areas of "seagrass berm" deposition (banquette)	Natural	Human-induced		
		10			
		11a, 11b			
		12			
		13			



# Sedimentary facies map



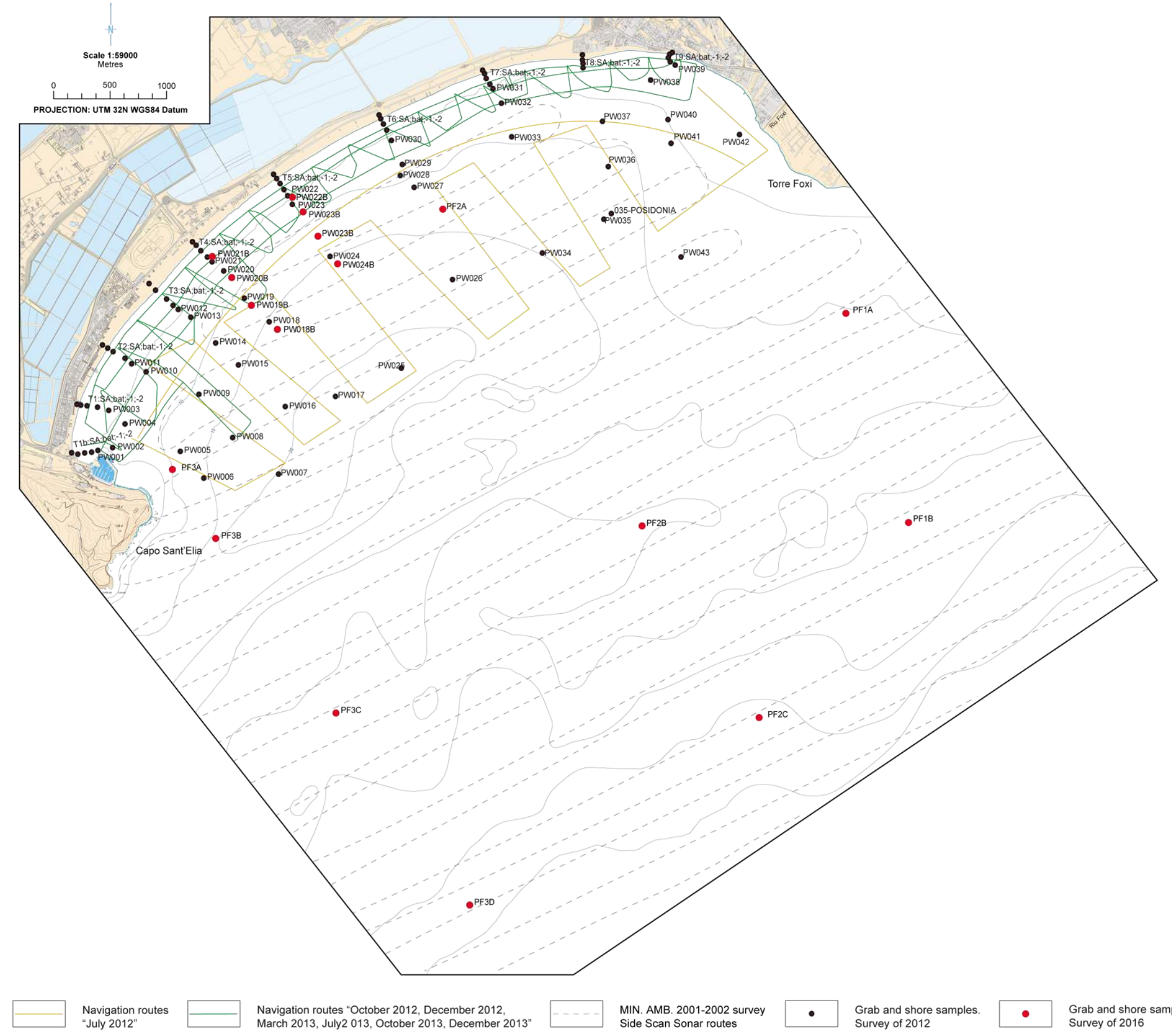
## Sedimentary facies

- A** Mixed siliciclastic-bioclastic sands: facies composed of backshore sands and beachface sands
- B** Siliciclastic sands: facies composed of shoreface sands, mainly siliciclastic
- C** Sands and gravely sands with calci-lithic and terrigenous components (Capo S. Elia calci-lithic facies; Lecca et al., 2005)
- D** Mixed bioclastic and siliciclastic sands: facies composed of biogenic and siliciclastic sands (transition from the shoreface to the Posidonia meadows' upper limit)
- E** Sediments by nourishment
- F** Biogenic gravely sands: facies composed of biogenic gravely sands linked to Posidonia oceanica (L.) Delile meadow (intermattes)
- G** Detritic gravely sands: facies composed of mainly bioclastic mixed gravely sands and gravels linked to the Posidonia meadows' lower limit

## Other seabottom features

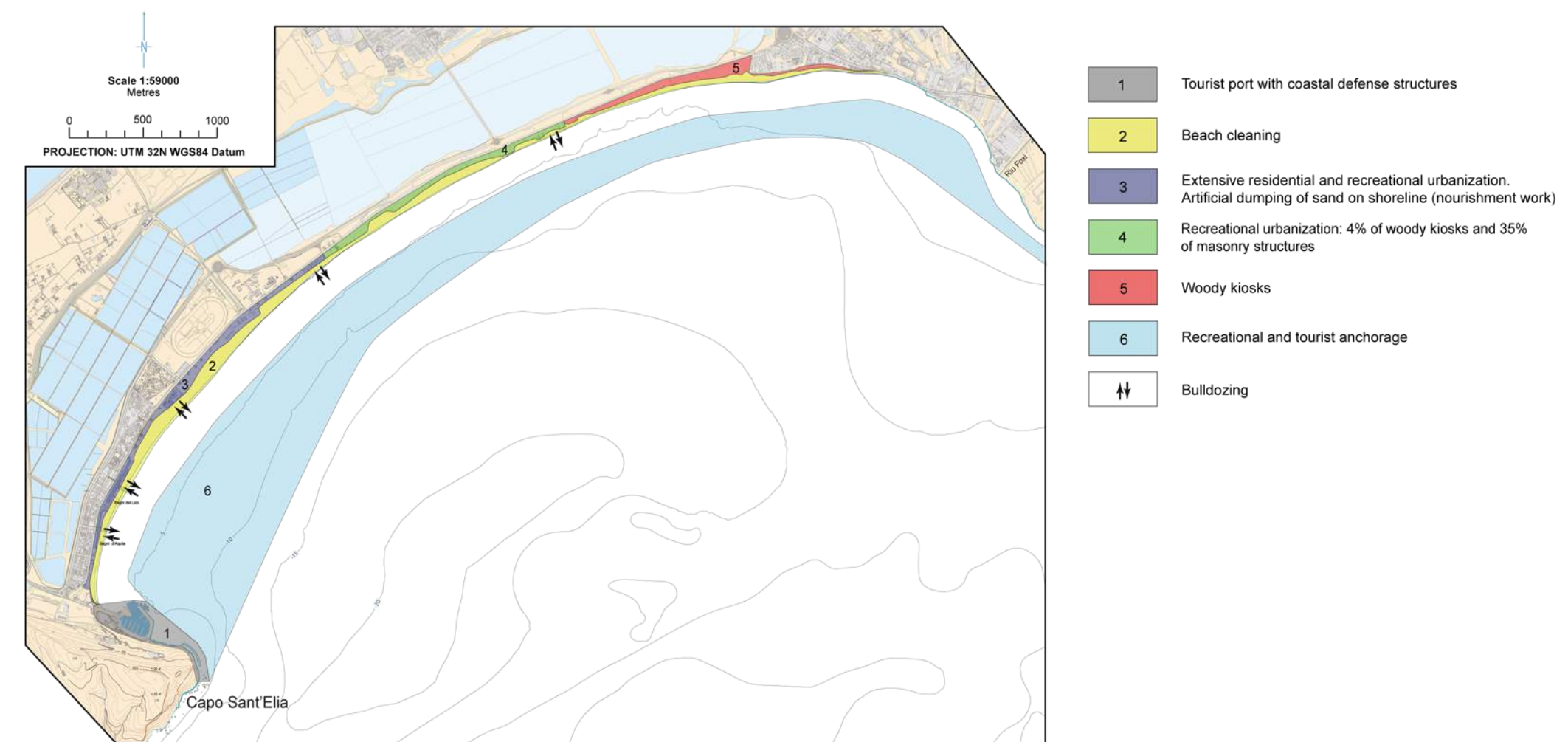
- H** Posidonia oceanica (L.) Delile meadow
- I** Deposit of Posidonia oceanica (L.) Delile leaves
- J** Rocky outcrops, gravels and pebbles
- Beach-rock (sandstone and conglomerates of foreshore and shoreface)
- Depth line (-5 metres intervall)
- Shoreline

# Routes and samples map



- Navigation routes "July 2012"
- Navigation routes "October 2012, December 2012, March 2013, July 2013, October 2013, December 2013"
- MIN. AMB. 2001-2002 survey Side Scan Sonar routes
- Grab and shore samples. Survey of 2012
- Grab and shore samples. Survey of 2016

# Human impact and use



- 1** Tourist port with coastal defense structures
- 2** Beach cleaning
- 3** Extensive residential and recreational urbanization. Artificial dumping of sand on shoreline (nourishment work)
- 4** Recreational urbanization: 4% of woody kiosks and 35% of masonry structures
- 5** Woody kiosks
- 6** Recreational and tourist anchorage
- H Bulldozing