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Metrics for short-term coastal characterization, protection and planning decisions of Sentina Natural Reserve, Italy

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ABSTRACT

Geomorphological and sedimentological surveys of the emerged and submerged beach-dune system are fundamental for a successful management and protection strategies for coastal planning and development. In particular, these surveys can reveal if coastal areas are affected by erosion, pollution and loss of habitats under the seasonal anthropic pressure related to tourism, leisure and professional fishing, urbanisation and/or other activities impacting the coastal marine resources.

In the present study we discuss the results of the multidisciplinary monitoring activities carried out within the Sentina Natural Reserve (Municipality of San Benedetto del Tronto, Adriatic side of Central Italy, at the south-eastern end of the Marche Region) proposing an exportable methodological approach. Due to the absence of buildings, the study area has not been considered in the coastal protection plan by regional and local authorities and, as a consequence, it is currently exposed to severe coastal erosion, the rate of which has been more precisely determined during the present study. This monitoring testifies that most of the seaward surface of the beach disappeared resulting in a general set back of the whole beach environment. In the last decades, several restoration strategies have been adopted to protect and restore the dunes and the back dunes habitats and the municipality also carried out an emergency action to nourish the beach, including the use of sand dredged from the nearby city harbor.

With this sediment management approach, a tradeoff between safety of navigation of harbor inlet and habitat conservation of Natural Reserve have been reached, since beach nourishment can reduce coastal vulnerability and risk, even though its sustainability in the long term is still debated.

1. Introduction

Coastal sedimentary deposits are strongly influenced by complex depositional mechanisms resulting from both meteorological and hydrodynamic conditions of the area, as well as from human activities (Carter, 1980; Pye, 1990; Carter, 1988). A number of human actions within hydrographic basins, such as extraction of sediments from river beds, construction of dams coupled with the abandonment of agricultural practices along slopes and the straightening of river mouths by artificial piers, have significantly reduced fluvial solid load (Acciarri et al., 2016). As a consequence coastal erosion takes place: therefore, barriers are built and beach nourishment are carried out to protect urban areas or maintain tourism (Cappucci et al., 2011, 2019). Several studies have examined the need and availability of the natural resources necessary to mitigate coastal erosion, evaluating the risk that coastal communities will face due to climate change and consequent sea-level rise and increase in storm energy (Hinkel et al., 2010; Lambeck et al., 2011; Bosello et al., 2012; Rhein and Rintoul, 2013; Fazzini et al., 2017).

In Italy during the last 30 years, many beach nourishment have been performed and a search of offshore sedimentary deposits is still going on to provide the resources necessary to carry out such interventions along the coasts. Recently, frequent and reduced sand transfer operations along the coast took place as the cost and technical complexity of capital dredging operations is becoming out of budget for competent

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Authorities. So, sediments are dredged from areas subject to accumulation towards areas subject to erosion. In other cases, the abandonment of deltas and non-urbanised areas has been considered in order to allow erosion and transfer of sediment along coasts (Pranzini, 2018). In other sites, Natural Reserves, Marine Protected Areas (MPA) and Natural Parks have been established to counteract urbanization and soil consumption, but this option forces the authorities to protect the ecosystem and to mitigate both the effect of erosion and the loss of habitats. This is a major challenge since in coastal areas beach erosion can affect dunes, wetlands and other vulnerable ecosystems, sometimes even destroying protected habitats (Davidson-Arnott, 1988; Pallottini and Cappucci, 2009).

Coastal dunes are an integral part of the beach system and constitute a reservoir of sediment capable of protecting coastal aquifers from salt-wedge intrusion and of building up a reserve of sand that can nourish the beach during extreme events. Their location, size and morphological characteristics are subject to high spatial and temporal variability: during storms, their demolition can take place even in a few hours or days, whereas their reconstruction requires years (Wal and Mc Manus, 1993; Taramelli et al., 2020). Dune development requires a minimum width of the beach: when beaches are compromised, coastal erosion can lead to dune retreat as well as to reduction or even elimination of vegetation cover (Carter and Wilson, 1993; Psuty, 1988; Brecciaroli and Onori, 2009; Valentini et al., 2020). Dunes currently survive in a restricted number of zones along the Mediterranean coast, as a consequence of the hydraulic reclamations that have resulted in their dismantling to facilitate urban development (Pascucci et al., 2018). The few remaining dune environments are threatened by serious and advanced degradation mechanisms linked essentially to widespread anthropogenic activity and erosion of the coasts, which in Italy affects over a third of the approximately 3,250 km of beaches. This is closely connected to the alteration of sedimentary cycles caused by anthropic interventions in the catchment areas and along the coast (Cappucci et al., 2017; Ciccarelli et al., 2017).

It is well known that the competing influences of uses are altering the structure and dynamics of the Adriatic coast, especially near river mouths (Dal Cin and Simeoni, 1987; Bisci et al., 1992; Materazzi et al., 2010; Acciarri et al., 2016) and that the Tronto River is suffering dramatic reduction of sediment transport. This latter process, common to most Italian rivers (Siviglia et al., 2004; Rinaldi and Simoncini, 2006; Manca et al., 2013; Cappucci et al., 2015), is considered the factor that has mainly influenced the evolution of the study area together with the creation, starting from the 1960s, of discontinuous emerged barriers to protect the adjacent town of Porto d'Ascoli, to the north, and of a long groyn at the southern end of the mouth of the Tronto River, to the south (Bisci et al., 1992; Acciarri et al., 2016).

Vegetation coverage plays an important role on size and evolution of coastal dunes, also in relation to variable climatic conditions (Corbau et al., 2015). Coastal sand dunes are highly dynamic aeolian landforms; their formation and evolution is strongly influenced by size and characteristics of the emerged beach and complex interactions and relationships with land cover (e.g. vegetated and non-vegetated areas; Bertoni et al., 2014; Valentini et al., 2020).

The complexity of deterministic numerical models and the huge amount of data needed to carry out reliable simulations of sediment dynamics, even in the short term, historically discouraged local authorities from sustaining the cost of these studies. Bagnold (1980) highlighted such difficulties in using mathematical deterministic models to obtain accurate expressions describing sediment dynamic processes. An alternative approach is represented by "data-driven" models, particularly suitable when the knowledge of the involved physical processes is limited (Cappucci et al., 2004) or where the boundary conditions are undefined (Pascucci et al., 2008, 2019). Very often, there is no possibility of applying reliable mathematical models to simulate complex natural processes: this is quite a common limitation in the case of remote areas that cannot be accurately characterized. However, there have been several applications based on real data that provided an adequate outcome (Ausili et al., 2012; Conti et al., 2009a; Govindaraju, 2000; Dibike and Solomatine, 2001; Bhattacharya and Buraimo, 2003; Bhattacharya et al., 2005; Liu and Huang, 2009; Wilkinson et al., 2009).

The aim of the present work is to analyse short-term evolutionary trends in the terrestrial aquatic interface of the Sentina Natural Reserve along the Adriatic cost, in order to formulate beach-dune restoration strategies compatible with a documented mid-term evolutionary trend for the area (Bisci and Cantalamessa, 2008; Conti et al., 2009b; Bisci et al., 2010). Protection and restoration of dunes have been part of an environmental remediation project of the Municipality carried out on the basis of the present research as an emergency action to nourish the beach, including the use of sand dredged from the nearby city harbour (Cappucci et al., 2011). With this sediment management approach, safety of navigation of harbor inlet and habitat conservation of the Natural Reserve have been considered, since beach nourishment can reduce coastal vulnerability and increase resilience, even though its sustainability in the long term is still debated (Cappucci et al., 2019).

Environmental management and conservation agendas commonly include requirements for mapping and monitoring both environmental pattern and process. Habitat types are considered spatially homogeneous recognizable areas with physical, chemical, and biological characteristics with respect to vegetation and environmental factors and recently the appreciable contribution from synergistic studies allows estimating landscape heterogeneity and provides basic knowledge for landscape conservation and sustainable management of the resources (Pascucci et al., 2018; Pozzebon et al., 2018).

Before the present study, no protection strategies existed and no monitoring was carried. Our research team was in charge to determine the geomorphological and evolutionary characteristics of this coastal system because no information and data were available. Frequently, coastal stretches are abandoned to themselves and classified as protected areas or parks in order to avoid urban development or anthrophic impacts (Cappucci et al., 2017). Without monitoring and data collection stakeholders are unable to implement conservation as well as short and long term protection actions which are fundamentals to planning of anthropogenic activity, risk recovery and prevention.

Morphological surveys of the whole beach, both emerged and submerged, performed in the period 2012–2015, are analysed jointly with multi-temporal data series collected over a longer interval. The dataset acquired in the present study is the base for models implementation: this allowed us to identify the spatial patterns of beach-dune metrics as well as the sedimentological properties of the landforms, highlighting threatened stretches and revealing a previously unknown behavior of longshore and offshore sediment transport processes (Mc Laren and Bowles, 1985).

Findings of the present paper are fundamentals to carry out coastal restoration in order to increase resilience of coastal zones considering different scenarios of sea level rise (Pascucci et al., 2019) and obtained results and methodological approach can be applied to all the networks of European Natura 2000 sites where coastal dunes are present; 39% of them are located in Italy but the replicability of the methodology is eligible at international level.

2. The study area and methodology

2.1. Study area

The Sentina Natural Nature Reserve, established with Regional Resolution n. 156 of 14/12/2004, is located in the Marche Region (Adriatic side of Central Italy); it is bordered to the north by the town of Porto d'Ascoli, to the south by the Tronto River mouth (also marking the border with the Abruzzo Region), to the east by the Adriatic Sea, and to the west by the Bologna-Bari railway (Fig. 1). In the last decades the beach of the study area has been subject to dismantling with severe retreat of the shoreline. Presently, the reserve has a surface of 177.5 ha

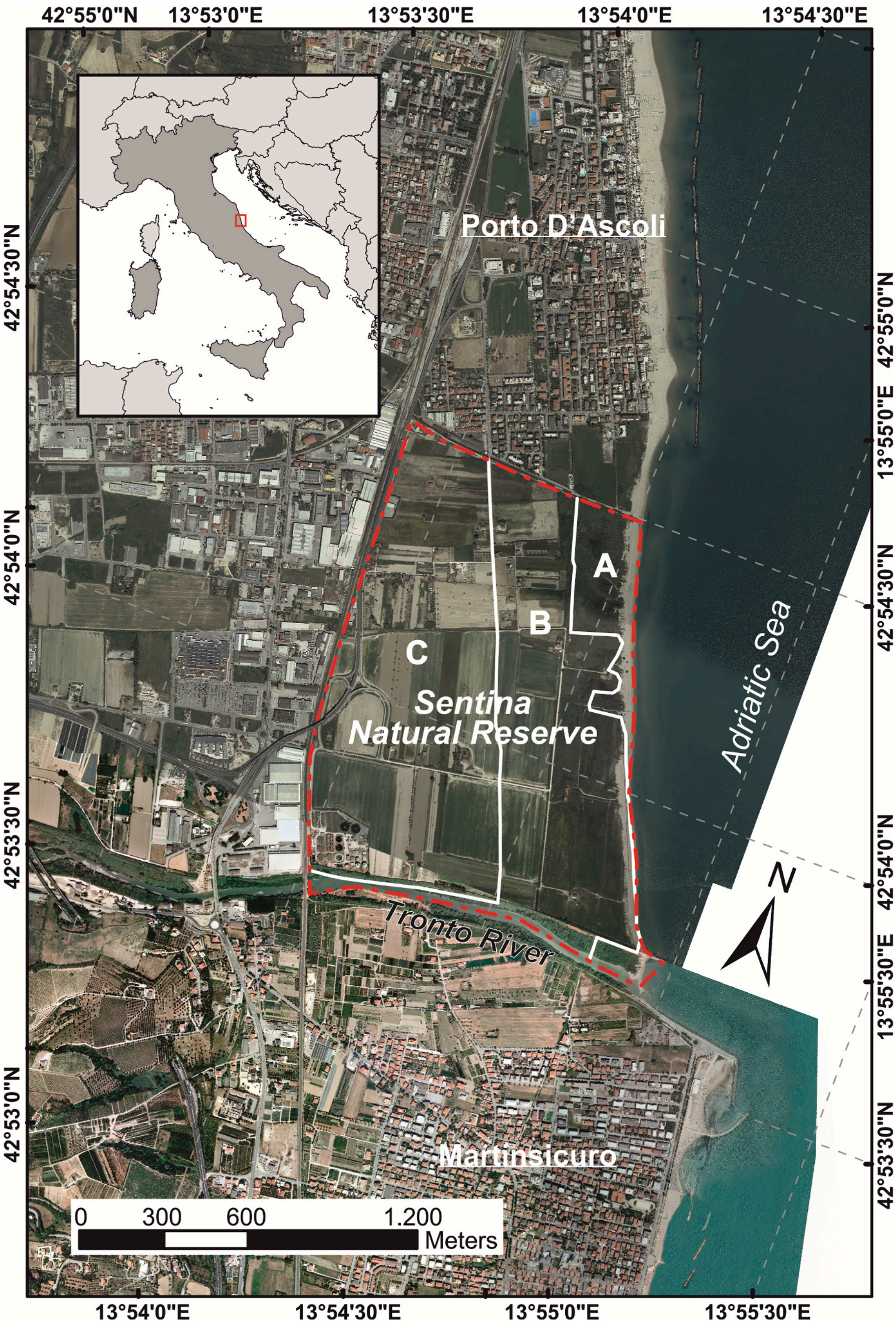

Fig. 1. Aerial photo of the study area. Note the transitional system in the landward side of the beach completely blocked by agricultural and urban landscapes.

and is divided into three different protection zones: A) 24.5 ha of Protection Zone for fragile natural areas; B) 67.2 ha of Protection Zone for mitigation of impacts on habitats and species; C) 85.7 ha of Economic and Social Promotion Area for human activities.

Due to the presence of relevant environmental features, about 90 ha of the Reserve, was defined as a Site of Community Importance (IT5340001, "Coast of Porto d'Ascoli") under the Habitats Directive 92/43/EEC and in 2003, the Site of Community Importance (SCI) consisted of 10% of dunes and beaches (Cod. 1150) and 15% of coastal lagoons (Cod. 2240, 2120), with some residual wetlands the emerged beach was about 30 m wide (Table 1).

About 121 ha were classified as a Special Protection Area (SPA 26 - IT5340022) under the Birds Directive 79/409/EEC. The Master Plan for Coastal Defence of the Marche Region (Regione Marche, 2005) identifies

Table 1
Code of habitat (EU Habitats Directive 92/43/EEC), denomination and superficial extent within the Site of Community Importance.

Code	Habitat	Extent
1310	Pioneer vegetation with annual *Salicornia* and other species in mud and sandy zones	25%
1410	Mediterranean salt meadows (*Juncetalia maritimi*)	25%
1420	Grasslands and Mediterranean fruticeti and thermo-Atlantic (*Sarcocornetea fruticosi*)	25%
1150	Coastal lagoons	15%
2240	Dune grasslands *Brachypodietalia* annuals	5%
2120	Shifting dunes along the sandbar with presence of *Ammophila arenaria* ("white dunes")	5%

along the regional coast 27 areas for management purposes: it places the Sentina within the 6.75 km long coastal stretch extending from the Harbor of San Benedetto del Tronto (to the north) to the mouth of the Tronto River (to the south). This sector has 4.6 km of coastal defence structures (69% of the total length) in its northern part, mainly represented by emerged (~3.6 km) and submerged (about 1 km) barriers parallel to the coastline and two perpendicular groynes.

In its southern part, the study area is characterized by the presence of a narrow vegetated dune separating an about 1.7 km long emerged beach from the coastal plain, which has been preserved from urbanization. Due to the lack of buildings, the study area has not been considered in the coastal protection plan by local authorities: as a consequence, it is currently exposed to severe erosion (Acciarri et al., 2017a), the rate of which has been more precisely determined during the present study. The emerged beach is the most vulnerable part of the studied physiographic unit: there, relict dunes, shrubs and tree cover are severely threatened as erosion is progressively reducing their extent (Fig. 1).

In the past, a large transition area, periodically flooded, linked the land to the sea through sandy beaches adjacent to the river mouth, where clastic deposition formed a bar at the inlet (Acciarri et al., 2016). Then, anthropogenic reduction of sediment transport occurred due to sand and gravel mining, irrigation and take out of canals, constructions of reservoir upriver etc. (Acciarri et al., 2016).

On average, the emerged beach is made up by 11% of gravel, 33% of sandy gravel, 23% of gravelly sand and 33% sand (Regione Marche, 2005; Dal Cin and Simeoni, 1994; Bisci and Cantalamessa, 2008). The presence of gravel and pebbles, particularly abundant along the shoreline, is partially due to the solid material brought by the Tronto River in the past and partially to the dismantling of defence works located to the north of the investigated stretch. Most of the sandy material removed from the emerged beach is transported by waves and currents to the submerged beach. The submerged beach has a very gentle slope (0.6%–0.9%) and is mainly composed of sand becoming finer seaward, where silt is progressively more abundant.

The net sediment transport is from south to north (AA.VV., 1990, 2006; Bisci and Cantalamessa, 2008; Di Celma, 2011; Acciarri et al., 2016, 2017a, 2017b), i.e. from the Tronto River mouth toward Porto d'Ascoli, the rate of which was unknown before the present study. The closure depth, defined as the boundary of the sand-sharing system in a time frame (Dean and Darlimple, 1991), has been calculated with Hellermeier's (1978; 1981) formula:

$$d_c = 2.28H_{12} - 68.5\frac{H_{12}^2}{gT_p^2}$$

where d_c [m] is the closure depth; H_{12} [m] is the average wave height not exceeded for more than 12 h a year; g [m/s^2] is the gravity acceleration; and T_p [s] is the peak period associated to H_{12}. These parameters have been calculated basing upon the 3-hourly data recorded by the Ortona buoy (80 km to the south) from 1989 to 2005: the resulting closure depth is 7.57 m (ISPRA, 2009).

The wave regime is mostly characterized by storms coming from NNE and ESE, the former being generally more intense and the latter more frequent (APAT, 2004). Tides are very weak, with average amplitudes around 40 cm; maximum amplitudes are around 70 cm. Regional data of relative sea level rise have been discussed by Antonioli et al (2019) and the influence of tectonics and the rate of subsidence seem not responsible of coastal erosion (Antonioli et al., pers. comm., in press).

2.2. Methods

The preliminary step of our methodology was to gather relevant data in order to characterize the study area. A full list is itemized in Table 2.

The experimental part of the study is based on the analysis of local

Table 2
Data and integrated sources. Note that same data sources have been used to carry out different analyses (*data used also for dune analysis).

Data	Source	Year
Vector Technical Map (CTR)	Marche Region	2000
Orthophoto	Marche Region	1985*, 2010
Orthophoto	Ministry of Environment	1995*, 2006, 2012
Topographic GPS survey	Authors	2007*, 2012*, 2013, 2014, 2015
Aerophotogrammetric survey using an eBee® wing drone	Authors	2015
Bathymetric surveys	Authors	2008, 2012*
Sediment samples	Authors	2008*, 2012*, 2015
Wave and wind climate	Ortona Buoy	1989*-2010
	Ancona Buoy	1999–2006, 2009–2012
Wind climate and tides	ISPRA – Mareografico: San Benedetto del Tronto station	2010–2015*

morphology and sedimentology through the interpretation of the multisource dataset referred to the time interval 1985–2015. Based upon sedimentological and topo-bathymetric data, we identified emerged and submerged features, evaluated their evolutionary trend, and depicted the increased vulnerability of the study area through multitemporal analysis of the following elements: a) shoreline; b) beach profiles; c) dunes; d) bathymetry; e) sediment properties.

2.2.1. Survey and monitoring of the shoreline

The shoreline position was analysed in both the mid- (2000–2015) and the short-term (2012–2015). Midterm analysis was based on the following four different data sources:

- 2000: Regional Technical Map (CTR) of the Marche Region, scale 1:10,000 (vector);
- 2006: Ortho-photo of the National Cartographic Service, scale 1:10,000 (http://www.pcn.minambiente.it/GN/);
- 2012–2015: GPS topographic survey made via Leica Viva GS15®;
- 2015: aero photogrammetric survey using an eBee® topographic wing drone.

The aero-photogrammetric survey was carried out on 24th April 2015 using an eBee® topographic wing drone (flight and pre-processing performed by GeoService, Fermo) equipped with differential GPS and high-resolution camera. All the images were acquired at an altitude of about 130 m, with a resolution of approximately 20 × 20 cm on the ground and accuracy greater than 5 cm in height. The acquired cloud of points allowed us to obtain a Digital Terrain Model (DTM), a Digital Surface Model (DSM), the contour lines of the area and an ortho-photo map. This orthophoto is the reference for the current status of the Sentina beach. From the DTM much information was extracted also for the acquisition of shoreline position and beach profiles.

Using ESRI® ArcGIS©, other older ortho-photos (scale 1: 10,000) were georeferenced in UTM WGS 84 system (33N) based on both the Regional Technical Map (2000) and the high-detail ortho-photo obtained using an eBee® wing drone (2015). All data were checked using a dense series of ground control points (GCP) and then compared to analyse the evolutionary trend of the beach.

Short term evolution was analysed using also data obtained from a series of topographic surveys executed by the authors using a GPS Leica Viva GS15®, in six different time intervals: 3rd November 2012, 20th October 2012, 14th December 2013, 26th February 2014, 14th March 2015 and, 24th April 2015.

Using the ArcGIS© application called Digital Shoreline Analysis System (DSAS; Thieler et al., 2009), shoreline variations were analysed both in the short- and mid-term. A reference line has been defined approximately parallel to the coast in the backshore at an average distance of about 50 m from the shoreline: then, 61 cross-cutting transects with an offset of 30 m, progressively numbered from north to south, were considered (Fig. 3a). For each time interval, the width of the shore (distance between the shore line and the foot of the dune) and the Net Shoreline Movement (NSM) were calculated. Then, multiplying the NSM value (that is the distance between two shoreline measured along the transects orthogonal to the coast) of each time interval by the spacing of the transects (30 m), it was possible to evaluate the loss of emerged beach area.

2.2.2. Survey and monitoring of beach profiles

The emerged beach was monitored along seven sections perpendicular to the shoreline and spaced with an offset of about 300 m (Fig. 3b). Monitoring started from a reference line almost parallel to the shoreline and located about 50 m inland. All surveys were carried out using a GPS Leica Viva GS15® in four different dates: 3rd November 2012, 20th Oct 2013, 14th December 2014, 24th April 2015.

The last survey was also used to verify the accuracy of the drone survey (see § 4.1). Topographic surveys, based upon the above transects, extended down to a depth of about −1 m. Due to the significant retreat of the southern portion of the beach, the markers of the reference points 6 and 7 were removed during a severe storm surge in February 2014: therefore, only the use of aero photogrammetric surveys allowed us to obtain profiles comparable with the previous ones for the last two sections.

2.2.3. Survey and monitoring of dunes

The characterization of coastal dunes was carried out considering all the available dataset (Table 2). Analyses based upon topographic profiles provided the extent of dune ridges; local attributes of dunes were determined in terms of vegetation cover and discontinuity elements (both natural and anthropogenic) and digitized (Table 3). This approach was previously adopted to generate the Italian National Database of Dunes, which resulted from the National Project "*The wind deposits and the dune beach sediments flow*" in 2002 and then implemented into a European protocol during the subproject POSIDUNE - *Interactions Posidonia Oceanica de Sable avec l'Environnement et des Dunes Naturelles*, OCR-BEACHMED (www.beachmed.it; Cappucci et al., 2007).

The extent of dune polygons has been defined by direct observation conducted during *in-situ* surveys (for images of 2007 and 2012) and by the analysis of contours and colour contrasts (for images of 1985 and 1995); such polygons were delimited considering the continuity of vegetation cover (Bianco and Menegoni, 2009). Then, the width of each dune (planimetric distance between the dune foots) has been calculated along each transect through the identification of the dune foot. Then, for each time interval, ArcGIS DSAS (Thieler et al., 2009) procedures were carried out following the End Point Rate (EPR) method.

Table 3
Legend and structure of the dune database.

ELEMENT	TYPE	ATTRIBUTES	CLASSES
Dune	Polygon	State of activity	Active or re-activated dune
			Dormant dune
		Vegetation	Arboreal vegetation
			Shrub vegetation
			Herbaceous vegetation
			Arboreal sparse vegetation (<20%)
			Shrub sparse vegetation (<20%)
			Denuded
		Anthropization	Urban area
			Urban patches
			Human alterations
		Evolutionary trend	Accreting shore
			Stable shore
			Eroding shore
		Beach Width	0–20 m
			20–60 m
			>60 m
Dune crest	Line		
Crest height	Point		
Accesses	Point/ Line		Ways and walk-Paths
			Natural accesses
Wind	Point		
Protection scheme	Line		Nourishment
			Attached groynes
			Nourishment and hard structures
Use of the Beach	Line		Temporary seaside resort
			Permanent seaside resort

2.2.4. Bathymetric survey and monitoring

Two bathymetric surveys were conducted from the isobath −1 m to a distance of about 5 km from the coast (down to a depth of around −20 m) in 2008 and 2012 using two dual-frequency professional cartographic sea-bottom scanners (Furuno® GP 7000F and Furuno® LS 4100) installed in a small Rio 500 motor boat with a shallow draft, owned by the University of Camerino.

Surveys were performed at slow speed (below 3 kn/h) during calm sea conditions, along routes perpendicular to the coastline; some routes parallel to the coast have been surveyed also in order to check the depth at the intersections. Until isobath −8 m, the spacing of the routes was set at 50 m, while above this depth a distance of 200 m was chosen due to the homogeneity of the seabed. Tidal and atmospheric pressure variations were removed using the records of the tide-gauge station located in the harbour of San Benedetto del Tronto, managed by ISPRA (www.mareografico.it). The three-dimensional pattern of the investigated sea floor was obtained using the ESRI®ArcGIS©3DAnalyst© extension, creating DTMs with a resolution of approximately 50 × 50 cm on the seafloor and accuracy of ~10 cm in depth.

. Then, depth variations were calculated comparing the two DTMs with the Raster Calculator function of ESRI®ArcGIS©SpatialAnalyst. Finally, the volume of sediment moved in the submerged beach was calculated.

2.2.5. Sedimentological characterization of the beach

A sedimentological characterization of the study area was carried out in order to determine the space and time variation of grain-size distribution in both the emerged and the submerged beach (Bisci and Cantalamessa, 2008). A total of 198 samples was analysed: 91 samples in 2008, 62 samples in 2012, 21 samples in 2013, and 24 samples in 2015. The submerged beach was sampled only in 2008 and 2012. Samples were taken at a distance of 1, 2, 5 and 10 m from the shoreline and at a depth of −1, −2, −3, −5, −7, −10 m (Fig. 3b); in addition, 17 samples were collected at a depth of −13, −15 and −20 m. Seabed sampling was carried out using a Rickly Hydrogeologic® Benthic Grab© bottom sediment sampler, whereas in sub-aerial environments, samples were taken manually, using a shovel.

Grain-size analysis was carried out using the sieve-pipette method by dry sieving, using 1 phi interval standardized sieves according to ASTM criteria for coarser grains. The silt and clay fractions (finer than 0.063 mm) were analysed using a pipette sampling method based on Stokes' law: this method measures the mass (%) for the defined grain-size classes. Since Stokes' law assumes that the particles are rigid, smooth spheres, rather than the plate-like shapes of many clay particles, the results are expressed as equivalent spherical diameters (Gee and Bauder, 1986).

In addition, microscopic observations of mineralogical-petrographic features were carried out to determine the average sediment composition. For peculiar fractions (i.e. pink sand selectively sorted by backwash, Fig. 2) X ray diffractometric analysis was performed.

Fig. 2. Erosion caused by an eastern strong storm in 2013. Note the presence of mini-cliff and scour on the shoreline and reddish garnet sand on the backshore due to selective sorting by the backwash.

3. Results

Seabed bathymetric surveys, topographic surveys of beach profiles and shoreline position, sampling and grain-size analysis of sediments were carried out more than once in different years and seasons. The collected data allowed us to characterize the study area and to achieve a better understanding of its evolutionary trend. In this section, these results are presented.

3.1. Shoreline variations and evolution of the emerged beach

Between 1985 and 2015, a significant decline affected the entire beach dune system, both in terms of shoreline retreat and reduced extent (Fig. 4). From 2000 to 2015 the Sentina beach constantly retreated even if some advances are locally observed. The analysis of shoreline position provided many results, summarized in Table 4 successive shoreline positions were plotted for the whole beach for each of the considered time intervals (Fig. 5).

Between 2000 and 2006 an average setback of 22.8 m was calculated (average annual value of 3.8 m/y). In the central portion of the beach (transects 38–42), a maximum value of 33.5 m was recorded, while the minimum rate of retreat is less than 10 m and occurred at both the northern and southern ends. In the following six years (2006–2012), the shoreline continued to retreat with an average of 17.6 m (average annual value of 2.9 m/y). Between 2012 and 2015, erosive processes have mostly affected the southern portion of the beach (transects 48 to 60), with peaks of retreat up to 55 m (average annual value of 13.8 m/y).

Based on these retreat rates it was possible to estimate the total loss of emerged beach which took place from 2000 to 2015, which is close to 100,000 m^2 along an approximate beach length of about 1.8 km (Table 4).

3.2. Volumetric changes

For each time interval between the topographic surveys (from November 2012 to April 2015) the volumetric variations of the beach were calculated (Table 5). A limited increase of about 10 m^3/m revealed stability of the beach close to sections 1 and 2 (see Fig. 3B), located in the northern part of the study area where beach ridges form by seaward accretion and vegetation stabilization were observed. On the other hand, in the central part of the study area, erosion led to the loss of about 70 m^3/m of sediment, while in its southern portion (Sections 6 and 7), about 150 m^3/m of sediment have been eroded. Overall, from November 2012 to April 2015 about 135,000 m^3 of sand was eroded from the whole beach (Table 6).

3.3. Evolution of the dune system

The main results of dune characterisation are summarized in Tables 5 and 6 The seaward foot of the dunes shifted landward with an average retreat around 6.5 m^2 per year in the last fifteen years, while its landward foot shifted seaward. This confirms that the entire beach-dune system is subject to both retreat and areal reduction (Fig. 5).

The southern part of the study area, close to the Tronto River mouth, is the most severely affected by erosion, and a reduction of the beach-dune system is clearly discernible every successive year. At the northern end of the beach, the seaward foot of the dune was set back about 10 m, whilst in its southern sector 15–20 m of retreat have been observed. It should be emphasized that in 2012 for the first time the polygon identifying the dune area presented a discontinuity in its central portion, with a 100 m wide blow out. This morphological feature provides evidence of how severely the recent erosion trend is compromising dune formation and conservation (Fig. 6).

Even though major storms do most of the damage and erosion takes place during short periods of a few days (Fig. 2), no investigation have been funded to determine what actually happens to the beach-dune system during a single storm event. Nevertheless, the monitoring carried out in the present study allows us to describe seasonal beach-dune morphological evolution. In particular, the shoreline variation under the effect of different incoming wind-waves affect the erosion of the foot-dune allowing to identify the most vulnerable part of the coastline (section profiles of Table 5).

3.4. Evolution of the submerged beach

The bathymetric surveys carried out in 2008 and 2012 gave results

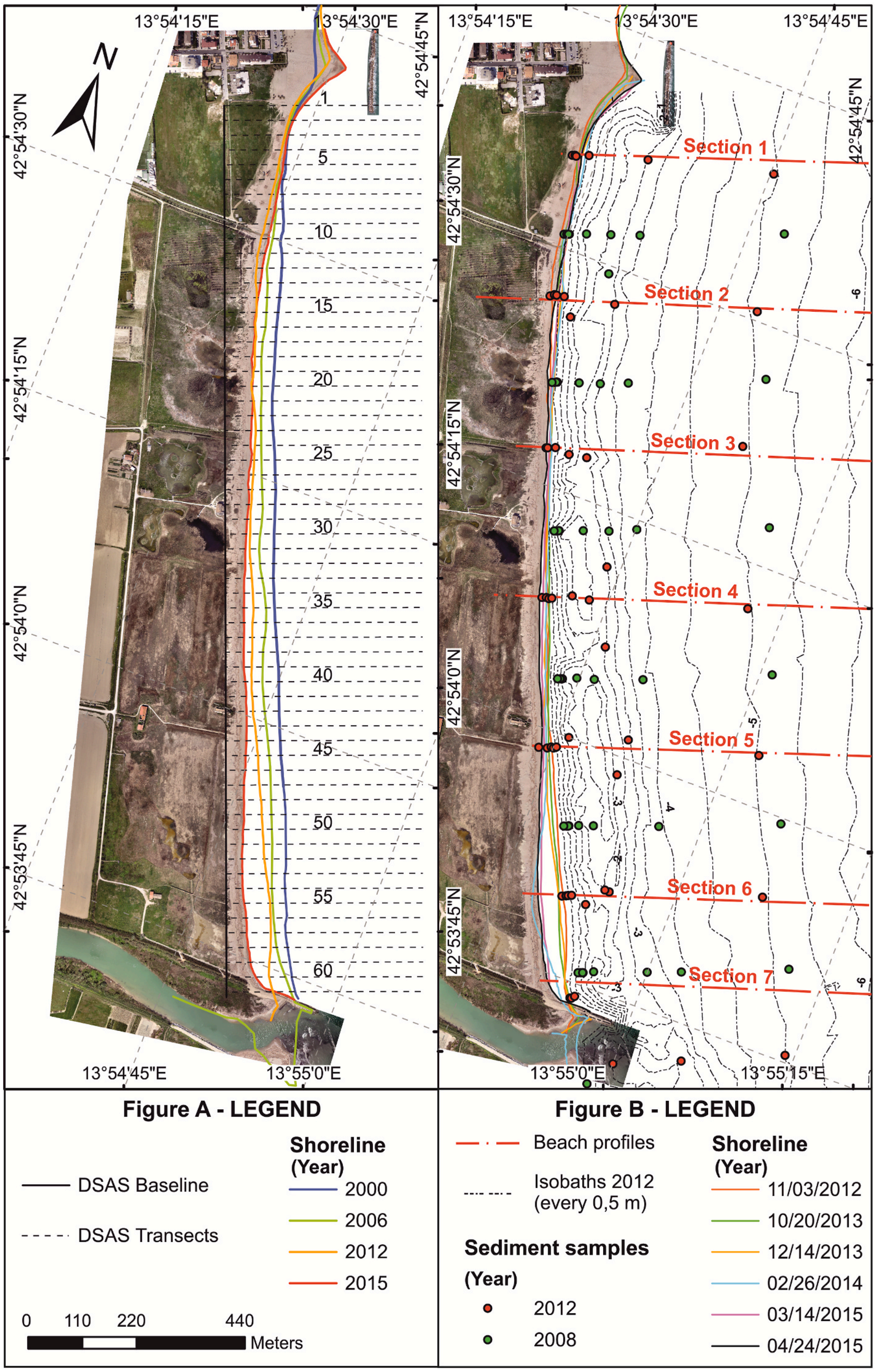

Fig. 3. a) Location of the transects used for the calculation of the shoreline variation by DSAS. b) Transects used for the detection of beach profiles carried out in the period November 2012–April 2015.

that were analysed and then compared (Fig. 7). The 2008 data show a fairly regular seafloor (Fig. 7a), with isobaths almost parallel to the coast and quite regular seaward-increasing depth. The only exception to this trend is the presence of an underwater valley located in front of the Tronto River mouth, almost perpendicular to the coast. This feature is better defined from a depth of about 8 m and reaches a width of around 500 m some 2.5 km from the shoreline, with a maximum incision (around 1.5 m) at a depth of 11–12 m (value below the closure depth), to disappear at depths greater than 14 m (Bisci and Cantalamessa, 2008; Bisci et al., 2010). In Fig. 7c, bathymetric differences between 2008 and 2012, up to the −6 isobath, are shown. Colours from orange to red indicate deepened areas, while blueish colours indicate a decrease of depth and the areas where the beach sediments are transported; with represents substantially unchanged bathymetries. We presume that the underwater valley results from the erosive power of the river, perhaps intensified when sediment supply has been reduced, and a tendency to move sediment more readily seaward, away from the beach-dune system during storm events and under the effect of ripcurrents.

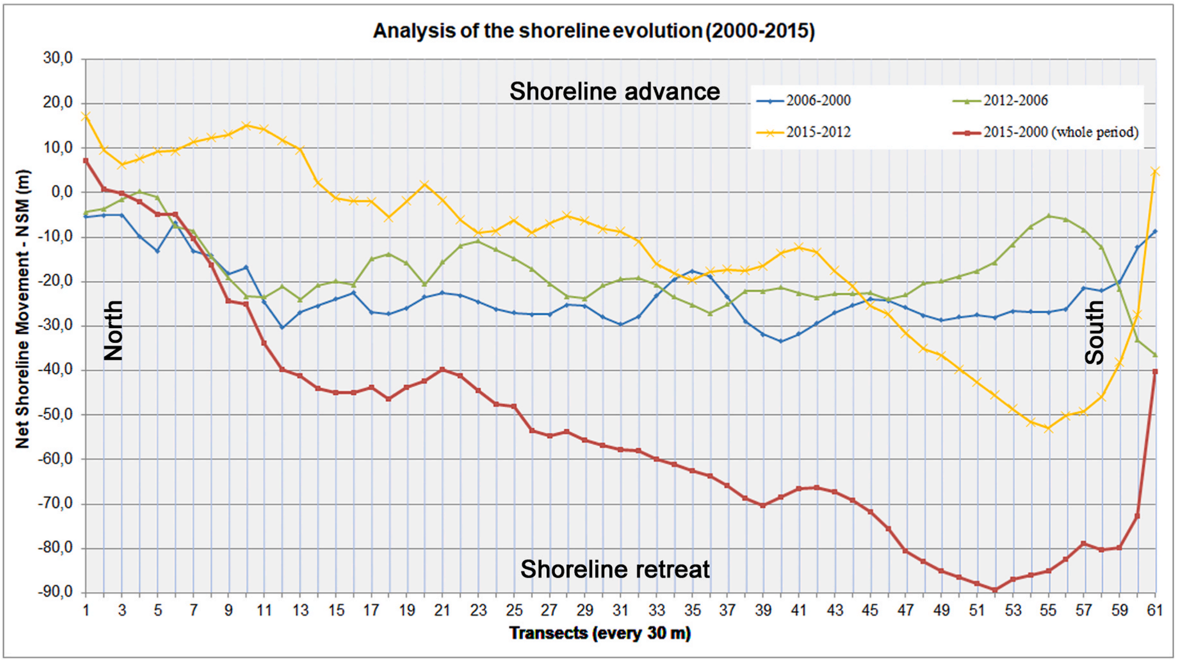

Fig. 4. Evolution of the coastline from 2000 to 2015.

Table 4
Net Shoreline Movement (NSM) expressed in average beach retreat (m), retreat rate (m/y), lost surface (m^2) and rate (m^2/y) occurred in the time interval 2000–2015.

	Avg. retreat	Avg. retreat rate	Lost surface	Avg. lost rate
Unit	(m)	(m/y)	(m^2)	(m^2/y)
NSM 2000–2006	22.8	3.8	41,809.13	6,968
NSM 2006–2012	17.6	2.9	32.168.19	5.,361
NSM 2012–2015	13.0	4.3	23,757.45	7,.919
NSM 2000–2015	53.4	3.6	97,734.79	19,546

3.5. Sedimentological characterization

The dunes, according to the classification of Nota (1958), are made up of very well sorted fine sand with a diameter of about 0.25 mm for 99% of the weight. Grain size remained almost unchanged during the whole period of observation, suffering only a general, minor decrease of the emerged beach (Table 7). Considering all samples collected, comparison of mean grain size values revealed that from 2008 to 2012 the emerged beach become slightly coarser (−0.2 phi from shoreline to +1 m above msl), while the submerged beach become slightly finer (+0,5 phi up to −3 m of depth and +0.4 phi between −5 and −7 m of depth).

The emerged beach varies from sand ($D_m \approx 0.5$ mm) to gravel ($D_m \approx$ 32 mm). The landward portion of the submerged beach shows high heterogeneity, with patches of gravel down to a depth of about 3 m: this makes the D_m to vary between 0.125 mm and 22 mm (Bisci and Cantalamessa, 2008). The coarse fraction significantly increases from south to north, and silt and clay are rare until a depth of −2 m and increase at greater depths to more than 30% in weight at a depth of about 15 m (Fig. 3b; Bisci and Cantalamessa, 2008).

Mineralogical and petrographic microscopic observations revealed a carbonate content of about 60%: quartz and rock fragments are present, along with mica, dolomite, potassium feldspar and plagioclase. The gravel fraction mainly consists of flattened and rounded limestone pebbles: flint, rubbles and sandstone are also present. Carbonate clasts are composed of clastic and organogenic debris with remains of undamaged and fragmented shellfish, lamellibranchs and gastropods (Bisci and Cantalamessa, 2008). A pink sandy fraction is often visible along the Sentina backshore (Fig. 2) because of selective sorting operated by backwash: X ray diffractometric analyses carried out on this fraction have shown the dominance of garnets, with presence of quartz, calcite, feldspar and magnetite.

4. Discussion

Within the Sentina Natural Reserve, the emerged beach has a strong erosive trend and the dunes have a very limited extent, both vertically (maximum height of 2.5 m) and horizontally (maximum width of 50 m). This demonstrates the high vulnerability of this coastal stretch and its low resilience to erosive action during storms when breakthroughs and wash overs can occur.

4.1. Costal erosion

The coastal dunes located in the study area are now widely compromised from both the morphological and the vegetation point of view degradation will continue if actions against erosion will not be adopted. Sedimentary structures indicate wind transport activity landward (Psuty, 1988; Nordstrom et al., 1990). Even though random distribution of ripples observed on the emerged beach demonstrates aeolian transport of fine sand toward the backshore, dune formation is taking place too slowly under the effect of migrating sand compared to other erosive forces acting on the beach (storm surges, incident waves and longshore currents). This is due to the narrow emerged beach, and the consequent reduced amount of sand transported landward by winds and, probably, to the low efficiency of vegetation to trigger deposition of sand and vertical accretion of the dune system (Pallottini and Cappucci, 2009).

Volumetric changes of the sediments forming the emerged beach were estimated based upon sections orthogonal to the coastline, thus also identifying potential directions of sediment transport in relation to the incident wave regime. Analyses allowed us to identify the areas affected by more severe erosion and to quantify its rates. Shoreline

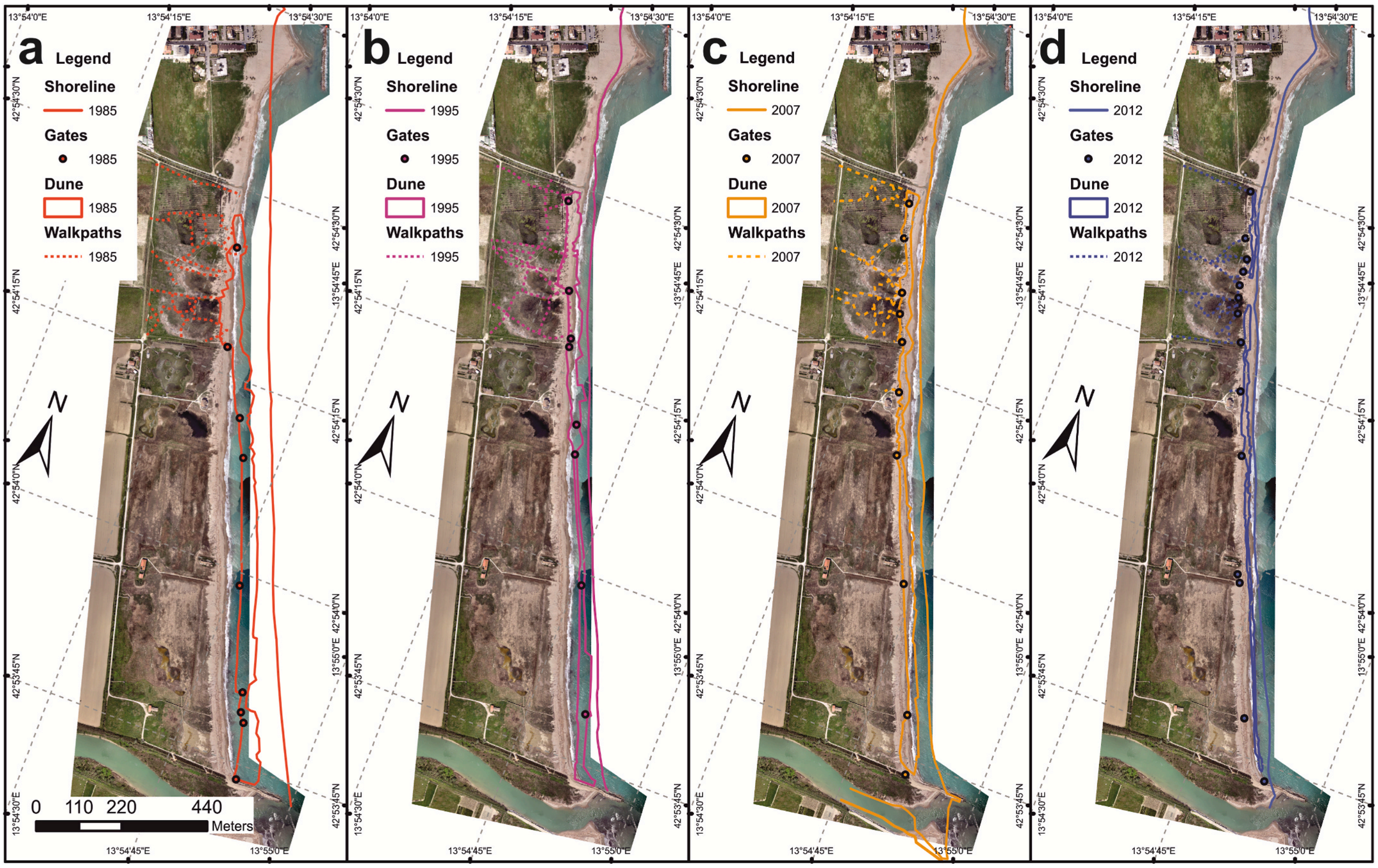

Fig. 5. Dunes, gates, pedestrian paths and shoreline features detected in 1985 (a), 1995 (b), 2007 (c) and 2012 (d) overlapped on the 2015 aerial orthophoto.

retreat during the last 15 years led to the disappearance of more than 90,000 m^2 (~5%) of the Natural Reserve area, since winter storms erode significant portions of both the emerged beach and the coastal dunes every year (Fig. 2). Between 2000 and 2015, the Sentina Natural Reserve underwent an average shoreline erosion of 53.4 m (roughly corresponding to 3.5 m/year), with a maximum value of more than 80 m in its southern part, between transects 47 and 60 (Figs. 3a and 4). On the other hand, in the northern part of the beach (transects 1 to 8) the shoreline has been subject to modest accretion: in detail, the northernmost 250 m of the beach were influenced by a tombolo induced by the nearby emerged barriers located parallel to the shoreline a little further to the north.

The average width of the dune system has decreased steadily and considerably. During the interval 1985–1995, it decreased from 40.3 m to 23.2 m, with a reduction of about one third of the area (approximately, from 57,661 m^2 to 38,246 m^2). In the interval 1995–2007, a total setback of about 30 m occurred along the entire coastal stretch (Fig. 6) with an areal decrease of more than 20% (approximately, from 38,246 m^2 to 30,698 m^2). Between 2007 and 2012 the coastal system suffered increased erosion, with dune area reduced from about 30,698 m^2 to about 12,338 m^2 in only five years. A temporal variation of dune extent is reported in Fig. 8.

Topographic surveys carried out along transects perpendicular to the shoreline indicate a loss of about 135,000 m^3 of sediment from November 2012 to April 2015, with an average of about 50,000 m^3/y: this phenomenon is more intense in the southern portion of the beach-dune system. Variations of the shoreline position confirm the above evolutionary trend and show an average retreat of approximately 4.3 m/y (period 2012–2015), with a loss of surface area of about 2.3 ha: during the last years such retreat was significantly faster than observed in the past (3.8 m/y in 2000–2006 and 2.9 m/y in 2006–2012). This rapid pattern change is occurred under the effect of storm events (Acciarri et al., in prep.)

According to Brink et al. (2013), the economic benefits deriving from Natura 2000 are of the order of 200–300 billion €/year. As the beach-dune system is the most important morphological element protecting coastal areas from erosion and regulating sea floods, the potential loss of such an important ecosystem should be carefully considered in planning.

The retreat of the shoreline and the demolition of the dune are both taking place in the study area; it is a widely investigated process and similar evolutionary trend has been recently documented in other sites (Valentini et al., 2020 and literature therein). Dune systems are, in fact, a natural embankment for high waters too (Manca et al., 2013). A possible protection strategy for the backshore environment should be specifically designed to favour accumulation of sand in order to trigger sand deposition and partly counteract erosion. Maintenance and enhancement of these systems involves a good state of conservation of connected environments, their ecological function and related economic value (Vassallo et al., 2017).

Of particular interest are the results of the present study which help to understand how the study area has evolved in the time interval 2000–2015. The bathymetric surveys carried out during summer of 2012 show an almost flat seabed with average slope around 0.5%; the −10 m isobath is less than 2 km from the shoreline. No seabed forms due to erosion, channels or rip-current features have been observed, but from the shoreline down to 4–5 m depth, erosion lowered the seabed up to about 1 m. There, at 110–130 m from the shoreline, a more than 1.5 km long underwater bar system has been observed, formed by narrow and elongate bars parallel to the shoreline, separated from it by a 3 m deep channel or trough. The height of the bars varies between 1.2 and 1.5 m and their width ranges from 20 - 25 m to 50–60 m (Fig. 7b).

Table 5
Change of sediment volume along the beach profiles from Nov 2012 to Apr 2015. On the right: profiles of morphological change are shown for the beach-dune system.

		Unit	03-nov-12	20-ott-13	14-dic-13	24-apr-15	Total ΔV
Section 1	V up to shoreline	(m^2)	134	140,9	138,9	130,1	---
	ΔV on previous survey	(m^3/ml)	---	+6,9	-2	-8,8	-3,9
	Total ΔV on previous survey	(m^3 x 100 ml)	---	+690	-200	-880	-390
Section 2	V up to shoreline	(m^2)	211,8	265,3	277,5	222,5	---
	ΔV on previous survey	(m^3/ml)	---	+53,5	+12,2	-55	+10,7
	Total ΔV on previous survey	(m^3 x 100 ml)	---	+16.050	+3.660	-16.500	+3.210
Section 3	V up to shoreline	(m^2)	163	162	142,2	114,8	---
	ΔV on previous survey	(m^3/ml)	---	-1	-19,8	-27,4	-48,2
	Total ΔV on previous survey	(m^3 x 100 ml)	---	-300	-5.940	-8.220	-14.460
Section 4	V up to shoreline	(m^2)	184	202	162,5	99,3	---
	ΔV on previous survey	(m^3/ml)	---	+18	-39,5	-63,2	-84,7
	Total ΔV on previous survey	(m^3 x 100 ml)	---	+5.400	-11.850	-18.960	-25.410
Section 5	V up to shoreline	(m^2)	151,1	132,2	78,1	68,2	------
	ΔV on previous survey	(m^3/ml)	---	-18,9	-54,1	-9,9	-82,9
	Total ΔV on previous survey	(m^3 x 100 ml)	---	-5.670	-16.230	-2.970	-24.870
Section 6	V up to shoreline	(m^2)	174	147,2	131	7,7	---
	ΔV on previous survey	(m^3/ml)	---	-26,8	-16,2	-123,3	-166,3
	Total ΔV on previous survey	(m^3 x 100 ml)	---	-8.040	-4.860	-36.990	-49.890
Section 7	V up to shoreline	(m^2)	139	118,6	110,1	5,8	---
	ΔV on previous survey	(m^3/ml)	---	-20,4	-8,5	-104,3	-133,2
	Total ΔV on previous survey	(m^3 x 100 ml)	---	-3.672	-1.530	-18.774	-23.976
Total volume loss from nov-2012 to apr-2015 (m^3)							135.399,9

Beach Profiles

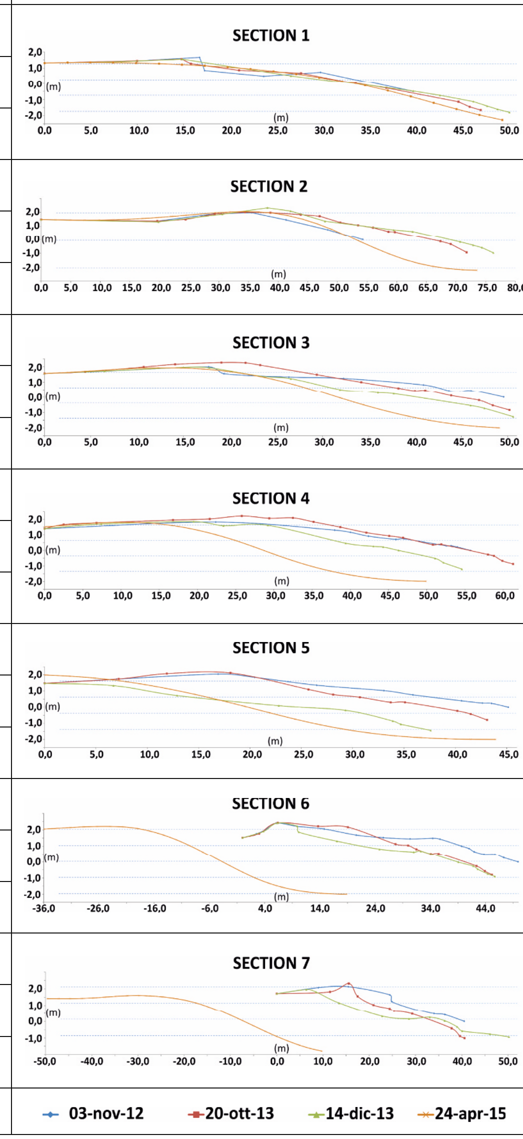

Table 6
Morphological elements used for the dune characterization in the time interval 1985–2015 (*thanks to restoration work of a Life Project).

Element	Unit	1985	1995	2007	2012
Surface of dune polygon	m^2	57,661	38,246	30,698	12,388
Average dune width	m	40.27	23.21	23.60	9.00
Surface of vegetated areas	m^2	34,576	21,898	18,920	3,921
Number of gates	No.	9	8	10	14
Length of walkpaths	m	2,197	2,262	1,907	1,670
Surface of wetland	m^2	10,021	Absent	Absent	33,700*
Defence structures	–	Absent	Absent	Absent	Absent

From 2008 to 2012, the whole investigated submerged beach suffered sedimentary losses of about 370,000 m^3 down to −6 m depth (Fig. 7c): approximately, 220,000 m^3 of those sediments were displaced to the north, towards Porto d'Ascoli where higher sedimentation rates have been observed after the realignment of the emerged barriers while about 150.000 m^3 have been directed offshore, beyond the limit of the active beach. A diagram of sediment input and output from the coastal system is shown in Fig. 9.

According to the beach-exposure model of Short and Masselink (1999), the study area has a transitional circulation with the presence of rip currents located symmetrically along the submerged beach. With increasing intensity of waves, the submerged beach can be classified as Transverse Bar & Rip (TBR), Low Tide Terrace (LTD) or reflective (Short, 1996): these attributions were confirmed during morphological monitoring (Taramelli et al., 2020). Short-term variations of the shoreline allowed us to assess the effects of individual storms on the study area. Annual trends highlight a rotation of the shoreline around its central part. Reorientations of the shoreline are influenced by the impacting storm surges: Sirocco wind, coming from the southeast, results in accretion of the emerged beach in its northern part of the study area and erosion to the south, while the Bora wind, coming from the north, has the reverse effect. No significant changes have been observed for the wave fronts coming from around 70° (east wind), perpendicular to the

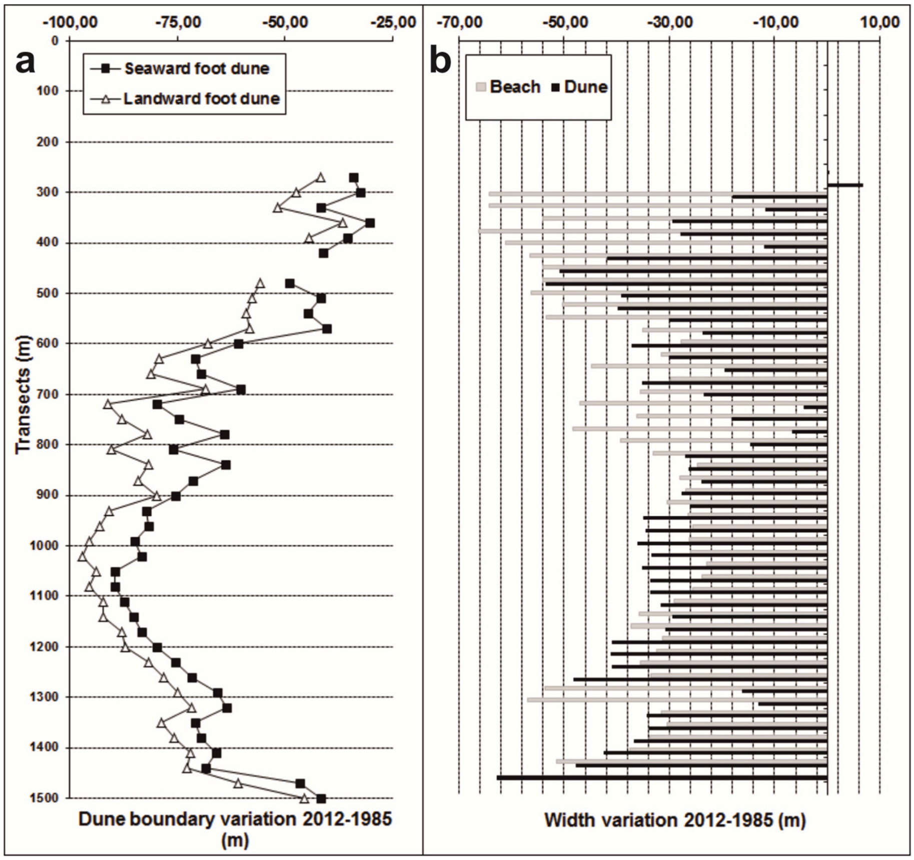

Fig. 6. a) Dune boundary variations (m; for both seaward and landward foots) in the time interval 2012–1985. b) Width variation (m) of the emerged beach and dune in the time interval 2012–1985.

beach (Acciarri, 2016).

Sediment collected in 2008 and 2012 at the same depth (Table 6) demonstrates that gravel and pebbles, particularly abundant close to the shoreline, partially depend to the solid material carried by the Tronto River in the past and to the dismantling of defence works located in the northern part of the study area. A general increase of particle size was observed: this is further evidence of the erosive action that washed away the finer material from the emerged beach. Around a depth of 2 m, a submerged bar has been observed, formed by finer sediments than those found in 2008. Finer sediments also have been observed at a depth of 3 m in the northern part, while in the southern reach sediments are coarser. Finally, at a depth of 5–7 m a reduction in grainsize has been found due to the increase of silty-clay content. Significant differences were observed also at intermediate depths along the central and northern sectors, where longshore transport is directed northward.

Therefore, it can be said that the hydrodynamics of the Sentina beach are comparable to that of a pocket beach (Carter, 1980; Hsu et al., 1989; Hsu and Evans, 1989; Klein Da Fontoura et al., 2002; Inman and Nordstrom, 1971; Short, 1991, 1996; Finkl, 2004). The structures located both to the south and to the north behave as manmade boundary headlands controlling the evolution, but considering the retreat rates of the shoreline, the southern portion of the beach is more exposed to storm events coming from the east or southeast and its erosion is more severe under such storms.

4.2. Sand management, beach restoration and protection strategies

Protection and restoration of dunes have been part of an environmental remediation project of the local Authority and the Natural Reserve. In 2008, they carried out an emergency action to nourish the beach by using about 10,000 m^3 of sand dredged from the city harbour. At that time the harbour was subject to severe siltation within the navigation channel, which caused severe inconvenience to fishery activities and compromised the security of navigation. Even though the limited budget allowed the dredging of only a small volume of sand, characterised by a fine grain size ($D_{50} \sim 0.125$ mm), the sand was distributed along the emerged beach of the studied area in order to protect coastal dunes. Dredged sand was finer compared with the coarser material constituting the beach, implying that wave action moved part of the fine sand long-offshore.

Thus, the dredged sand did not end up replenishing the beach as expected. Galvin et al. (1987) investigated a similar management approach in Virginia beach, suggesting that sand placed on the shore should have a minimum median diameter of 0.2 mm to efficiently benefit the beach. However, the dunes are composed by fine sand, so dredged sand might help to stabilise and extend them. The second limitation of this nourishment, given the emergency nature of the work, is that it was not followed by an accurate monitoring, but the project has been funded for two management issues: safety of navigation of the San Benedetto Harbor and habitat conservation of the Sentina Natural Reserve.

Habitat conservation is widely practiced in Italy, but not in coastal management (Corbau et al., 2015). A beach nourishment intervention to protect dunes was never authorized and it is an innovative option for sediment management in the study area and more generally in Italy (AA. VV., 2006). For the first time a beach nourishment has been considered a strategy for conservation of coastal habitat. Herbaceous species such as *Brachypodietalia* (on fixed dunes) or *Ammophila arenaria* (on mobile dunes), are both present in the study area and have been considered habitats to be preserved by temporary enlargement of the shore, since beach nourishment can reduce coastal vulnerability and risk. Sustainability in the long term is still debated as this emergency action resulted

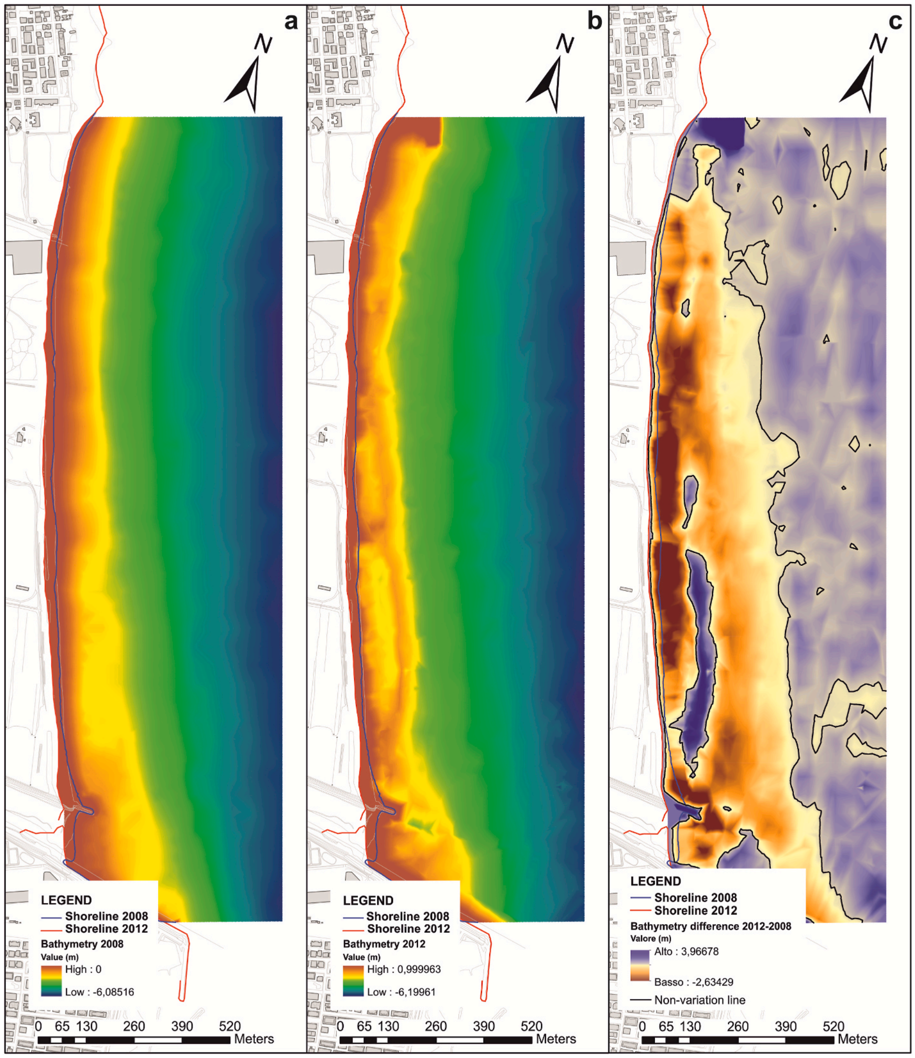

Fig. 7. Nearshore bathymetric map of 2008 (a); and 2012 (b); and bathymetric differences nearshore map occurred between 2012 and 2008 (c).

in a temporary enlargement of the emerged beach, thus protecting habitats classified within the SIC (in accordance with Directive 92/43/EEC). It did not contribute to change dune morphology (height and width), since this is possible only when the emerged beach width is above certain thresholds (20–40 m in the Mediterranean Sea: Simeoni et al., 2008; Speranza et al., 2008) and eolian transport can efficient to transfer particles landward (Bertoni and Sarti, 2011).

The preliminary results of the present study were considered by the local administration, since they identified the most vulnerable part of the coast, close to transect 6 and 7 of Table 5, where the coastal dune is more exposed to storm surge due to landward migration of the shoreline. Drawing on preliminary data collected by the authors, the National Institute for Environmental Protection (ISPRA) developed two different strategies for the coastal restoration of the Sentina Natural Reserve (ISPRA, 2009).

The first strategy was an emergency action carried out for safety of navigation by dredging about 10,000 m^3 of sand from the San Benedetto harbour and using this material for beach nourishment. To mitigate the impact of this intervention, settling for the separation of the fine fraction was carried out and only wheeled vehicles were used to transport it along the shore, trying to avoid damage to dune vegetation. The colour of the fill material was darker than the local material, due to anoxic conditions of the seabed (Pranzini and Vitale, 2011), and the grain size of the sand used was excessively fine compared to the pebbles and gravel characterizing the beach, Considering the high vulnerability of the dunes, this emergency action was nevertheless adopted by local authorities. Beach nourishment should have been coupled with dune restoration to favour sediment deposition and stabilisation as well as the growth of pioneering vegetation (Nordstrom et al., 1990; Bovina et al., 2003, Speranza et al., 2008; Grosset and Heurtefeux 2008, AA.VV., 2009). As expected, these added sediments quickly vanished, as testified by the survey we carried out in 2012 and by the continuous retreat of both the shoreline and the dunes.

The second strategy was a long-term evaluation of the sand volume needed to maintain and restore the beach for at least thirty years. By using GENESIS model, eight different scenarios have been considered for beach nourishment (both protected and unprotected by groynes and barriers) in order to maintain the width of the emerged beach between 30 and 60 m over a 30-year period. This approach, based on numerical models, was a theoretical exercise, useful to plan the use of natural and economic resources to counteract coastal erosion. Anyhow, it is taken into account that sea-level rise could worsen future scenarios (Nicholls and Cazenave, 2010; Antonioli et al., 2019; Pascucci et al., 2018, 2019).

Since in many studies of coastal management it is essential to have an acceptable estimate of sediment transport, several models were built to predict bed material transport.

Rather than using long-term and uncertain restoration approaches, on the basis of preliminary output deriving from our dataset, since 2009 we suggested starting a restoration and consolidation of the dunes using techniques compatible with the natural features of the site, such as

Table 7
Comparison of grain size mean value (Folk and Ward, 1957) in 2008 and 2012: data in phi (Φ) units (Krumbein and Pettijohn, 1938). The + symbol indicates coarser sediments, the symbol - finer ones. Nc stands for "not comparable" samples: samples were considered Nc when they were not picked up in the same place in both years. The numbers in the grey line indicate the section along which samples were collected (Fig. 3b): only not Nc samples were compared (113 out of 178).

2008	1	2	3	4	5	6	7
Dune	1.51	0.772	1.46	1.54	1.52	1.5	**Nc**
Beach +1 .0 m	1.13	1.49	−0.73	−2.66	−1.61	−0.,44	**Nc**
Beach +0 .5 m	0.41	0.41	0.28	0.21	−0.24	0.13	**Nc**
Shoreline	−0.47	0.23	−0.41	0.73	1.04	1.36	1,24
−1	−2.51	−2.27	−1.79	−1.58	1.15	1.54	**Nc**
−2	−1.39	−1.99	−1.19	1.32	1.06	0.99	1.05
−3	−1.15	−1.45	0.55	2.17	2.73	1.9	3
−5	2.83	2.8	3.02	2.9	2.62	2.06	3.36
−7	2.91	1.97	2.61	2.69	2.92	2.65	2.85
2012	1	2	3	4	5	6	7
Dune	**Nc**	**Nc**	**Nc**	1.68	1.66	1.79	1.52
beach +1,0 m	−0.16	1.81	**Nc**	**Nc**	1.64	Nc	**Nc**
beach +0,5 m	−2.69	−2.92	−2.011	−0.23	−0.088	0.19	**Nc**
Shoreline	0.76	0.76	−1.14	0.18	−0.06	0.7	−0.12
−1	2.23	−0.94	−1.94	−0.51	1.42	1.8	−0.24
−2	**Nc**	2.14	1.58	2.06	2.45	1.94	−1.97
−3	2.44	2.1	2.19	2.06	2.69	0.92	2.34
−5	2.94	3.03	3.09	2.93	2.86	3.15	2.72
−7	3.03	3.06	3.23	3.04	3.12	3.15	3.07
2012/2008	1	2	3	4	5	6	7
Dune	**Nc**	**Nc**	**Nc**	-	-	-	**Nc**
beach +1,0 m	+	-	**Nc**	**Nc**	-	**Nc**	**Nc**
beach +0,5 m	+	+	+	+	-	-	**Nc**
Shoreline	-	-	+	+	+	+	+
−1	-	-	+	-	-	-	**Nc**
−2	**Nc**	-	-	-	-	-	+
−3	-	-	-	+	+	+	+
−5	-	-	-	-	-	-	+
−7	-	-	-	-	-	-	-

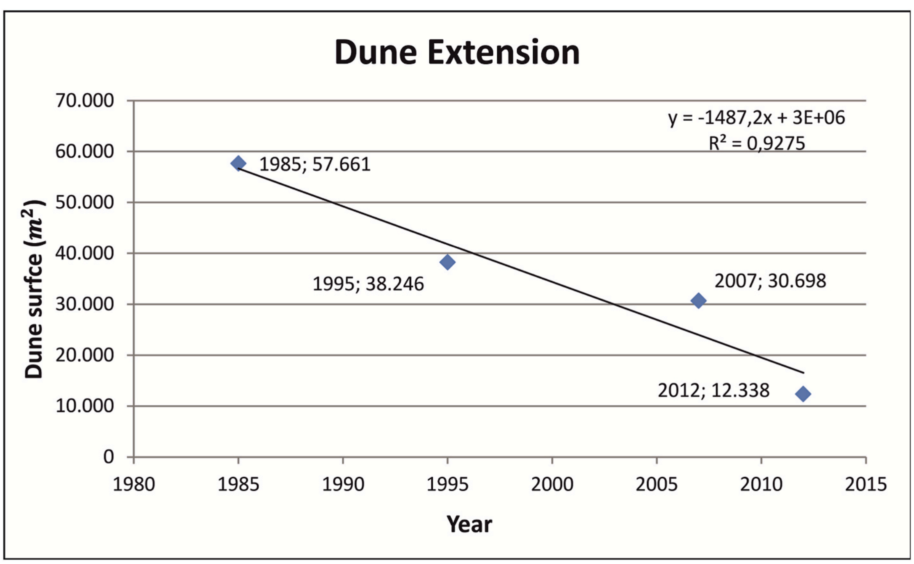

Fig. 8. Temporal variation of dune extent within the study area.

installation of windscreens (Bovina et al. 2003, 2007, 2009). Beyond this the integration of bioengineering restoration strategies with sediment deposition on the backshore can be favoured. Such structures are modular, cheap and easy to realise: moreover, they do not have any significant impact on the environment in case they are destroyed during storm surges, since they are flexible and made up of natural material (wood). Natural and local vegetation can be used to reinforce the backshore and residual dunes, reintroducing *Psammophila* species that disappeared from the protected area. Such intervention can increase resilience of the coastal area because beach nourishment strategy will be able to maintain the width of the emerged beached in front of the dunes (Scottish Natural Heritage, 2000; Bovina et al., 2003).

The orthophoto mosaic taken in 2015 can be considered representative of the current state of conservation of the dune system of the Sentina Natural Reserve, considering that the cross-cutting wooden folding screen barriers were placed during summer 2012. The beach (both emerged and submerged) is under erosion but the present rate is unknown as no monitoring have been carried out after 2015 by competent authorities.

It is still debated whether nourishment intervention alone (and its

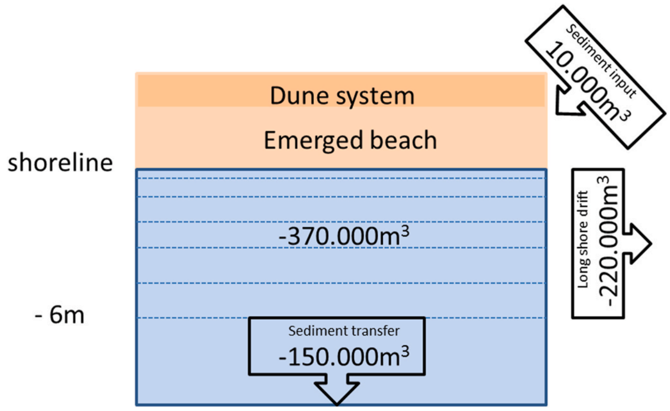

Fig. 9. Schematic diagram showing a summary of the sediment budget that occurred at the Sentina Natural Reserve for the period 2008–2012.

maintenance through time) can be considered a possible solution to counteract coastal erosion and mitigate the effects of climate change. There is no plan for beneficial changes to the Tronto River. So, the Authorities are still pondering if a submerged barrier should be constructed to reduce long- and offshore sediment dispersion. In fact, this choice will facilitate the enlargement of the beach in front of the Natural Reserve but it will reduce the nourishment to the nearby beaches which is needed. It could be carried out by using the study area as a sand engine input. The management model implemented by the authors is still under discussion and it can be schematically represented in Fig. 10.

5. Conclusion

In the studied period (1985–2015) more than 10 ha of lands of the Sentina Natural Reserve have been lost as result of coastal erosion. It corresponds to a loss of ~5% of the surface, corresponding to an economic damage of 123 million of € if the average value of the Italian beaches (about 1,228 €/m^2; Nomisma, 2003; Cappucci et al., 2011; 2017), is considered. The emerged beach is the most vulnerable part: there, relict dunes, shrub and tree cover are severely threatened as erosion is progressively reducing the surface area. Morphological analyses showed a temporal and spatial variability of the study area resulting in a general contraction of the dune-beach system within the framework of the above described trend. This evolutionary behavior is due to sediment exchange between the beach and the dunes as well as to the migration of sandbars attached and detached from the shoreline.

A comparison of bathymetric surveys carried out in 2008 and 2012 highlighted that erosion affects the seabed also, with a net loss of about 370,000 m^3 of sediment between the isobath-6 m and the coastline. Maintaining or increasing the water and sediment discharge from the river is the best way to reduce or prevent erosion in the long term. With an average output of about 50,000 m^3/y, we noticed that nourishment can reduce the erosion rate and shoreline variation, triggering dune morphological accretion. In case of periodic intervention, the sand transfer from the navigation channel of the harbor to the study area seems the most sustainable strategy to counteract the on-going retreat in the short term.

Detailed analyses allowed us to identify the most vulnerable stretches of the investigated coastline, thus constituting a noteworthy support for the decisions for nourishment and short-term protection of the whole ecosystem with its habitat and natural resources (Natura 2000). So, the methodological approach used in the present study can be a reference for a scientific based coastal defense strategy as sediment were transfer from a siltation area (the navigation channel of the nearby San Benedetto del Tronto Harbor) to a protected area (beach-dune System within Natural Reserve). The collected data can be useful also for the implementation of numerical models, accurately calibrated in order to simulate scenarios of environmental remediation and their estimated cost in the long term.

The implemented management model is still under discussion by the authorities, but it represents a strategy to couple habitat conservation, tourism, and safety of navigation that must be considered carefully by

Fig. 10. Management scheme showing a summary of the sediment transport path implemented for the Natural Reserve of Sentina (background picture).

stakeholders in terms of economic and environmental sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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