SOCIETÀ TOSCANA DI Scienze Naturali

RESIDENTE IN PISA

ATTI DELLA SOCIETÀ TOSCANA DI SCIENZE NATURALI

MEMORIE • SERIE A • VOLUME CXXV • ANNO 2018

Edizioni ETS

UNIVERSITÀ DI PISA
MUSEO DI STORIA NATURALE

Con il contributo del Museo di Storia Naturale dell'Università di Pisa

Fondazione
Cassa di Risparmio
di Lucca

e della Fondazione Cassa di Risparmio di Lucca

INDICE - *CONTENTS*

Atti Soc. Tosc. Sci. Nat., Mem., Serie A, 125 (2018)
pagg. 55-68, fig. 6; *doi: 10.2424/ASTSN.M.2018.23*

http://www.stsn.it/it/AttiA2018/bertonisupplmat.pdf

Duccio Bertoni [(1)], Marco Mencaroni [(1)]

FOUR DIFFERENT COASTAL SETTINGS WITHIN THE NORTHERN TUSCANY LITTORAL CELL: HOW DID WE GET HERE?

Abstract - D. Bertoni, M. Mencaroni, *Four different coastal settings within the Northern Tuscany littoral cell: how did we get here?*

In this paper the historical evolution of the Northern Tuscany littoral cell has been investigated through a detailed bibliographic research in order to give an in-depth look at the reasons why four different coastal environments are recognizable within the stretch of coast comprised between the Magra River mouth and the Port of Livorno. Along with the natural sandy beach, there are also sectors dominated by fully-anthropized beaches, constituted by either sand and mixed sand and gravel, and even artificial coarse-clastic beaches made of marble pebbles. The focus of the analysis is on the recent evolution of the littoral cell, especially the last two centuries: human pressure is the major factor that led to the present configuration of the coast, as a response to an increase of the demand for tourism activities, which are the prevalent income source of this area, and to the erosion processes that began striking the coast of the Northern Tuscany since the middle of the Nineteenth century. The long list of interventions this paper highlights over time, either on a table and on images, may serve as a visual database and, maybe more importantly, as a warning that a different management of the coastal areas, involving prevalently sand redistribution rather than hard protection structures, is mandatory for future actions along this sector of the Tuscany coast.

Key words - beach, coastal erosion, human influence, protection structures, Northern Tuscany.

Riassunto - D. Bertoni, M. Mencaroni, *Quattro diversi ambienti costieri all'interno della cella litoranea della Toscana settentrionale: come siamo arrivati a questo punto?*

Nel presente lavoro l'evoluzione storica dell'unità fisiografica della Toscana settentrionale è stata ricostruita per mezzo di un'accurata ricerca bibliografica allo scopo di illustrare le ragioni per cui quattro diversi tipi di ambiente costiero possono essere riconosciuti all'interno del settore di costa che va dalla foce del Fiume Magra al Porto di Livorno. Infatti, accanto alle spiagge sabbiose che ancora mantengono caratteri naturali, è possibile trovare spiagge totalmente dominate dall'influenza dell'uomo, sia in sabbia sia miste, e addirittura spiagge ghiaiose artificiali costituite da ciottoli di marmo. L'analisi si concentra principalmente nell'evoluzione recente del settore investigato, in particolare durante gli ultimi due secoli: il fattore antropico è infatti l'elemento che maggiormente ha influenzato l'attuale configurazione della costa, sia in risposta alla crescente domanda legata alle attività turistiche che costituiscono la maggior risorsa finanziaria per le comunità locali, sia come necessità imprescindibile di difendere il territorio dai fenomeni erosivi che hanno iniziato ad investire l'area dalla metà del diciannovesimo secolo. La lunga lista di interventi di cui il presente lavoro ne riporta informazioni, sia sottoforma di tabella sia col supporto di immagini, potrà essere utile come database visuale e, forse ancora più importante, come avvertimento che una diversa modalità di gestione delle coste, che coinvolga la ridistribuzione dei sedimenti presenti piuttosto che l'utilizzo di protezioni costiere rigide, sia fondamentale per le future scelte che saranno prese lungo la costa della Toscana settentrionale.

Parole chiave - spiaggia, erosione costiera, influenza dell'uomo, strutture di protezione, Toscana settentrionale.

1. Introduction

The Tuscany coast extends for 330 km (630 km including the islands of the Tuscan Archipelago) and is mainly characterized by low sandy beaches at times interrupted by promontories defined by rocky coasts. Four major littoral cells can be pointed out (Aiello *et al.*, 1975), the longest (64 km) being that comprised between the Magra River mouth and the Port of Livorno (Fig. 1). The so-called Northern Tuscany littoral cell, whose northernmost stretch belongs to the Liguria Region (about 2.5 km), is presently characterized by natural sand beaches, anthropized sand beaches, mixed sand and gravel beaches, and artificial gravel beaches. Just two among the above-mentioned kinds of coastal environment are natural: sand and mixed sand and gravel beaches. As a matter of fact, this uncommon variability within a single littoral cell is owed to intense human activity along this sector of the Tuscany coast. Anthropic pressure in response to urbanization and coastal erosion vastly modified the littoral area, leading to the development of human-related coastal settings. From a natural standpoint, the Northern Tuscany cell is fed by three major rivers: Arno, Serchio, and Magra. The Arno River is the most important in terms of catchment (about 8200 km^2) and sediment load (1524000 t/yr; Cavazza, 1984), its discharge refills the coast on both sides of its mouth. To the south, its influence reaches the southernmost sector of the cell (Tirrenia and Calambrone); to the north, the sediments transported to the sea by the Arno move northwards and get past Viareggio up to Marina di Pietrasanta (Gandolfi & Paganelli, 1975). Serchio River's input is subordinate to that of the Arno (23000 t/yr; Cavazza, 1984), which is confirmed by the formation of a spit that borders the left side of Serchio mouth.

(1) Dipartimento di Scienze della Terra, Università di Pisa, via Santa Maria 53, 56126 Pisa, Italy. *Corresponding author e-mail*: duccio.bertoni@unipi.it

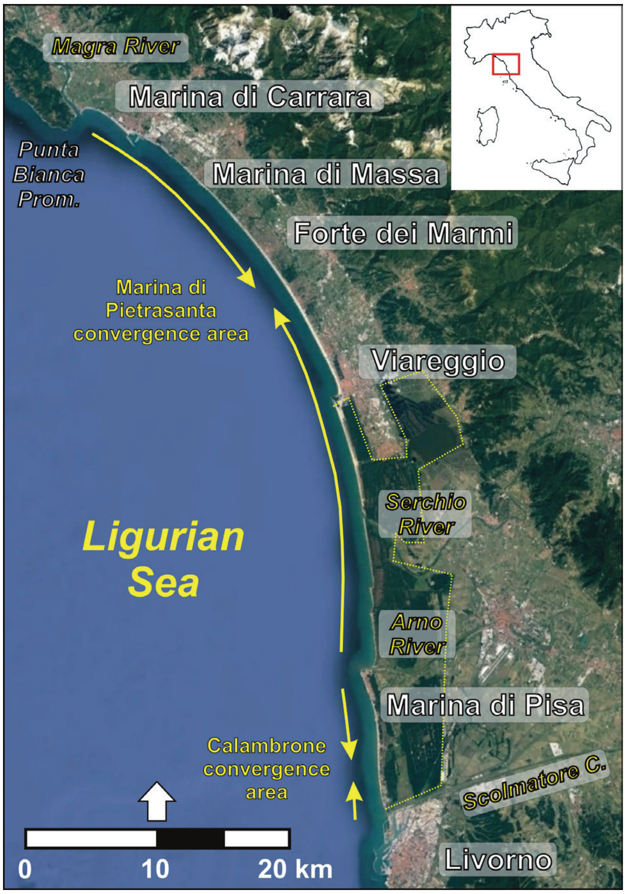

Fig. 1 - Geographical map of the Northern Tuscany littoral cell. The dotted line points out the limits of the Migliarino – San Rossore – Massaciuccoli Regional Park; the yellow lines represent the direction of the littoral drifts (background map from GoogleEarth database).

In the northernmost sector, the beach is constituted by sediment coming from the Magra River (Gandolfi & Paganelli, 1975), whose bedload supply is significant (632000 t/yr; Cavazza, 1984) even though the catchment area is similar to that of the Serchio River (about 1600 km^2 each). Magra River's sediments are distributed by the littoral drift southwards up to Marina di Pietrasanta, which is where the opposing longshore currents merge to define the convergence point (Cipriani *et al.*, 2001): here sand deposition is favoured as the current flow energy decrease, causing an accumulation that reflects on the submarine topography, whose isobaths show a slight seaward prominence. In terms of grain-size, the littoral cell is characterized by fine-medium sands (Anfuso *et al.*, 2011; Bertoni & Sarti, 2011a), which get coarser from the convergence area to the north; nearby Marina di Massa the gravel fraction is progressively increasing, as Magra River's sediment load was characterized by a relevant gravel and pebble supply (Sarti & Bertoni, 2007; Anfuso *et al.*, 2011). As already mentioned, the direction of the littoral drift is not uniform throughout the cell (Aiello *et al.*, 1975; Gandolfi & Paganelli, 1975). It is directed southwards from the Magra River mouth to Marina di Pietrasanta; the Arno River mouth identifies two divergent drifts (Fig. 1): a northward current flowing up to Marina di Pietrasanta, and a southward current flowing past Tirrenia; a limited northward-trending drift has been located towards the southernmost edge of the cell. However, the natural features have been intensely modified by human activities since the Nineteenth Century (Aminti *et al.*, 2000; Nordstrom *et al.*, 2008; Anfuso *et al.*, 2011). Based on a detailed reconstruction of all the human interventions occurred in the past century, the aim of this paper is to describe the present configuration of the Northern Tuscany littoral cell, pointing out how much the human activities factored in the eventual identification of four different kinds of coastal environment, spanning from artificial gravel beaches to natural sandy beaches.

2. The study area

2.1. Geological setting

The Northern Tuscany littoral cell is roughly north-south oriented and is defined by the Punta Bianca promontory to the north and the Port of Livorno to the south (Fig. 1). This sector of coast is developed on coastal plains overlying the Viareggio extensional basin, within which a minor extensional basin, the Magra basin, is located. They run parallel to the Apennines chain (NW-SE) and formed during the extensional regime related to the opening of the Tyrrhenian Sea back-arc basin (Malinverno & Ryan, 1986; Pascucci, 2005; Antonioli *et al.*, 2009). The Magra extensional basin is a graben confined between the Punta Bianca horst to the west and the Apuan Alps to the east. It originally formed during the Pliocene due to high angle normal faults that are visible on the Punta Bianca promontory (Federici & Raggi, 1975; Raggi, 1988; Storti, 1995). The progressive infilling of this graben with alluvial deposits from the Magra River eventually formed the coastal plain that extends up to Marina di Massa (Storti, 1995). The coastal plain developed southwards as the Punta Bianca promontory prevented Magra River's sediments to spread to the north. Presently, the subsidence rate of this area is about 0.9 mm/yr (Chelli *et al.*, 2017). The Viareggio extensional basin is a half-graben active since late Miocene; it is bounded by a listric fault that was active during the mid- and late Pliocene. It is presently centred on the Arno River mouth, and is confined within different geological features such as the Pisan mounts to the NE, the Livornesi mounts to the SE, the Secche della Meloria to the SW; the NW boundary is not clearly defined, as the plain develops up to Marina di Massa (Pascucci, 2005). Two separate coastal plains overlay the Viareggio basin: *i*) to the north the Versilia plain was formed by the alluvial deposits brought by small streams, and *ii*) to the south the large Pisa plain (about 450 km^2), formed by the Arno and Serchio rivers, is now among the major delta systems in the Mediterranean Sea (Rossi *et al.*, 2011). From a stratigraphic standpoint, multiple transgressive-regressive sequences can be identified, whose evidences are constituted by alternations of continental deposits and nearshore deposits related to glacial-interglacial cycles (Amorosi *et al.*, 2013; Sarti *et al.*, 2017). The Pisa plain is characterized by a subsidence rate of about 2-5 mm/yr due to the geological component (Pranzini, 2007), and an additional 1 cm/yr due to the anthropic pressure (Palla, 1978; Pranzini, 2007).

2.2. Sea weather climate

The sea weather climate in this sector of the Ligurian Sea is quite consistent throughout the entire littoral cell: southwesterly winds have the highest frequency in each velocity range, while northwesterly winds are frequent, but subordinate to the former. Major storms also come from the SW, even though high-energy events can also be related to northwesterly winds (Cipriani *et al.*, 2001). The northernmost sector of the littoral cell is an exception to this climate, as it is not exposed to northwesterly winds due to the geographical position. In terms of tidal range, the littoral cell can be defined a microtidal environment as the spring tide is about just 30 cm, which produces a minimum effect on the morphodynamics.

3. Overview of the Northern Tuscany littoral cell

The Northern Tuscany littoral cell (Fig. 1) is defined by two drift convergence areas (Marina di Pietrasanta and, subordinately, Calambrone) and just one main drift divergence area (Arno River mouth). During the last century, the fast growth of this area in terms of urbanization led to profound modifications of the natural morphodynamics configuration, as a response to the increasing human activities. The major variations occurred in the aftermath of the construction of the two large ports at Viareggio and Marina di Carrara, whose offshore jetties disturbed the natural sediment redistribution eventually preventing the sand from feeding the downflow beach (Fig. 1). The port structures acted as a barrier, confining the sediments within a sector of the wider littoral cell. The immediate consequence was an uncontrolled erosion of the downdrift beaches, whereas the updrift side of the jetties was constantly accreting. The reaction of local administrations when they were called upon to deal with the erosion effects were proportionated to the entity of the problem, as retreat rates were different within the littoral cell: the sector centered on Marina di Massa has always faced the most intense setback since the inception of the erosion trend. Protection structures such as seawalls, breakwaters, and groynes were soon built to reduce or mitigate the most serious effects (Pranzini, 2018). The hard approach fixed the coastline locally, often offsetting the erosion processes further downdrift though. Owing to the presence of the large port structures, three subcells can be pointed out within the Northern Tuscany littoral cell, sorted from north to south: i) Riviera Lunense (Magra River mouth – Port of Marina di Carrara); ii) Riviera Apuo-versiliese (Port of Marina di Carrara – Port of Viareggio); iii) Arno River mouth (Port of Viareggio – Port of Livorno). As the aim of this paper is to explain the reasons why four different coastal settings can be identified within the littoral cell, we elected not to follow the subcell subdivision brought by Anfuso *et al.* (2011). In the cited paper, the Authors subdivided the littoral cell in accordance with the natural littoral drift circulation; as we prefer to focus on the influence of the human factor rather than the natural morphodynamics, the actual sand redistribution is strongly driven by the presence of the port jetties, in that creating the three above-mentioned coastal sectors that act as separate, individual entities. The detailed identification of the anthropic interventions that have been realized as protection schemes within the Northern Tuscany littoral cell since the initial erosion processes in the Nineteenth century has been carried out based on satellite image analysis (Google Earth database, online information system of Regione Toscana "Geoscopio" for the historical aerial photographs, historical aerial photographs from the Regione Liguria website), in-depth bibliographic research, and personal interviews with local citizens. The figures are arranged to show the configuration of the protection structures that are currently present along the coast (continuous green lines) and those that have been dismantled but still are possible to get track of (dashed yellow lines). The progressive number each structure is associated refers to Table 1 (available as online supplementary material) showing in detail more information about the type of intervention, the size (where applicable), the construction year, modifications and integrations to the original project, and the source.

3.1. "Riviera Lunense" subcell

The evolution of the northernmost sector of the Northern Tuscany littoral cell is related to the early growth and the late retreat of the Magra River. As it is the only relevant stream flowing within this stretch of coast, the Magra River has been the main source of sediment supply for the beach up to the Marina di Pietrasanta convergence area (Gandolfi & Paganelli, 1975). Since the Roman times the Magra River built up the coastal plain, as nicely pointed out by the development of the ancient harbour of Luni, even though its location is yet to be defined (Raggi & Sansoni, 1993; Bini *et al.*, 2006). The progradation trend went on up to the second half of the Nineteenth century (Pratellesi *et al.*, 2018): as in any other sector of the littoral cell, the erosion processes began hitting the coast mainly due to the decrease in sediment supply. The erosion drive was first felt close to the Magra River mouth, later spreading southwards up to Marina di Carrara (Albani, 1940; Ferri *et al.*, 2008; Piccardi *et al.*, 2018). A huge modification took place within this sector of the cell in the early Twenties of the Nineteenth century, mostly related to the construction of the structures of the Port of Marina di Carrara (Da Pozzo, 1982; Bernieri *et al.*, 1983; Autorità Portuale Marina di Carrara, 2015). Large jetties were built normal to the coastline, which had a major impact on the littoral currents (Cappucci *et al.*, 2011). Soon sand accumulation started to grow on the updrift side of the port, while the downdrift side stopped receiving any sediment input. Only the finest fraction would find a way over the structures (Gandolfi & Paganelli, 1975; Anfuso *et al.*, 2011), but with no chance to feed the beach downflow as that grain-size is hardly depositing onshore due to the high energy of the swash zone. Even though the coarse fraction is blocked by the jetty, the sediments that characterize the grain-size along the downdrift beach are also constituted by coarse sand and gravel (Sarti & Bertoni, 2007): this coarse population was brought there in accordance with the littoral drift before the construction of the port structures and the groynes. A small amount was likely injected during the artificial replenishments that took place in this sector: as a matter of fact, marble is not native along this beach as Magra River does not intercept marble formations along its basin (Gandolfi & Paganelli, 1975). As the erosion processes kept on striking the coast towards the Magra River mouth, local administrations decided to intervene according to the hard approach (*sensu* French, 2001), building a series of groynes, breakwaters, and small circular islands made of boulders and a concrete core (Ferri *et al.*, 2008, Pranzini, 2018). These structures did not solve the original problem but served to fix the coastline to avoid even harsher consequences. Lately, replenishments became an increasingly frequent practice in this sector of the littoral cell, sometimes using non-native sediments, which did not meet appreciation by local citizens. Some has been reported in 2005/2006 and in 2008 (Ferri *et al.*, 2008); minor beach fills have also been carried out locally, in the effort to support individual stakeholders whose beach sector they have in concession was seriously starving (personal communication). As in the Riviera Apuo-versiliese, the beach along the Riviera Lunense is highly anthropized, being characterized by an uninterrupted series of beach resorts. As a lot of protection structures and replenishments have been implemented during the last decades (Fig. 2), nothing of the natural mixed sand and gravel beach has being preserved.

3.2. "Riviera Apuo-versiliese" subcell

The recent evolution of the so-called Riviera Apuo-versiliese is tightly connected to the sediment load history of the two major rivers, Arno and Magra, that feed the beach throughout this sector of the littoral cell. As a matter of fact, the contribution of the other streams, such as Serchio, Frigido and Versilia rivers, is negligible. Though Arno and Magra rivers do not flow within the limits of the Apuo-versiliese subcell, the littoral drifts redistribute the sediments towards this sector, northwards and southwards respectively. The progradation of the Riviera Apuo-versiliese underwent different rates in historical times, but during the last 2500 years the trend has been generally positive (Mazzanti & Pasquinucci, 1983). The southern sector of the subcell (Marina di Pietrasanta – Port of Viareggio) developed in accordance with the general trend, in large part thanks to the littoral drift convergence area, which was first pointed out by Saggini (1967), and later confirmed by many studies (Gandolfi & Paganelli, 1975; Aiello *et al.*, 1975; Fanucci *et al.*, 1976; Pranzini, 2004); conversely, the northern sector (Port of Marina di Carrara – Marina di Pietrasanta) was subjected to intense modification due to anthropic activities. However, unlike the Arno River mouth area, this stretch of coast has been negatively affected by human pressure not just indirectly (river sediment bedload decrease), but also through a direct impact on the territory. Two large harbours have been built in the first half of the Twentieth century at Viareggio and Marina di Carrara (Fig. 1). The offshore structures, such as jetties and piers, interrupted the natural distribution of the sediments according to the littoral drifts, causing the onset of serious screening effects: updrift accumulation and downdrift erosion (Cipriani *et al.*, 2001; Anfuso *et al.*, 2011). The end results at the two sites have been quite different though.

3.2.1. *Northern Sector, Port of Marina di Carrara - Marina di Pietrasanta*

The northern sector of the Riviera Apuo-versiliese subcell has been fed by the Magra River, as other minor streams and ditches do not contribute to the sediment budget (Fig. 1). It basically extends for about 17 km from the convergence point (Marina di Pietrasanta) to the Port of Marina di Carrara. The natural configuration and evolution of this stretch of coast were drastically modified after the construction of the harbour at Marina di Carrara. The northern jetty prevented any sediment exchange with the southern sector (Cappucci *et al.*, 2011), which eventually led to the complete loss of the beach in the downdrift area (Anfuso *et al.*, 2011). However, early erosion processes (late Nineteenth century) struck the northernmost area close to the River Magra mouth due to its incipient decrease in sediment discharge to the sea (Pratellesi *et al.*, 2018). In this sense, the harbour emphasized an ongoing retreating trend, spreading the erosive drive further to the south (Albani, 1940). As a matter of fact, soon after the acute episodes at Marina di Carrara, another downdrift village, Marina di Massa, was rapidly struck (Cortemiglia, 1977; Aminti *et al.*, 2002): as erosion went on, the littoral avenue connecting the two settlements was dismissed and never fixed again (Pranzini, 2018). Several defence structures were built in the subsequent years (mainly breakwaters and groynes), resulting in a hard stabilization of coastline retreat (Aminti *et al.*, 1999; Mancinelli *et al.*, 2005); the drawback was the further spread of the erosive processes southwards. As a matter of fact, in the period between 1999-2002 local administrations at Marina di Ronchi elected to test innovative submerged groynes made of geotextile sandbags in an effort to reduce the construction of emerged, invasive structures (Aminti *et al.*, 2004; Pranzini, 2018), often coupled to localized replenishments (Sarti & Bertoni, 2007). Unfortunately the sandbag experiment did not pan out as the ultimate solution, as they were displaced by the wave motion faster than expected. In subsequent years, a new set of submerged groynes were built at Marina di Ronchi, but they were later replaced by traditional emerged groynes (Pranzini, 2018). Again, this protection system fixed the coastline in the small sectors within the structures, inevitably offsetting the erosion trend further southwards. Aside from the hard approach schemes, at Marina di Carrara a sediment bypass was active towards the end of the Sixties of the Twentieth century through a water pump (Berriolo & Sirito, 1972), but it did work just for a few years due to administrative issues (Pranzini, 2018); according to Autorità Portuale Regionale Porto di Viareggio (2015), the reasons it was dismissed were related to a ship colliding into it during an intense storm. Spot replenishments were also set up during the last two decades,

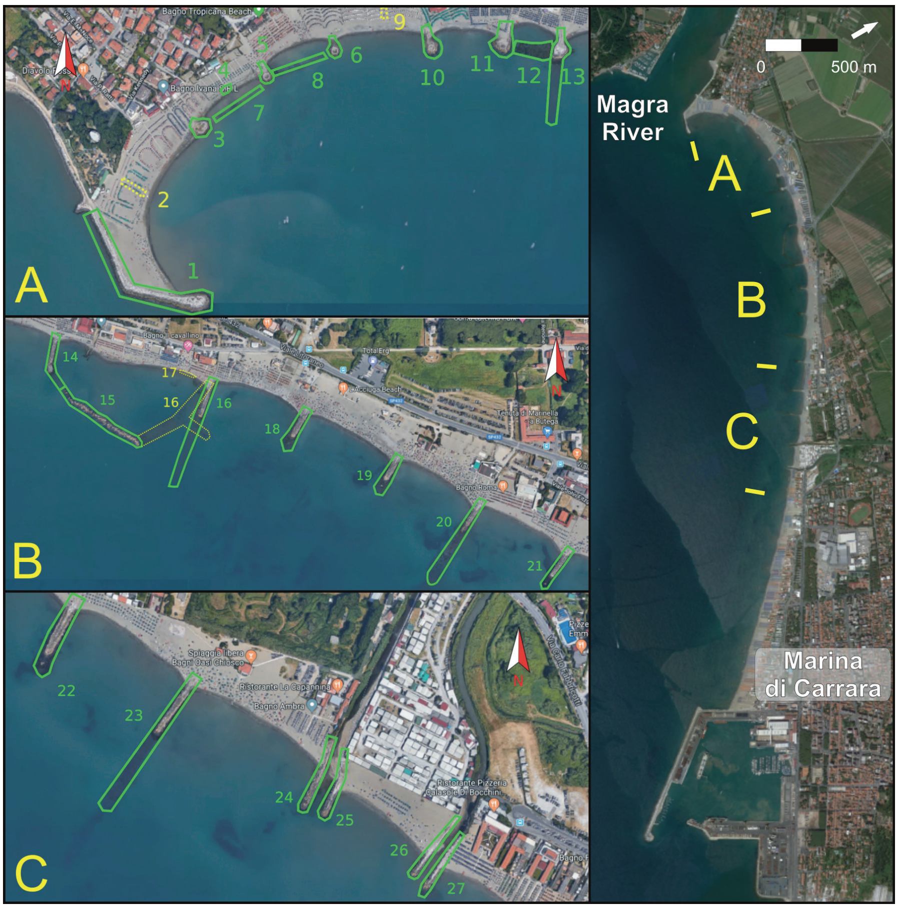

Fig. 2 - Location of the protection structures along the northern subcell (Riviera Lunense) of the Northern Tuscany littoral cell (background maps from GoogleEarth database). Refer to the online table for further information about each structure.

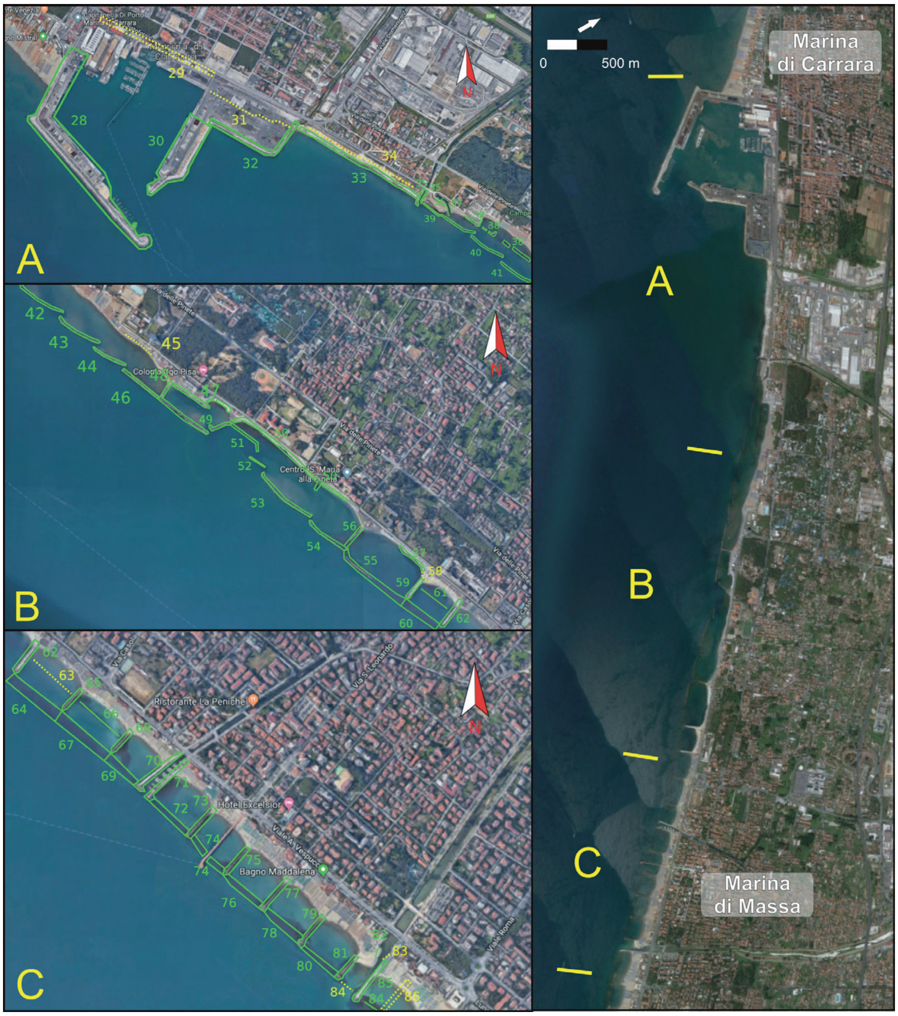

Fig. 3 - Location of the protection structures along the northern sector of the Riviera Apuo-versiliese subcell, Port of Marina di Carrara – Marina di Pietrasanta (background maps from GoogleEarth database). Refer to the online table for further information about each structure.

using both sand and gravel (Aminti *et al.*, 2002; Sarti & Bertoni, 2007; Nordstrom *et al.*, 2008; Anfuso *et al.*, 2011). By now this sector shows the highest variability in terms of coastal environments: the tourism-wise anthropized sandy beach defines the southern sector up to Forte dei Marmi, where a single, 500 m long area is charachterized by natural coastal dunes. As short as it may be, this 500 m sector is the only sort of preserved site along the 30 km long tract between the Magra River mouth and Viareggio. The situation radically changes north of Forte dei Marmi (Figs. 3, 4): the sandy beach still is anthropized due to the well-established presence of beach resorts, but dozens of protection structures punctuate the coast from here up to Marina di Carrara. Further to the north, coarser sediments tend to characterize the beach, which gradually becomes a mixed sand and gravel beach, although the proliferation of defense structures such as breakwaters, groynes, and seawalls thwarted any chance of preservation of the old natural beach.

3.2.2. *Southern Sector, Marina di Pietrasanta - Port of Viareggio*

The Versilia coast still benefits from the erosion of the right side of the Arno River delta (Cipriani *et al.*, 2001). Huge volumes of sediments get past the Serchio River mouth and reach the beach of Viareggio, eventually accumulating in the convergence area (Pranzini, 2004), which is located nearby Marina di Pietrasanta, about 8 km to the north of the Port of Viareggio (Fig. 1). The construction of the afore-mentioned harbour acted as a screen (Gandolfi & Paganelli, 1975), but the orientation of the southern jetty still allowed the finer sand to overpass the offshore structures (Anfuso *et al.*, 2011): as a matter of fact, silting up issues are reported at the port entrance, which requires recurring dredging operations since the middle of the Twentieth century (Milano, 1986; Autorità Portuale Regionale Porto di Viareggio, 2014; Pranzini, 2018). The downdrift sectors did experience serious erosion processes (Pellegrinetti, 1925; Cipriani *et al.*, 2001), but not as harsh

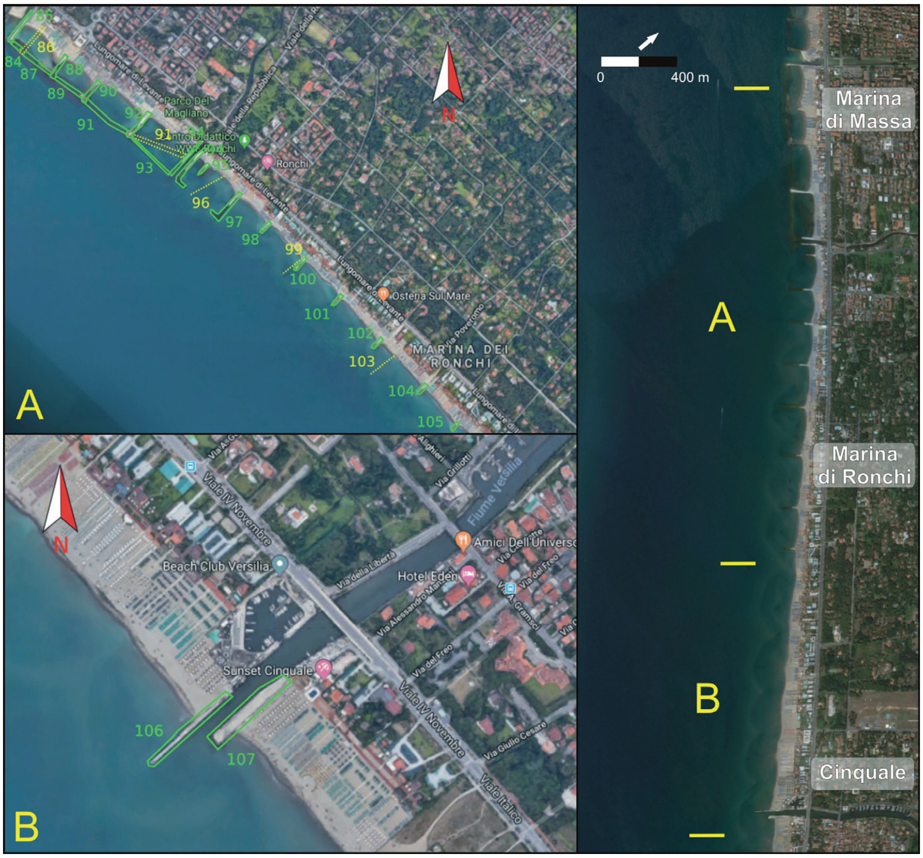

Fig. 4 - Location of the protection structures along the southern sector of the Riviera Apuo-versiliese subcell, Marina di Pietrasanta – Port of Viareggio (background maps from GoogleEarth database). Refer to the online table for further information about each structure.

as in Marina di Carrara or at the Arno River mouth. The by-passing practice has also been frequently used here (Milano, 1986; Autorità Portuale Regionale Porto di Viareggio, 2015), which can be responsible of the moderate beach retreat relative to that of other sectors of the littoral cell: beach width in the downdrift side is hardly less than 100 m. The sediments coming from the Arno River and coastal dune erosion at the Tenuta di San Rossore are distributed northwards up to the Marina di Pietrasanta convergence point, which acts as a sort of barrier for the southern drift (Aiello *et al.*, 1975; Gandolfi & Paganelli, 1975; Pranzini, 2004). Presently, the beach between Viareggio and Marina di Pietrasanta is highly anthropized, even though there are no protection structures. The coast is characterized by a continuous sequence of beach resorts that clearly epitomizes the tourism vocation of this sector of the Northern Tuscany littoral cell.

3.3. "Arno River mouth" subcell

First historical data about the Arno River mouth date back to the Roman times: according to Strabone, the Arno River flowed along three different channels (Sarti *et al.*, 2010). In Medieval times the Portolan charts provided representations of the Mediterranean Sea coastlines; as the accuracy level is low, the reliability of the Arno River mouth location is weak as well (Piccardi & Pranzini, 2014). The first map showing a reliable positioning of the Arno River mouth and meanders was realized by Leonardo da Vinci in 1503 (after da Vinci's Codice Madrid): an emerging mouth bar was evidence of significant sediment bed load. The map already showed signs of a wider development of the right side of the delta. However, the coastline prograded quite rapidly in the area nearby the Arno River mouth as a response of a huge intervention at the beginning of the Seventeenth century (Sarti *et al.*, 2010), which consisted in cutting the last tract of the river to offset its mouth to the northwest. As a matter of fact, in 1606 the mouth was moved 1547 m northwards under the guidance of Grand Duke Ferdinando (Borghi, 1970; Piccardi & Pranzini, 2014). This action was deemed necessary to avoid the concurrence of river overflows and southwesterly sea storms, which usually determined serious inland floods. No more deposited on the Pisa plain, river sediment load increasingly reached the sea building a huge delta cusp at the river mouth, while contributing to continuous beach feeding along the entire coast. The increase in coastline progradation is pointed out by a sharp transition between straight beach ridges, which indicates a normal sediment supply, and curved beach ridges, which implies a stronger sediment supply (Pranzini, 2001; Pranzini, 2007). Eventually, the fast progradation rates tend to decrease in the late Eighteenth century (Piccardi & Pranzini, 2014); in the period within 1850-1870 this area began undergoing harsh erosive processes that determined a constant retreat of the coastline, which is highlighted by the erosion of the large, emerged mouth bar (Toniolo, 1910; Borghi, 1970). The absence of the emerged mouth bar is related to the decrease of sediment bed load that apparently began in that period. Several factors were responsible for the erosion trend, mainly connected to human activities: river bed dredging, mountain reforestation, widespread river bed armouring, river damming, all combined to cause the drastic decrease of the Arno River sediment load, which eventually led to a deficit in the sediment budget (Pranzini, 2001). Human response to coastline retreat was different on either side of the mouth, based on the presence of a settlement founded on the left side of the Arno River delta around 1872, that needed protection against sea ingression: Marina di Pisa (Fig. 1). Conversely, the right side did not need any defence scheme as there were no major anthropic structures to be preserved. The different evolution determined the asymmetric development of the Arno River delta.

3.3.1. *Right Side, Port of Viareggio - Arno River mouth*

The right side of the Arno River mouth is defined by the Tenuta di San Rossore, which is a protected natural area within the broader Migliarino – San Rossore – Massaciuccoli Regional Park (Fig. 1). The stretch of coast has been fed by the Arno River's sediments and is about 20 km long, from the Arno River mouth to the Port of Viareggio (Fig. 1). The area is characterized by a wide dune field which extends landward for about 6 km. The dune field is formed by a series of dune ridges that get older in age in the landward direction (Pranzini, 2001; Bertoni & Sarti, 2011a). Presently, the ridges are no more easily recognizable due to dense, wooded vegetation that covered the original morphology (pines and holm oak in particular). The inactive dunes, called steady dunes, change smoothly into semi-mobile dunes within about 300 m from the coastline (Bertoni & Sarti, 2011a). These dunes can be at times subjected to erosion and accretion processes, and are characterized by shrubbery. Seaward, there are the so-called frontal dunes, which represent the active portion of the dune field and are covered with the typical psammophile vegetation (Bertoni *et al.*, 2014b; Ruocco *et al.*, 2014; Bertacchi *et al.*, 2016; Ciccarelli *et al.*, 2017). Unfortunately, the frontal dunes are struck by intense erosion processes (Alquini *et al.*, 2016), which confirm the huge coastline retreat and dune loss that has been reported in literature since the early Twentieth century (Toniolo, 1910; Borghi, 1970; Rapetti & Vittorini, 1974; Palla, 1983). Likewise for the left side, the recent evolution of this area is connected to that of the Arno River delta (Pranzini, 2001; Bini *et al.*, 2008). The factors that have primed the erosive processes are the same, the only difference being how local authorities responded to counteract the effects. As it is a natural reserved area, no protection structures were built at first. As a consequence, in about a century the right side of the delta experienced a retreat of more than 1 km, whereas the left side lost approximately 300 m (Noli, 1982; Pranzini, 2001). First defence schemes were set up in the mid-Sixties in the effort to prevent further retreats: ten groynes were built close to the Arno River mouth, whereas small gravel replenishments were carried out to partially fill the cells identified by the groynes (Nordstrom *et al.*, 2008; Pranzini, 2008). Five detached breakwaters were placed further to the north, close to the locality named Gombo (Rapetti & Vittorini, 1974). This intervention produced temporary gains as sediment loss was slowed down and, in particular at Gombo, the detached breakwaters generated sand accumulation on their back such as a tombolo (Rapetti & Vittorini, 1974; Bowman & Pranzini, 2003). The recent evolution showed a reverse response that led to the erosion of the northern tombolo, minimizing the positive effects of the structures and determining further erosion on the downdrift sector of the beach (Bowman & Pranzini, 2003; Ciampalini *et al.*, 2015). Meanwhile, the mouth of the Morto Nuovo River, a small artificial distributary channel of the Arno River, was protected from silting up by means of two concrete jetties of about 200 m length (Fig. 1). A different protection scheme was applied in 2009: geotubes were connected to the fourth breakwater, and a small replenishment filled the space within the geotubes. Two additional geotube groynes were built about 150 and 400 m northwards of the fourth breakwater (Cipriani *et al.*, 2010; Casarosa, 2016). Along with the geotubes, a dune reconstruction attempt was realized in a 100 m long sector within the area between the fourth breakwater and the first geotube groyne (Casarosa, 2016). At present, the sand removed from the southern sector of this area is transported northwards according to the littoral drift up to the southern jetty built at the Morto Nuovo River mouth. The jetty determines an updrift deposition of sediments, resulting in a slight increase in beach width; however, it also exerts a downdrift screening effect that produces significant sediment loss (Bini *et al.*, 2008). In turn, the sediments entrained in this area end up feeding the downdrift sectors of the cell, as it was in the past: the coastline north of the Morto Nuovo and the Serchio rivers always showed accretion (Bini *et al.*, 2008; Piccardi & Pranzini, 2016). Aside from the protection structures

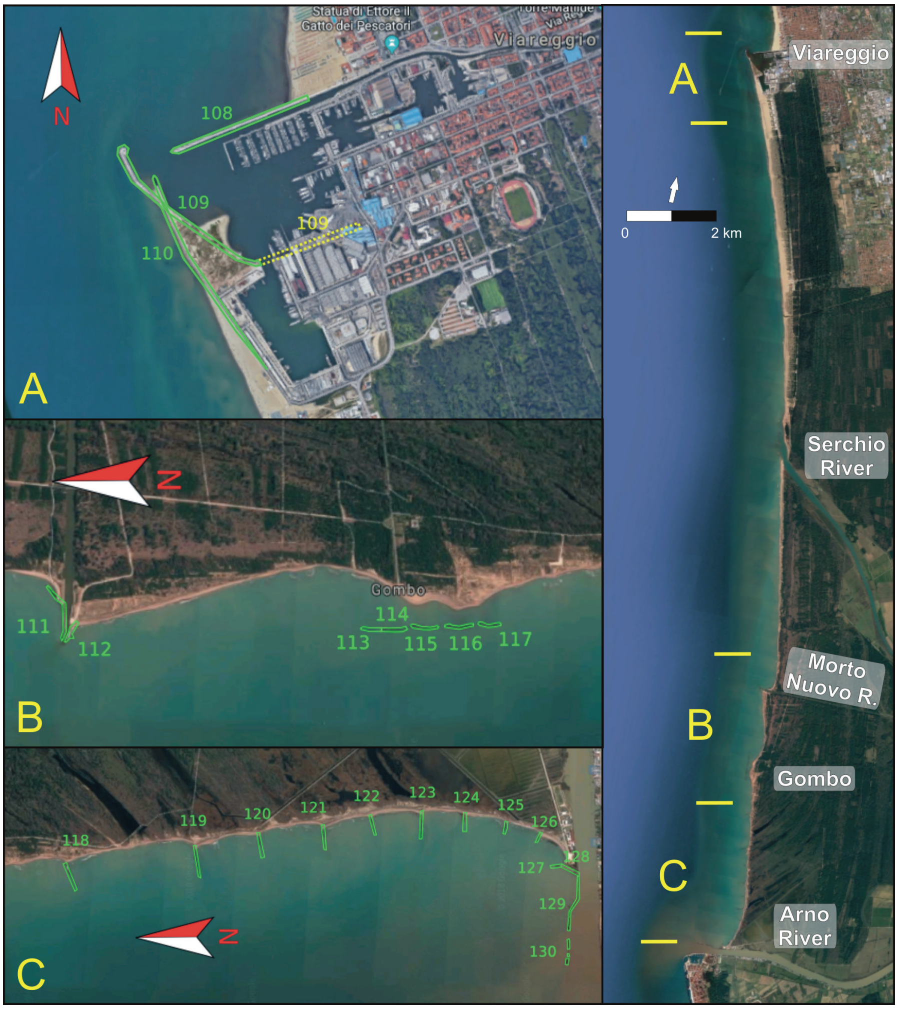

Fig. 5 - Location of the protection structures along the northern sector of the Arno River mouth subcell, Port of Viareggio – Arno River mouth (background maps from GoogleEarth database). Refer to the online table for further information about each structure.

built in the southernmost sector of the subcell, a long, natural sandy beach currently characterizes the whole stretch of coast between the Port of Viareggio and the Arno River mouth (Fig. 5). Just north of the Serchio River mouth there are a few beach resorts, but they do not overly affect the evolution of the beach. The beach gets more anthropized towards the northernmost sector, close to the Port of Viareggio: here, the beach resorts were constructed on the coastal dunes, eventually obliterating the natural environment. Owing to its accretive evolutionary state, human pressure never affected this sector of the littoral cell.

3.3.2. *Left Side, Arno River mouth - Port of Livorno*

The left side of the Arno River mouth extends for about 11 km up to the Port of Livorno (Fig. 1): this stretch of coast is naturally fed by sediments coming from the Arno River, except for a small sector in the southernmost area, which shows a different mineralogical composition (Gandolfi & Paganelli, 1975). As a matter of fact, a convergence of littoral drifts has been identified in the area of Calambrone (Aiello *et al.*, 1975; Ciampalini *et al.*, 2015). The historical evolution of this sector of the littoral cell is akin to that of the Arno River mouth, being characterized by a progradation of the coastline up to the mid-Nineteenth century (Pranzini, 2001; Piccardi & Pranzini, 2014). The erosion was particularly intense close to the mouth, where the sandy beaches were completely wiped out; conversely, the southern sector experienced accretion or equilibrium, thanks to the sediments upcoming from the erosion of the updrift beach (Bini *et al.*, 2008; Casarosa, 2016). Based on the erosion processes that eventually put in jeopardize the existence of Marina di Pisa, the small village located on the left side of the Arno River delta about 11 km south-west of Pisa (Fig. 1), local authorities were forced to start protecting the area because the settlement was threatened by the erosion effects (Aminti *et al.*, 2000). Since the early Twentieth century sea walls, detached breakwaters and groynes were

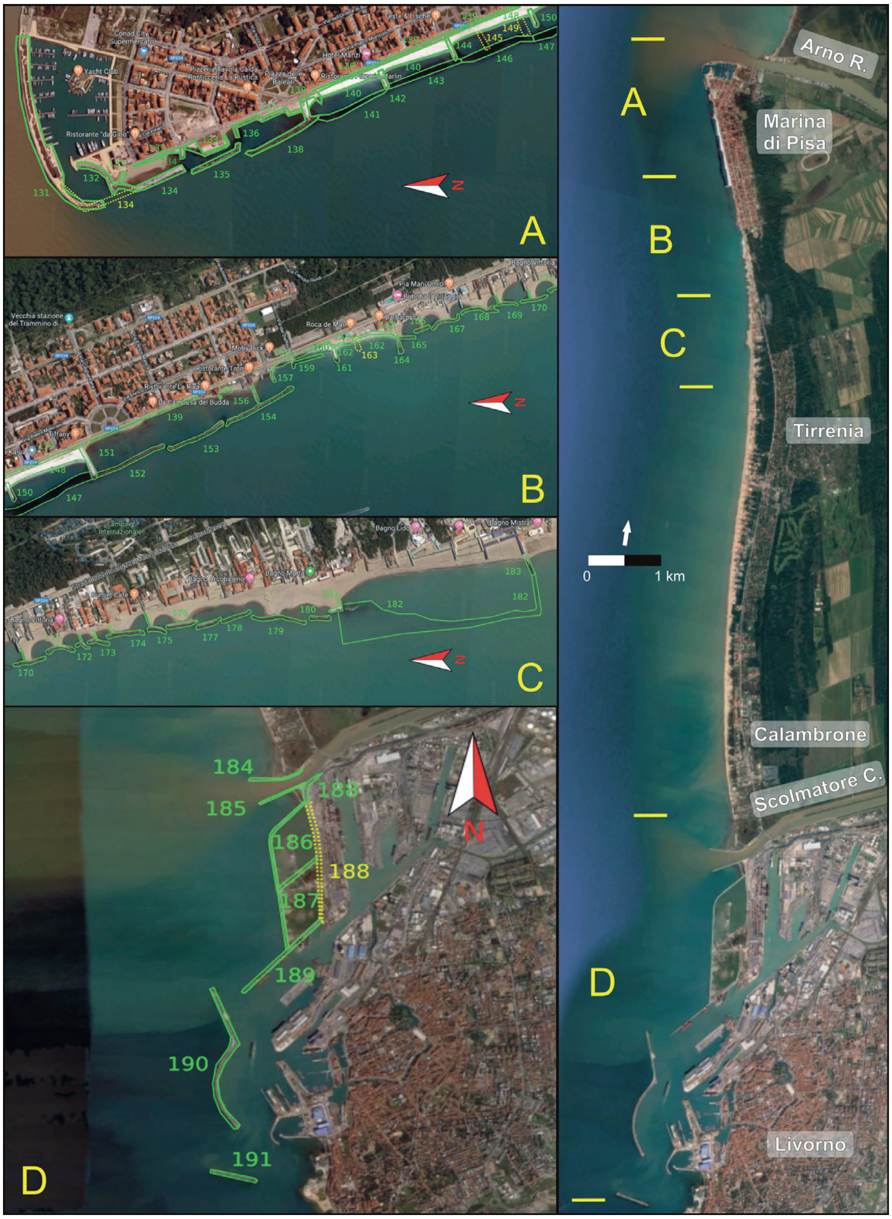

Fig. 6 - Location of the protection structures along the southern sector of the Arno River mouth subcell, Arno River mouth – Port of Livorno (background maps from GoogleEarth database). Refer to the online table for further information about each structure.

built to defend the promenade and the buildings (Bini *et al*., 2008). As a consequence, about ten cells were created to fix the coastline in a stable position, but wave reflection caused by the breakwaters determined a steady deepening of the sea floor fronting the structures. In the early 2000, a gravel replenishment was set up and achieved (Aminti & Pranzini, 2000; Cammelli *et al*., 2006), but very strong storms, virtually unaffected by the breakwaters, hit the beach with as much energy to toss coarse sediments onto the littoral promenade (Bertoni *et al*., 2012b). Those sensational events compelled local authorities to look for alternatives. As coarse-clastic replenishments seemed to fit in the Marina di Pisa coastal area, the idea to replace sand with coarser sediments was not abandoned. Rather, a huge replenishment was carried out in 2006, unloading impressive volumes of marble pebbles (40-to-70 mm diameter) on three different sectors of the coast in order to create three coarse beaches about 30 m wide (Nordstrom *et al*., 2008; Bertoni & Sarti, 2011b). Two beaches are bound at both edges by large boulder groynes, while the emerged breakwater was converted into a submerged breakwater 60 m offshore (Cappietti, 2011); the third beach is akin to the former, but there is no offshore breakwater. Few years later, two other cells were converted to pebble beaches identical to those built in 2006. As a matter of fact, in terms of stability and duration, this kind of intervention proved to guarantee a satisfactory reliability, provided that an artificial flattening of the storm berm prior to the summer would be operated (Bertoni & Sarti, 2011b; Ellis & Cappietti, 2013). Only concerns raised on regard to the mass loss of the coarse sediments used as beach fill (Bertoni *et al.*, 2012a): the abrasion rate measured on marked pebbles resulted in more than 50% of mass loss in a 13-months timespan (Bertoni *et al.*, 2016), which likely is the main responsible of the volume loss on the artificial beaches. In 2017-2018 two large jetties have been erected by Regione Toscana at the mouth of the Scolmatore Canal (Boninsegni & Mori, 2014), an artificial channel built in the second half of the Twentieth century to reduce the flow of the Arno River (Fig. 1). The structures prevent the mouth to silting up, but it likely induces diffraction of littoral currents. The huge intervention also involved dredging of the fronting offshore bars and the ensuing replenishment of the beach at Calambrone. In addition, a sector of about 250 m, formerly characterized by natural coastal dunes, has been restored by the artificial implantation of autochtonous vegetation species. Presently, the coast comprised between the Arno River mouth and the Port of Livorno is constituted by a long stretch of sandy beach, for the most part largely anthropized (Fig. 6): the southern sector does not present many structures, coastal dunes are occasionally preserved. To the north the human pressure is far more intense: the beach tends to narrow and eventually disappears even though protected by groynes and breakwaters. At Marina di Pisa the sandy beach environment is replaced by the artificial coarse-clastic beaches constituted by marble pebbles, which are the utter expression of the anthropic influence along this sector of the littoral cell.

4. Concluding remarks

The historical evolution of the Northern Tuscany littoral cell taught that human pressure is the main factor driving the development of coastal areas. The variety of coastal environments along this sector is peculiar, and it would not be such without the intense anthropic activities of the last couple of centuries. Fixed coastlines, replenishments with allochthonous sediments, artificial coarse-clastic beaches contributed to vastly modify the landscape to the point that natural preserved sectors are confined in just a few sites. The example from the Northern Tuscany littoral cell is blatant: stretches of fully-anthropized, artificial coarse-clastic beaches can be pointed out between the Magra River mouth and the Port of Livorno, as the natural sandy beach is basically confined within the boundaries of a reserved area belonging to the Migliarino – San Rossore – Massaciuccoli Regional Park. Several defence schemes applied over time were crucial to protect the countless activities that are so deeply-rooted in the territory, which are the main driver for the economy of the communities, in that in dire need of protection. Some that did not meet the expectations were state-of-the-art at the time of the construction. However, the approach to the problem has to drastically change: this is the focal aim of the Team COSTE, a research equipe grouping departments from all three Tuscany universities, Pisa, Siena and Firenze, whose first scientific products preached a strong multidisciplinary attitude to research (Bertoni *et al.*, 2014a; Pozzebon *et al.*, 2018a; Pozzebon *et al.*, 2018b). In particular, the coastal environment must be considered not just a narrow stretch at the interface between continental and marine environments. Rather, each factor has to be taken into account, from the processes acting on the catchment basin of the rivers to those that influence the offshore sectors of the submerged beach (Bartolini *et al.*, 2018). Along the coast, the natural redistribution of sediments according to the littoral drift proved that spot beach fills need integrations and repetitions through time, and are popularly perceived as ephemeral solutions. A proper management of the sediments along the coastline may be a fittier approach, taking into close consideration practices such as sediment by-passing and backpassing (Anfuso *et al.*, 2011; Bartolini *et al.*, 2018; Pozzebon *et al.*, 2018a; Pozzebon *et al.*, 2018b). Coordinated actions that routinely put into effect these concepts would likely imply a better management of the littoral cell, and it would also be a useful example for other Italian and foreign sites.

Acknowledgements

We are sincerely thankful to the Regione Toscana for sharing the historical documentations about the interventions made over time along the investigated sector of the Tuscany coast. We are also in debt with friends and private citizens willing to share with us their collective knowledge and memories about the place they learned to love during their lives. Two anonymous reviewers helped improve the first version of the manuscript thanks to their useful insights and suggestions.

REFERENCES

Aiello E., Bartolini C., Caputo C., D'Alessandro L., Fanucci F., Fierro G., Gnaccolini M., La Monica G.B., Lupia Palmieri E., Piccazzo M., Pranzini E., 1975. Il trasporto litoraneo lungo la costa toscana tra la foce del fiume Magra ed i Monti dell'Uccellina. *Bollettino della Società Geologica Italiana* 94: 1519-1571.

Albani D., 1940. Le spiagge della Toscana settentrionale dalla foce del fiume Magra ai Monti Livornesi. In: Ricerche sulle variazioni delle spiagge italiane. II - Le spiagge toscane, CNR, Roma, 11-86.

ALQUINI F., BERTONI D., SARTI G., 2016. Extreme erosion of a dune crest within a short timespan (January-September 2016): The recent case in the Migliarino - San Rossore - Massaciuccoli Regional Park (Tuscany, Italy). *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 123: 5-16.

AMINTI P., CAMMELLI C., CAPPIETTI L., JACKSON N.L., NORDSTROM K.F., PRANZINI E., 2004. Evaluation of beach response to submerged groin construction at Marina di Ronchi, Italy, using field data and a numerical simulation model. *Journal of Coastal Research* SI33: 99-120.

AMINTI P., CIPRIANI L.E., PRANZINI E., 2000. «Back to the beach»: converting seawalls into gravel beaches. Proceedings of the First International Soft Shore Protection Conference, Patras, Greece, 187-196.

AMINTI P., IANNOTTA P., PRANZINI E., 1999. Morfodinamica di un sistema costiero intensamente protetto: il litorale di Marina di Massa. *Atti dei Convegni Lincei - Accademia Nazionale dei Lincei,* 154: 263-270.

AMINTI P., PELLICCIA F., PRANZINI E., 2002. Evoluzione del profilo di spiaggia a seguito di un ripascimento artificiale in ghiaia su di una spiaggia altamente protetta. *Studi Costieri* 5: 47-57.

AMINTI P.L., PRANZINI E., 2000. Indagine sperimentale per la ristrutturazione delle difese di Marina di Pisa. *Studi Costieri* 3: 57-70.

AMOROSI A., BINI M., GIACOMELLI S., PAPPALARDO M., RIBECAI C., ROSSI V., SAMMARTINO I., SARTI G., 2013. Middle to late Holocene environmental evolution of the Pisa coastal plain (Tuscany, Italy) and early human settlements. *Quaternary International* 303: 93-106.

ANFUSO G., PRANZINI E., VITALE G., 2011. An integrated approach to coastal erosion problems in northern Tuscany (Italy): Littoral morphological evolution and cell distribution. *Geomorphology* 129: 204-214.

ANTONIOLI F., FERRANTI L., FONTANA A., AMOROSI A., BONDESAN A., BRAITENBERG C., DUTTON A., FONTOLAN G., FURLANI S., LAMBECK K., MASTRONUZZI G., MONACO C., SPADA G., STOCCHI P., 2009. Holocene relative sea-level changes and vertical movements along the Italian and Istrian coastlines. *Quaternary International* 206(1-2): 102-133.

AUTORITÀ PORTUALE MARINA DI CARRARA, 2015. Piano regolatore portuale di Marina di Carrara. Relazione generale, 108 pp.

AUTORITÀ PORTUALE REGIONALE PORTO DI VIAREGGIO, 2014. Proposta progettuale per la gestione ed il dragaggio dei fondali del Porto di Viareggio. Studio di fattibilità, Regione Toscana, 106 pp.

AUTORITÀ PORTUALE REGIONALE PORTO DI VIAREGGIO, 2015. Realizzazione di un sistema continuo di dragaggio e trasferimento di sedimenti. Progetto preliminare, Regione Toscana, 38 pp.

BARTOLINI S., MECOCCI A., POZZEBON A., ZOPPETTI C., BERTONI D., SARTI G., CAITI A., COSTANZI R., CATANI F., CIAMPALINI A., MORETTI S., 2018. Augmented virtuality for coastal management: a holistic use of in situ and remote sensing for large scale definition of coastal dynamics. *ISPRS International Journal of Geo-Information* 7: 92.

BERNIERI A., MANNONI L., MANNONI T., 1983. Il porto di Carrara. Storia e attualità. SAGEP Editrice, Genova (Italia), 240 pp.

BERRIOLO G., SIRITO G., 1972. Spiagge e porti turistici. U. Hoepli editore, Milano (Italia), 428 pp.

BERTACCHI A., ZUFFI M.A.L., LOMBARDI T., 2016. Foredune psammophilous communities and coastal erosion in a stretch of the Ligurian sea (Tuscany, Italy). *Rendiconti Lincei* 27: 639-651.

BERTONI D., ALQUINI F., BINI M., CICCARELLI D., GIACCARI R., POZEBON A., RIBOLINI A., SARTI G., 2014a. A technical solution to assess multiple data collection on beach dunes. *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 121: 5-12.

BERTONI D., BIAGIONI C., SARTI G., CICCARELLI D., RUOCCO M., 2014b. The role of sediment grain-size, mineralogy, and beach morphology on plant communities of two Mediterranean coastal dune systems. *Italian Journal of Geosciences* 133: 271-281.

BERTONI D., SARTI G., 2011a. Grain size characterization of modern and ancient dunes within a dune field along the Pisan coast (Tuscany, Italy). *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 116: 11-16.

BERTONI D., SARTI G., 2011b. On the profile evolution of three artificial pebble beaches at Marina di Pisa, Italy. *Geomorphology* 130: 244-254.

BERTONI D., SARTI G., BENELLI G., POZZEBON A., 2012a. In situ abrasion of marked pebbles on two coarse-clastic beaches (Marina di Pisa, Italy). *Italian Journal of Geosciences* 131: 205-214.

BERTONI D., SARTI G., BENELLI G., POZZEBON A., RAGUSEO G., 2012b. Transport trajectories of "smart" pebbles on an artificial coarse-grained beach at Marina di Pisa (Italy): Implications for beach morphodynamics. *Marine Geology* 291-294: 227-235.

BERTONI D., SARTI G., GROTTOLI E., CIAVOLA P., POZZEBON A., DOMOKOS G., NOVÁK-SZABÓ T., 2016. Impressive abrasion rates of marked pebbles on a coarse-clastic beach within a 13-month timespan. *Marine Geology* 381: 175-180.

BINI M., CASAROSA N., RIBOLINI A., 2008. Multitemporal (1938-2004) evolution of the Pisan shoreline based on the comparison of georeferenced aerial images. *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 113: 1-12.

BINI M., CHELLI A., PAPPALARDO M., 2006. Geomorfologia del territorio dell'Antica Luni (La Spezia) per la ricostruzione del paesaggio costiero in età romana. *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 111: 57-66.

BONINSEGNI G., MORI E., 2014. Adeguamento idraulico del Canale Scolmatore d'Arno Lotto 1 – Opere a mare. Capitolato speciale d'appalto, Provincia di Pisa, 120 pp.

BORGHI L., 1970. Apporto allo studio sulle cause di variazione del litorale pisano. Rassegna Periodico culturale e di informazioni, estratto nn. 1-2, 11-12, anno sesto, Comune di Pisa.

BOWMAN D., PRANZINI E., 2003. Reversed responses within a segmented detached breakwater, the Tuscany coast Italy-a case study. *Coastal Engineering* 49: 263-274.

CAMMELLI C., JACKSON N.L., NORDSTROM K.F., PRANZINI E., 2006. Assessment of a gravel nourishment project frontin a seawall at Marina di Pisa, Italy. *Journal of Coastal Research* SI39: 770-775.

CAPPIETTI L., 2011. Converting emergent breakwaters into submerged breakwaters. *Journal of Coastal Research* SI64: 479-483.

CAPPUCCI S., SCARCELLA D., ROSSI L., TARAMELLI A., 2011. Integrated coastal zone management at Marina di Carrara Harbor: sediment management and policy making. *Ocean & Coastal Management* 54: 277-289.

CASAROSA N., 2016. Studio dell'evoluzione del litorale pisano tramite rilievi con GPS differenziale (2008-2014). Monitoraggio dell'evoluzione della linea di riva del litorale pisano. *Studi Costieri* 23: 3-20.

Cavazza S., 1984. Regionalizzazione geomorfologica del trasporto solido in sospensione dei corsi d'acqua tra il Magra e l'Ombrone. *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 91: 119-132.

Chelli A., Pappalardo M., Bini M., Brückner H., Neri G., Neri M., Spada G., 2017. Assessing tectonic subsidence from estimates of Holocene relative sea-level change: An example from the NW Mediterranean (Magra Plain, Italy). *The Holocene* 27(12): 1988-1999.

Ciampalini A., Consoloni I., Salvatici T., Di Traglia F., Fidolini F., Sarti G., Moretti S., 2015. Characterization of coastal environment by means of hyper-and multispectral techniques. *Applied Geography* 57: 120-132.

Ciccarelli D., Pinna M.S., Alquini F., Cogoni D., Ruocco M., Bacchetta G., Sarti G., Fenu G., 2017. Development of a coastal dune vulnerability index for Mediterranean ecosystems: A useful tool for coastal managers? *Estuarine, Coastal and Shelf Science* 187: 84-95.

Cipriani L.E., Ferri S., Iannotta P., Paolieri F., Pranzini E., 2001. Morfologia e dinamica dei sedimenti del litorale della Toscana settentrionale. *Studi Costieri* 4: 119-156.

Cipriani L.E., Perfetti A., Pranzini E., Vitale G., 2010. Azioni di tutela delle dune costiere del Parco Regionale Migliarino San Rossore Massaciuccoli (Toscana settentrionale). *Studi costieri* 17: 165-179.

Cortemiglia G.C., 1977. Caratteri generali della situazione evolutiva del litorale di Marina di Massa in riferimento ad eventuali provvedimenti ed interventi di salvaguardia e di stabilizzazione. Proceedings of the Conference Riequilibrio della costa fra il fiume Magra e Marina di Massa, 21-29.

Da Pozzo C., 1982. Il porto di Marina di Carrara: geografia di un porto minore. Felici Editore, Pisa (Italia).

Ellis J.T., Cappietti L., 2013. Storm-driven hydrodynamic and sedimentological impacts to an engineered coast. *Journal of Coastal Research* SI65: 1461-1466.

Fanucci F., Fierro G., Piccazzo M., 1976. Caratteri geomorfologici e sedimentologici del litorale. In: Programma Speciale per la Conservazione del Suolo – Ricerche sul Regime e la Conservazione dei Litorali, Rapporto 1976. *Quaderni de La Ricerca Scientifica* 92: 80-88.

Federici P.R., Raggi G., 1975. Una nuova interpretazione della tettonica dei monti della Spezia. *Bollettino della Società Geologica Italiana* 94: 945-960.

Ferri S., Pelliccia F., Pranzini E., Rizzo M., Vitale G., 2008. Prima risposta della spiaggia di Marina di Carrara ad un ripascimento artificiale non protetto. *Studi Costieri* 15: 57-72.

French P.W., 2001. Coastal defences. Processes, problems and solutions. Routledge, London (UK). 366 pp.

Gandolfi G., Paganelli L., 1975. Il litorale pisano-versiliese (Area campione Alto Tirreno). Composizione, provenienza e dispersione delle sabbie. *Bollettino della Società Geologica Italiana* 94: 1273-1295.

Leonardo da Vinci. Codice Madrid, Biblioteca Nacional, ms. 8937 (II), cc. 52v-53r.

Malinverno A., Ryan W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. *Tectonics* 5: 227-245.

Mancinelli A., Aminti P., Archetti R., Atzeni A., Canu V., Cappietti L., Lorenzoni C., Zanuttigh B., 2005. Opere di difesa realizzate con strutture sommerse ed a cresta bassa ad Alghero (SS), Perd'e Sali (CA), Marina di Massa (MS), Marina di Pisa (PI), Porto Recanati (MC), Marina di Montemarciano (AN), Lido di Dante (RA) e Pallestrina (VE). *Studi Costieri* 9: 7-50.

Mazzanti R., Pasquinucci M., 1983. L'evoluzione del litorale Lunense-Pisano alla metà del XIX secolo. *Bollettino della Società Geografica Italiana* 12: 605-628.

Milano V., 1986. Studio sull'accessibilità del porto di Viareggio e sull'equilibrio della spiaggia a Nord. Atti del Convegno di Idraulica e Costruzioni Idrauliche, Padova (Italia), 255-264.

Noli A., 1982. Studio su modello matematico delle modalità di evoluzione del litorale toscano tra le foci dell'Arno e del Serchio. Relazione Generale, 1-29.

Nordstrom K.F., Pranzini E., Jackson N.L., Coli M., 2008. The marble beaches of Tuscany. *Geographical Review* 98: 280-300.

Palla B., 1978. Linee di livellazione di precisione per il controllo della subsidenza nella pianura a sud dell'Arno e a est di Pisa. Proceedings of the Conference "I problemi della subsidenza nella politica del territorio e della difesa del suolo", Pisa (Italy), 9-10.

Palla B., 1983. Variazioni della linea di riva tra i Fiumi Arno e Serchio (Tenuta di S. Rossore-Pisa) dal 1878 al 1981. *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 90: 125-149.

Pascucci V., 2005. Neogene evolution of the Viareggio basin, northern Tuscany (Italy). *GeoActa* 4: 123-138.

Pellegrinetti G.A., 1925. La costruzione del porto di Viareggio e le conseguenti erosioni. Atti del IX Congresso Geografico Italiano, Genova (Italia), 70-78.

Piccardi M., Pranzini E., 2014. Carte a piccola, grande e grandissima scala negli studi sull'evoluzione del litorale. Cosa è successo a Bocca d'Arno tra il XVI e il XIX secolo. *L'Universo* 5: 760-790.

Piccardi M., Pranzini E., 2016. Le foci del Serchio e del Fiume Morto nelle restituzioni cartografiche pre-geodetiche. *Studi Costieri* 23: 21-58.

Piccardi M., Pranzini E., Rombai L., 2018. Historical cartography and coastal dynamics of the Apuan littoral in the modern and contemporary periods: the port of Marina di Carrara (Tuscany, Italy). *e-Perimetron* 13: 32-49.

Pozzebon A., Andreadis A., Bertoni D., Bove C., 2018a. A wireless sensor network framework for real-time monitoring of height and volume variations on sandy beaches and dunes. *ISPRS International Journal of Geo-Information* 7: 141.

Pozzebon A., Cappelli I., Mecocci A., Bertoni D., Sarti G., Alquini F., 2018b. A wireless sensor network for the real-time remote measurement of aeolian sand transport on sandy beaches and dunes. *Sensors* 18: 820.

Pranzini E., 2001. Updrift river mouth migration on cuspate deltas: two examples from the coast of Tuscany (Italy). *Geomorphology* 38: 125-132.

Pranzini E., 2004. Caratteristiche morfologiche e sedimentologiche di una zona di convergenza del trasporto litoraneo (Versilia, Toscana). *Studi Costieri* 8: 135-149.

Pranzini E., 2007. Airborne LIDAR survey applied to the analysis of the historical evolution of the Arno River delta (Italy). *Journal of Coastal Research* 50: 400-409.

PRANZINI E., 2008. L'intervento di stabilizzazione del litorale de Le Lame (Parco San Rossore Migliarino Massaciuccoli, Toscana). *Studi Costieri* 14: 29-42.

PRANZINI E., 2018. Shore protection in Italy: From hard to soft engineering… and back. *Ocean & Coastal Management* 156: 43-57.

PRATELLESI M., CIAVOLA P., IVALDI R., ANTHONY E.J., ARMAROLI C., 2018. River-mouth geomorphological changes over > 130 years (1882–2014) in a small Mediterranean delta: Is the Magra delta reverting to an estuary? *Marine Geology* 403: 215-224.

RAGGI G., 1988. Neotettonica ed evoluzione paleogeografica plio-pleistocenica del bacino del Fiume Magra. *Memorie della Società Geologica Italiana* 30: 35-62.

RAGGI G., SANSONI G., 1993. Variazioni storiche e tendenza evolutiva della linea di riva lunense. *Memorie della Accademia Lunigianese di Scienze* 62-63: 3-43.

RAPETTI F., VITTORINI S., 1974. Osservazioni sulle variazioni dell'ala destra del delta dell'Arno. *Atti della Societ*à *Toscana di Scienze Naturali, Memorie Serie A* 81: 25-88.

ROSSI V., AMOROSI A., SARTI G., POTENZA M., 2011. Influence of inherited topography on the Holocene sedimentary evolution of coastal systems: an example from Arno coastal plain (Tuscany, Italy). *Geomorphology* 135(1-2): 117-128.

RUOCCO M., BERTONI D., SARTI G., CICCARELLI D., 2014. Mediterranean coastal dune systems: Which abiotic factors have the most influence on plant communities? *Estuarine, Coastal and Shelf Science* 149: 213-222.

SAGGINI F., 1967. Alterazioni del litorale toscano per cause naturali e artificiali. Atti del Convegno "Indirizzi di piano per il territorio della costa toscana", *Quaderni de La Provincia di Livorno*, 11.

SARTI G., BERTONI D., 2007. Monitoring backshore and foreshore gravel deposits on a mixed sand and gravel beach (Apuane-Versilia coast, Tuscany, Italy). *GeoActa* 6: 73-81.

SARTI G., BERTONI D., CAPITANI M., CIAMPALINI A., CIULLI L., CERRINA FERONI A., ANDREUCCI S., ZANCHETTA G., ZEMBO I., 2017. Facies analysis of four superimposed Transgressive-Regressive sequences formed during the two last interglacial-glacial cycles (central Tuscany, Italy). *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* 124: 133-150.

SARTI G., BINI M., GIACOMELLI S., 2010. The growth and decline of Pisa (Tuscany, Italy) up to the Middle Ages: Correlations with landscape and geology. *Il Quaternario* 23: 311-322.

STORTI F., 1995. Tectonics of the Punta Bianca promontory: Insights for the evolution of the Northern Apennines-Northern Tyrrhenian Sea basin. *Tectonics* 14(4): 832-847.

TONIOLO A.R., 1910. Sulle variazioni di spiaggia a foce d'Arno. Editore Giardini, Pisa.

(ms. pres. 02 settembre 2018; ult. bozze 24 ottobre 2018)

Edizioni ETS
Palazzo Roncioni - Lungarno Mediceo, 16, I-56127 Pisa
info@edizioniets.com - www.edizioniets.com
Finito di stampare nel mese di febbraio 2019