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Anthropogenic Impact on Beach Heterogeneity within a Littoral Cell (Northern Tuscany, Italy)

Duccio Bertoni ¹ , Monica Bini ¹ , Marco Luppichini ^{1,2} , Luigi Enrico Cipriani ³, Andrea Carli ⁴
and Giovanni Sarti ^{1,*} 

¹ Department of Earth Sciences, University of Pisa, 56126 Pisa, Italy; duccio.bertoni@unipi.it (D.B.); monica.bini@unipi.it (M.B.); marco.luppichini@unifi.it (M.L.)

² Department of Earth Sciences, University of Florence, 50121 Florence, Italy

³ Directorate Soil Defense and Civil Protection, Region of Tuscany, 50127 Florence, Italy; luigi.cipriani@regione.toscana.it

⁴ Port Authority of Livorno and Piombino, 57123 Livorno, Italy; a.carli@portialetirreno.it

* Correspondence: giovanni.sarti@unipi.it; Tel.: +39-050-221-5734

Abstract: In this paper the evolution of the Northern Tuscany littoral cell is documented through a detailed analysis of the increasing anthropogenic pressure since the beginning of the 20th century. This sector of the Tuscany coast has been experiencing strong erosion effects that resulted in the loss of large volumes of sandy beaches. The anthropogenic impact on natural processes have been intensified by the construction of two ports in the early decades of the 20th century. Competent authorities reacted by building hard protection structures that tried to fix the position of the shoreline but offset the erosion drive downdrift. Therefore, in the last 20 years a regional Plan was undertaken to gradually replace the hard defense schemes with a softer approach, which involved a massive use of sediment redistribution activities. Many nourishments have been done ever since, using both sand and gravel. All these hard and soft protection operations have been archived in a geodatabase, and visualized in maps that clearly show the progressive change from hard to soft defense. This database may improve the approach to any future analysis of the littoral cell both in terms of research and management, while providing a practical example that may be easily replicated elsewhere.

Keywords: coastal erosion; coastal protection; sediment redistribution; beach nourishment; anthropogenic cell; geodatabase; GIS; Tuscany; Italy



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1. Introduction

The increase of greenhouse effect related to human activities is negatively affecting global warming (e.g., [1–5]), and this is becoming a must-win challenge in order to save the future of human beings on the planet. One of the most significant consequences of climate change is the acceleration of sea-level rise rate and the ensuing disastrous effects in terms of erosion and flooding of coastal areas [6–10]. The IPCC scenarios indicate a sea-level increase of about 50 up to 82 cm for the next 80 years depending on the ability of each country to adhere to the Paris agreement to decrease the emission of greenhouse gases [11–13]. These data represent a major concern particularly for the low-lying sandy coasts, where only a relatively small increase of the sea level may cause extensive inundation [14–17]. In addition, natural and anthropogenic-induced subsidence may locally increase the rate of relative sea-level rise. As coastal areas are heavily populated, the huge socio-economic impact deriving from this situation is easy to imagine. Unfortunately, this is the present-day context that coastal managers are dealing with. Within this reality, the heavy anthropogenic impact that characterizes many coasts in the world represents a further critical element for the management of the sea-level rise threat. The anthropogenic impact involves many concurrent factors that are drastically changing the natural morphodynamic condition along the coasts. The presence of ports and beach facilities, the decrease of sediments

supplied by rivers caused by riverbed quarrying and dam construction, the increase of subsidence due to excessive water extraction from the aquifer, the proliferation of protection structures, the sediment dredging from harbors, and the artificial nourishment at sites hit by erosion have permanently changed the natural characteristics of many inhabited coasts [18–20]. In-depth understanding of how all these human-induced factors combine in determining the morphology and the evolution of the coast is essential to understand the issue of sea-level rise and requires a multi-disciplinary approach [21]. Such a multi-disciplinary approach has been applied in many coastal monitoring studies e.g., [22,23]. In particular, many approaches are based on a mix between in situ surveys and remote sensing data acquisition e.g., [24,25]. More recently, aerial and camera photogrammetry and drone-derived datasets have been widely used e.g., [26–29]. Many approaches use modelling as a coastal monitoring tool e.g., [30,31]. Models can also be applied to evaluate areas prone to risk related to coastal processes e.g., [32,33]. Lately, citizen science is also considered a viable option to collect more data from specific settings [34,35].

Here we present the case-history of the Northern Tuscany littoral cell (western Italy). This stretch of coast is a natural laboratory because it encompasses a large area characterized by strong human pressure, where a variety of defense schemes have been implemented over the years, and an extended natural reserve area where human settlements and activities have been limited. The aim of the research is (i) building a geodatabase to store all the artificial interventions (e.g., breakwaters, groins, nourishments) made along this littoral cell, and (ii) making an assessment about the anthropogenic impact on the coastal morphodynamics.

2. The Study Area

The Northern Tuscany littoral cell is approximately 65 km long and extends from the Punta Bianca promontory up to the Livornesi Mounts to the south (Figure 1). The northernmost 2.5 km belong to the Liguria region, whereas the rest of the cell lies within the boundaries of Tuscany. The rocky coasts at both edges prevent any sediment exchange between adjacent sectors [36]. Aside from the 18 km long sector belonging to the Migliarino–San Rossore–Massaciuccoli Regional Park, that is virtually devoid of anthropogenic structures, the rest of the coast is highly anthropized and affected by strong human pressure, as the local economy is mainly based on tourism beach facilities, port, and shipping yards (in Viareggio, Marina di Carrara, and Marina di Pisa).

The beaches within the littoral cell are largely characterized by medium-to-fine sand supplied by the major streams that outflow into this sector of the Ligurian Sea, in particular Arno and Magra rivers; the sedimentary supply of other rivers (Serchio, Versilia, Frigido), creeks, and ditches is negligible [36]. Only the northernmost part of the cell is made up of mixed sand and gravel beaches [37], the coarsest fraction being delivered by the Magra River and other minor streams that flow directly into the sea from the nearby Apuan Alps (Figure 1). The different mineralogical composition is what allowed to discern the provenance of the sediments within the cell [38,39]: the sand from the Punta Bianca promontory to Marina di Pietrasanta has a clear origin from the Magra River, whereas the sand from Marina di Pietrasanta to Tirrenia comes from the Arno River. The analysis of sediment provenance and redistribution along the cell implies a southward-directed transport from the Magra River mouth to Marina di Pietrasanta. A convergence zone can be pointed out here as the drift coming from the Magra River runs into the northward-directed drift coming from the Arno River [40,41]. A second convergence zone generates farther to the south, in Calambrone, where the southward-directed drift coming from the Arno River faces a northward-directed drift (Figure 1), whose characteristics have yet to be clearly defined.



Figure 1. Map of the study area. The white dashed lines identify the anthropogenic sub-cells within the Northern Tuscany littoral cell. The yellow lines represent the direction of the longshore drifts, which generate two convergence zones at Marina di Pietrasanta (Cp1) and at Calambrone (Cp2). The background image has been retrieved from the Google Earth database.

Sea floor profile is not uniform in terms of slope along the cell, as the sectors mainly affected by human activities are locally characterized by configurations owed to the presence of hard protection structures [20,41]. The natural nearshore slope is about 1% [36]. The depth of closure for the area has been recently calculated at the isobath -9 m [41] in contrast to a previous estimation that located it at a depth of -14 m [42]. Sea state characterization is provided by the data collected through two buoys located in the northern and in the southern sectors of the littoral cell, in La Spezia and in the Gorgona Island [36,43]. Over the years, both devices recorded that the direction of most frequent waves and strongest storms is similar, as they come from a sector centered at $210\text{--}260^\circ$ N. The Northern Tuscany

littoral cell can be defined a microtidal environment in terms of tidal range, as it is hardly over 0.3 m even during spring tides [36,43].

3. Materials and Methods

The detailed reconstruction of hard (e.g., breakwaters, groins, port structures) and soft interventions (e.g., nourishments, artificial dunes) along the Northern Tuscany littoral cell has been completed through a careful revision of the scientific literature [44–48]. As an impressive variety of activities was made on this sector of the Tuscany coast in the last 150 years, and in particular in the last 4 decades [20], many details about them were not available on scientific papers. The archives of the Region of Tuscany have been combed through to collect any document reporting information about protection schemes and nourishments. Personal interviews with people in charge at the time of the interventions were also carried out as an additional validation of the data retrieved from the official reports.

A dedicated geodatabase, specifically realized and organized by the Department of Earth Sciences of the University of Pisa, storing all the data used in this paper (e.g., protection structures and nourishments) was created in PostgreSQL (v. 12) with PostGis extensions (v. 3.2.1). The data were all checked and standardized after the acquisition. They were archived using the open-source software QGIS v. 3.10; Gauss Boaga Monte Mario Italy zone 1 (EPSG: 3003) was used as reference system. The hard structures (e.g., breakwaters, seawalls, groins) were manually mapped using polygons that trace the shape visible on the airborne images. The construction time intervals of each hard structure were derived from official documents of the Region of Tuscany or from its presence/absence in dated airborne images. The sites that have been characterized by soft operations (e.g., nourishments, sand redistribution) are indicated with dots, as a precise localization of the extension of the area where the replenishments have been done is not always feasible. The chronology of each beach fill was acquired from the official documents provided by the competent Authorities. The use of the colors is based on how both hard and soft interventions have been sorted, that is by the year/s of occurrence (Table 1). The time intervals have been selected based on the most important defense scheme projects that were done along the littoral cell.

Table 1. The time intervals that were selected to sort out hard and soft protection interventions.

Time Intervals	Color in the Maps
Pre–1954	Red
1954–1978	Orange
1978–1988	Yellow
1988–1998	Cyan
Post–1998	Blue

1 #: number of such interventions.

The shoreline position in five different years (1938, 1954, 1978, 1996, 2019) was also documented in order to appreciate the evolution of the coast in accordance with the numerous protection schemes that have been implemented in the Northern Tuscany littoral cell (Table 2). A linear shapefile with the position of the shoreline (derived from manual operator delimitation and digitalization) was created for each analyzed year. These years were selected in order to be as consistent as possible with the time intervals we sorted out for the hard and soft protection schemes (Table 1). The data were processed using the open-source software QGIS v. 3.10.

Table 2. The selected shoreline positions with the year of survey, the ownership Organization, type and properties of the origin data, the margin of error of the digitalization and the corresponding color in the maps.

Year	Ownership Organization	Data Type	Properties	Error ¹	Color in the Maps
1938	IGM ²	Cartography	Scale 1:100,000	1.5–11 m	Black
1954	Region of Tuscany	Aerial imagery	Black-and-white film	<2.5 m	Red
1978	Region of Tuscany	Aerial imagery	Black-and-white film	<1.5 m	Orange
1996	Region of Tuscany	Aerial imagery	Black-and-white film	<1.5 m	Cyan
2019	Region of Tuscany	Satellite imagery	RGB	~1 m	Blue

¹ The error has been estimated in accordance with the analysis proposed by Crowell et al. [49]. ² Istituto Geografico Militare (Italian Army Geographical Institute).

4. Results

The indication on a georeferenced map of the anthropic interventions carried out on the Northern Tuscany littoral cell in about a century shows how strong and pervasive human pressure has been especially on those sectors characterized by settlements. Basically, the increase of protection structures is proportional to the evolution of the anthropogenic activities; this is particularly emphasized where the erosion effects hit the most [50].

4.1. Ports

During the last 150 years, the anthropogenic pressure in the Northern Tuscany littoral cell increased, determining fast modifications to the natural morphodynamic of the area. The most significant variations occurred in the 1920s, when two ports were built as a response to the increasing claim for economic growth. The structures were raised in sites where the demand was higher, but for different reasons (Figure 1): (i) In Marina di Carrara, where the commercial activities revolving around marble extraction from the worldwide famous Carrara quarries were lively and in need of a further step, which an efficient port would have guaranteed [51,52], and (ii) in Viareggio, where the tourism industry started to be increasingly perceived as a viable option to exploit the wide sandy beaches [53]; later it also became a crucial node for luxury shipyard activities.

The Marina di Carrara port structures were built normal to the coastline and acted as barriers for the natural drift, here flowing southwards [42]. Sediments began accumulating on the updrift side of the breakwater, and the downdrift area starved in a short timespan [52]. Finest fraction distribution over the breakwater would still be feasible, but those sediments would not contribute to feed the downdrift beaches as the grain-size was too fine to be deposited in an environment as energetic as the shoreface. Huge erosion effects were reported in the subsequent years, which led to the loss of the downdrift beach up to Marina di Massa [42].

The configuration of the Viareggio port structures is different than that in Marina di Carrara. The breakwater acted as a partial screen as it was built with a low angle relative to the coastline. Such orientation did alter the natural dynamics of the littoral drift, flowing northwards in this sector of the coast. Sand started amassing at the southern breakwater leading to a large updrift accumulation [48]. The sediments trapped here were not available for the downdrift sector, which experienced immediate erosion effects [53]. However, once the coastline reached the tip of the breakwater, sediments began overpassing the structures [54], thus creating an additional issue related to the siltation of the harbor. Regular dredging operations are required to maintain the access way to the harbor clear [20,55]. The downdrift beach suffered especially in the earlier years, but the erosion processes in Viareggio were never as harsh as in Marina di Carrara.

4.2. Hard Protection Structures

The ports were built while a general decrease of the sediments naturally feeding the coast had already begun. The sediment bedload of the rivers outflowing into the Ligurian Sea was dwindling, and an incipient coastline retreat was already pointed out [19]. At first, erosion effects were observed close to the Magra River mouth, but they soon spread

south towards Marina di Carrara [56,57]. Breakwaters, groins, and small circular islands were built over the years to contain the erosion [58]. These structures fixed the coastline preventing any further coastline retreat (Figure 2). Hard protection schemes have never been used south of the Parmignola Creek mouth because that sector was strongly affected by the presence of Marina di Carrara port structures, resulting in the large accumulation of sediment coming from updrift beach erosion (Figure 2).



Figure 2. Identification of hard and soft operations along the sector comprised between the Magra River mouth and the Port of Marina di Carrara. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

The negative effects of port structures clearly emphasized a tendency that started in the second half of the 19th century [19]. However, the contribution of port structures to

the erosion effects was so huge that competent Authorities had to respond immediately in order to protect the local communities that were impacted by such a fast shoreline retreat (Figure 3): South of the Port of Marina di Carrara the littoral avenue was damaged by storm waves, dismissed, and never refitted [59]. As the erosion spread further southwards, the downdrift village of Marina di Massa was impacted soon thereafter [37,60].



Figure 3. Identification of hard and soft operations along the sector comprised between the Port of Marina di Carrara and Marina di Massa. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

A long series of hard protection structures was built in the aftermath of port construction (Figure 3): Detached breakwaters, seawalls, and groins were raised to stabilize the coastline retreat [44,61,62]. However, the proliferation of these protection schemes caused a domino effect, because additional structures had to be built further to the south (Figure 4).



Figure 4. Identification of hard and soft operations along the sector comprised between Marina di Massa and Cinquale. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

A set of four submerged groins composed of geotextile sandbags was built in Marina di Ronchi in the years 1999–2002 [63]. This attempt was made in an effort to decrease the negative visual impact of emerged structures, and the early response was appreciable. Unfortunately, in the long-term issues such as sandbag displacement and breakage, burying and sinking led to the decision to stop using such an innovative technique, and the more traditional boulder groins were used to protect the area [59]. Later, a few more groins were built and now characterize the beach up to less than 1.5 km to the Versilia River mouth, which is protected by two jetties that prevent the mouth from siltation (Figure 5).



Figure 5. Identification of hard and soft operations along the sector comprised between Cinquale and Forte dei Marmi. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

The sector between the Versilia River mouth and the Port of Viareggio does not evidence any kind of intervention (Figures 5 and 6), as this area is characterized by the convergence of the littoral drifts that come from the Magra River mouth and the Arno River mouth respectively (Figure 1). As the shoreline evolution clearly shows, natural accretion has always occurred up to Viareggio, where erosion effects were reported after the construction of the port. However, no hard structures have ever been required in order to stabilize the coastline (Figures 5 and 6).



Figure 6. Identification of hard and soft operations along the sector comprised between Forte dei Marmi and Viareggio. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

Barring the breakwaters and docks at the Port of Viareggio, the next hard protection structure after the last groin in Poveromo is about 30 km to the south, specifically at the Morto Nuovo River mouth (Figure 7). The mouth of this artificial channel was armored,

and a couple of jetties were built to prevent its siltation, as a lot of sediments were already coming from the loss of the updrift beach nearby the Arno River mouth (Figure 1).

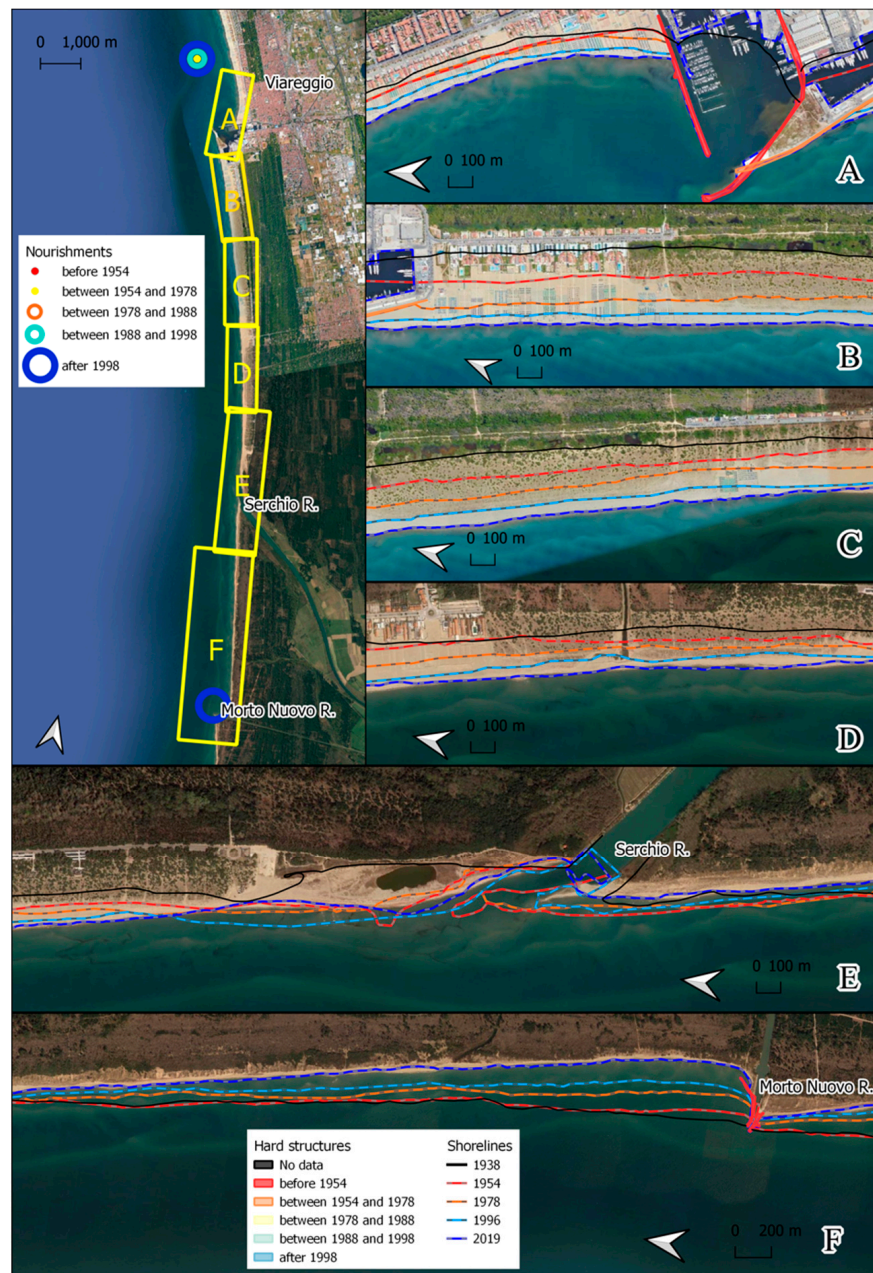


Figure 7. Identification of hard and soft operations along the sector comprised between Viareggio and the Morto Nuovo river mouth. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

The whole right side of the Arno River delta is still experiencing severe erosion processes, mainly caused by the reduction of river sediment discharge. At the beginning, competent Authorities decided not to respond to the early effects of the erosion, and the coastline retreated as a result [18,64]. This decision was made because this sector of the coast belongs to a natural reserve area (namely, the Migliarino–San Rossore–Massaciuccoli Regional Park) where no human settlements were present. Aside from the structures at the Morto Nuovo River mouth, the first defense schemes were implemented to protect the only building in the area (a summer residence originally belonging to the President

of the Italian Republic, at Gombo). Five detached breakwaters were built in the late 1960s [65], which generated the formation of a tombolo at the back of each structure (Figure 8). This accumulation was temporary, as processes of reverse erosion began to affect the northernmost tombolo and progressively destroyed the others in a southward direction [66]. Further to the south, just north of the Arno River mouth, a series of nine groins were built in the early 2000s in order to contain the excessive erosion in that sector (approximately 20 m/year) [67], where the valuable wet back-dune areas (the so-called “Lame”) were endangered by frequent over-washing events during storms (Figure 8).



Figure 8. Identification of hard and soft operations along the sector comprised between Gombo and Tirrenia. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

The evolution of the left side of the Arno River delta does not resemble that of the right side. While the northern sector was left free to retreat, the southern required a fast response to the early erosion effects because of the presence of the village of Marina di Pisa, which was founded in the second half of the 18th century, at the beginning of the erosional

phase (Figure 1) [18]. After the loss of the sandy beach at Marina di Pisa, each storm would put at risk the safety and conservation of the buildings along the littoral promenade. Therefore, a scheme made of seawalls, detached breakwaters, and groins was progressively implemented in order to protect the settlement and prevent the coastline from a gradual retreat [68]. The hard approach worked perfectly because it fixed the coastline at the current position, precluding any future erosion (Figure 8). Unfortunately, the combination between little sediment discharge from the Arno River and the wave reflection created by the presence of the structures also precluded any chance of sand deposition in the area, leading to the unfeasibility of maintaining a sandy beach there. In addition, the structures affected the natural morphodynamics of the sector, resulting in the propagation of the erosion drive southwards according to the littoral drift direction. As a consequence, an additional set of seawalls, detached breakwaters, and groins was built in the 1954–1978 period, replicating the first protection scheme. That way the entire length of the Marina di Pisa village was engineered according to the hard approach (Figure 8). Again, that would not stop the erosion processes, which started to hit the downdrift sector at the end of the 1970s. A narrow strip of sand was still present at the time, and it was protected with a third round of hard structures (1978–1988), but with a different design relative to the first two sets (Figure 8): No more seawalls, just groins and breakwaters characterized by a smaller size to protect beach resorts. The sediments were trapped inside the groin compartments and quickly the beach assumed a curved configuration typical of the diffraction processes the structures generated. As early hints of retreat were reported towards the village of Tirrenia [64,69], five breakwaters were built as a response (1988–1996); this protection scheme was later rounded out with the construction of a large, submerged breakwater (2001) (Figure 9). No other hard structures were implemented south of Tirrenia, except for two long jetties at the mouth of the Scolmatore Channel, which is a distributary channel of the Arno River. These structures were built in the 2017–2018 interval in order to prevent the mouth from siltation (Figure 9).

4.3. Soft Protection Structures

Once the past experiences of hard approach application along the littoral cell made it apparent that fixing the coastline would be often achieved at the expense of sediment deposition and generating downdrift erosion, a lot of interventions involving the redistribution of sand and gravel along the Northern Tuscany coast have been completed, especially in the last decades [20]. Nourishment activities have been realized according to many project designs [68,70]: Using sand from inland sites or gravel and pebbles from the nearby Carrara quarries; or rather, dredging the sand from accumulation areas within the littoral cell and redistributing it to the starving spots along the cell.

Even though the northernmost sector of the littoral cell between the Magra River mouth and the Port of Marina di Carrara experienced erosion processes since the second half of the 19th century [19,48], significant nourishment activities are reported extensively only after the year 2003 [41]. The large part of these interventions involved sediments dredged from the bed of the Magra River and redistributed in the area between the Magra River mouth and the Parmignola Creek (Figures 1 and 2). The sector towards the Marina di Carrara breakwater has been for many years an accumulation spot, but the sediment supply there started to decrease once the updrift areas were engineered and protected with hard structures. Therefore, a large nourishment (about 120,000 m³) with sand coming from authorized quarries along the Po River was realized in the 2006–2011 interval at the Marina di Carrara beach [58,71]. To a lesser extent, sand collected from the Po River has also been used to nourish the updrift beach in the same timespan (Figure 2).



Figure 9. Identification of hard and soft operations along the sector comprised between Tirrenia and the Scolmatore Channel mouth. Polygons represent the hard structures; dots represent the nourishments. The yellow frames in the top left panel correspond to the zoom in panels to the right and at the bottom. The background image has been retrieved from the Google Earth database.

The scenario was quite harsh downdrift of the port structures. As mentioned above, this area was subjected to strong erosion processes that led to the complete loss of the beach. Artificial nourishment activities were implemented since the 1980s and 1990s of the 20th century especially in the sector that suffered the most [72], that is the area just downdrift of the Port of Marina di Carrara (Figures 3 and 4). In addition, in later years (2000–2013), the large part of replenishments here was realized within redistribution projects of the sediments dredged from the access way to the port [42]. Many interventions were also carried out within the compartments confined within the breakwaters and groins built in previous years or along with the beach fills, some using sand and gravel from inland

quarries [37,60], some others using sand dredged from submerged bars at the mouth of Frigido and Versilia rivers and redistributed along the coast from Marina di Massa to Cinquale (Figures 3 and 4). A large sediment redistribution project is presently ongoing (first phase in 2020, second phase in 2021). The volumes involved are not comparable with those from the recent experiences at the Delft coast in the Netherlands or in Northern France [73,74], nonetheless about 100,000 m³ of sand has been dredged at the accumulation spot nearby the Port of Viareggio access way and redistributed in the adjacent sub-cell, about 17 km to the north nearby Poveromo (Figure 1). This virtuous example of sand management was not a first-time occurrence in the Northern Tuscany littoral cell, as a transfer of sand from Viareggio to Marina di Massa had already been done in the year 2000 [20]; the redistributed volume was definitely smaller though (just 8000 m³).

The sector between the Versilia River mouth and the convergence zone at Marina di Pietrasanta does not include any hard structure or beach fill intervention (Figure 5). The only area that has been subjected to erosion processes is the sector downdrift of the Port of Viareggio, where coastline retreat has been reported in the aftermath of its construction [53]. Sediment bypass systems were installed at Viareggio as well as Marina di Carrara in order to bring some sand from the updrift to the downdrift sector in the 1970s [59,75], but clearly it was not enough to mitigate the erosion effects. They were dismantled soon thereafter due to technical/maintenance problems. Therefore, the dredging/dumping approach began being implemented since the 1980s. More than 30 replenishments were realized just north of the Port of Viareggio using the sediments dredged from areas nearby the port and its access way (Figure 6). More than 2 million cubic meters of sand were collected and redistributed that way in the last 40 years [20].

The beach stretching from the Port of Viareggio to the Serchio River mouth did not require any replenishment (Figure 7), as it is still accreting or in equilibrium [64]. Erosion effects have been reported in the past (e.g., [18,65]) and in recent years (e.g., [48,76]) basically everywhere south of the Serchio River mouth: The shoreline evolution highlights such a severe retreat (Figures 7 and 8). Artificial nourishments were then realized alongside some hard protection schemes, for instance at Gombo in order to contain the reverse erosion at the five detached breakwaters and at the Morto Nuovo River mouth during a massive intervention to stabilize the jetties (Figure 8); both operations were realized in the 2010–2013 time interval [20]. The sediments used for these sites were borrowed from accumulations located in the backdune area at Torre del Lago. Further to the south, just north of the Arno River mouth (Lame delle Gelosie), additional replenishments were completed in the years 2001–2003, and repeated in 2013, using sand and gravel from inland quarries (Figure 8). They were placed within the compartments created after the construction of the nine groins in the early 2000s in order to stabilize the coastline [67].

The left side of the Arno River delta is renowned for the artificial marble beaches that constituted the major evidence of a huge coastal protection scheme designed and realized in the years 2006–2008 [46]. Except for one case during the implementation of this greater intervention, no sand beach fills were ever done there because fine sediments would have been lost in a matter of weeks based on the wave energy and nearshore morphology of that sector of the coast. In fact, the sand was used to stabilize the background where the pebbles would have been distributed. Preliminary replenishments using gravel (3–7 mm) were completed in 2001–2002 [45], but they resulted being short-lived under extreme storm conditions, which are not uncommon especially in the last 20 years [77]. The above-mentioned project was conceived on the wake of these first attempts to revitalize the seaside activities at Marina di Pisa (Figure 8), because during the summertime the artificial beaches are full of beach-goers eager to appreciate the sunbathing leisure this sector of the Tuscany coast offers especially in the hot season. Even though the extreme storms occurred before the completion of the gravel replenishments, the newer beach fills involved the use of pebbles of about 40–70 mm from the Carrara marble quarries and were realized in the compartments identified by the groins and a submerged breakwater (Figure 8). They worked so well that such a scheme was replicated in other two compartments in 2014–2016.

However, it was also carried out at the site where no offshore protection was present, namely Barbarossa beach, and the end result was not as good as at the compartments based on the high abrasion rate that was reported due to the more energetic wave condition [78]. After more than 10 years, the average diameter of the pebbles has been reduced to less than 35 mm [79].

The southernmost sector of the Northern Tuscany littoral cell has been only characterized by seasonal redistribution of sand at Tirrenia (Figure 8). This practice is officially documented in dedicated, unpublished documents by the Province of Pisa in the 2009–2015 time interval, but it is not ruled out that it might have been done earlier as well. However, the volume involved in such a redistribution scheme is hardly higher than 20,000 m³ for the considered time interval. At last, the largest beach fill intervention ever made in the sector south of the Arno River mouth was carried out in Calambrone, a small village close to the mouth of the Scolmatore Channel, in the year 2017 (Figure 9). It was done within a wider project that also included the construction of the jetties at the mouth of the channel, as mentioned in the previous paragraph. The total volume of the nourishment (about 222,000 m³) comes from dredging operations realized part in the submerged bar in front of the mouth (about 128,000 m³) and part in the mouth bar inside the river (about 94,000 m³).

5. Discussion

Except for the Migliarino–San Rossore–Massaciuccoli Regional Park area, the natural coastal landscape of the study area, which was a wide sandy coastal plain characterized by dune systems, is now lost. The analysis of the results clearly shows how the anthropogenic impact on the study area interfered with the natural environment since the beginning of the 20th century. However, these last decades represent only a short phase in the evolution of the area in regard to human influence. Significant modifications of the coastal area related to anthropogenic activities occurred since the bronze age about 3000 years ago, when widespread inland deforestation commenced [80–82]. The drastic increase of sedimentary supply and the stabilization of the sea level rise [83,84] caused a strong acceleration in the rate of coastal progradation, which resulted in the development of a wide coastal plain. This seaward shift of the coastal system is recorded by the juxtaposition of several outcropping beach ridges roughly oriented parallel to the coastline and, in the subsurface, by the sharp transition from a lagoon to shallow marine deposits [85].

The progradation rate increased during Roman times, leading to a seaward shift of the coastline of about 6 km up to the 19th century. Due to several hydraulic operations over time to improve the navigation in the Arno River, such as cutting off a meander loop (1338) and shifting to the west the Arno River mouth (1606) to prevent upstream flooding and siltation, a local supplementary increase of the coastal plain progradation rate took place north and south of the river's mouth [18]. The analysis of coastline changes shows how this progradation trend went on until the end of the 19th century and reversed in the first half of the 20th century (Figures 2–9). Based on the decrease of Magra and Arno river sediment supply caused by human activities such as reforestation, river damming, hill slope stabilization, and riverbed quarrying, a general trend of coastal retreat began towards the end of the 19th century. Later, the overall trend was aggravated by the construction of the ports at Marina di Carrara and Viareggio, which created the need to protect the coast through many defense constructions (Figures 3, 4 and 6). The present-day situation shows how human interference has changed the natural landscape of the coast. The destruction of coastal dune systems to make room for beach resorts, facilities and roads, the presence of seawalls, detached breakwaters and groins (Figures 2–4, 7 and 8), and nourishments made with non-native sand or with gravel and pebbles (Figures 2–4, 6, 8 and 9) are all aspects that either boosted the tourism industry or saved the infrastructures from being lost, but at the same time contributed to alter irreversibly the original landscape of this coastal area, leading to a vast heterogeneity of beach types: Artificial marble and gravel beaches, nourished sand beaches, confined beaches, anthropized beaches, alongside the only true untouched sector, namely the coast between the Serchio River mouth and Gombo (Figure 1).

Though important for local communities, such a landscape change requires caution, as in the case of a bypass operation at Poveromo using sand from the accumulations nearby the Port of Viareggio [20]. The construction of additional hard structures should be avoided: while fixing the local coastline position, they often shift the erosion drive downdrift as shown by the shoreline evolution in this sector of the Tuscany coast. This mechanism generates a domino effect, which results in the proliferation of defense structures. The original problem is not solved, the landscape is marred, and the morphodynamic processes altered and fragmented.

However, this issue is not just characteristic of the Western Italian coast, as many coastal areas continue to experience erosion despite the massive construction of coastal protections [59,86]. Human pressure has been a driver for erosion processes all over Europe: Coastal retreat due to anthropogenic activities such as hard defense schemes and building dams have been documented in many countries e.g., [87–91], and on rocky coasts as well [92–94]. Among these general experiences, there are some that specifically report the impact of human pressure on the evolution of littoral cells. Study cases from Spain and Portugal clearly highlight how man-made interventions may affect the evolution of a coast both in the medium and in the long-term [95,96]. Furthermore, risk and vulnerability of coastal areas do not depend on the extension of the considered littoral cells, as both large and small sectors might experience varying degrees of erosion-related issues [97–100]. As suggested by some studies [101], an in-depth comprehension of littoral cell distribution is essential for an appropriate coastal management strategy. Northern Tuscany represents a case study: Before the construction of ports and hard structures, this physiographic unit was characterized by four littoral sub-cells identified by the converging direction of the drifts (Figure 1). Due to anthropogenic activities these natural sub-cells have been subjected to such pressure that additional boundaries emerged based on man-made structures, as reported by Anfuso et al. [54]. According to [54], sub-cell limits have been identified following morphological criteria [102,103]. However, the proliferation of hard and soft protection schemes along the Northern Tuscany coast modified the natural morphodynamics. The progressive loss of natural systems here documented encourages the use of a term such as “anthropogenic sub-cell”, which clearly takes into account the increasing human pressure along a coastal setting.

Based on these results, this sub-cell arrangement is confirmed between the Magra River mouth and the Arno River mouth. The Port of Marina di Carrara creates a modification to the nearshore morphodynamics preventing the sediments from distributing in accordance with the southward-trending drift. Likewise, the Port of Viareggio creates two sub-cells within the larger sector between the convergence zone at Marina di Pietrasanta and the Arno River mouth (Figure 1). However, the analysis of the present results enables the separation of the sector between the Arno River mouth and the village of Calambrone into two sub-cells, since the northern part at Marina di Pisa and Tirrenia is entirely characterized by hard protection structures (Figure 8), which strongly affect sediment redistribution and deposition. Conversely, the southern sector is devoid of coastal defenses, and the morphodynamics system is more natural than to the north (Figure 9). In addition, a small sub-cell is also present in the southernmost sector of the wider littoral cell, between the village of Calambrone and the Scolmatore Channel mouth (Figure 9). The mineralogical composition of the sand that constitutes the beach in this sector is not compatible with the provenance from the Arno River, just like in the northern sector at Tirrenia and Calambrone [104,105], thus suggesting the presence of a longshore drift with a northward direction. Further studies are needed after the recent construction of the two long jetties at the mouth of the Scolmatore Channel (Figure 9). The latest expansion of the structures at the Port of Livorno may have also induced variations in wave reflection and diffraction processes worth of additional investigation.

6. Conclusions

This study highlights the substantial modifications that this multifaceted coastal system, where high anthropization and natural reserved areas coexist, experienced in just one century. The modifications do not concern the natural landscape only, but also the morphodynamic processes: All this contributed to the total or partial transformation of the natural sub-cells of the wider Northern Tuscany littoral cell into anthropogenic sub-cells.

The increasing human impact on the environment both on a global scale (e.g., climate changes) and at a local scale (e.g., sediment starvation, coastal erosion) shows the need for an integrated approach in the framework of a medium-to-long term planning. Addressing the coastal erosion problem with a short and local space/time view is not strategic if we think about the reasonable risk of the next paradigm shift looming at the horizon: Coastal erosion and coastal flooding. On the other hand, an in-depth comprehension of the anthropogenic impact that characterizes many coasts in the world and the morphodynamic processes is an essential element for the management of the sea-level rise threat and for future adaptation strategies. A medium- to long-term planning at all scales (global and local) should be mandatory. We think that a dedicated geodatabase may represent a good tool for medium- to long-term management. Existing coastal monitoring systems can also take advantage of the implementation of such a geodatabase, which would be a nice complement to any other technique used to collect data in the coastal environment. The method presented in this paper is applicable for most of the world's anthropized coastal areas.

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