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Beach Erosion in the Gulf of Castellammare di Stabia in Response to the Trapping of Longshore Drifting Sediments of the Gulf of Napoli (Southern Italy)

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Abstract: The results of this study have allowed verification that longshore sediment transport along the coast of Napoli Gulf (southern Italy) takes place from Northwest to Southeast. The current analysis describes the results of an integrated sedimentological and geomorphological study of the Neapolitan coastal area. A sedimentological and morphosedimentary study was carried out by bathymetric survey and sampling of bottom sediments. The analysis of modal isodensity curves shows that all the sediments are moved from NW to SE by longshore currents parallel to the coastline. The morphological evolution of the Castellammare di Stabia Gulf coastal area, based on historical coastline changes, starts from 1865, when the sandy littoral was wide and in its natural state. Since the construction of the Torre Annunziata harbor in 1871, sediments transported by a NW-SE longshore drift have become trapped, inducing the genesis of a new wide triangular-shaped beach on the updrift side (NW) of the harbor breakwall. This process induced a significant shoreline retreat of the south-east sector of the littoral. Widespread beach erosion of the coastal physiographic unit of Castellammare di Stabia Gulf (delimited by two ports) is more developed in the southern portion. This study highlights a slight rotation of the shoreline toward the East and a general trend of regression, with typical overall accentuation of shoreline concavity, and significant widening of the triangular-shaped beaches at the end of the falcate. This reduced sediment input removed from the sedimentary budget a large amount of deposits, which are hardly restorable due to the scarce supply of sediment load by the Sarno river and its tributaries. In addition to this new and important derived morphologic feature, other recent human interventions have contributed to further modifications of morphologic characteristics of emerged and submerged beach. The intense use of the territory caused modifications on both the fluvial course and river mouth with direct and indirect effects on the shoreline and the drainage network of the Sarno River.

Keywords: coastal geomorphology; longshore sediment transport; historical maps; Gulf of Castellammare di Stabia; Gulf of Napoli

1. Introduction

Longshore sediment transport is important on most of the coastline; the direction of the net longshore sediment transport of the coastline may be manifested from natural features and by the accumulation of sediment behind obstacles such as harbors, breakwalls and groynes. Interference with the natural longshore sediment transport is caused by human-induced problems.

It has been largely demonstrated that human impact and port construction can significantly modify the pattern of sediment transport, promoting dramatic changes in coastline evolution and longshore sediment budget ([1–4]; among others).

Morphosedimentary analysis, coastline changes, long-term reconstruction of progradational and erosion processes and sediment budget estimation represent the key data to investigate the human-induced modification of coastal areas and to constrain sediment transport modeling.

In this paper, a detailed geomorphological and sedimentary study of a coastal area largely affected by human-induced alteration of the coastline and longshore sediment budget. The coastal sector of Castellammare di Stabia Gulf is the minor physiographic unit of the main one located in the Napoli Gulf (Figure 1).

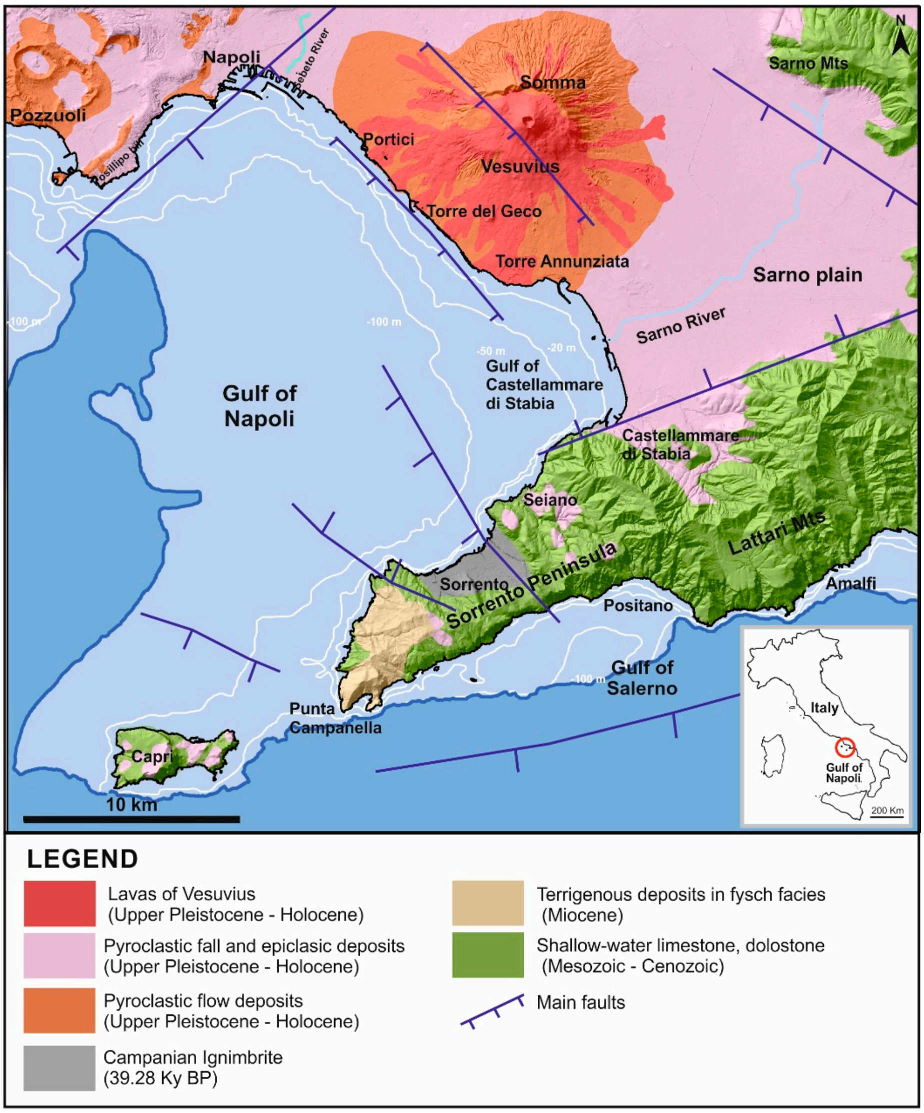

Figure 1. Geological map of Gulf of Napoli, southern Italy (after [5], mod). Inset shows a geographical sketch of southern Italy (the study area is shown in the circle).

It consists of a narrow sandy beach, surrounded by the artificial harbors of Torre Annunziata to the Northwest and Castellammare di Stabia to the Southeast (Figure 2), and cut in the middle by the Sarno River mouth. The presence of artificial harbors located at the extremes of the units implies a different transport by wave-generated longshore currents, which causes a weak rotation of the shoreline towards the East, linked to an overall erosion on the downdrift side of the sandy beach, that is more evident on its Southern sector. Therefore, the changes carried out by human activities on the coastal system are studied with the same methods used for the investigation of other coastal areas [6–15].

Human activities and coastal engineering works cause both direct and indirect transformations on coastal processes, having an environmental impact on the coastal system [16–20]. Therefore, these activities and their effects must be analyzed before their origin, even outside the physiographic unit in question, to define the coastal morphoevolution tendency.

Our results allowed identification of the critical area where appropriate actions can be developed for the mitigation of impacts and can represent a basic contribution to the coastal zone management.

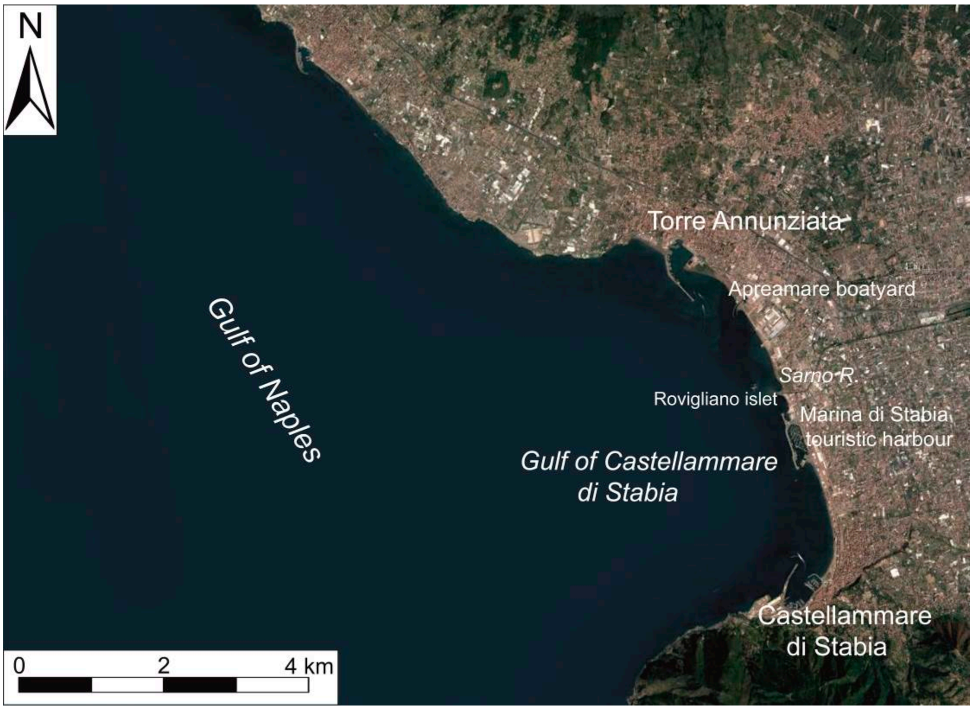

Figure 2. Location, map, and main toponyms of Castellammare di Stabia gulf.

2. Methods

Reconstruction of the historical morphosedimentary evolution of the study area has been carried out through an integrated geomorphological and sedimentological analysis supported by meteomarine data and morphobathymetic surveys. Classical analysis of the shoreline evolution based on multitemporal analysis of aerial photogrammetry and topographic maps has been also integrated using historical maps (years 1867 and 1906), which furnished relevant—although qualitative—information about the geomorphological features of the ancient coastal landscape. More specifically, analysis of the coastline evolution based on the comparison of topographic maps (years 1865, 1906, 1941 and 2000) and ortophoto (year 2018) has been integrated with the geological, geomorphological, and sedimentological data to infer the prograding and eroding sectors of the study area.

Detailed analysis of geomorphological and sedimentological features of the Gulf of Napoli and Castellamare di Stabia gulf is based on a large amount of data collected during topographic and bathymetric surveys and sediment sampling along emerged and submerged beach.

The sedimentary morphodynamics along the coast of the Castellammare di Stabia Gulf was deduced from the analysis of sediment transportation vectors along the entire coastline, based on the study of the modal analysis of each sediment sample and their appearance frequency [21,22]. This analysis allows identification of the grain size fractions involved in the sedimentary dynamics of the physiographic unit of interest.

The sedimentological study of the physiographic unit (Castellammare di Stabia Gulf) is based on the grain size analysis of 40 samples of bottom sediment and on 12 samples of emerged beach sediment [23]. The analysis, carried out with sieving and pipetting, allowed obtaining of the grain size composition and statistical parameters of [24].

Moreover, meteomarine climate has been inferred by a previous study of the direction and intensity of the main climate events of the coast [25]. The study is based on the analysis of the main wind direction using data from the Ponza Island oceanographic buoy (period 1989–2003).

All the above-mentioned information has been used to infer the long-term morphosedimentary evolution of the coast and the effect of human activities on the coastal morphoevolution and sediment transport. These results have been summarized in a map of sediment transportation vectors, which represent a basic contribution to the long-term evaluation of effect of the Torre Annunziata harbor construction on the longshore processes of sediment transport.

3. Geological and Geomorphological Setting

The beach in the Castellammare di Stabia Gulf borders seawards the Sarno River alluvial plain (southern Italy) (Figure 1). The geomorphological evolution of the plain conditioned the physiography of the coast, on which the effects of the human activities have been superimposed.

The coastal plain of the Sarno River represents the emerged portion of a morphotectonic depression bounded by carbonate morphostructures (Figure 1), originated between the end of the Pliocene and the beginning of the Pleistocene [26,27]. It was filled by successions of alluvial, volcanoclastic, marine and lagoon deposits reworked in different quantity by the widespread runoff of surface waters and gravitational phenomena [28–30]. The plain expands for about 200 square kilometers, from the harbor of Torre Annunziata to that of Castellammare di Stabia, extending for about 13 kilometers in length. It is delimited to the north by Somma-Vesuvio volcanic complex, eastward by the Sarno massif, southward by carbonate highs of the Sorrento Peninsula and westward by the Gulf of Napoli (Figure 1).

The slopes are covered by volcanoclastics alternating with detritic limestone and disturbed pyroclastics [31]. The widespread presence of tuff, lapilli, scoria and ash is mainly due to intense explosive activity of the Somma-Vesuvius [32] and the Phlegrean Fields [33] volcanoes.

The present-day morphology of the study area is largely controlled by the complex interaction between tectonic and volcano-tectonic movements, sea-level rises promoted by long- and short-term climate changes and human impacts. Previous work highlights the predominant role of volcanic activity as the main endogenic controlling factors of the Holocene coastal evolution [5]. Historical seismic activity (earthquakes of AD 62 and AD 64 [30]) is older than the AD 79 eruption and the crustal deformations are presumably caused by the inflation of magma bodies underneath the Somma-Vesuvius volcanic complex [30]. The Vesuvian coast has been strongly modified by the effects of the Plinian eruption of Vesuvius in AD 79 (Aucelli et al., 2017). In the Sarno coastal plain a subsiding trend, partially due to regional tectonics and the compaction of loose sediments, was compensated by substantial clastic contributions related to the emplacement and reworking of pyroclastic products of the Vesuvius volcano [5].

Along the coast, there are rare traces of paleoshorelines [30] and dunes, partially obliterated, while present dunes are completely absent. The latter has been completely leveled and urbanized with the construction of industrial complexes and houses.

The Sarno River is a resurgent river and its solid contribution has always been relatively modest, the exception being the periods of volcanic activity. It originates from the Palazzo, Santa Marina and Cerola springs; two other springs—the San Mauro and the Santa Marina di Lavorate—are practically exhausted due to the excessive uptake [34]. In the past, the river was characterized by a meandering path (Figure 3). The morphostratigraphic study of some sedimentary successions has allowed the reconstruction of the trace of ancient meanders of the Sarno River during the Holocene age, located in the Northern portion of the plain [31], to the N of the current mouth.

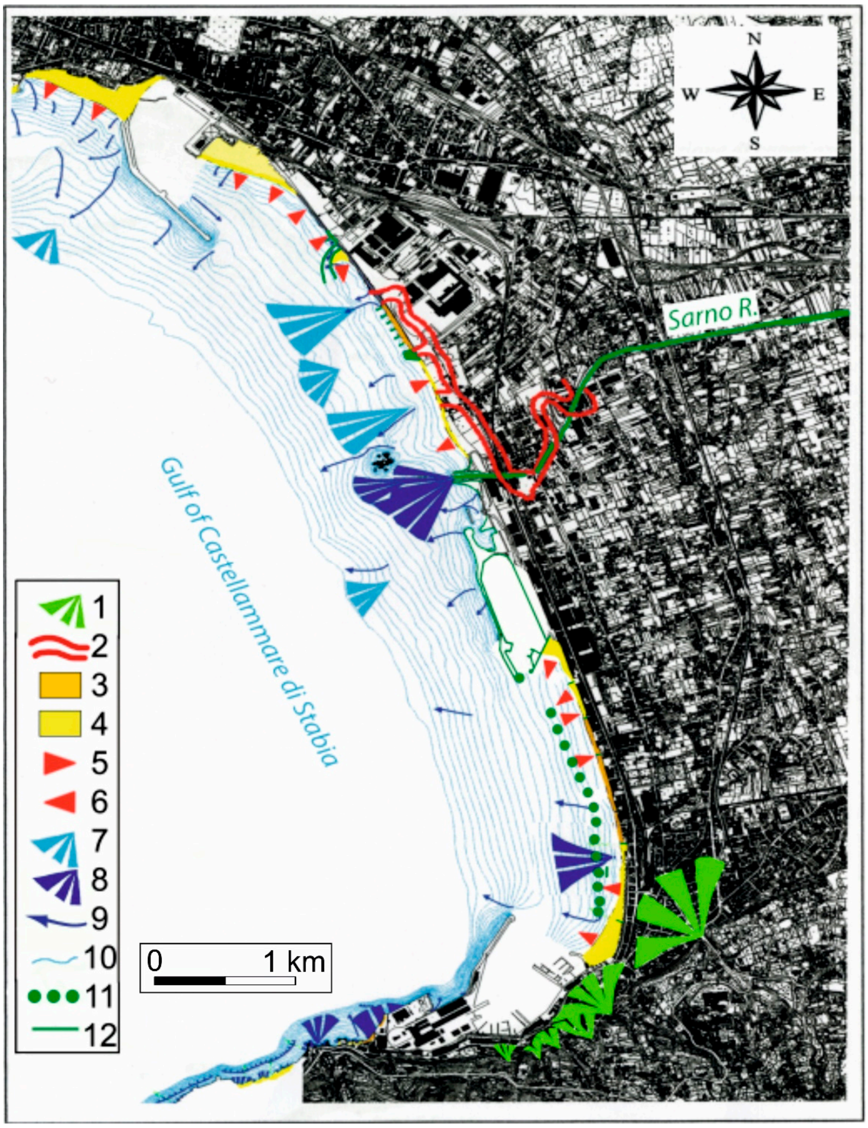

Figure 3. Schematic geomorphological map of Castellammare di Stabia coastal area. Legend: (1) alluvial fan deposits in piedmont areas (Holocene); (2) Sarno paleo-riverbed; (3) sandy, gravelly beaches; (4) sandy beaches; (5) erosional beach; (6) progradational beach; (7) Sarno river's ancient mouth complex; (8) Sarno river's current mouth complex; (9) channel incised in the bottom; (10) isobaths (1 m interval); (11) detached submerged breakwaters; (12) Recent coastal engineering works.

4. Geomorphological Features of the Coastal Area

The coastal area we studied has a NW-SE orientation and it is cut in the middle by the Sarno River (Figures 2 and 3). The beach is sandy, and it has superficial accumulations of flattened gravels. The gravels, reworked by the sea action, are likely linked to a dejection phase of the Sarno River and of its streams (Gragnano-S. Marco and Calcarella). This process was studied in the Sarno coastal plain and it is verified during the maximum marine ingression related to the Holocene sea-level highstand (5.8 ky BP).

At present the beach is eroding overall (Figure 3), reaching a width that ranges from 15 to 30 m, except for two triangular-shaped sectors in progradation at the extremities, adjacent to the harbor's inner breakwaters of Torre Annunziata (wide beach of up to 200 m) and of Castellammare di Stabia (wide beach of up to 150 m). The sand towards the North is predominantly of volcanic origin and of dark gray color. Gradually, starting from the intermediate stretch, it becomes carbonate, assuming S shades that are always clearer than gray. Its nature is to be ascribed to the lithology of the geological complexes that are present at the boundaries of the physiographic unit.

The submerged morphology of the study area (Figure 3) has been reconstructed from the analysis of bathymetric surveys using a single beam echo sounder [23]. It appears to be regular and characterized by weak gradients of inclination, on average equal to 2% for the interval between the shoreline and the bathymetric of 20 m placed at about 1000 m from the shoreline.

The sedimentation passes gradually from medium sand near the coast to fine sand up to transition offshore (see paragraph Morphodynamic of sediments). In the central sector of the study area, there is a fine sandy accumulation related to the current Sarno River mouth complex, which extends beyond the bathymetric of −20 m. In front of the sea, between the 5 m and 10 m bathymetrics, there is the limestone Rovigliano islet, which constitutes the morphological expression on the surface of the structural high of the Monti di Sarno [35].

There are also evidences of ancient mouth complexes of the Sarno River (Figure 3) that extend up to 7 m of depth, characterized by the gradual change in grain size of sediments from fine sandy, near the coast, to very fine sandy offshore, and to strips of ancient depositional elements related to river mouths flowing into the Southern portion of the gulf, partly obliterated by both the coastal defense works and the Castellammare di Stabia harbor. Just North of the Sarno River mouth, there are ancient accumulations of mouth complex at the Holocene river plan (Figure 3). Only in front of this stretch, the emerged beach is made up of gravelly deposits with rounded pebbles of about 10 cm average diameter, mainly of volcanic origin. The identification of these deposits at sea and on land allows confirmation of the presence in this sector of an ancient thalweg of the Sarno River, which probably dated back to the Holocene.

To complicate this morphological structure even further, accumulations of sediments or channels incised in the bottom (Figure 3) are evident as a response to the development of coastal defense works or harbor structures. In particular, at the mouth of the Torre Annunziata and Castellammare di Stabia harbors, there are areas with sediment accumulations, while, at the mouth of the Marina di Stabia touristic harbor (Figure 2), there is a deep channel incised at the bottom. In the Southern sector of the gulf, in front of some detached breakwaters that were placed seaward of the shoreline approximately in the year 2000, the seabed is shallow, particularly in the areas that are in between the coastal-protection structure and the shoreline. In this area, there is also a tendency to progradation of the beach, which is made evident by the 1 m bathymetric trend, especially in the Southern portion. At the end of these structures, there are incised channels in the bottom that can be associated with the evacuation of sea water.

5. Influence of Human Activities on the Coastal Morphoevolution

5.1. Historical Activities

The comparison of historical topographic maps of the area (e.g., [18]) allows detection of the genesis and the morphoevolution of a new beach North of the Torre Annunziata harbor, outside of the analyzed physiographic unit and the field identification of longshore sediment transport [36–40]. In particular, in a topographic and bathymetric map of 1865 with a 1:25,000 scale (Figure 4), which was used as topographic base with an early reference the railway station (that was also used for all subsequent maps), the harbor of Torre Annunciata (today Torre Annunziata) was still not present.

A large natural beach is also visible on the map, the Salera, the "Mezza Chiaia" and "La Chiaia" (Figure 5A), a large structure associated with the Sarno River mouth located around the present one, with a large sandy bar to the right site of the mouth, beyond a natural meandering river. In the bottom part of the map, the Castellammare di Stabia harbor is evident, built in 1723, along with the Northern sector of Monti Lattari of the Sorrento peninsula with its waterways (Rivi) at their natural state flowing into the Gulf of Castellammare di Stabia. At present, Rivi and Sarno rivers are regimated and tombed. Historical reports show that the construction of Torre Annunziata harbor started in

1867 and was completed in 1871; the new harbor rested on a modest promontory called La Storta (Figures 5A and 6), which is made up of Vesuvian lithic volcanic deposits of the debris flow type. A historical IGM map which dates to 1906 (Figures 5B and 6) shows the Torre Annunziata harbor for the first time. In this map, a new narrow beach is evident to the NW of the artificial harbor, between the "La Storta" headland and the harbor.

Figure 4. Historical map (year 1865) at a 1:25,000 scale. Please note that the Torre Annunciata harbor (today Torre Annunziata) is not present in the map.

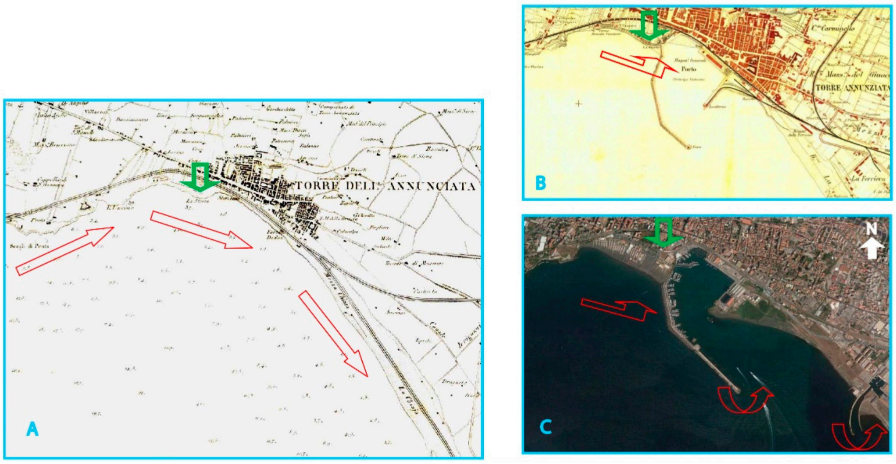

Figure 5. Torre Annunziata coastal area morphoevolution from 1865 to 2018. (**A**) 1865 map: the harbor of Torre Annunziata was not shown on maps yet. The red arrows indicate the direction of longshore currents; the green arrow indicates a promontory called La Storta; (**B**) a historical IGM map from 1906 shows the Torre Annunziata harbor for the first time. Gradually, the sediments carried by NW-SE longshore currents became trapped. A new narrow beach is evident to the NW of the artificial harbor; (**C**) 2018: a wide triangular-shaped beach on the updrift side (NW) of the breakwall of the Torre Annunziata harbor. The red curved arrows indicate the effect of the wave diffraction processes around both the outer breakwaters of the Torre Annunziata harbor and the outer jetty of the Apreamare boatyard. These processes have led to the gradual growth of new triangular-shaped beaches in down drift sides.

The outer harbor breakwater promotes sediment deposition on the updrift side. The gradual development of this beach (Figure 6) is already evident in subsequent historical maps, for example the one dated 1941, and it continues to become larger until 2018 (Figures 5C and 6).

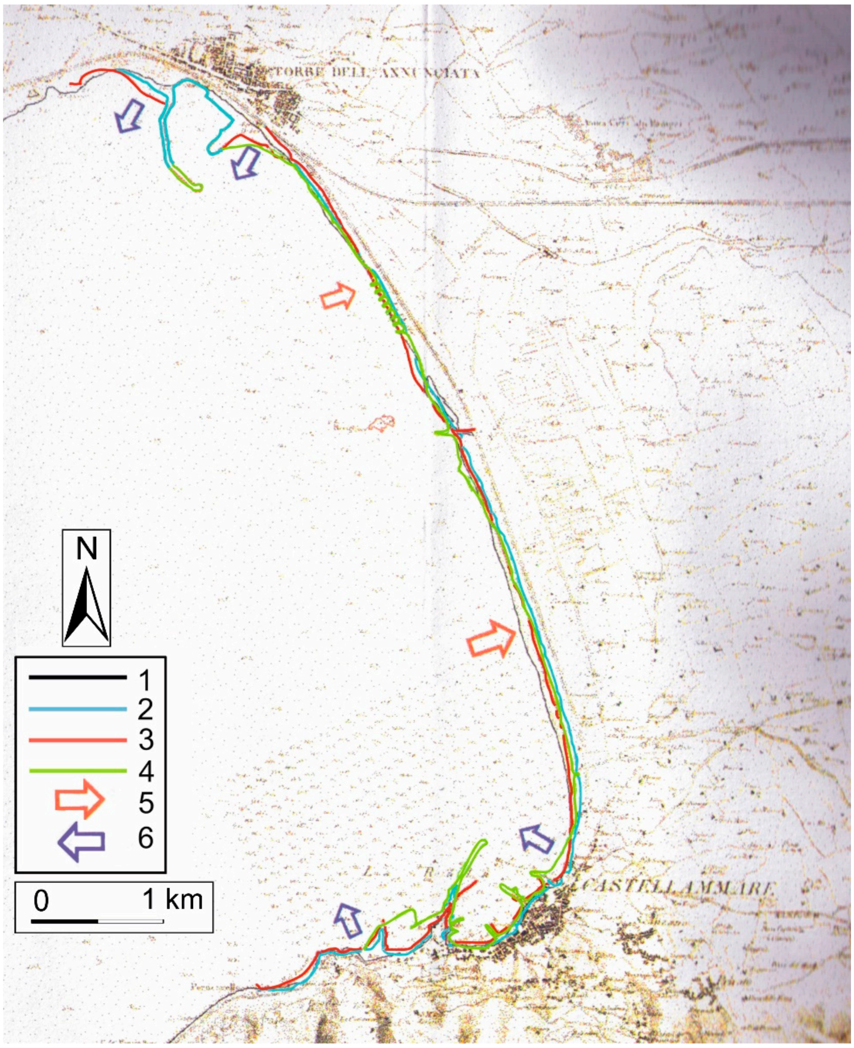

Figure 6. Shoreline evolution from 1865 to 2018. Legend: 1—1865 shoreline before the Torre Annunziata harbor was built; 2—1872/76 shoreline after the Torre Annunziata harbor was built; 3—1941 shoreline; 4—2018 shoreline; 5—erosional beach; 6—progradational beach.

The outer harbor breakwater promotes sediment deposition on the updrift side. The gradual development of this beach (Figure 6) is already evident in subsequent historical maps, for example the one dated 1941, and it continues to become larger until 2018 (Figures 5C and 6).

Recently, the Torre Annunziata harbor caused a radical modification in the natural morphological structure of the coastal zone located to the South, in the Gulf of Castellammare di Stabia, resulting into a general coastal erosion on the downdrift side (Figure 6).

The harbor, located at the Northern edge of the gulf, has strongly modified the longshore sediment transport processes, with direction from NW to SE; in fact it traps the sediments carried by the longshore currents, allowing them to be accumulated in a new wide beach (Figures 3 and 5C), now about 200 m wide (Figure 7), in the updrift area on the North edge of the harbor. This new sandy beach, which is about 150 years old, was built close to a high rocky coast formed by lava deposits and it is affected by progradational processes of approximately 1 m/yr. In fact, it constitutes the point of final delivery of the sediments transported in the physiographic unit that borders to the North the one in object.

The continuous subtraction of drifting sediments trapped by Torre Annunziata harbor has led to a marked coastal erosion in the Gulf of Castellammare di Stabia, located on the downdrift side (Figure 6). This has shaped a first new important morphological structure of this coastline, defined by a concave coast in erosion, surrounded by large beaches protected by the outer breakwater of the Torre Annunziata harbor to the North and by the Castellammare di Stabia harbor to the South. The harbor structures also define and delimit a new physiographic unit.

Figure 7. Panoramic view of the 200 m-wide new sandy beach of the Torre Annunziata showing a triangular shape.

The reduced sedimentary input removed a strong amount of sediments from the sedimentary budget of the Gulf of Castellammare di Stabia, no longer replaceable due to the low solid contribution of the Sarno River, the resurgence river, its tributaries and the Rivi.

Ultimately there is a weak rotation of the shoreline [41] toward the East (Figure 6), to be associated with the general tendency to shoreline retreat with a typical generalized accentuation of the concavity of the shoreline, more marked in the Southern portion and a strong progradation of the beaches, with triangular morphology, at the ends of the gulf (Figures 3 and 6). These wide sandy shores, with a width of about 150 m today, located on the harbor inner breakwaters perpendicular to the coast (Figures 5C, 8 and 9), have accumulated due to the waves diffraction process around the harbors outer breakwaters. The great width of the beaches does not allow their periodic washing by the waves of the sea; this means that dust is accumulated causing the growth of grass.

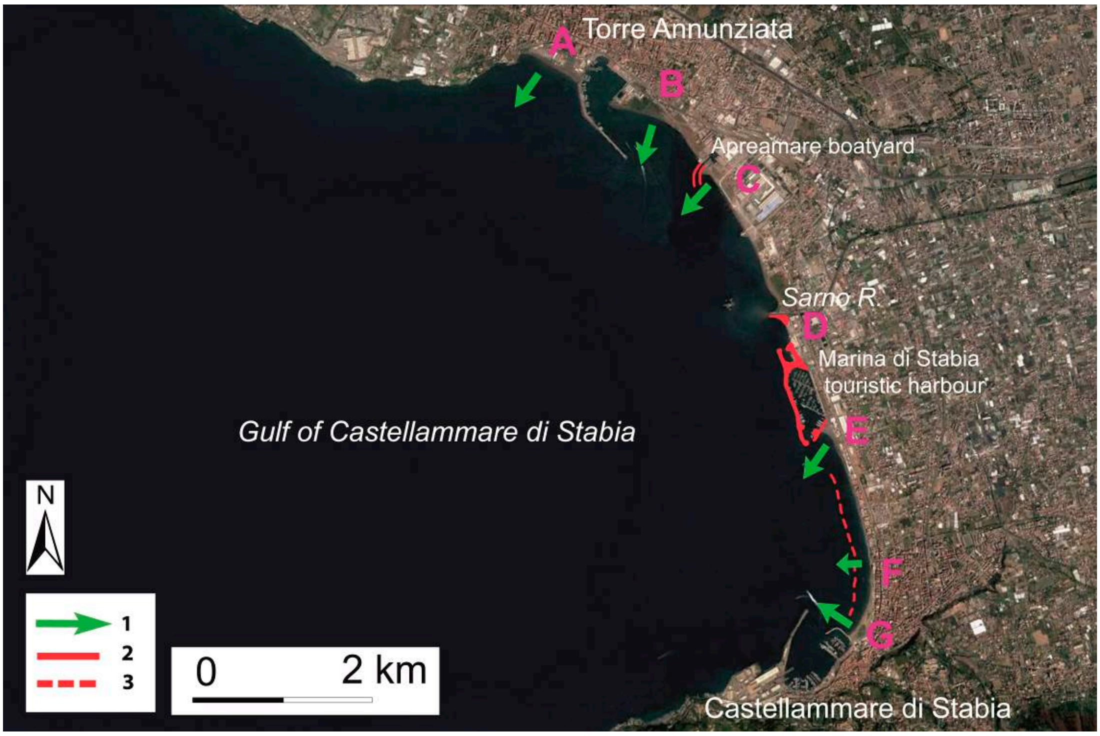

Figure 8. Shoreline response after the built up of coastal engineering works (the letters indicate the stretches of the beach that are under progradation). Legend: (1) progradational beaches; (2) coastal engineering works; (3) detached submerged breakwaters.

Figure 9. Wide triangular-shaped sandy beach of Castellammare di Stabia with a maximum width of about 150 m.

5.2. Recent Activities

Recently coastal engineering, including other human activities, have further conditioned the new morphological setting. To the South of Torre Annunziata harbor, two curved jetties, which were built in about 2005 in defense of the Apreamare boatyard (Figures 2 and 3), caused the growth of a sandy beach—due a waves diffraction process—over 80 m wide (Figures 3, 5C and 8) adjacent to the inner jetty of this stretch of the beach, which was characterized by a historical tendency to erosion before the construction of this structures.

More to the South, in an almost central position, there is the Sarno River mouth, strongly stiffened by two jetties that protrude into the sea and by breakwaters built parallel to the shoreline (Figure 8). They are static features in conflict with the dynamic beach changes and they impede the exchange of sediment between land and sea. In particular, to the North of the mouth, the shoreline retracted about 30 m in the period 1968–1989, due to the construction of the jetty by the right mouth.

South of the Sarno River mouth, there is the new Marina di Stabia touristic harbor (built in 2004) located in correspondence of the area already affected by six detached breakwaters placed before 1956, due to generalized erosive phenomena. Also in this case, the waves diffraction process caused by outer breakwaters of the touristic harbor promotes sediments deposition in a new triangular-shaped beach, adjacent to the inner breakwater, with a maximum width of about 80 m (Figures 3 and 8).

Finally, the outer breakwater of the Castellammare di Stabia harbor, which was extended first between 1936 and 1941 and later in 1970 and in 1990, has promoted sediments deposition due to waves diffraction process adjacent to the inner breakwater. As a result, a wide triangular-shaped sandy beach with a maximum width of about 150 m has been progressively generated (Figures 8 and 9). This beach developed over the old mouth deposits of San Pietro stream. In the submerged beach, the mouth complex partially dismantled by a series of detached submerged breakwaters is visible.

These breakwaters that were placed in about 2000 at a depth of 3–5 m, consist of 9 boulders elements (Figure 3), aimed at containing ongoing erosion processes that were threatening the road system of Castellammare di Stabia town. Furthermore, the erosion had partially uncovered the foundations of a hotel structure on the beach (ex Hotel Miramare, Figure 10A,B). As the original breakwaters were not providing an effective protection, after about ten years, these were reinforced to include up to twelve elements. The subsequent morphological surveys up to 2018 have allowed verification of a weak trend towards the progradation of the beach, now about 20 m width, in addition to a substantial recovery of the beach profile (Figure 10C).

Figure 10. Recent evolution of the beach of the Miramare hotel. (**A**,**B**) the erosion processes had partially uncovered the foundations of the hotel structure. (**C**) weak progradation of the beach, now about 20 m wide.

Finally, the buildings, walls, artefacts, and fences on the back of the beaches strongly limit the natural expansion of the beach towards the inner part, giving the beach an unusual profile with high gradients and sand accumulation near the structures.

6. Morphodynamic of Sediments

The sedimentological study of the physiographic unit (Castellammare di Stabia Gulf) is based on the grain size analysis of 40 samples of bottom sediment and on 12 samples of emerged beach sediment [23]. The analyses, carried out with sieving and pipetting, allowed obtaining of the grain size composition and statistical parameters of [24]. The results are summarized in Table 1.

Table 1. Sediment samples collected along the shoreline and at the sea bottom Castellammare di Stabia gulf. Grain-size data and statistical parameters of the beach and marine sediments according to the graphic method of Folk and Ward (1957): Mz, mean size; σ, sorting; S_{KI}, skewness; K_G, kurtosis, and related textural group. Depths are expressed in meters and they refer to current mean sea level.

Sample	Depth (m)	Gravel	Sand	Mud	Mz	σ	K_G	S_{KI}	Classification
10	0	0	100	0	2.19	0.42	1.09	−0.07	fine sand
11	0	0	100	0	2.23	0.39	1.08	−0.04	fine sand
36	0	0	99.97	0.03	2.32	0.42	1.11	−0.08	fine sand
90	0	0	99.99	0.01	1.5	0.49	1.11	0.02	medium sand
93	0	3.9	96.1	0	−0.35	0.33	1.05	−0.05	very coarse sand
95	0	29	99.71	0	0.66	0.38	1.26	−0.01	coarse sand
96	0	0	100	0	−0.02	0.33	1.05	0.08	very coarse sand
97	0	0.7	99.28	0.02	0.53	0.71	1.43	0.24	coarse sand
98	0	0	99.95	0.05	2.04	0.48	1.25	−0.04	fine sand
99	0	0.18	99.82	0	1.65	0.71	0.86	−0.15	medium sand
100	0	10.99	88.54	0.47	1.23	1.69	0.72	−0.15	medium sand
179	−5	0	93.46	6.54	2.67	0.25	−1.19	0.77	fine sand
180	−6.5	0	93.79	6.21	2.65	0.27	−1.23	−0.2	fine sand
181	−7.9	0	65.05	34.95	2.99	0.79	2.14	−0.3	fine sand
182	−9.5	0	94.95	5.05	2.6	0.44	6.68	−0.29	fine sand
183	−12.5	0	100	0	2.35	0.55	13.01	−0.08	fine sand
184	−15	0	93.6	6.4	2.45	0.7	0.87	0.09	fine sand
185	−4	0	99.81	0.19	1.38	0.42	1.25	−0.22	medium sand
186	−7	0	99.07	0.93	1.57	0.42	22.02	0.41	medium sand
187	−8.5	0	81.24	18.76	2.9	0.85	0.67	0.11	fine sand
188	−11	0	67.8	32.2	3.17	0.68	1.21	0.26	very fine sand
189	−14	0	67.42	32.58	3.37	0.64	1.36	0.71	very fine sand
190	0	0.11	99.87	0.02	1.45	0.65	0.89	0	medium sand
191	0	0.51	99.44	0.04	0.45	0.74	0.77	0.45	coarse sand
192	−1	0	99.95	0.05	1.35	0.35	1.52	1.94	medium sand
193	−3	0	93.66	6.34	2.62	0.6	1.48	−0.21	fine sand
194	−5.1	0	90.01	9.99	2.66	0.88	1.29	0.35	fine sand
195	−10	0	70.26	29.74	3.03	0.96	0.85	0	very fine sand
196	0	0	93.88	6.12	2.29	0.74	1.23	0.5	fine sand
197	−18.7	0	63.04	36.96	3.45	0.68	3.92	0.26	very fine sand
198	−1.2	0	81.17	18.83	3.15	0.52	1.2	−0.39	very fine sand
199	−4	0	79.58	20.42	2.96	0.8	0.82	−0.5	fine sand
200	−6	0	51.12	48.88	3.2	0.99	1.11	−0.49	very fine sand
201	−9.5	0	77.89	22.11	3.02	0.93	1.4	0.4	very fine sand
202	−12	0	86.03	13.97	2.56	0.95	1.55	0.06	fine sand
203	−13.9	0	77.65	22.35	3.06	0.88	0.76	−0.28	very fine sand
204	−16	0	78.42	21.58	2.79	1.05	0.76	−0.21	fine sand
205	0	1.15	98.85	0	0.51	0.83	0.83	0.54	coarse sand
206	−1	0.02	99.94	0.04	1.59	0.71	0.85	0.05	medium sand
207	−5.1	0	88.91	11.09	2.92	0.43	20.66	1.12	fine sand
208	−10.2	0	92.03	7.97	2.72	0.52	−14.23	−0.74	fine sand
209	−17.2	0	94.51	5.49	2.81	0.37	−2.16	0.89	fine sand
210	0	0.16	99.82	0.02	1.44	0.66	0.95	0.03	medium sand
211	−1	1.96	97.36	0.68	1.44	1.21	0.63	−0.49	medium sand
212	−6.8	0	93.81	6.19	2.18	1.14	0.67	−0.44	fine sand
214	−19	0	91.02	8.98	2.8	0.75	2.55	0.46	fine sand
215	−1	0	99.13	0.87	2.07	0.14	−0.56	0.19	fine sand
216	−4.8	0	95.44	4.56	2.37	0.64	16.12	−0.35	fine sand
217	−11	0	88.2	11.8	2.92	0.51	3.7	0.03	fine sand
218	−16.4	0	80.87	19.13	2.98	0.39	1.07	−2.64	fine sand
219	−18.7	0	85.16	14.84	2.81	0.88	1.15	−0.31	fine sand

The sampling station location is shown in Figure 11, while the areal distribution of the mean grain size (Mz), up to a depth of 20 m, is shown in Figure 12. All the maps are created on geo-referenced bathymetric map with geographic coordinates according to the WGS 84 UTM System.

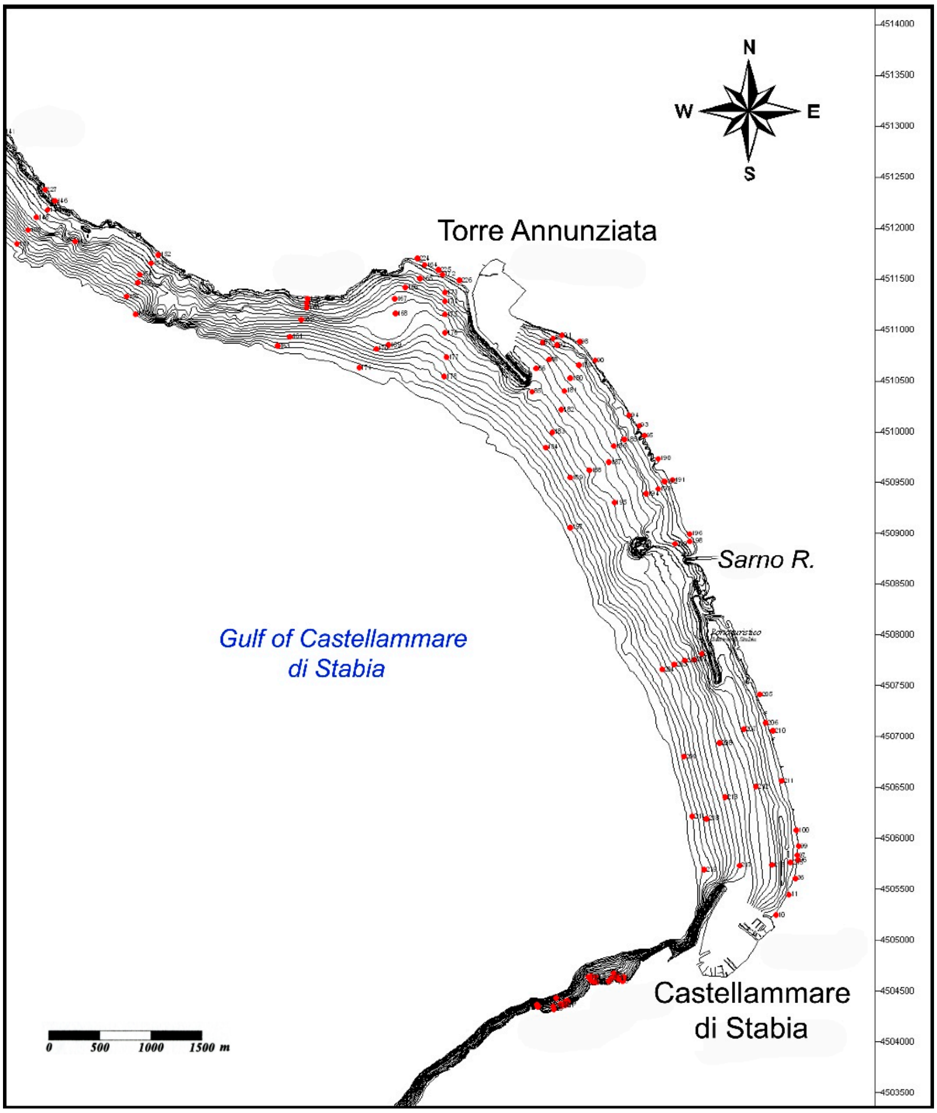

Figure 11. Location of sampling sites; isobaths: 1 m interval.

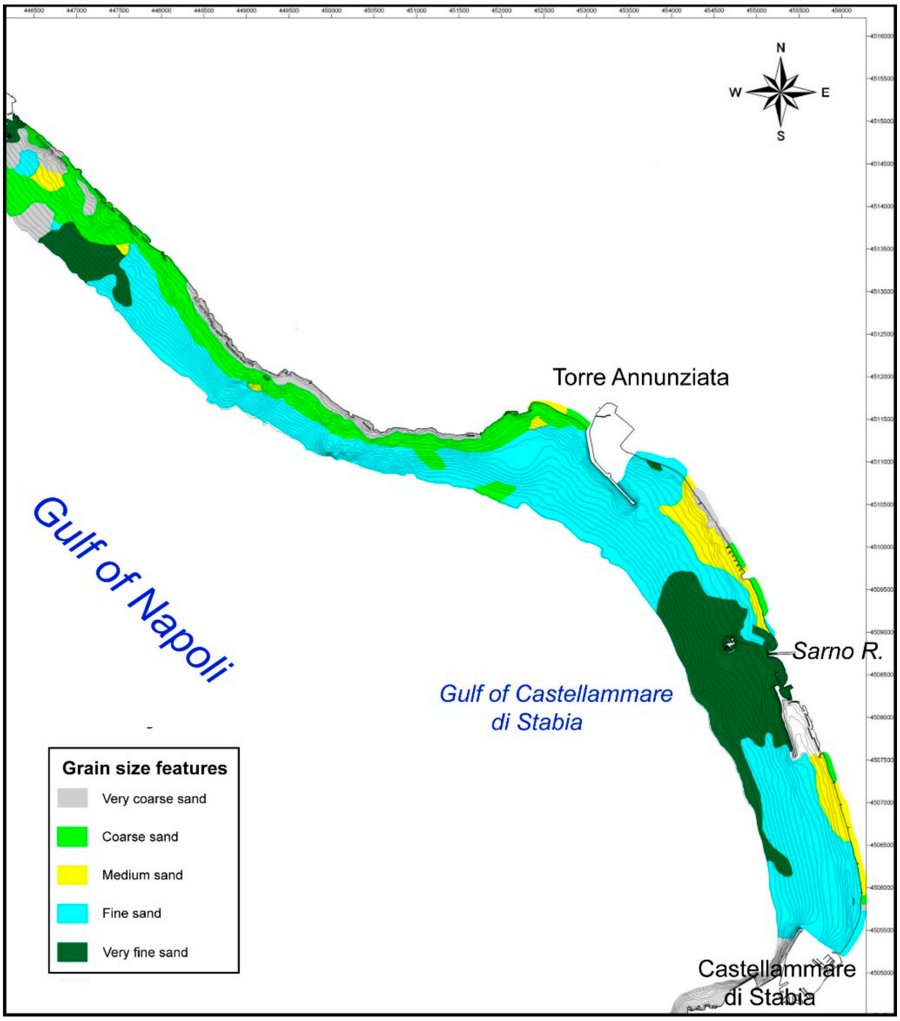

Figure 12. Grain size features of sediments and zonation within a 20 m depth.

Therefore, for the physiographic unit stretch placed to the North of the studied area, it has been found that the grain size fractions that most effectively contribute to the sedimentary dynamics of the area consist of 25% coarse sand (0.89–0.56 mm grain size range), of 45% medium sand (grain size between 0.43 and 0.25 mm) and fine sand (0.24–0.14 range). Instead in the physiographic unit of interest, the grain size fractions consist of 10.29% very coarse sand (range between 1.67 and 1.07 mm), of 23.53% coarse sand (range between 0.9 and 0.51 mm), of 16.18% medium sand (grain size range between 0.43 and 0.25 mm) and of 38.24% fine sand (grain size range between 0.24 and 0.13 mm).

These results were used to plot the sedimentary transit axes maps along the entire coastline (Figure 13). The longshore currents movement of the three subpopulations in the areas near the coast, within the 10 m bathymetric, appears to be, overall, from NW to SE, both in the physiographic unit to the North of Torre Annunziata harbor and in the physiographic unit of Castellammare di Stabia Gulf.

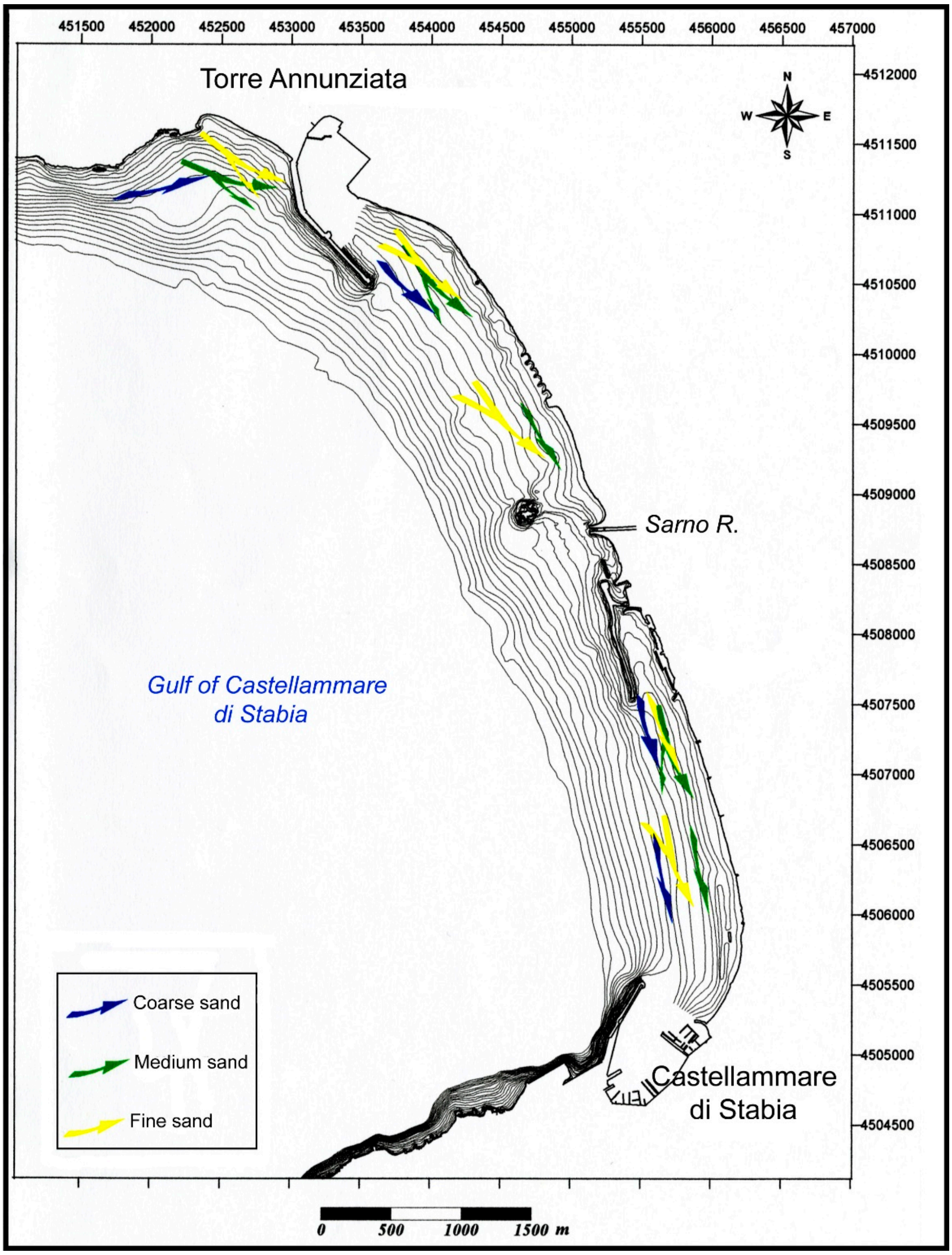

Figure 13. Vector axes of the main direction of sediment transport along the Gulf of Napoli and Castellammare di Stabia coast.

Therefore, also the results of such analyses allowed confirmation of the sediment transport model we identified thanks to historical maps analysis.

Finally, the data of the main wind direction and the main climate events were acquired from the [25]. The resulting vector of the offshore energy flows is oriented in the direction 258.29° N (Figure 14). The resulting directions of the wave energy flows near the coast are: North of Sarno River 247.06° N, near the mouth of the river 254.44° N and South of Sarno River 262.90° N. Having verified the NW–SE orientation of the coastal stretch, it has been inferred that the incidence of wave approach on the coast is mainly orthogonal. The results of these simulations allowed us to believe in the genesis of a longshore current going South, due to main climate events generated current from about the 260° N direction.

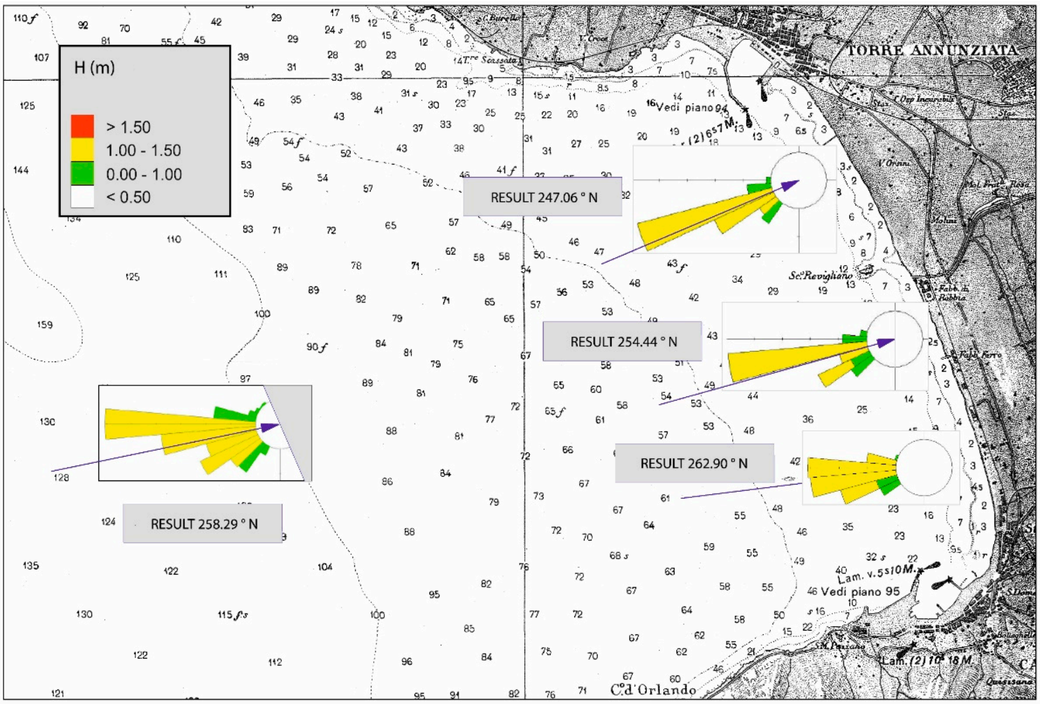

Figure 14. Results of hydrodynamics and wave patterns (from [25]).

7. Conclusions

Morphological research, analysis of historical maps and analysis of sedimentological characteristics of bottom sediments carried out along the area on Neapolitan coast enabled to define the processes and their evolution in time and space. The results of this study have allowed verification that the predominant longshore current direction and sediments transport along the coast of Napoli Gulf (southern Italy) happens from Northwest to Southeast. Indeed, the Torre Annunziata artificial harbor acts as a dam to littoral drift, blocking the sediment movement along the Neapolitan coast and causing a significant shoreline retreat on the down-drift side, which is in the coastal stretch which extends from Torre Annunziata to Castellammare di Stabia. Also, meteo-marine and anemometric results revealed that the predominant wave direction from W sector is responsible for the generation of longshore southward current.

This work determined that the natural morphology of the coast of Castellammare di Stabia Gulf was intensely altered by the construction of the Torre Annunziata harbor, which was completed in 1871. The harbor was built near the northern edge of the Gulf, intensely altering the sedimentary morphodynamic of the nearby physiographic unit, oriented NW-SE. The structure of the harbor now traps the sediments carried by the longshore currents, causing deposition North of the outer breakwater area (on the updrift side of the structure) and a genesis of a new beach which is currently growing. Consequently, the coastal system of the Gulf di Castellammare located down drift side is now being intensely marked by erosional processes. The new morphology of the shoreline is made of a large arch currently eroded and delimited at the ends by wide beaches protected by breakwalls of two harbors: Torre Annunziata on the Northern side, and Castellammare di Stabia on the Southern side. The erosional processes are more intense on the South side of the arch, while the triangular-shaped beaches developed gradually thanks to progressive extension of the outer breakwaters. Lastly, it weak Eastward rotation of the shoreline related to its retreat can be detected.

Further structures were built on this new morphology, causing further modifications of the emerged and submerged beaches. Between 2003 and 2006 new structures were built perpendicularly to the direction of the waves, causing the formation of new beaches, which are connected to the alteration of the beach drift. The morphology of the coast has also been altered by the construction of structures aimed at protecting the shoreline, draining channels, and seawalls. The area of the dunes located on the back of the shores has been intensely modified, with the construction of industrial and residential complexes which block access to the beaches but also to the sediments supply.

The human activity has also modified the morphology of the submerged beach, causing both deposition and erosion with the genesis of channels incising the bottom.

The lower basin of the Sarno River and the overlooking shoreline have been intensely modified by human development, both agricultural and industrial, with alterations of the river bed, flow, banks, and the enclosure of its path in urban areas.

This work on the morphological evolution of the coast of Castellammare di Stabia Gulf during an intense phase of human development shows that the latter clearly prevailed over the natural forces, and it highlights that, when examining a coastal area, it is of paramount importance to focus on the onset and the climax of local human development. Late phases of development are usually comparatively less relevant; however, they still need to be examined within the evolutional framework of the whole area. The study area represents an indicative example of a highly-urbanized coast in which human impact and the construction of a port have dramatically changed the long-term natural evolution and the longshore sediment distribution. Similar results have been obtained by scientists in different parts of the world [1,4,19,38,42,43] and suggest the crucial role of morphosedimentary data in coastal management plans.

Conflicts of Interest: The authors declare no conflict of interest.

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