Journal of
Marine Science and Engineering

MDPI

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Shoreline Changes Due to the Construction of Ports: Case Study—Calabria (Italy)

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Abstract: An important process that began in many Mediterranean countries in the last century, after the end of the Second World War, concerns the displacement of a large part of the population from inland to coastal areas, expanding many existing cities and building new ones. Following this expansion, some existing ports were expanded, and many new ports were built, mainly for commercial and tourist purposes. This strong anthropogenic pressure has modified not only the landscape but also the coastal dynamics, and significant shoreline erosion processes have often been observed, even at considerable distances from the ports. This paper analyzes shoreline changes due to the construction of ports in Calabria, based on geomorphological factors and wave forcings. Calabria is a region of Southern Italy, on the Mediterranean Sea, that is characterized by geomorphological, climatic, and anthropic peculiarities. In addition, other important effects caused by the construction of ports were also analyzed, such as shoreline advancement updrift, construction of coastal protection structures, siltation, and anthropogenic pressure. The main finding of this analysis is that coastal morphology plays a key role in the extent of shoreline changes due to the construction of ports. In fact, the greatest shoreline retreats were observed downdrifts of ports built in straight coastal areas. Furthermore, this analysis highlights that there is no direct correlation between wave climate and shoreline changes near the examined ports. The analysis described in this paper may be of interest both to the scientific field and to the planning and management of coastal areas. Furthermore, it is based on open-access data and was carried out using free software such as QGIS, so it is easily replicable and applicable in any coastal context.

Keywords: shoreline erosion; anthropogenic pressure; port; remote sensing; Calabria

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Citation: Foti, G.; Barbaro, G.; Barillà, G.C.; Mancuso, P. Shoreline Changes Due to the Construction of Ports: Case Study—Calabria (Italy). *J. Mar. Sci. Eng.* **2023**, *11*, 2382. https://doi.org/10.3390/jmse11122382

Academic Editors: Niki Evelpidou, Anna Karkani and Miltiadis Polidorou

Received: 5 November 2023
Revised: 13 December 2023
Accepted: 15 December 2023
Published: 18 December 2023

1. Introduction

Generally, a port allows the exchange of people and goods, contributing to the socio-economic development of its territory. Historically, ports have been built on the Mediterranean Sea since the third millennium BC [1].

Since the end of the Second World War, many areas of the Mediterranean have been affected by a process of displacement of a large part of the population from inland to coastal areas [2,3], expanding many existing cities and building new ones, often substituting dune systems and coastal and river areas [4–15]. This strong anthropogenic pressure has caused the expansion of numerous existing ports and the construction of numerous new ports and has also modified not only the landscape but also the coastal dynamics, causing shoreline advancement on their updrift side and triggering shoreline erosion processes on their downdrift side, even at considerable distances from the ports [16–27]. These equilibrium conditions can also be altered by natural factors, the main ones being the wave climate and the balance between river and longshore sediment transport [28–37].

Another important effect of these anthropogenic pressures concerns the increase in vulnerability of coastal areas to natural hazards such as floods and sea storms [38], whose effects are amplified in the case of compound events [39–41] and can cause significant critical issues in the case of ports located near river mouths.

To improve the design phases of both new ports and the expansion of existing ports, it is very important to consider the effects induced by the port itself on the neighboring coasts. From this point of view, both the use of morphodynamical models and the analysis of case studies can be particularly useful. In the latter case, the availability of good quality historical and current cartographic data is important [42–46]. Through these data it is possible to obtain the shoreline position, through remote sensing and GIS (Geographical Information Systems) techniques. The shoreline position can be obtained manually, through photointerpretation, or automatically, through extraction algorithms [47–51]. In addition, starting from the knowledge of the shoreline positions over several years it is possible to estimate the relative changes [52–63].

The paper analyzes shoreline changes due to the construction of ports in Calabria, based on geomorphological factors and wave forcings, evaluating not only the shoreline changes but also other important effects such as shoreline advancement updrift, construction of coastal protection structures, siltation, etc. In the following paragraphs, the geomorphological, climatic, and anthropic peculiarities of the Calabria region will first be described. Methodology, results, and discussion will then be described.

2. Materials and Methods

2.1. Site Description

Calabria is a region of Southern Italy, on the Mediterranean Sea (Figure 1). It is an interesting case study from many points of view, including the geomorphological, climatic, and anthropic ones.

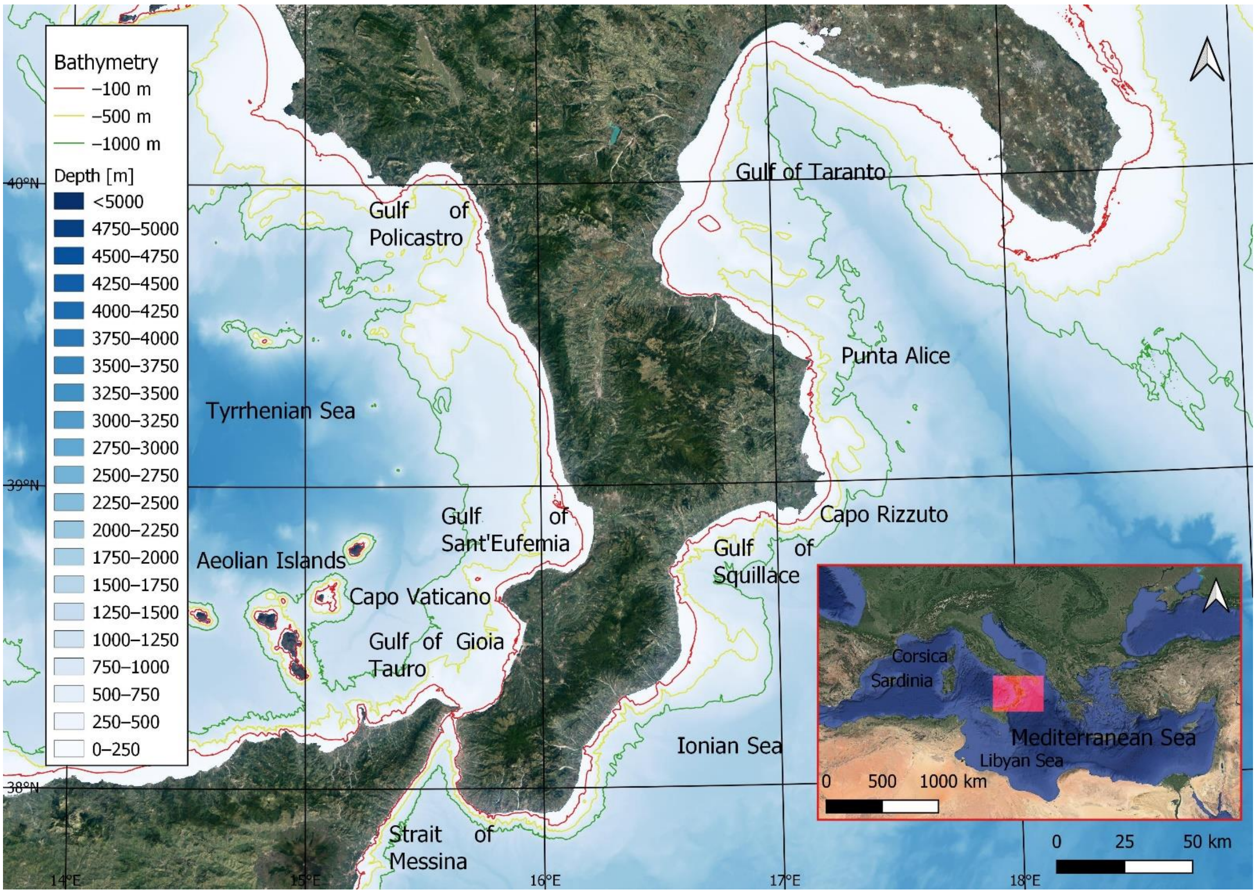

Figure 1. Calabria region (**large panel**) and its geographical position at the center of the Mediterranean Sea (**small panel**).

Indeed, regarding the geomorphological peculiarities, Calabria has a peninsula shape with a predominance of mountains and hills, accounting for over 90% of the territory, and the remaining part being flat. The coast is mainly characterized by sandy and pebbly beaches and by headlands. The mountain massifs are present throughout the region, and the main ones are Pollino, in the northern part on the border with the Basilicata region, Sila, in the central part, and Aspromonte, in the southern part. Pollino is the only massif that exceeds 2000 m in altitude, while the other two massifs have a maximum altitude of just under 2000 m. Another important massif is the Catena Costiera, located in the central-northern part of the region, not far from the Tyrrhenian Sea, and characterized by a maximum altitude of just over 1500 m. Other parts of the region are also characterized by reliefs very close to the sea, especially on the Tyrrhenian coast.

Due to its peninsula shape, Calabria has a considerable coastal length, over 700 km, overlooks two seas, and has an irregular morphology due to the presence of gulfs, headlands, and straits. The western coast is bathed by the Tyrrhenian Sea, and it contains three main gulfs: Policastro, Sant'Eufemia, and Gioia Tauro, in the northern, central, and southern parts, respectively. Between these last two gulfs there is the headland of Capo Vaticano. The eastern coast is bathed by the Ionian Sea, and it contains two main gulfs, Taranto and Squillace, in the northern and central parts, respectively. Between these two gulfs there are the headlands of Punta Alice and Capo Rizzuto. The two seas are connected by the Strait of Messina, which is in the southern part of Calabria, near the north-eastern part of Sicily. This irregular coastal morphology causes notable differences between the various coastal areas in terms of wave climate, fetch, and bathymetry, both at a macro-area level (Ionian and Tyrrhenian coasts) and at a smaller scale [64]. The Tyrrhenian macro-area is exposed to wave climate coming from the fourth quadrant (between the west and the north) and is characterized by fetch lengths up to over 700 km and depths up to approximately 4000 m, with slopes generally between 2 and 5%. Instead, the Ionian coast is exposed to wave climate coming from the first, second, and third quadrants (between north-east and south-west) and is characterized by fetch lengths up to over a thousand kilometers and depths up to 5000 m deep, with slopes generally less than 2%. With an observation scale at the level of gulfs and main straits, it is observed that the Gulf of Taranto and the Strait of Messina differ significantly from the related macro-areas. The first is directly exposed only to the wave climate coming from the east and south-east and is characterized by internal fetch lengths up to around 150 km and depths up to 1500 m ca. The Strait of Messina is directly exposed only to the wave climate coming from the south and south-west and is characterized by internal fetch lengths up to around 30 km and depths up to 2000 m, with slopes often exceeding 10%. Other significant differences compared to the relative macro-areas are observed in the Gulf of Policastro, shielded from the wave climate coming from the north, and in the Gulf of Gioia Tauro, partially covered from the wave climate coming from the east by the presence of the Aeolian Islands.

This geomorphological complexity also causes considerable climatic variability between mountainous areas, characterized by a mountain climate, and coastal areas, characterized by a Mediterranean climate. This climatic variability is also evident between the two coasts. Indeed, the highest temperatures are observed along the Ionian coast, while the highest rainfall is observed along the Tyrrhenian coast. Furthermore, precipitation is mainly concentrated in the autumn and winter seasons. Another climatic peculiarity concerns the sea temperature, with values generally between 26 °C in the summer, 14 °C in the winter, and high values also in the autumn months of the order of 22–23 °C. These high values in the autumn season are one of the factors generating atmospheric disturbances that, in the most intense conditions, resemble hurricanes, hence the name Medicane (Mediterranean hurricane) or even TLC (tropical-like cyclones). An example of a Medicane is that of autumn 2015 in Bruzzano, on the southern Ionian coast [41]. This climatic variability, together with the geomorphological peculiarities mentioned above, leads to a notable variability in sea and weather conditions between the various Calabrian coastal areas.

From an anthropic point of view, over the last 70 years, a notable expansion of anthropized areas has been observed, caused by the displacement of a large part of the population from inland areas towards coastal areas [2,3]. The main effect of this expansion is a notable increase in inhabited centers. All of this often happened in a disorganized and unplanned manner and by means of constructing buildings and infrastructures in place of dunes and coastal and river areas. This process was observed, above all, along the northern Tyrrhenian coast [65–68].

2.2. Methodology

This paper analyzes the shoreline changes due to the construction of ports in Calabria. This analysis was divided into the following four phases and was carried out using the QGIS software version 3.10 'A Coruna':

1. Acquisition of historical and current cartographic data (shapefiles, cartography, and satellite imagery).
2. Digitization of the shorelines.
3. Classification of the shoreline changes.
4. Analysis of the shoreline changes due to the construction of ports.

The first phase was developed starting from the shapefiles of the shorelines of 1954, 1998, 2000, and 2008, taken from the Open Data section of the Calabrian Geoportal (http://geoportale.regione.calabria.it/opendata, accessed on 15 June 2023), the orthophotos of 1989, 1996, 2006, and 2012 taken from the Open Data section of the Italian Geoportal (http://www.pcn.minambiente.it/mattm/servizio-wms/, accessed on 15 June 2023), and Google satellite imagery, provided by Google Earth Pro. Google satellite images have been available since the beginning of this century; the coverage varies from one location to another, but, from 2015 to today, the coverage is generally annual or biennial.

Regarding the first two phases, it should be highlighted that the historical shorelines photos taken from the Calabrian Geoportal are available directly in a shapefile format, while, for all the other cartographic sources (orthophotos from the Italian Geoportal and satellite images from Google), it was necessary to carry out manual digitization using QGIS for the orthophotos and Google Earth Pro for the Google Satellite images.

In detail, the shorelines of the Calabrian Geoportal were obtained starting from CASMEZ, "*Cassa del Mezzogiorno*", cartography from 1954, in a scale of 1:10,000, on CTR, "*Carta Tecnica Regionale*", cartography of the years 1998 and 2000, both in a scale of 1:5000, and on the infrared orthophotos from 2008, in a scale of 1:5000. Instead, regarding the manually digitized shorelines, the reference line chosen was the wet/dry line that closely approximates the high-water line (HWL) [52]. The shorelines of the years 1989 and 1996 were obtained starting from orthophotos in black and white, acquired with a Leica RC30 digital camera and in a scale of 1:10,000; those of the years 2006 and 2012 were obtained starting from orthophotos in color, acquired with a Leica AD40 digital camera and in a scale of 1:10,000. All these shorelines have since been digitalized on QGIS in a scale of 1:1000. In addition, the manual digitization based on Google satellite imagery was carried out on Google Earth Pro using its spatial analysis tools at an eye altitude of 200 m, corresponding to a scale greater than 1:1000. These shorelines were initially saved on Google Earth Pro as kml files, subsequently imported into QGIS, and then saved as shapefiles.

The manual digitization procedure is characterized by uncertainties, especially about georeferencing error, scanning error related to orthorectification processes, and physical error related to the position of the shoreline based on phenomena such as tidal range and impact of sea storms [69,70]. These uncertainties were quantified following Del Rio and Garcia [71]. Regarding the georeferencing error, the baselines and the control points were drawn in correspondence with fixed points such as structures and infrastructures that identify the upper limits of the beaches or in correspondence with dune systems in cases where these fixed points were not present near the beach. With this choice, the error was contained within a few tens of cm. About the scanning error, it is of the order of a meter for scales of 1:1000. Regarding the physical error, the formula of Allan et al. [72]

was used to estimate it. This formula depends on beach slope, average values of tide height, and maximum values of tide height. The estimate of the tidal values was carried out starting from tide gauges recordings and literary [73] and scientific sources [74]. In the study area, there are only two tide gauges, near Crotone, in the Ionian Sea, and near Reggio Calabria, in the Strait of Messina. In both gauges, the average values are less than 50 cm; the minimum values are less than −70 cm, and the maximum values are less than 80 cm. Consequently, Calabria is a microtidal environment. Regarding the beach slope, it was estimated starting from the 1 m side square mesh LIDAR DTMs available on the Italian Geoportal (http://www.pcn.minambiente.it/mattm/, accessed on 15 June 2023) through the QGIS Profile tool plugin, obtaining values between 5 and 15%. Consequently, a physical error can vary from a few centimeters up to a maximum of 15 m depending on the beach slope and on the tidal conditions at the passage of the satellite. The maximum value of this error can occur in the case of gently sloping beaches and the passage of the satellite coinciding with high-tide condition. However, by not knowing the exact time of the passage of the satellite, it is not possible to accurately estimate this error. Therefore, uncertainties are generally of the order of a meter, and, thus, both the shoreline position and its changes were approximated to the order of a meter. These uncertainties are in agreement with the main aim of this paper, which does not concern the precise quantification of shoreline changes but focuses on the evaluation of the effects caused by the construction of a port on the neighboring coast in terms of shoreline advancement and retreat intensity.

About the third phase of our analysis, the shoreline erosion intensity was evaluated along some transects traced where the greatest shoreline movements were observed and was classified considering the maximum values of shoreline retreat and advancement, using a scale with four classes. For the shoreline retreat the classes were as follows: slight, for maximum values of up to 20 m; moderate, for maximum values of between 20 and 50 m; intense, for maximum values of between 50 and 100 m; severe, for maximum values exceeding 100 m. For the shoreline advancement the classes were the same as the previous ones. In addition, the percentage of shoreline erosion was also evaluated, comparing the width of the pre- and post-port beach in correspondence with the transects where the maximum shoreline retreats had been observed.

In the last phase of our analysis, the shoreline changes due to the construction of the ports were evaluated by analyzing various geomorphological factors and wave forcings and carrying out a temporal analysis. Regarding the geomorphological factors, the type of coast (for example straight, bay, etc.), the type of sediment characterizing the beaches near the ports, and the depth at the head of the breakwater updrift were analyzed. The type of sediment was evaluated based on a technical report that shows data regarding the Calabrian coast [75], in accordance with the Wentworth grain size classification [76], while the depth at the head of the breakwater updrift was estimated based on the Navionics Chart Viewer (https://webapp.navionics.com/#boating, accessed on 15 November 2023). Regarding the wave forcings, the wave climate was evaluated starting from the research of Foti et al. [64] in terms of maximum significant wave height ($h_{s,max}$), average significant wave height ($h_{s,av}$), difference between the significant wave height of a return period of 1 year and the significant wave height of a return period of 100 years (Δh_{1-100}), average annual energy flux (ϕ), main sector (MS), and angle between the main sector and the coast in the absence of the port (α). Finally, the temporal analysis covered the period of construction of the ports, coastal protection structures, and siltation.

3. Results

In Calabria, there are twenty-six ports, on average one every 30 km of coast. Regarding the location, most of them, twenty-three out of twenty-six, were built along the coast, while the other three ports, Sibari, Corigliano, and Gioia Tauro, are inland and present a mouth which is protected by jetties (Figure 2). Furthermore, eleven ports are located on the Ionian coast, including those of Sibari and Corigliano; eleven ports are located on the Tyrrhenian coast, including that of Gioia Tauro, and four are in the Strait of Messina.

From a temporal point of view, six ports were built before 1954, and eleven ports were built between 1954 and 1989. Of the remaining nine ports, three were built between 1989 and 1996, four between 2000 and 2006, and the other two were built between 2008 and 2012.

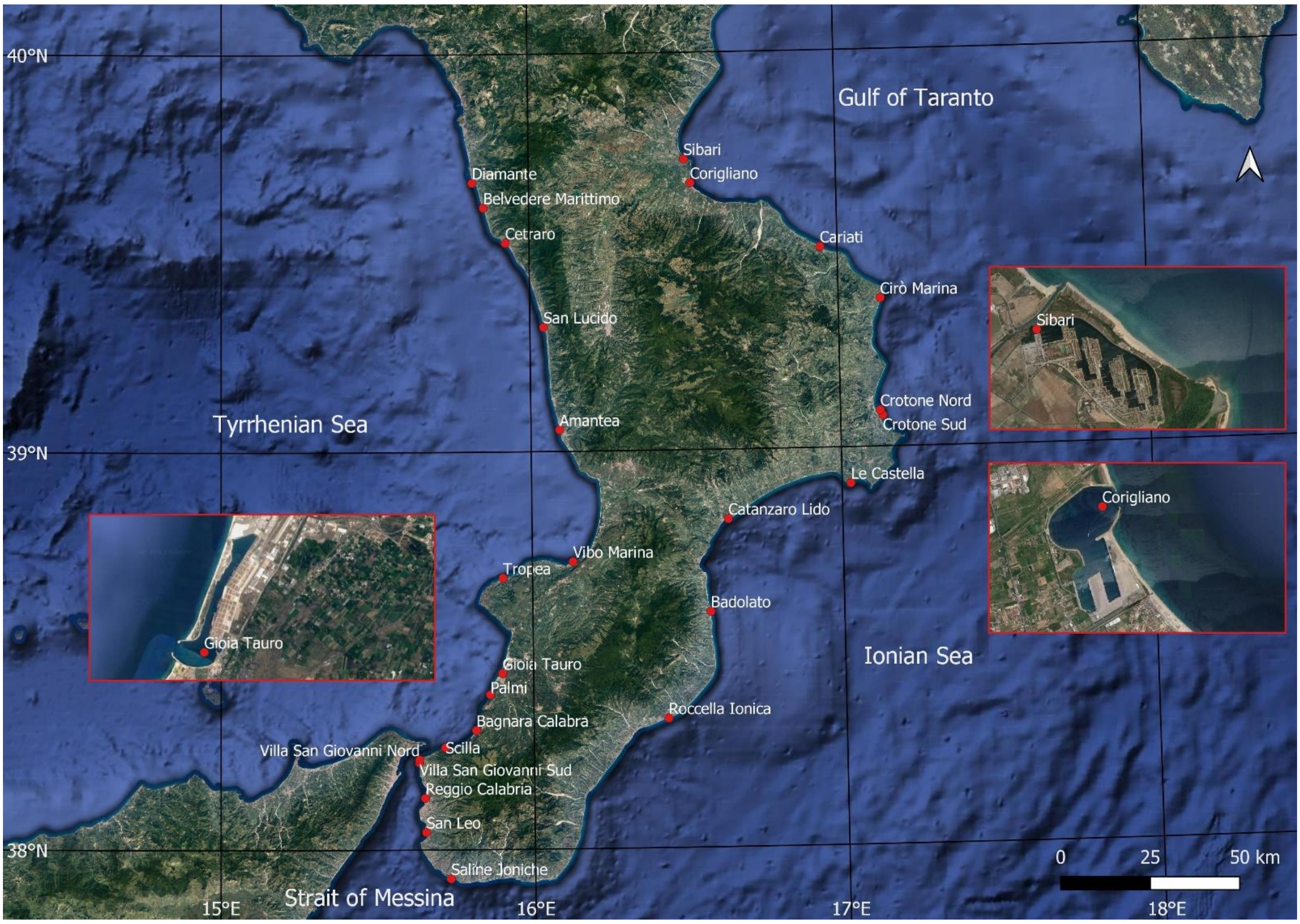

Figure 2. Location of the Calabrian ports.

The analysis focused only on the 23 ports built along the coast, identified with suffixes I for the ports on the Ionian Sea, S for the ports of the Strait of Messina, and T for the ports of the Tyrrhenian Sea, followed by increasing numbers in a clockwise direction (Figure 3). Of these ports, seven were built in straight coastal areas; thirteen ports were built in bays; one port was built on ahigh coast, and two were built within coastal protection structures. Regarding the type of beach sediments, our analysis highlighted that the majority of the Calabrian coast is characterized by a coarse grain size and that the beaches close to the analyzed ports are characterized by the following: medium sand in two cases, coarse sand in five cases, very coarse sand in two cases, sand and cobbles in six cases, pebbles and coarse sand in three cases, pebbles and very coarse sand in two cases, pebbles and cobbles in two cases, and boulders in one case (Table 1). Therefore, for the three ports built on a high coast and within coastal protection structures, it was not possible to estimate the impacts of port construction in terms of shoreline changes. However, for a further seven ports, for a total of ten out of the twenty-three ports considered, it was not possible to estimate these impacts either, as four ports were built before 1954, the year for which the oldest cartographic source is available, and the other three were built in heavily anthropized coastal areas without beaches. Instead, for 13 out of the 23 ports, it was possible to estimate the impacts of port construction in terms of shoreline changes (Table 2). However, in three of these thirteen ports, it was possible to evaluate only the shoreline retreat. In fact, the updrift stretches of the ports of Crotone nord, Bagnara Calabra, and Tropea were built on headlands so there was no updrift beach. Of the thirteen ports, only in Saline Joniche, Catanzaro Lido, and Bagnara Calabra the depth at the head of the breakwater updrift was greater than 10 m, with the maximum value in Saline Joniche equal to 17 m.

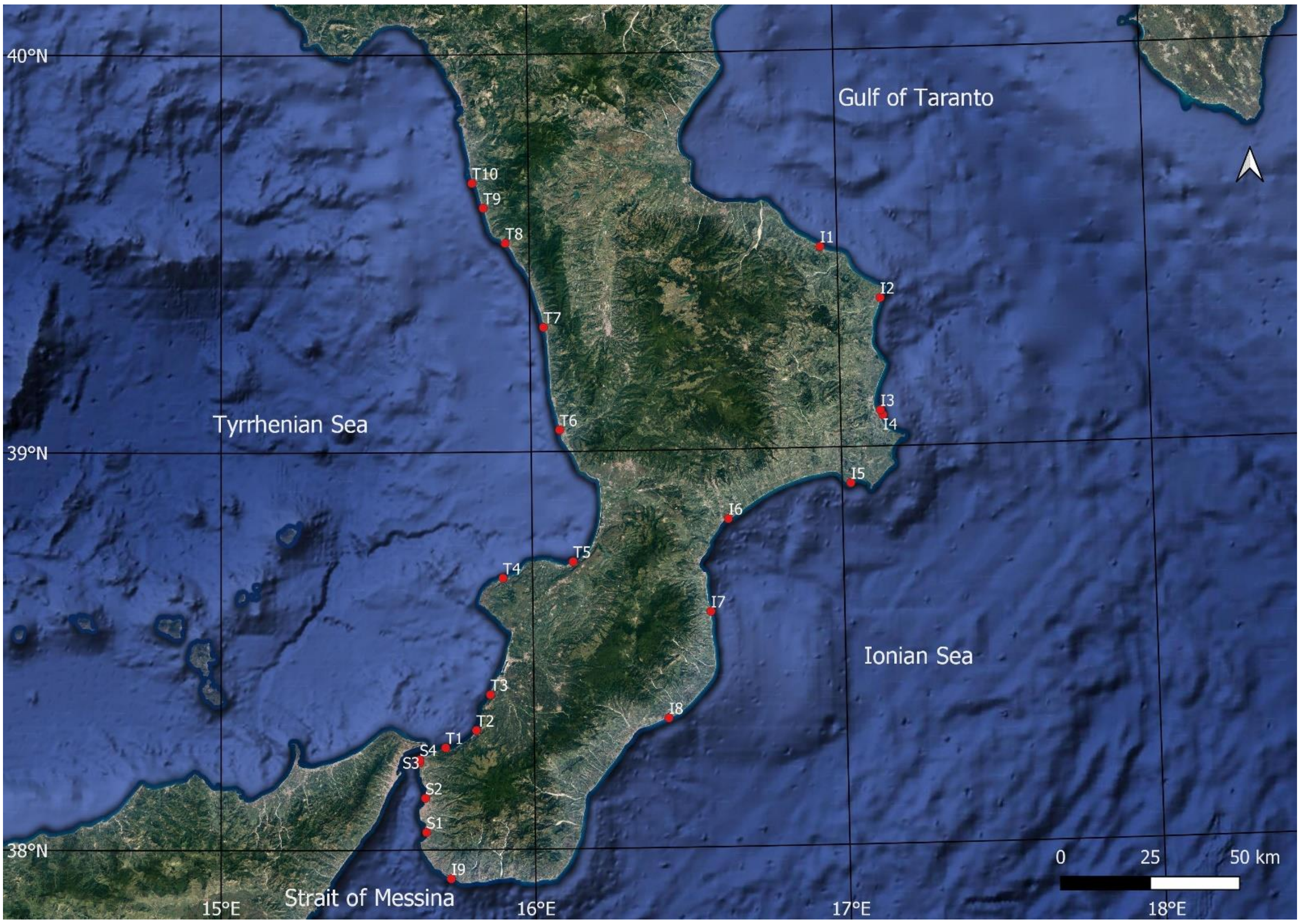

Figure 3. Calabrian ports analyzed, identified with suffixes I for the ports of the Ionian Sea, S for the ports of the Strait of Messina, and T for the ports of the Tyrrhenian Sea, followed by increasing numbers in a clockwise direction.

The analysis carried out highlighted severe erosion for three ports, intense erosion for seven ports, moderate erosion for only one port, and slight erosion for two ports (Table 2). The maximum values of shoreline retreat, greater than 260 m, were observed in Amantea, on the Tyrrhenian coast, and were related to the year 2022. The other two ports where severe erosions were observed were Badolato, on the Ionian coast, and Saline Joniche, also on the Ionian coast but not far from the southern mouth of the Strait of Messina. In the first case, the maximum shoreline retreat was about 110 m and was observed in 2022; in the second case, the maximum shoreline retreat was about 175 m and was observed in 2008. All three ports where intense erosion was observed were built in straight coastal areas. From the point of view of the shoreline erosion percentage, the maximum values were observed in Saline Joniche and Amantea, equal to 95% and 93%, respectively, while in Badolato a value equal to 71% was observed. Another very high value, equal to 88%, was observed in Cirò Marina, on the Ionian coast, and this port was also built on a straight coastal area. Coastal protection structures had been built on the downdrift of nine of these thirteen ports, with the exceptions of Catanzaro Lido and Badolato on the Ionian coast and of Bagnara Calabra and Palmi on the Tyrrhenian coast. Regarding the shoreline advancement updrift, in six cases out of ten a severe shoreline advancement was observed, while in the other cases one intense shoreline advancement, one moderate shoreline advancement, and two slight shoreline advancements were observed. In the ports of Badolato, Roccella Ionica, Saline Joniche, and Amantea silting of the mouth was observed, and in two of them, Badolato and Saline Joniche, this process is still underway.

Table 1. Summary of Calabrian ports analyzed in terms of period of construction (PC), coastal typology (CT), type of beach sediments (TBS), period of construction of coastal protection structures (CPS), and period when siltation was observed (Siltation). Each port has been identified with suffixes I for the ports of the Ionian Sea, S for the ports of the Strait of Messina, and T for the ports of the Tyrrhenian Sea, followed by increasing numbers in a clockwise direction.

Port	ID	PC	CT	TBS	CPS	Siltation
Cariati	I1	1954–1989	Bay	Pebble and very coarse sand	1989–1996 [3]	
Cirò Marina	I2	1989–1996	Straight	Pebble and coarse sand	1989–1996 [4]	
Crotone nord	I3	before 1954 [1]	Bay	Coarse sand	1954–1989	
Crotone sud	I4	before 1954	Bay	Coarse sand		
Le Castella	I5	1989–1996	High Coast	Boulder		2006–2012
Catanzaro Lido	I6	1954–1989	Bay	Sand and cobble	1989–1996	2006–2012
Badolato	I7	2000–2006	Straight	Sand and cobble	1954–1989	2000–2006
Roccella Ionica	I8	1954–1989	Straight	Coarse sand	2017–2018	
Saline Joniche	I9	1954–1989	Straight	Very coarse sand		
San Leo	S1	2008–2012	Bay	Sand and cobble		
Reggio Calabria	S2	before 1954	Bay	Sand and cobble	1989–1996	
Villa San Giovanni sud	S3	before 1954	Straight	Sand and cobble	2014–2017	
Villa San Giovanni nord	S4	2008–2012	Straight	Sand and cobble	1954–1989	
Scilla	T1	before 1954 [2]	Bay	Pebble and cobble		
Bagnara Calabra	T2	1954–1989	Bay	Pebble and cobble		
Palmi	T3	2000–2006	Bay	Coarse sand		
Tropea	T4	1954–1989	Bay	Coarse sand		
Vibo Marina	T5	before 1954	Bay	Very coarse sand		
Amantea	T6	2000–2006	Straight	Pebble and coarse sand		
San Lucido	T7	1989–1996	Inside CPS	Pebble and very coarse sand		
Cetraro	T8	1954–1989	Bay	Pebble and coarse sand		
Belvedere Marittimo	T9	2000–2006	Inside CPS	Medium sand		
Diamante	T10	1954–1989	Bay	Medium sand		

[1] expanded between 1954 and 1989. [2] expanded between 1989 and 1996. [3] expanded between 2006 and 2012.
[4] a part of the port was built in place of some coastal protection structures.

Table 2. Summary of Calabrian ports where it was possible to estimate the impacts of the port construction in terms of shoreline changes. Legend: depth at the head of the breakwater updrift (Depth), shoreline retreat classification (SRC), year when the maximum shoreline retreat was observed (SRCY), shoreline erosion percentage (SEP), shoreline advancement classification (SAC), and year when the maximum shoreline advancement was observed (SACY). Each port has been identified with suffixes I for the ports of the Ionian Sea, S for the ports of the Strait of Messina, and T for the ports of the Tyrrhenian Sea, followed by increasing numbers in a clockwise direction.

ID	Depth [m]	SRC	SRCY	SEP [%]	SAC	SACY
I1	7	Intense	2008	75	Severe	1989
I2	5	Intense	2021	88	Moderate	2008
I3	4	Intense	1989	74		
I6	11	Intense	1996	57	Severe	2012
I7	2	Severe	2022	71	Severe	2022
I8	8	Intense	2019	62	Severe	2008
I9	17	Severe	2008	95	Severe	1989
S1	9	Slight	2021	33	Slight	2021
T2	15	Intense	2021	74		
T3	8	Slight	2019	33	Slight	2019
T4	7	Moderate	1989	53		
T6	5	Severe	2022	93	Severe	2006
T8	4	Intense	1989	57	Intense	2012

Regarding the wave climate, Table 3 shows the results extrapolated from the research by Foti et al. [64]. As Table 2, this table also shows the results obtained only for the ports where it was possible to estimate the impacts of port construction in terms of shoreline changes. Only the port of San Leo is missing as it is located within the Strait of Messina in a coastal area where the wave climate is significantly lower than the Ionian and Tyrrhenian coasts due to modest fetches. In general, the highest values of $h_{s,max}$ and Δh_{1-100} are observed along the Tyrrhenian coast, while the values of $h_{s,av}$ and ϕ observed in the two coasts are of the same order of magnitude. Furthermore, most ports were built in coastal stretches where the main sector is inclined with respect to the coast, with a minimum value of 15° observed in Saline Joniche.

Table 3. Summary of Calabrian ports where it was possible to estimate the impacts of port construction in terms of shoreline changes. Legend: maximum significant wave height ($h_{s,max}$), average significant wave height ($h_{s,av}$), difference between the significant wave height of a return period of 1 year and the significant wave height of a return period of 100 year (Δh_{1-100}), average annual energy flux (ϕ), main sector (MS), and angle between the main sector and the coast in the absence of a port (α) [64]. Each port has been identified with suffixes I for the ports of the Ionian Sea, S for the ports of the Strait of Messina, and T for the ports of the Tyrrhenian Sea, followed by increasing numbers in a clockwise direction.

ID	$h_{s,max}$ [m]	$h_{s,av}$ [m]	Δh_{1-100} [m]	ϕ [kW/m]	MS	α [°]
I1	6.18	0.57	2.46	3.4	0	145
I2	7.42	0.79	3.08	7.1	140	130
I3	7.34	0.8	3.1	7.4	140	35
I6	6.28	0.68	3.01	5.1	130	55
I7	6.51	0.71	3.27	5.9	130	45
I8	6.37	0.69	2.85	5.5	130	55
I9	6.39	0.78	2.69	6	120	15
T2	6.71	0.48	3.34	3.10	310	85
T3	8.29	0.62	3.64	5.20	300	100
T4	9.22	0.69	4.02	6.80	290	25
T6	9.58	0.73	3.97	7.60	270	105
T8	9.49	0.80	3.84	8.40	260	120

Finally, from a temporal point of view, in about half of the ports where shoreline retreat had been observed, Cirò Marina, Badolato, San Leo, Bagnara Calabra, Palmi, and Amantea, the downdrift shoreline erosion processes are still ongoing, as the maximum shoreline retreat observed was in the most recent satellite image available. Furthermore, in the ports of Badolato, San Leo, and Palmi both downdrift shoreline erosion processes and updrift shoreline advancement processes are still ongoing. Finally, in the ports of Cirò Marina, Roccella Ionica, Saline Joniche, and Amantea the shoreline erosion processes continued even after the construction of coastal protection structures.

4. Discussion

The main aim of this paper was to analyze the shoreline changes due to the construction of ports in Calabria starting from geomorphological factors and wave forcings and carrying out a temporal analysis. In addition to this, other important effects caused by the construction of ports were also analyzed, such as shoreline advancement updrift, construction of coastal protection structures, siltation, and anthropogenic pressure.

The main finding of this analysis is that coastal morphology plays a key role in the extent of shoreline changes caused by the construction of ports. In fact, the greatest shoreline retreats were observed downdrifts of ports built in straight coastal areas, and, in all the analyzed cases, these retreats were classified as intense or severe. A similar result was obtained regarding the shoreline advancement updrift. The highest shoreline erosion percentages were also observed in ports built in straight coastal areas, with values of about 90% or higher in Cirò Marina, Saline Joniche, and Amantea. Instead, in the other two ports built in straight coastal areas, Badolato and Roccella Ionica, the percentages were slightly higher, 70 and 60%, respectively. These lower values, compared to the three ports in which the highest percentages were observed, may be related to the construction of coastal protection structures, in the case of Roccella Ionica, and to the river sediment transport, in the case of Badolato, as described in detail below.

In contrast, the construction of ports within bays causes smaller shoreline changes than those related to the construction of ports in straight coastal areas. In fact, in none of the analyzed cases of ports built in bays severe erosion was observed, even resulting in moderate and slight erosion. Regarding the shoreline erosion percentages, in all the cases this was less than 80%, and in more than half of the analyzed cases, five out of eight, this was less than 60%, with minimum values equal to 33% in the cases of San Leo and Palmi, the only two cases in which slight erosion was observed.

The conclusion that coastal morphology plays a key role in the extent of shoreline changes caused by the construction of ports is supported by the fact that the three ports where the most intense shoreline erosion processes were observed, Badolato, Saline Joniche. and Amantea, are in coastal areas with very different exposures to the wave climate between them. In fact, the port of Badolato is on the Ionian Sea, the port of Amantea is on the Tyrrhenian Sea, and that of Saline Joniche is located a short distance from the southern mouth of the Strait of Messina. The two Ionian and Tyrrhenian coasts are very different from a wave climate point of view [64]. Indeed, in the Tyrrhenian Sea, intense wave conditions are coming mainly from the north-west, along a few directions. Instead, in the Ionian Sea, intense wave conditions are coming between the north-east and the south-east, and there are secondary and tertiary sectors. Furthermore, the average and frequent wave conditions are slightly higher on the Ionian coast, while the extreme wave conditions are much greater on the Tyrrhenian coast, as shown in Table 3. Even the difference between significant wave heights with return periods of 1 and 100 years, which allows us to consider both frequent and extreme events, is of the same order of magnitude between the two coasts but slightly higher in the Tyrrhenian Sea, and a similar condition is observed for the average annual energy flux. Instead, analyzing the angle between the main sector and the coast in the absence of a port shows that the smallest angle, equal to 15°, is observed in Saline Joniche. Such a small angle means that the most intense wave climate is significantly inclined with respect to the coast, so the port blocks the longshore sediment transport, with consequent sediment imbalances between the updrift and downdrift sides of the port. This blocking action is strengthened by the observation that this is the port characterized by the greatest depth at the head of the breakwater updrift, about 17 m. Consequently, Saline Joniche is the case where the highest percentage of shoreline erosion was observed and, furthermore, where a severe shoreline advancement updrift coastline was also observed, which caused the silting of the port mouth. Other cases where the most intense wave climate is inclined with respect to the coast are those of Cariati, Catanzaro Lido, Badolato, and Roccella Jonica, and in all these cases severe shoreline advancement updrifts are observed. Therefore, there was no direct correlation between frequent, medium, and extreme wave climate and shoreline changes near the examined ports. Instead, a direct correlation was highlighted between the inclination of the most intense wave climate with respect to the coast and the processes of shoreline retreat downdrift and, above all, shoreline advancement updrift of the ports. This result shows how, in many cases, the construction of ports in Calabria was not preceded by an adequate design phase that effectively considered and predicted the effects caused by the ports on the neighboring coast.

Other important results of this analysis were obtained considering the construction of coastal protection structures downdrift of ports and the siltation phenomenon. Regarding the first aspect, it was observed that, in almost all the analyzed cases, coastal protection structures were built downdrift of ports after the construction of the ports and after the triggering of the erosion processes. The exceptions concern ports built in bays, Catanzaro Lido, Bagnara Calabra, and Palmi. In the first case, the beach still maintains a width of the order of 50 m, despite intense erosion having occurred. In the other two cases, however, the port was built close to headlands' downdrift. Instead, the only case of a port built in straight coastal areas where no coastal protection structures have been built downdrift of it is Badolato. In this case, the absence of such works is correlated to the absence of inhabited centers and of infrastructures to protect. In most cases the construction of coastal protection structures has blocked the shoreline erosion processes. However, in Cirò Marina, Roccella Ionica, Saline Joniche, San Leo, and Amantea the shoreline erosion processes continued even after the construction of these works. In the case of Cirò Marina, the further shoreline erosion processes could have been caused by the damage to the existing works (a series of breakwaters) observed in recent years. In the case of Roccella Ionica, the erosion processes have intensified in the coastal area not yet protected by these works (a series of groynes). Instead, the port of San Leo is a particular case because it was built about 15 years ago in a bay, in a highly anthropized coastal area characterized by a modestly wide beach, less than 20 m. For this reason, the related erosion is also modest, and, in fact, it is the only port where slight erosion has been observed. Furthermore, the cases of Saline Joniche and Amantea will be discussed in detail later, together with the case of Badolato.

Regarding siltation, it has been observed that all the ports subject to this phenomenon are in straight coastal areas. Furthermore, in the case of Badolato and Amantea the phenomenon started shortly after the construction of the ports, while in the cases of Roccella Ionica and Saline Joniche the phenomenon started many years later. Only in Roccella Ionica did the siltation cause partial obstruction of the port mouth, while in the other three cases the siltation caused the total obstruction of the port mouth. The siltation observed in Roccella Ionica occurred between 2006 and 2012 and is still present, despite the fact that dredging operations have been carried out over the years. The maximum shoreline advancement updrift occurred in 2008, with a value exceeding 270 m, and this is the greatest shoreline advancement observed in all the examined ports. Therefore, siltation could be related to an excessive accumulation of sediments updrift, reaching the port mouth.

From the point of view of anthropogenic pressure, most of the Calabrian ports were built after the Second World War, in the period of the greatest anthropic expansion in Calabria. The more evident effects of anthropogenic pressure have been observed in the northern Tyrrhenian coast, where many inhabited centers have expanded in a disorganized manner and without planning, built a short distance from the coast and often in place of beaches and coastal dunes [65–68]. Consequently, coastal protection structures have been built in most of these inhabited centers, and in two locations, San Lucido and Belvedere Marittimo, both located on the northern Tyrrhenian coast, ports have been built within the coastal protection structures themselves, probably due to the lack of space on the land side for where the port could be located. Indeed, in both locations the beach near the ports is almost totally absent, and a few meters from it, on the land side, there is a railway.

Most of the previous research carried out in Calabria in the field of shoreline changes focused on the classification of shoreline erosion processes or on the analysis of their causes, for example anthropization, destruction of coastal dunes, etc. However, what is missing is a detailed analysis of the effects caused by the construction of ports based on geomorphological factors and wave forcings, such as the one described in this paper. Indeed, this analysis evaluated not only the shoreline changes but also other important effects such as the shoreline advancement updrift, the construction of coastal protection structures, siltation, etc., and all of this in a territory characterized by geomorphological, climatic, and anthropic peculiarities such as Calabria. In fact, most of the studies carried out in other countries focus on single ports or single effects. For example, Ayalke et al. [77] analyzed the shoreline changes around the area of the Derekoy Portin and Tekkekoy Shipyard in Turkey. Dev et al. [78] estimated the shoreline change along Ponnani Fishing Harbour, India, also analyzing the main causes of shoreline erosion processes. Franklin et al. [79] analyzed the impact of port development on the northern Yucatan Peninsula coastline, in the southeast of the Gulf of Mexico, especially in terms of their downdrift effects. Zilinskas et al. [80] analyzed the impact of Klaipėda Port's (Lithuania) entrance channel's dredging on the dynamics of the coastal zone. Prumm and Igliesias [22] analyzed the impacts of port development on estuarine morphodynamics in Ribadeo (Spain). Mohanty et al. [81] analyzed the impacts of ports on shoreline change along the Odisha coast, in the Bay of Bengal. Sarma [21] analyzed the problems of siltation and coastal erosion along the east coast of India, in areas characterized by high longshore sediment transport. Uda et al. [82] analyzed the beach changes near Pengambengan fishing port in the western part of Bali, Indonesia. Kudale [17] analyzed the impacts of port development on the coastline in terms of shoreline erosion processes and the consequent construction of coastal protection structures and in terms of the implementation of dredging interventions.

Finally, the cases of Badolato, Saline Joniche, and Amantea are analyzed in detail below. The port of Badolato (Figure 4) was built at the beginning of the 2000s, with the completion of the works in 2005. Already in 2009, a silting-up of the mouth was observed, which required an inconclusive dredging intervention as, in 2012, the entrance was again blocked, even though only partially. For about ten years the mouth remained partially blocked, with limited port operations, until 2022, when total obstruction was observed [23]. In Badolato, severe shoreline erosions downdrift of the port are observed but of a lesser extent than in the cases of Saline Joniche and Amantea. This may be related to the proximity to the mouth of the Gallipari river, which is located close to the downdrift side. In fact, most of the Calabrian rivers are characterized by a torrential and irregular hydrological regime, high slopes, and coarse grain size. This combination of hydrological and granulometric characteristics often causes high sediment transport; therefore, such rivers significantly contribute to shoreline evolution near river mouths [13,33,34,83,84]. To quantify the sedimentary transport of the Gallipari river, the Erosion Potential Method (EPM) was applied, which is particularly reliable for torrential rivers such as those in Calabria [85–87], obtaining a value of the order of ten thousand cubic meters per year.

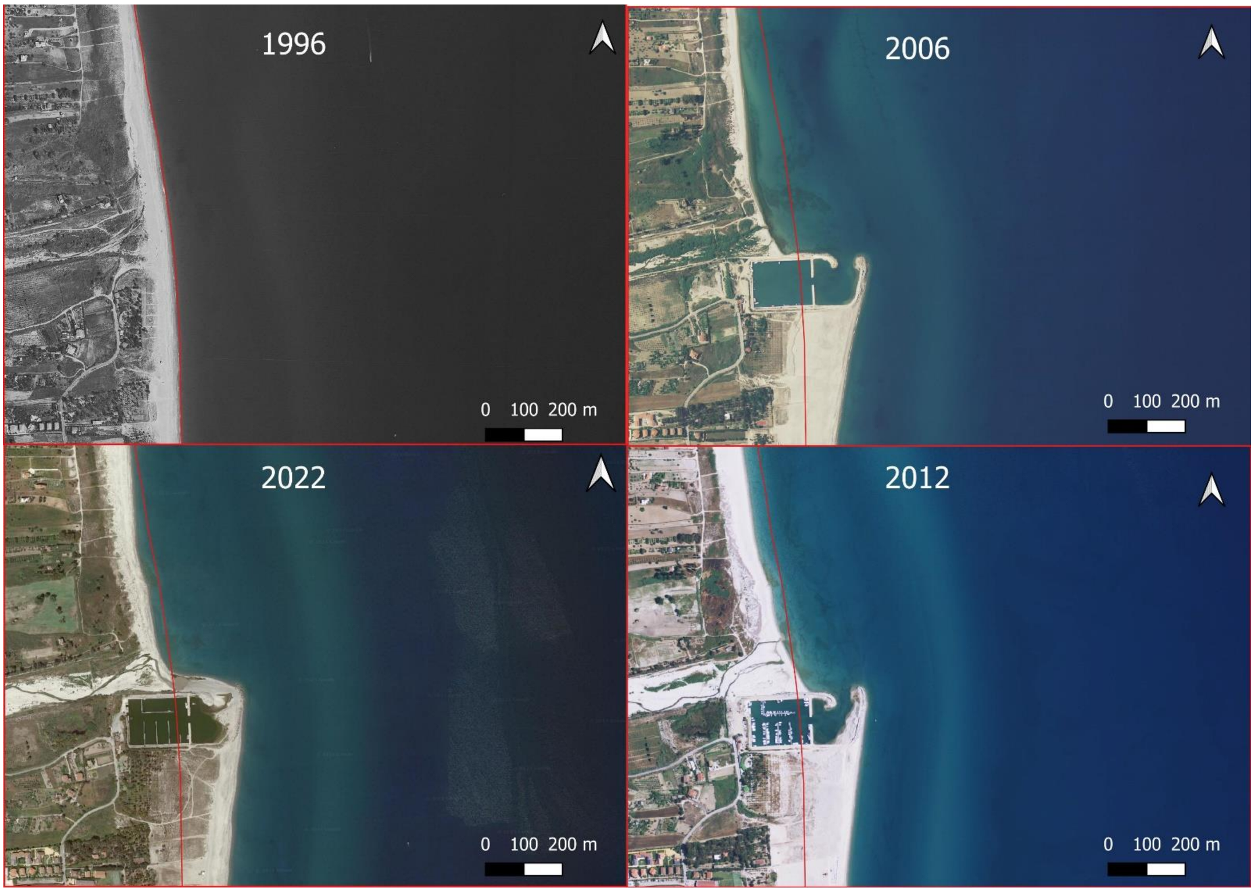

Figure 4. Port of Badolato. Clockwise: orthophoto from 1996, orthophoto from 2006, orthophoto from 2012, and Google satellite image from 2022. The red line is the shoreline of the year 2000.

The port of Saline Joniche (Figure 5) was built in the 1970s to serve an industrial site that never became operational. The shoreline erosion process began shortly after construction and reached its peak in 1989, also because of the coastal protection structures built during that time interval. At the beginning of the 2000s, the entrance was completely silted up, and, subsequently, the downdrift breakwater collapsed. In the second half of the 2000s, dredging interventions were carried out that never solved the problem [20]. In the last 10 years, the entrance has been completely blocked, and no further dredging interventions have been carried out also due to the inactivity of the industrial site. Since then, the sediments that accumulated inside the port have been redistributed along the coast, so shoreline advances downdrift of the port are observed. This case of Saline Joniche is a particularly complex case, and many technical reports and scientific research analyses have been carried out, for example, that of Arena et al. [88]. The main identified solution concerns an initial dredging operation to restore port operations, followed by the construction of a by-pass system. This system would serve as a way to move the sediments accumulated from the updrift side towards the downdrift side, at a distance, so that they could not be transported by wave motions back towards the port. However, the considerable depth of the mouth, greater than 15 m, caused the accumulation of a large quantity of sediments; so, the dredging operation carried out in the second half of the 2000s was not performed again due to a lack of funds. The by-pass system would also be particularly costly due to the high longshore sediment transport of the order of hundreds of thousands of cubic meters per year [20].

Figure 5. Port of Saline Joniche. Clockwise: orthophoto from 1989, orthophoto from 2006, orthophoto from 2012, and Google satellite image from 2022. The red line is the shoreline of the year 1954.

The port of Amantea (Figure 6) was built at the beginning of the 2000s, and, shortly after its construction, there was a total silting-up of the mouth, which was resolved through dredging. Subsequently, only partial obstructions of the mouth occurred, always resolved through dredging. The shoreline erosion processes observed downdrift of the port are the most intense of all the ports analyzed and are still ongoing. In fact, the maximum value of shoreline retreat, greater than 260 m, was observed in 2022, the year of the most recent Google satellite image available.

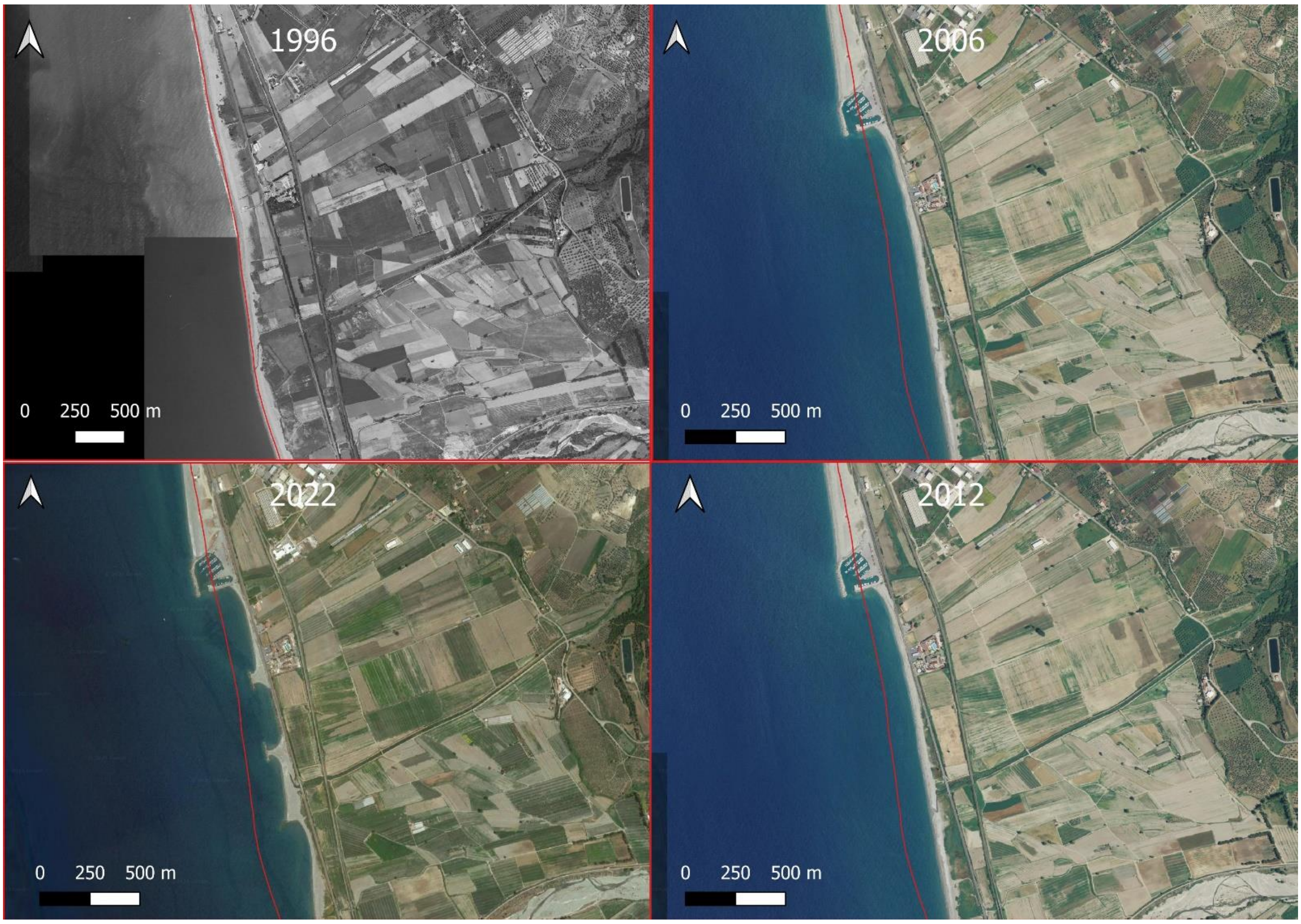

Figure 6. Port of Amantea. Clockwise: orthophoto from 1996, orthophoto from 2006, orthophoto from 2012, and Google satellite image from 2022. The red line is the shoreline of the year 2000.

5. Conclusions

This paper analyzes the shoreline changes due to the construction of ports in Calabria. This is a region located in Southern Italy, at the center of the Mediterranean Sea, and is an interesting case study from many points of view, including the geomorphological, climatic, and anthropic ones. The novelty of this research is a detailed analysis of the effects caused by the construction of ports based on geomorphological factors and wave forcings, evaluating not only shoreline changes but also other important effects such as shoreline advancement updrift, construction of coastal protection structures, siltation, etc.

The main finding of this analysis is that coastal morphology plays a key role in the extent of shoreline changes caused by the construction of ports. In fact, the greatest shoreline retreats were observed downdrifts of ports built in straight coastal areas, and a similar result was obtained regarding the shoreline advancement updrift of ports. In contrast, the construction of ports within bays causes smaller shoreline changes than those related to the construction of ports in straight coastal areas. Instead, there was no direct correlation between wave climate and shoreline changes near the examined ports, but there was a direct correlation between the inclination of the most intense wave climate with respect to the coast and the processes of shoreline retreat downdrift and, above all, of shoreline advancement updrift of the ports observed. This last result is very important for the correct design of ports, to avoid situations such as Saline Joniche, Badolato, and Amantea, for example. Indeed, some of the main shortcomings highlighted by this analysis concern both the design phase and the planning phase during which the choice of the area where locate a port is made, which often seems not to consider all the main geomorphological factors and wave forcings. Both aspects are of particular importance in complex areas from an anthropic, geomorphological, etc., point of view like Calabria.

Other important results of this analysis are that, in almost all the analyzed cases, coastal protection structures were built downdrift of ports after the construction of the ports and after the triggering of shoreline erosion processes and that all the ports subject to the silting phenomenon are located in straight coastal areas.

This analysis is based on open-access data and was carried out using free software such as QGIS, meaning that it is easily replicable and applicable to any coastal context, and it is of interest both to the field of scientific research and to the field of planning and management of coastal areas and their related protection interventions.

Author Contributions: Conceptualization, G.F.; methodology, G.F., G.B., G.C.B. and P.M.; software, G.F. and G.C.B.; validation, G.F., G.B., G.C.B. and P.M.; formal analysis, G.F. and G.C.B.; investigation, G.F. and G.C.B.; resources, G.F. and G.C.B.; data curation, G.F. and G.C.B.; writing—original draft preparation, G.F.; writing—review and editing, G.F., G.B., G.C.B. and P.M.; visualization, G.F.; supervision, G.B.; project administration, G.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

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