Long-term evolution of the shoreline of the south Lazio region (Italy) littoral cell by combining historical aerial photography and satellite imagery

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Abstract. Historical maps, aerial photos, and satellite images are often used to investigate coastal area conditions and their historical evolution, in terms of shoreline location, coastal structures deployment, and anthropic pressure. The application of multi-temporal shoreline extraction by combining historical aerial photographs and tri-stereo Pleiades images of the littoral cell bounded by Capo d'Anzio and Circeo headlands (Central Italy, Lazio region, Tyrrhenian Sea) is illustrated and discussed in this paper. The analyzed coastal area presents great environmental and tourism values, mainly due to the presence of the Circeo National Park, and its Special Protection Areas (SPAs) and Sites of Community Interest (SCI), belonging to the Natura 2000 network. The area is also characterized by its own high morphological vulnerability due to the absence of sediment supplies and the presence of coastal structures in the updrift area that trap, at least partially, the incoming longshore sediment transport. The available aerial photographs and satellite images have been orthorectified by using aerotriangulation and rational function techniques, respectively. The digitized shorelines, spanning from 1954 to 2019, have been used to gain insight into the advancing/retreating coastal stretches along the area, by applying the Transect Based Analysis and the Area Based Analysis. The obtained results have been related to the Lazio region coastal management measures, implemented within the same time frame.

Keywords: Long-term Shoreline Evolution, Coastal Zone Management, Digital-Photogrammetry, Coastal Diagnostic Tool, GIS, Natura 2000 network

1 Introduction

The coastal zone is a dynamic area where human activities act directly (e.g., occupation of coastal areas, dismantling of coastal dunes, etc.) or indirectly (e.g., reduction of river sediment transport, climate change, etc.) on the natural processes leading to coastal evolution (e.g., [1]). Being of invaluable environmental and economic value, the coast needs to be managed by drawing up sustainable strategies. Just as an example, the European Union has established the Protocol on Integrated Coastal Zone Management (ICZM) in the Mediterranean Sea [2]. The management strategy involves monitoring shoreline and beach profile changes, monitoring hydrodynamic data (such as waves, tides, winds, currents), mapping coastal defense structures and infrastructures [3]. In this framework, the use of remote sensing techniques has increasingly become a useful tool for monitoring coastal areas, coupled with shoreline change analysis, to measure significant shifts of shoreline position during time. Typically, after integrating maps, aerial photographs, and satellite images in a Geographic Information System (GIS), the shoreline position can be identified [4, 5]. Then, the shoreline change analysis can be performed by applying widespread methods, such as the Transect Based Analysis (TBA) and the Area Based Analysis (ABA). The annual rates of shoreline change, resulting from the TBA, and the annual sediment volume change, estimated by the ABA, are used as common indicators to identify significant retreat and loss of sand along coastal stretches. The present work focuses on the historical reconstruction of shoreline position of the littoral cell bounded by Capo d'Anzio and Circeo headlands (Lazio region, Italy). The study enables the analysis of the long-term morphological changes, by combining aerial photographs [6] and satellite images acquired within a 65-year time span (i.e., from 1954 to 2019). To allow a better understanding of the long-term shoreline evolution, the obtained results have been related to hydro-climatic processes and to anthropogenic actions, such as the construction of infrastructures and coastal defense strategies applied by Lazio region. Information about applied coastal management measures have been obtained from the ICZM monitoring center of Lazio Region [7] and available from 1985-2015. This study is intended to be a baseline to address appropriate strategies for sustainable management of coastal areas [8].

2 Study area

The coastal area under study is located in the South of Lazio Region (Central Italy, Tyrrhenian Sea) and extends for about 45.0 km, bounded by the promontory of Anzio, to the north-west and the Circeo promontory, to the south-east (see Fig. 1). This coast constitutes the southern part of the Tiber River littoral cell, which stretches from Capo Linaro, northward, to the Circeo promontory, southward. Up to the beginning of the past century, the Tiber sediment transport has been the main sediment source for the entire physiographic unit. Over the last hundred years, the Tiber has gradually reduced its sand supply due to the placement of several dams along the river and protection measures against the erosion of the inland watershed, inducing evident erosive phenomena at the river delta. Indeed, the latter has been counteracted by hard coastal defense structures (e.g., [9, 10]). The sub-physiographic unit presented herein, mainly sandy [11], presents some rocky outcrops both along the coast and on the seabed close to the shore. The promontory of Torre Astura divides the coast into two parts. North of Torre Astura headland, the sub-unit is located in the Anzio and Nettuno municipalities, where the two homonymous ports are respectively set. South of the same headland, the sub-unit resides in the Latina and Sabaudia municipalities. The last 25.0 km of the sub-unit includes the Circeo National Park, which extends from Capo Portiere (Latina) to Circeo promontory. This area presents a high environmental and touristic-economic value, due to the great variety of habitats, including the coastal dune [12, 13], which reaches about 27.0 m height to the south, close to Torre Paola locality [14]. The dune separates the beach from a large area of coastal lakes [15], which are connected to the sea by channels that break the continuity of the dune. The beach-dune-coastal lake system represents a high-value natural ecosystem, which hosts a number of marine flora and fauna species. The habitats of the Circeo National Park are Special Protection Areas (SPAs) and Sites of Community Interest (SCI), that belong to the European network Natura 2000. In addition to being an important habitat, the coastal dune plays two further fundamental roles. On the one hand, the dune constitutes the sand reservoir for the emerged and submerged beaches, through eolian and cross-shore sand transports. On the other hand, the dune ensures the coast stability, and protects the hinterland, which is in some areas under the mean sea level, from marine ingression. Recently, eolian transport has been reduced by the flattering of the dune to make space for tourist infrastructures, such as the coastal road, build in the 1930s on the top of the dune along its longitudinal axis. Moreover, beach-related tourism results in beach occupation by several private buildings and resorts, which affects the natural morphodynamic evolution of the coastal ecosystem beach-dune [16, 17, 18, 19]. Information on solid river supplies is extremely limited. Since the area is micro-tidal (maximum tidal variations are about 0.5 m), waves and currents can be considered the only driving forces for sand transport. The statistical analysis of the hindcasting wave series, inferred from DICCA MeteOcean Wave Hindcast Dataset [20, 21] and spanning from 1979 to 2019, revealed that the wave climate is dominantly characterized by wave coming from west (18.6%) and south-west (13.2%), followed by waves from the south (11%). The values of significant wave height H_s and peak wave period T_p range between 0.5-8.0 m and 2.0-14.0 s, respectively (see Fig. 2). Due to south-east shoreline orientation, the coast is primarily exposed to western and south-western storms. The net longshore energy flux, estimated on the basis of nearshore propagation of the offshore wave series, is mainly directed south-eastward along the stretch from north of Capo d'Anzio to Sabaudia Lake, whereas up to Circeo promontory the energy flux is mostly north-west directed.

3 Material and methods

The long-term morphological evolution of the study area has been analyzed according to the following steps: (i) acquisition and orthorectification of aerial photographs and satellite images; (ii) digitalization and extraction of shorelines; (iii) shoreline change analysis to estimate annual retreat/advance rates.

In the assessment of geomorphological changes, the databases of historical aerial photographs are essential to delineate and generate sequential information revealing static (or stable) and dynamic (or unstable) landforms. To select the existing photographs of the study area, the catalogs of the Military Geographic Institute (IGM) have been explored. Non-photogrammetric scanned images at the resolution of 2400 dpi of 1954, 1985, 2003 have been used with different spatial coverages, flight directions, and qualities. In addition to the datasets of photographs provided by the IGM, two image datasets belonging to the PLEIADES satellite constellation have been used to get the shorelines of 2014 and 2019. With the purpose of establishing the reference shoreline, the Web Map Service of the Lazio Region Geoportal has been exploited to delineate shoreline from the orthomosaic, already generated from the flight of the Agency for Agriculture Payments in 2014 (AGEA 2014).

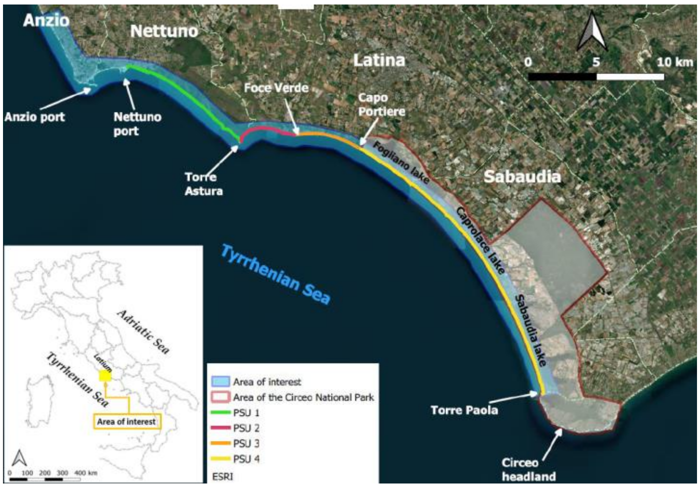

Fig. 1. Location of the study area and PSU.

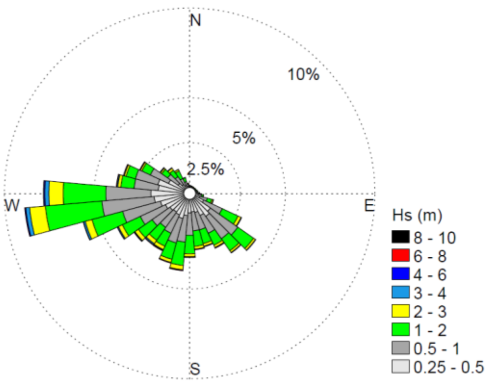

Fig. 2. Polar diagram of joint-occurrence frequency of wave height/direction at the coordinates 12.56 °E, 41.34 °N, located about 13.0 km offshore Capo d’Anzio, at 124.0 m isobath.

The total number of the used photographs and images is equal to 83, the Ground Sample Distance varies between 0.2 to 0.7 m and the spatial extension covered by flight or satellite dataset varies between 20.0 km to 60.0 km. To perform the aero-triangulation procedure with the external orientation, the Ground Control Points (GCP) are obtained from the orthomosaic of the AGEA 2014 [22] orthophotos in terms of X-Y coordinates. The elevation has been extracted from a detailed Digital Terrain Model (DTM) obtained from the LiDAR (Laser Detection and Ranging) data from 2009, provided by the General Directorate for the Protection of Land and Water – Italian National Geoportal, belonging to the Ministry of Environment and Energetic Security. The DTM has a resolution of 2.0 m in coastal areas. In addition, the bathymetry of the submerged foreshore has been merged with the LiDAR data to obtain a single model across the entire coastal profile. The aerial and satellite stereo-pairs have been first oriented and then orthorectified. For the case of aerial photographs, it is common to apply the aero-triangulation method [23, 24], that carries out the adjustment of blocks of aerial photography. However, it is common to deal with non-metric cameras such as film cameras without fiducial marks or, in general, any analog or digital cameras without specified interior orientation or calibrating parameters. This case matches the present study, and these missing parameters are derived by applying the well-known procedure of the bundle adjustment (or Bundle Block Adjustment) which also performs the self-calibration, also known as in-situ camera calibration [25, 26, 27]. Furthermore, for satellite images, a pan-sharpening process has been followed from the application of the Rational Function Orientation method. This task took a few hours, given their ground coverage (three images are sufficient to cover the entire area with a width of 46.0 km) and radiometric quality to select and measure appropriate GCPs and perform an iterative calculation. A dense network of accurate GCPs has been established to support the model adjustments even in the case of the oldest aerial photographs that has not provided enough sharpness and contrast to identify many ground objects. Finally, the orthorectification of the original images and the generation of the orthomosaic has been carried out. By orthorectification, the geometrical distortions of the original images have been removed, creating a planimetric image at every location with consistent scale across all parts of the image. This process needs of an intermediate process to create a DEM: since the different perspectives of the topography, the distortions can be correctly removed.

The long-term shoreline change analysis has been carried out over four periods: 1954–1985, 1985–2003, 2003–2019 and 1954-2019. To calculate advance/retreat rates, the End Point Rate (EPR) technique has been employed. This method, widely used, consists in dividing the distance between two shorelines by the time span between the two shorelines. To highlight local phenomena and changes, the coastal area has been divided into four sectors. Based on the presence of headlands, river mouths, and ports, starting from the northwest to the southeast, the following littoral sectors have been identified (see Fig. 1): sub-unit PSU 1 covers about 10 km from the south of the port of Nettuno to the promontory of Torre Astura; Sub-unit PSU 2 extends for about 4.5 km from east of Torre Astura to the west of Foce Verde mouth; sub-unit PSU 3 stretches about 5 km from east of Foce Verde to Capo Portiere; sub-unit PSU 4 covers Circeo National Park beaches, approximately 25 km long, from Capo Portiere to Torre Paola, located on the west of the Circeo promontory. The coastal stretch, about 2.0 km long, bounded by the ports of Anzio and Nettuno, has been excluded from the analysis due to the presence of coastal defense structures. For each of the zones and for each analyzed time interval, shoreline change analysis has been performed by applying TBA and ABA approaches, by using a constant spatial step equal to 10 m. The first morphological analysis has been carried out to estimate the maximum and average annual rates of shoreline retreat and advance. The second analysis has allowed quantifying the annual sediment flow incoming or outgoing of the analyzed sectors. Multiplying advanced or retreated areas by the depth of closure (estimated of about 7.0 m by applying Hallermeier's formula [28, 29] and in according with the study of [30]) the gain (positive value) and loss (negative value) of sediment in m^3/year have been then evaluated. In both studies the quantities have been determined considering the curvature of the beach; the differences, in terms of width between two epochs, have been calculated along the local normal with respect to a zero-reference value, defined as the position of the earliest measurement (i.e., the oldest shoreline) available for each considered time interval.

4 Results

In this section, the results of the long-term shoreline change analysis are presented and discussed according to their location, presence or absence of human settlement, infrastructures and coastal structures, and longshore wave energy flux. The computed rates of shoreline changes, with reference to Table 1, for the four coastal sectors are summarized in Fig. 3, Fig. 4, Fig. 5 and Fig. 6 respectively, in which the color scales are superimposed on the 2019 satellite image, and Table 2.

Table 1. Colour scale for classification of shoreline change rates.

Colour scale	EPR (m/year)	Shoreline Classification
●	> 2.00	Very High Advance
●	1.00 to 2.00	Hight Advance
●	0.10 to 1.00	Moderate Advance
●	0.10 to -0.10	Stable
●	-0.10 to -1.00	Moderate Retreat
●	-1.00 to -2.00	High Retreat
●	< -2.00	Very High Retreat

With reference to PSU 1, the lack of information relative to 1954 orthomosaic has not allowed analyzing the area over 65 years (from 1954 to 2019), hence the results are provided just from 1985 to 2019. The only meaningful element, that can be observed in the orthomosaic relative to 1954, is the absence of the Nettuno port, built in 1986, due to the strong demographic increase of the city. Fig. 3 shows the main results obtained for PSU 1. The sector did not experience significant retreat over the period 1985-2019, since the maximum of the estimated average retreat rate is about

-0.50 m/year in 1985-2003. Great advance rates (with a maximum annual value of +2.70 m/year during the period 1985-2003 and +4.60 m/year during the period 2003-2019) have been observed in correspondence of the area, which extends for about 1.5 km downdrift of the Nettuno port, where coastal management measures have been applied. Indeed, at first, the area has been protected by a system made of ten breakwaters, built simultaneously with the port construction. In 2001, the breakwater system has been replaced by a groin system, made of four groins, connected to a 1.2 km long submerged breakwater. The same area has been also restored with two nourishments, one in 2001 and the other one in 2013, for a total sand volume of 152’000 m^3, coming from the Anzio harbor dredging activities. Going southward up to Torre Astura, the coastal stretch is characterized by a succession of short sectors of moderate retreat and advance, mainly due to natural local phenomena, as the area is not protected by coastal structures and the backshore area is not anthropized. In particular, the retreat trend has prevailed on the southern side. The analysis of the shoreline changes of PSU 2 reveals that the area has been affected by significant retreat over the entire period of 65 years. The maximum annual retreat rate of about -3.4 m/year occurred in 1985-2003, whereas the annual average retreat rate of about -1.4 m/ year occurred in 1954-1985. The loss of sand in 65 years (from 1954 to 2019) has been estimated at about 31’600 m^3/year, with a maximum value of about 43’500 m^3/year during the first period 1954-1985. The results may suggest a reduction of Astura River sediment discharge over the analysed periods. Shoreline defence measures have not been introduced along this stretch, except for a 600.0 m long seawall, built between 1985 and 2003, which corresponds to the stable area on the southern side (see Fig. 4). Moreover, since the Latina nuclear power plant seawater cooling system, made of two 700.0 m long submerged pipelines protected by a submerged rubble mound, reaches the 6.0 m isobath, it can be considered as a long-submerged groin that acts on the long-shore sand transport [31]. The limited extents of areas of advance shown in Fig. 4 in 1985-2003 can be caused by local phenomena. Significant differences in shoreline evolution along PSU 3 have been observed during the analyzed periods. With reference to Fig. 5, the PSU 3 can be further divided into two stretches due to its shoreline evolution patterns. The first one corresponds to the Lido di Latina locality, which extends for about 2.0 km downdrift of Foce Verde, and the second one is the stretch, about 3.0 km long, downdrift of the Lido di Latina locality up to Capo Portiere. The period 1954-1985 (see Fig. 5) has been characterized by an annual average retreat rate of about -0.5 m/year up to a maximum rate of -2.0 m/ year, both occurring at Lido di Latina. During the same period, the downdrift area has experienced an advance trend with averaged and maximum annual rates of about +0.3 m/year and +1.0 m/year, respectively. During the period 1985-2003, a number of nourishments have been performed, for a total volume of about 170’000 m^3 of sand coming from land quarries. Moreover, between 2003 and 2005, a cells coastal defence system made of a submerged breakwater and groins have been built at Lido di Latina locality and further sand nourishment of 85’000 m^3, coming from sea borrow, has been placed in that area. These measures were motivated by the exploitation of urbanization and tourism in the area, which induced a change in the sediment budget along the stretch. Indeed, looking at Fig. 6, it can be observed that the coast has been subjected to a clear and significant turning point in terms of shoreline evolution. During 2003-2019, the Lido di Latina shoreline advanced, characterized by maximum and average annual advance rates of about +5.0 m/year and +2.0 m/year, respectively. Whereas, a shoreline retreat trend has been observed in the southern coast, shaped by maximum and average retreat rates of -3.5 m/year and -1.2 m/year, respectively. This trend may be related to the coastal defence management of the area, which has been focused to protect the northern part of the sub-unit, where during the last analysed period, further nourishments of 122'000 m^3 of sand has been coupled with the defence system made of the submerged breakwater and groins, making a sediment trapping zone. The latter is the cause for the downdrift shoreline retreat, as the wave energy flux is directed southwestward along the PSU 3. Due to the several nourishments and the potential material coming from PSU 2, the subunit was not affected by loss of sand. The PSU 4 (see Fig. 6), which corresponds to Circeo National Park beach, can be defined as a natural area, free of coastal defence structures and ports, except for six armoured mouths of drainage channels that connect coastal lakes to the sea. These canals do not transport sediments of interest for the stability of the coasts. Thus, due to the absence of solid river supplies and the reduced aeolian transport, the only natural sand source is represented by the longshore sediment transport. The analysis has revealed an increase of the average and maximum annual retreat rates, passing from values of about -0.30 m/year and 1.30 m/year, respectively, during the period 1954-1985, to -0.70 m/year and -2.90 m/year, respectively, during the period 2003-2019. During the period 1985-2003, the coast has been nourished with a total volume of sand of about 117'000 m^3, coming from land quarries.

Table 2. Classification of PSU average shoreline evolution trend with respect to coastal management measures during the analysed periods.

Period	Area	Average shoreline evolution trend	Evolution coastal management
1954 - 1985	PSU-1	Lack of data	Lack of data
	PSU-2	High retreat	No measures
	PSU-3	Moderate retreat	No measures
	PSU-4	Moderate retreat	No measures
1985 - 2003	PSU-1	Moderate advance	1) Cell defence system (groins and submerged breakwater) 2) Beach nourishment
	PSU-2	High retreat	Seawall
	PSU-3	Moderate advance	1) Cell defence system (groins and submerged breakwater) 2) Beach nourishments
	PSU-4	Moderate retreat	Beach nourishment
2003 - 2019	PSU-1	Moderate advance	Beach nourishments
	PSU-2	High retreat	No measures
	PSU-3	Moderate retreat	Beach nourishment
	PSU-4	Moderate retreat	No measures

By observing Fig. 6, retreat areas alternate with advance areas along the whole stretch, due to local phenomena and the bi-modal wave energy flux. Over the long-term (i.e., from 1954 to 2019), the subunit has mainly experienced a slow retreat of about 0.2 m/year and a loss of sand of about 17’000 m^3/year.

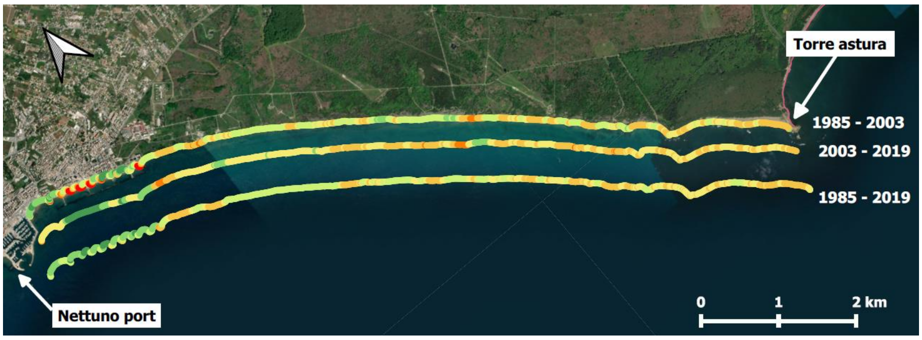

Fig. 3. Annual advance and retreat rates along PSU 1.

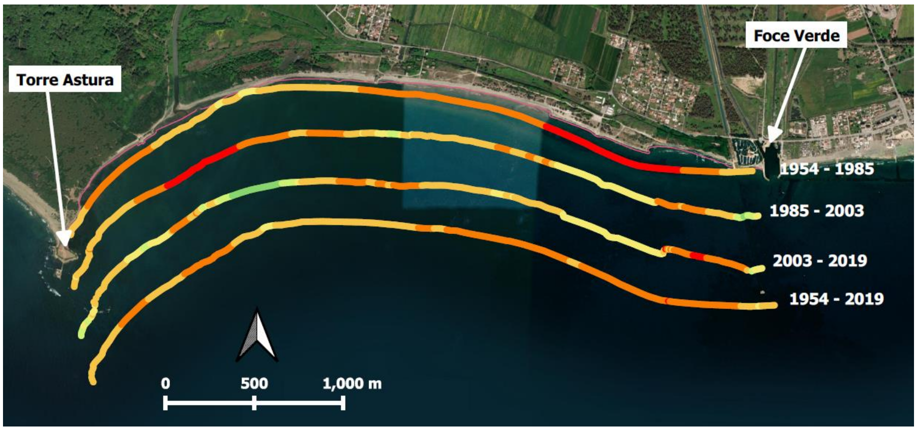

Fig. 4. Annual advance and retreat rates along PSU 2.

Fig. 5. Annual advance and retreat rates along PSU 3.

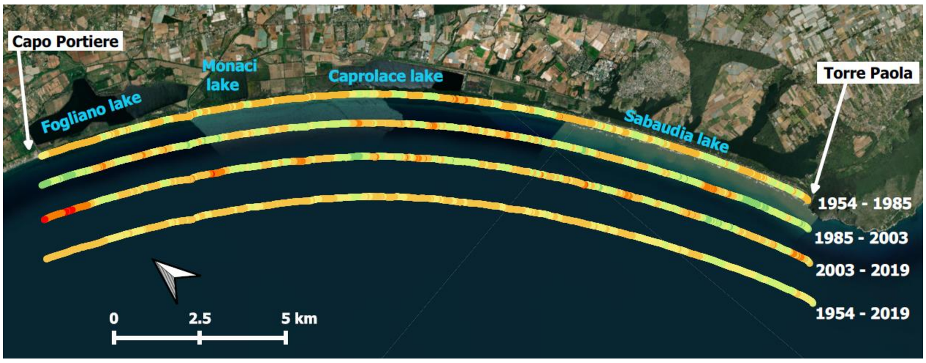

Fig. 6. Annual advance and retreat rates along PSU 4.

5 Concluding remarks

Literature review, data acquisition, imagery processing and database implementation, GIS elaboration and shoreline analysis have allowed to carry out a comprehensive study on the Lazio region physiographic sub-unit bounded by Anzio port, to the northwest, and Circeo headland, to the southeast. The study aims to investigate shoreline evolution and identify the most critical areas from a morphological point of view. Comparison and analysis of orthomosaics and the relative shorelines have allowed to gain accurate knowledge of the coastal area and how it has changed over time. Several factors, such as natural processes (e.g., waves, river discharge variation), human activities (e.g., buildings, infrastructures, coastal management), influence shoreline stability. Therefore, the analysis carried out shows how the spatial distribution of advance and retreat areas have been influenced by ports and coastal management, such as the placement of coastal defense structures and beach nourishments. Ports and protection systems, which interact with waves and therefore with longshore sediment transport, produce advance where they have been deployed and expose the downdrift areas to retreat, as observed along Nettuno and Latina coasts. Moreover, the management of the sediment trapped by Anzio port represents an important factor influencing the sediment budget, and thus the retreat phenomena of the studied beaches [32]. Based on the calculated direction of the longshore wave energy flux (usually according to the direction of the longshore sediment transport, [33]), the trapped material does not naturally reach the downdrift PSU-1, 2, 3, 4. In the past, the dredged material has been used to nourish the port updrift beach. Between 1989 and 2003, it has been estimated the volume of sand dredged from the port of about 616’400 m^3, of which 504’400 m^3 was used for the nourishments of the port updrift beach and 122’000 m^3 to restore the downdrift coast of Nettuno port. During the same period, the total amount of sand placed along the Latina and Circeo National Park beaches has been about 483’000 m^3. Furthermore, during 2003-2015, about 327’000 m^3 of dredged sand have been used to restore the updrift beaches from Tor Caldara to Anzio port. Such findings suggest reconsidering the policy management of the Anzio port dredged material, since the latter represents a potential source to restore the downdrift coasts, which have experienced sediment deficit and retreat, and recover the sand balance of the physiographic unit, instead of using quarry material.

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