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Historical Evolution of the Salento Leccese Coastal Landscape (Southern Apulia, Italy)

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Abstract: The Salento Leccese coast (southern Apulia, Italy) is marked both by primary and secondary coasts (cliffs and beaches); beaches, in particular, constitute about a quarter of the coastal perimeter. The Salento Leccese coast experienced dramatic change over the last two centuries due to natural and anthropic causes. This change was reconstructed through a geomorphological survey, historical cartography, and an aerial photo analysis. In particular, two case studies are described: the first one stretches along the Adriatic coast of the peninsula (Torre dell'Orso locality), and the second one is located along the Ionian coast (Torre Pali locality). For these coastal tracts, the main geomorphological features and the natural evolution that occurred during the Holocene are described, along with the anthropic modifications induced in the coastal landscape over the last two centuries. This study represents a useful knowledge background for coastal planners and decision makers, which will be utilized by the National Restoration Plans to be implemented in the near future, with the aim of restoring degraded ecosystems according to the recent Nature Restoration Law of the European Commission (2024).

Keywords: coastal change; anthropic impact; Salento; southern Italy

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1. Introduction

The coastal landscapes of the Italian peninsula underwent important changes throughout the last few centuries due to natural and anthropic causes. In fact, the natural evolution of the coastal area, mainly led by hydrodynamic conditions, the sedimentary budget, the local sea level history, and major climate change, has been strongly modified over the last two centuries by industrial, defense, and harbor constructions, as well as touristic exploitation. Along the Italian coast, in particular, the impact of tourism has increased significantly over recent decades; every year, despite the 300 m strip of coastal land being protected by a national law, uncontrolled coastal urban development due to a lack of policy and governance integration and coordination has led to the unsustainable overexploitation of fragile ecosystems, triggering phenomena of land degradation and increasing the exposure of the population and ecosystems to hazards [1]. In fact, in the 1950s, approximately two-thirds of the 1472 km of the Adriatic coastline of Italy was free from buildings and other structures; this value dropped drastically to less than one-third after 2000 (466 km), with a dramatic average speed of advancing urbanization equal to about 10 km per year (just under 30 m per day) [2].

Looking to the future, the diffuse urbanization of the coastline will produce a strong need for a strategy for erosion mitigation. In fact, the present level of climate change will produce a sea level rise ranging from a low of ~50 cm to as high as ~310 cm by the end of the

century (2100) [3]. The potential loss of public infrastructure and private development due to the sea level rise will have enormous economic impacts, especially on beaches that are more vulnerable to flooding from wave actions as well as the most touristic areas. In fact, an accelerated sea level rise is likely to result in the permanent inundation of unprotected low-lying land and more frequent/intense episodic coastal inundation. Both permanent and episodic inundation will be exacerbated at locations that are subject to land subsidence. Another well-known impact of sea level rises is long-term coastline retreat (recession). The commonly used Bruun rule [4] predicts an upward and landward movement of the coastal profile (Bruun effect) in response to a sea level rise, suggesting a recession of 50–100 times the sea level rise amount along beaches, even if the exact nature of the local response will be governed by the total sediment budgets [5].

This general situation of the Italian coast is also recognizable in the Salento Leccese area, a narrow peninsula located at the southernmost part of the Apulia region that stretches for about 120 km in the NW–SE direction between the Ionian and Adriatic Seas (Figure 1). It is a low-elevation region attaining a maximum altitude of 195 m a.m.s.l., constituted by a 6 km thick Mesozoic limestone basement covered by thin deposits from the Paleogene, Neogene, and Quaternary ages. The widespread presence of carbonate rocks promoted the development of karstic landforms during three main emersion periods of variable temporal lengths occurring in the Paleocene and in the Middle–Upper Pleistocene [6].



Figure 1. Geographical position of the Salento Leccese peninsula. The geographical position of the Salento Leccese peninsula is marked by the yellow area.

All around the Salento peninsula, a low-elevation landscape made of a Pleistocene marine terrace sequence, bordered by differential erosion scarps and relict cliffs, can be recognized. Its development was strictly connected to repeated marine regression–transgression cycles produced by glacio-eustatic sea level oscillations, which have occurred since the Middle Pleistocene and are superimposed on the tectonic uplift of the region [6]. The present-day coastal landscape shows very different features, with a prevalence of rocky coasts; coastal plains are lacking because of the absence of a hydrographic network.

The Salento Leccese coast presently supports increasing touristic attention. In fact, during the year 2023, 1,239,100 arrivals and 5,173,700 visitors were recorded in this area; the trend in the period 2019–2023 was +15% for arrivals and +8.5% for visitors [7].

This study aims to reconstruct the historical evolution of the Salento Leccese coast caused by natural and anthropic processes, which can support integrated management plans to ensure that the coastal zone is able to mitigate the impact of growing tourism. In particular, two representative areas were investigated: one on the Adriatic side (Torre dell'Orso locality) and the other on the Ionian one (Torre Pali locality).

2. Materials and Methods

The data collated for this study came from different approaches, including a geomorphological survey for the reconstruction of the oldest phases of coastal evolution and a GIS-based analysis of historical maps and aerial photographs, as well as the consultation of historical photo collections.

Geomorphological data for the two selected coastal areas were collected through a field survey, which allowed the coastal landscape to be described and the local stratigraphy to be reconstructed, with a particular focus on the Pleistocene and Holocene deposits.

Historical maps were selected from the archives available at the Archivio di Stato di Lecce; they were digitalized and georeferenced using a GIS, which allowed the extent of past coastal marshes to be compared to the present situation. Furthermore, valuable data for the reconstruction of the historical evolution of the Salento coastal landscape were obtained from the Atlante Geografico del Regno di Napoli, completed by Rizzi Zannoni in 1812. These data are composed of 31 sheets at a 1:114,545 scale; the geographical maps related to the Salento Leccese coast were published in 1808 [8].

The morphology of the coastal dunes occurring at the back of the Salento Leccese main beaches in the middle of the last century, i.e., before the main phase of coastal urbanization, was reconstructed using topographic maps at a 1:25,000 scale produced by the Istituto Geografico Militare (I.G.M.).

The growth of the urbanized area at the two specific sites was calculated by overlaying aerial photos of different years, available from Geoportale Nazionale. Finally, the main coastal changes that have occurred since the beginning of the last century were defined using historical photo collections published in recent years by local editors.

3. The Coastal Landscape of Salento Leccese Peninsula

The Salento peninsula is in the southernmost part of the Apulia region (Figure 1) that constitutes the emerged part of the Adria Plate, the foreland domain of both the Apenninic and Dinaric orogens. It comprises a Variscan basement covered by a 3–5 km thick Mesozoic carbonate sequence (the Calcari delle Murge unit), which in turn is overlain by thin deposits of Paleogene, Neogene, and Quaternary age. The Salento Leccese peninsula shows a rather flat landscape marked by low-elevation Mesozoic carbonatic ridges separated by grabens filled with Cenozoic sediments. All around the Salento peninsula, a low-elevation landscape made of a number of Pleistocene marine terraces bordered by erosion scarps and relict cliffs can be recognized [4]. Its development has been strictly connected to repeated marine regression–transgression cycles produced by glacio-eustatic sea level changes that have occurred since the Middle Pleistocene and were superimposed on the tectonic uplift of the region. Some of these terraces display a thin sedimentary cover composed of calcareous sandstones very rich in fossil remains (*panchina*), associated in some places with dune deposits, whereas others are only wave-cut platforms.

The Salento Leccese peninsula is bordered by a 215 km long coastline that has been studied over the last 60 years to determine its geomorphological and sedimentological

features. In recent years, research has focused on the reconstruction of the Holocene local sea level history, integrating archeological, radiometric, and morphological data [9], while several studies have also focused on the morphological effects of historical tsunamis on the Salento Leccese coast [10,11]. More recently, particular attention has been devoted to cliff retreat [12] and coastal sinkhole evolution [13]. However, very few studies have been dedicated to the historical evolution of selected Salento Leccese coastal sites over the last few centuries. For example, the origin and evolution of the Laghi Alimini coastal lakes, linked to the local Holocene sea level history, were defined by Boenzi et al. [14]. Aerial and satellite photos were analyzed in geo-archaeologic research to document the dramatic transformation of the coastal landscape in the Torre San Giovanni–Torre Mozza area, along the Ionian coast of Salento Leccese [15]. Finally, the historical evolution of San Cataldo, located on the Adriatic Sea coast, about 10 km east of Lecce, was defined from ancient times to the present [16].

3.1. The Morphological Coastal Types of Salento Leccese

The coast of the Salento peninsula shows different morphological features due to varying geological characteristics and evolution. In detail, four main morphological coastal types can be identified: rocky convex coasts, rocky plain coasts, cliffs, and beaches (Figure 2). The first type comprises coastal tracts constituted by a steep coastal slope stretching from about 100 m of altitude to 50 m of depth, forming the most suggestive landscape of the Salento coast. This coastal type makes up 25% of the Salento Leccese coast (Figure 3); it can be recognized from the Otranto to Santa Maria di Leuca localities (Figure 4a) and in the surroundings of Capo San Gregorio (Patù municipality) and Porto Selvaggio (Nardò municipality). This coastal type can be classified as primary coast [17] because it is the result of the partial submersion of a steep fringing reef slope that grew on a carbonatic platform margin during the Late Oligocene (Otranto–Leuca tract). On the Ionian side of the peninsula, along the Capo San Gregorio and Porto Selvaggio tracts, the coast is the seaward slope of a morphostructural ridge.

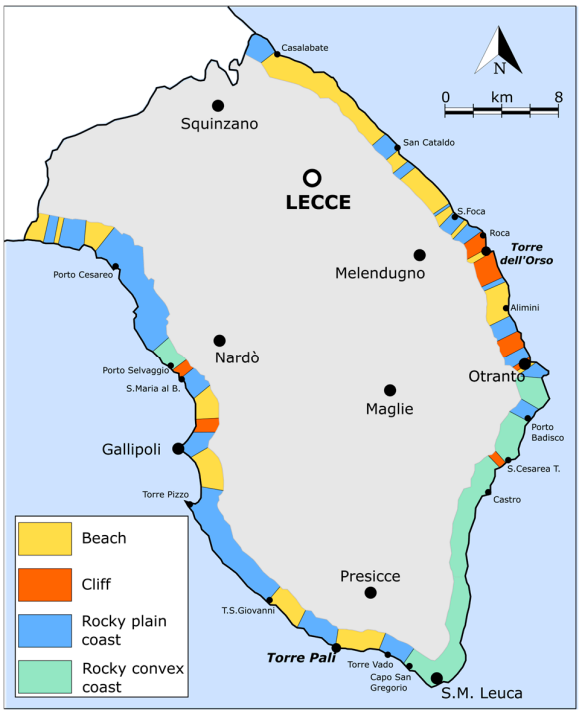


Figure 2. Geographical distribution of main coastal morphological types in the Salento Leccese peninsula. Positions of representative Torre dell'Orso and Torre Pali areas are also reported.

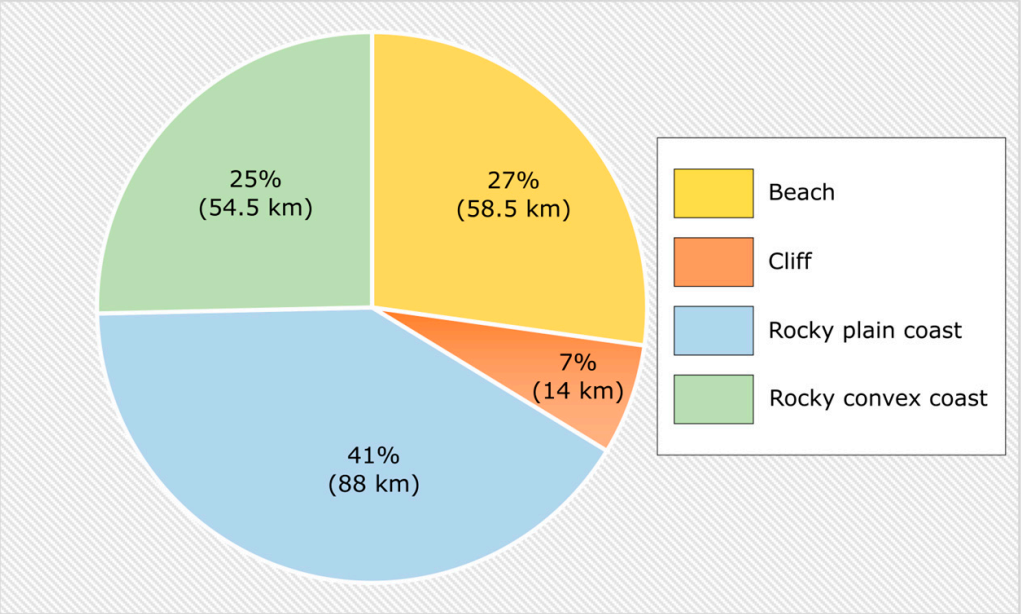


Figure 3. Frequency distribution of main morphological types of the Salento Leccese coast.



Figure 4. The main coastal morphological types of the Salento Leccese peninsula. (**a**) The convex coast of Otranto–Santa Maria di Leuca formed due to the partial submersion of a steep fringing reef slope developed during the Late Oligocene; (**b**) the partial submergence of wide Middle–Upper Pleistocene wave-cut platforms has formed plain coasts mainly on the Ionian side of the Salento Leccese; (**c**) active rock falls have induced cliff retreat in the area of Santa Cesarea Terme; (**d**) about a quarter of the Salento Leccese coast is made up of sandy beaches.

Rocky plain coasts mainly mark the landscape of the Salento peninsula's Ionian side; they constitute 41% of the entire coast (Figures 3 and 4b). This type of coast can also be classified as primary coast because it is produced by the partial submersion of a staircase of wave-cut platforms.

Cliffs are subvertical slopes affected by mass movements that are enhanced by effective wave erosion processes at mean sea level. This coastal type can be classified as secondary coast because its genesis is due to marine processes. Cliffs constitute 7% of the Salento Leccese coast (Figure 3) and characterize the coastal tract stretching from Roca (Melendugno municipality) to Otranto, in the areas of Santa Cesarea Terme (Figure 4c) and Santa Maria di Leuca, as well as in the area closely to the north of Gallipoli.

The secondary coasts also include beaches occurring from the Casalabate to San Foca localities (Figure 4d), at the Torre dell'Orso (Melendugno municipality) and Alimini (Otranto municipality) localities, on the Adriatic side of the Salento peninsula, from the Torre Vado and Torre San Giovanni localities, and from Torre Pizzo to Gallipoli and to the west of Porto Cesareo on the Ionian side. Beaches constitute 27% of the Salento Leccese coast (Figure 3).

3.2. The Dune Belts of the Salento Peninsula

The development of dune belts along the Salento peninsula coast occurred in different periods during the Late Pleistocene and the Holocene, mainly on its Ionian side.

Late Pleistocene aeolian deposits constitute well-preserved dune belts found at different localities, mainly along the Ionian coast of the Salento Leccese. A good exposure of Pleistocene aeolian deposits with different ages can be found in the area of Gallipoli, where cemented fine bioclastic calcarenite with high-angle cross-lamination, light brown in color, has formed; late Pleistocene aeolian deposits (Figure 5) can also be found in the area of Torre San Giovanni (Ugento). On the Adriatic side of the Salento Leccese peninsula, Late Pleistocene aeolian deposits crop out in the area of Casalabate (Figure 6); they are marked by deformational structures interpreted as seismites [18] or as deformations in soft sediments induced by ancient sinkhole activity [19].



Figure 5. The Late Pleistocene cemented dune belt occurring at the Torre San Giovanni locality (Ugento municipality).



Figure 6. The Late Pleistocene aeolianites of Casalabate (Trepuzzi and Squinzano municipalities) with deformational structures interpreted as seismites.

The Holocene was marked by two main phases of dune belt development along the coast of the Salento Leccese peninsula. The first occurred at the end of the rapid postglacial transgression during the Holocene Climatic Optimum and was characterized by the deposition of beach deposits placed slightly above the present mean sea level backed by well-developed dune belts radiometrically aged about 6000 years BP. Good examples of these dune belts can be found at Torre Sabea, to the north of Gallipoli, and along the coastal tract from Gallipoli to Torre del Pizzo (Figure 7).



Figure 7. The well-developed dune belt formed in the mid-Holocene along the coast of Gallipoli.

A younger phase of dune development dates to about 2500 years BP. Archeological and morphological evidence collected along the Ionian coast of the Salento peninsula [20] suggests that this phase is probably related to a low sea level stand that increased the availability of bioclastic sediments coupled with an increased frequency and intensity of southerly winds.

Along the Adriatic coast of the Salento peninsula, dune belts up to 16 m high developed from the end of the 18th century in response to an increase in Ofanto solid discharge due to very severe and frequent flood events and to the deforestation of drainage basin slopes [21,22]. In fact, from the end of the 18th century and the end of the first half of the 20th century, the Ofanto River formed a wide lobate delta and fed beaches and dune belts placed along the Adriatic coast of Apulia. These sediments are marked by the presence

of volcanic minerals coming from Monte Vulture, a relict volcano placed in the Ofanto drainage basin (Figure 8).



Figure 8. Beaches stretching along the Adriatic side of the Salento Leccese peninsula are marked by the presence of volcanic minerals coming from Monte Vulture (province of Potenza).

The analysis of topographic maps at a 1:25,000 scale, produced in the middle of the last century by the Istituto Geografico Militare (I.G.M.), allows the natural morphology of coastal dunes occurring at the back of the main beaches to be identified because these maps were constructed before the main phases of coastal area urbanization. In the middle of the last century, continuous dune belts could be identified at the back of the main beaches; their maximum heights varied from 4 to 16 m above m.s.l. In detail (Figure 9), they were well developed along the coastal tract from Casalabate to S. Foca, at Torre dell'Orso bay and at the Alimini locality (Otranto municipality), along the Adriatic coast of the Salento peninsula. On the Ionian coast, high dune belts occurred along the main beaches located to the west of Porto Cesareo, while lower dune belts occurred at the back of the main beaches in the surroundings of Gallipoli and along the coastal tract from Torre San Giovanni to Torre Vado.

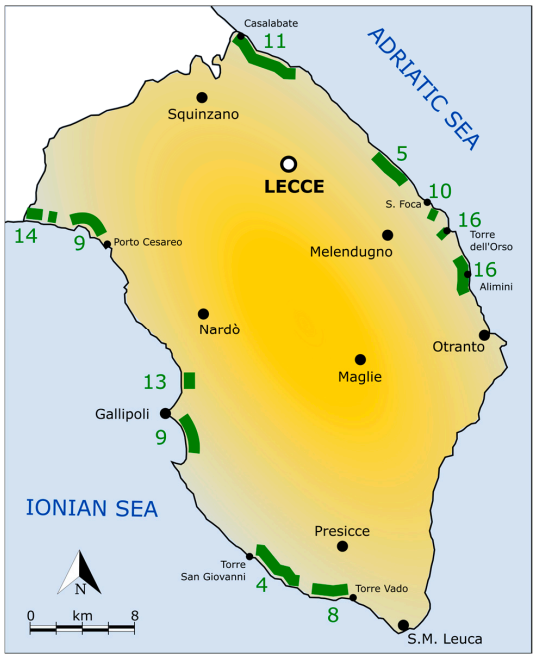


Figure 9. Position and maximum altitude (in meters above mean sea level) (green numbers) of the present dune belts occurring along the main beaches of the Salento Leccese coast as reported by IGM cartography carried out in the middle of the last century.

4. The Historical Evolution of the Salento Leccese Coastal Landscape

A valuable starting point for the reconstruction of the historical evolution of the Salento coastal landscape is the analysis of the Atlante Geografico del Regno di Napoli, completed by Rizzi Zannoni in 1812; it comprises 31 sheets at a 1:114,545 scale [12].

The geographical maps related to the Salento Leccese coast were published in 1808. The maps of the Atlante Geografico del Regno di Napoli show that at the beginning of the 19th century, a wide belt of marshes marked the Salento Leccese coastal area (Figure 10), as did a lack of roads and coastal villages, except for the historical towns of Otranto and Gallipoli. The negative influence of coastal marshes on public health due to malaria is described in great detail by Pareto [23]. This author stresses the importance of land reclamation works to avoid surficial water stagnation and to use these wide areas for agricultural purposes as well as to eradicate malaria. The Salento Leccese coastal marshes and the related severe public health problems that remained at the end of the 19th century are well described by De Giorgi [24].

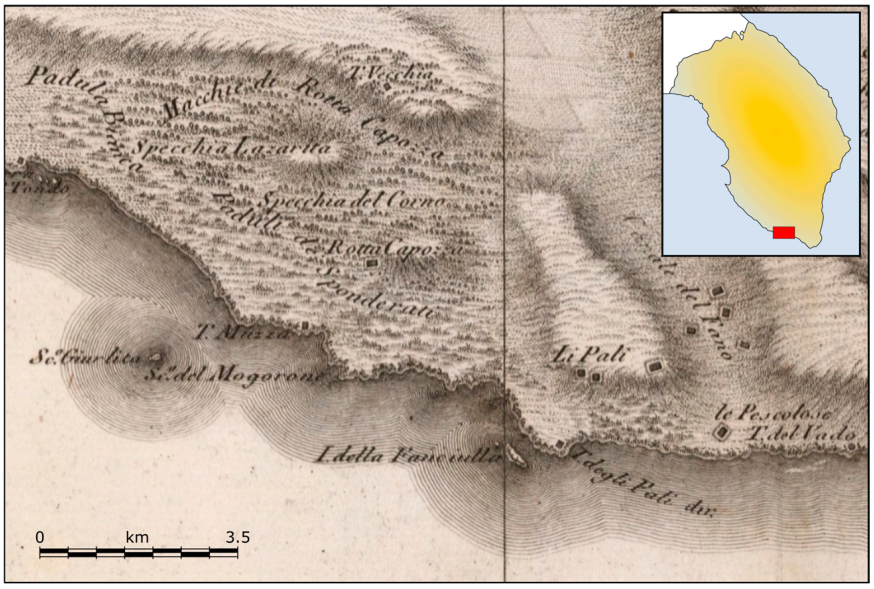


Figure 10. Detailed map from Rizzi Zannoni (1808) showing a coastal tract of the Salento Leccese peninsula in the surroundings of Torre Pali (Salve municipality), marked by a wide extension of coastal marshes (courtesy of David Rumsey Map Collection, David Rumsey Map Center, Stanford Libraries; mod.). The red box marks out the geographical position of the mapped area.

Coastal marshes generally developed along the Salento Leccese coast at the back of beach/dune systems. However, in the northeastern sector of Salento Leccese, coastal marshes formed because of the outcropping of surficial phreatic water tables corresponding to numerous morphological depressions due to the collapse of karst cavities. These depressions show a rapid karstic evolution due to the mixing of phreatic waters with sea water intruding from the coast [25–27] (Figure 11). Furthermore, marshes were also diffused in the coastal area from Roca to Otranto due to the presence of a tectonic depression system elongated in the NNW–SSE direction; the deepest of these depressions host the Alimini lakes.

Small marshes were reclaimed from 1860 mainly through private investments. However, a decisive impulse for the land reclamation of Salento Leccese marshes was promoted by the Italian government in the period between the World Wars of the last century. It involved the First World War veterans (*Opera Nazionale Combattenti*) and two national organizations (*Consorzio di Bonifica "Arneo"* and *Consorzio di Bonifica "Ugento"*), both founded in 1927.



Figure 11. The northeastern Salento coastline, stretching for more than 35 km between the Casalabate and S. Cataldo localities, is composed of sandy beaches of limited length comprising small rock promontories. They are backed by dune belts, extensively eroded by sea waves and anthropogenic actions, and coastal marshes that occupied morphological depressions due to the collapse of karst cavities.

The land reclamation works involved digging basins and channels to connect the main depressions among them and the shoreline (Figures 12–14), and the filling of back dune areas using dune belt sediments (Figure 15) [28]. Pine trees were extensively planted on the dune surface (Figure 16) [29].

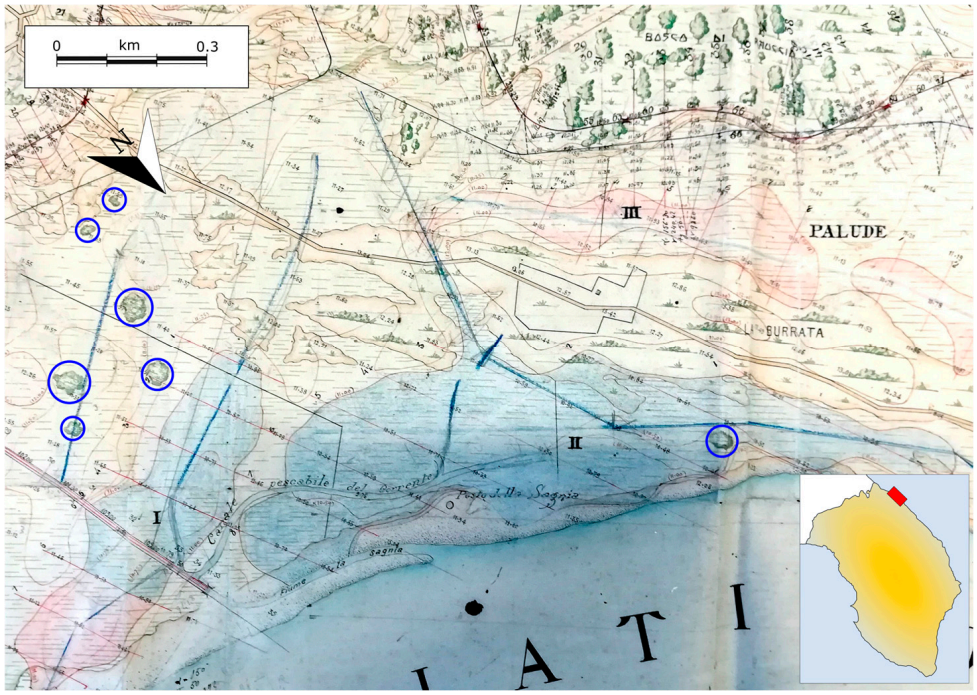


Figure 12. The coastal area stretching from Torre Chianca to Torre Rinalda along the Adriatic side of the Salento Leccese peninsula on a map from 1916. The area is marked by wide coastal marshes as well as springs, mapped with small circles (courtesy of Archivio di Stato di Lecce, mod.). The red box marks out the geographical position of mapped area.

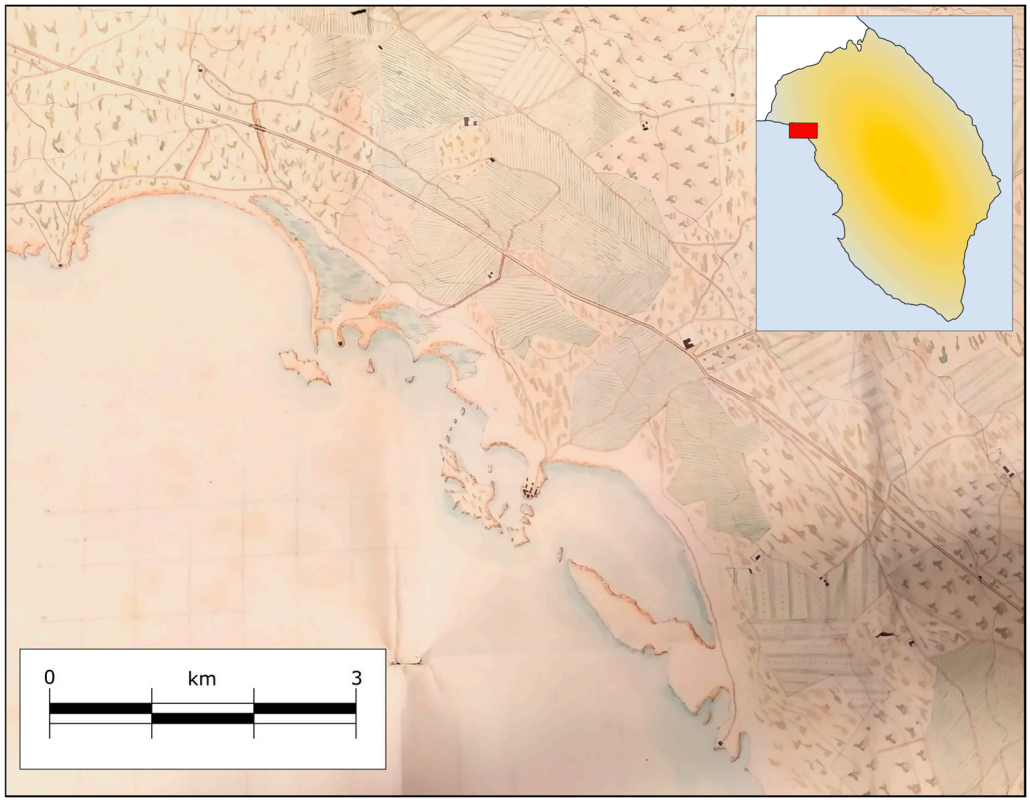


Figure 13. The coastal area of Porto Cesareo on a map from the end of the 19th century (courtesy of Archivio di Stato di Lecce, mod.). The red box marks out the geographical position of mapped area.

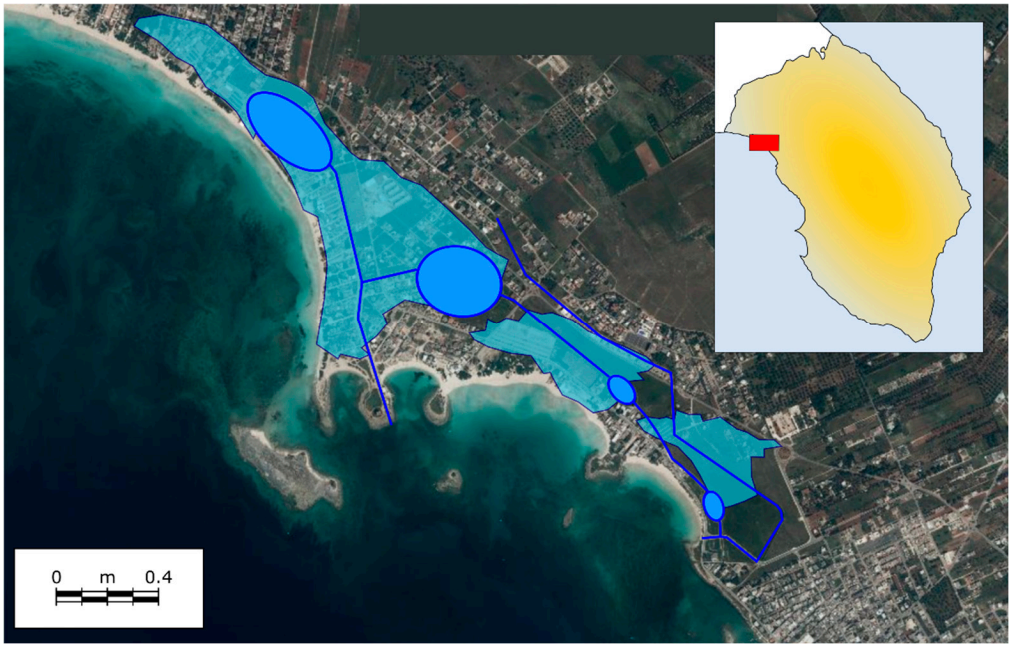


Figure 14. The area of coastal marshes reported in the map of Figure 13 (light blue) along with the reclamation works carried out at the beginning of the last century in the area of Porto Cesareo. The red box marks out the geographical position of mapped area.

A new phase of heavy modification of the coastal landscape occurred from the 1960s to the 1980s, linked to the development of the tourist industry. During this period, the coastal road was constructed and the main coastal agglomerates grew (Figure 17).



Figure 15. The back dune depressed areas were reclaimed by excavating dune belts. Aeolian sands were transported using wagons pulled by donkeys on mobile rails (Decauville) (from [28]).



Figure 16. The plantation of pine trees on the dune belt backing the Alimini beach carried out in the 1930s (from [29]).



Figure 17. Torre San Giovanni locality (Gallipoli). The construction of the coastal road and bathhouses in the 1960s severely modified the dune/beach system morphology along numerous coastal areas of Salento Leccese (from [30]).

5. Case Studies

The historical evolution of the Salento Leccese coast can be illustrated by describing in detail two particular coastal tracts: one placed on the Adriatic side of the Salento peninsula (Torre dell'Orso locality), and the other on the Ionian coast (Torre Pali locality). They can properly describe two different models of coastal evolution recognized in the Salento peninsula. The Torre dell'Orso site is representative of beaches placed along the Adriatic coast, marked by well-developed dune belts covered by a dense vegetation cover. On the other hand, Torre Pali is backed by a low, degraded dune belt, similar to many other coastal tracts occurring on the Ionian side of the Salento peninsula.

5.1. Torre dell'Orso (Melendugno)

Torre dell'Orso beach is inside a small bay bordered by cliffs, up to 15 m high, shaped in Upper Pliocene calcareous clayey sandstones (Sabbie di Uggiano formation). The beach is about 800 m long and 30 m wide; it is backed by a dune belt whose height increases southward in response to most frequent and strong winds, locally blowing from northerly sectors.

The beach sediments are medium-fine sands mainly composed of calcite (64%), quartz (24%), heavy minerals (6%), plagioclases (5%), and dolomite (1%) (Figure 18) [31]; this composition suggests a significant nourishment from Ofanto River alluvial sediments.

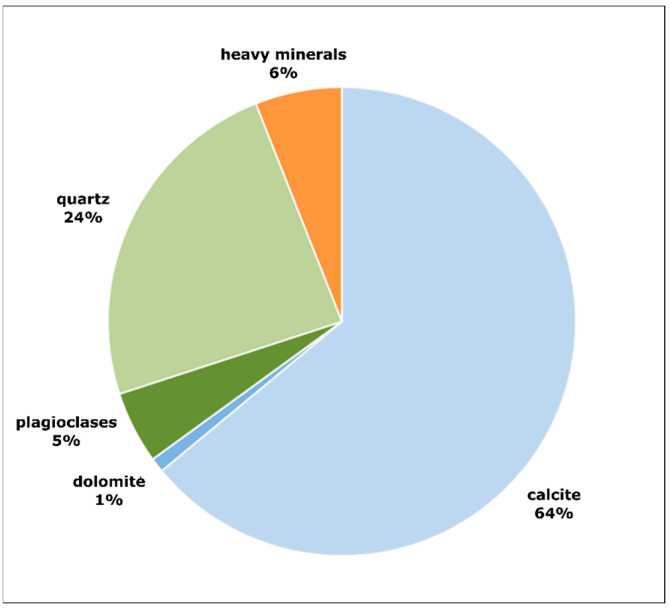


Figure 18. Mineralogical composition of Torre dell'Orso beach sediments (from [31], mod.).

According to Sansò et al. [32], the small bay was formed in correspondence to a relict river valley mouth in response to the rapid cliff retreat promoted by a local sea level still-stand at about 3.5 m below the present mean sea level; this occurred between 3400 and 2400 years BP. Regarding the eastern coast of the Salento peninsula, in fact, a local sea level curve was defined based on data from the analysis of Alimini piccolo lake sediments [33]; the results of this analysis differ from those proposed for a number of Mediterranean coastal sites [34,35]. The local sea level curve is characterized by a slow rise between 5500 and 3900 cal. BP, followed initially by a drop culminating at around 2500 cal. BP and then by a new, steeper rise up to the present position.

The wide beach and the high dune belt developed inside Torre dell'Orso bay only over the last four centuries in response to the above-described increase in the Ofanto River's carry load. Beach sediments accumulated inside the bay over the last four centuries,

allowing the development of a high dune belt that was affected by the extensive plantation of pine trees during the 1930s. The coastal road was built in the 1950s, while in the 1960s, the old bathhouses built using wooden structures (Figure 19) were replaced by concrete structures built on the beach just above the storm wave limit, partly destroying the dune belt (Figure 20).



Figure 19. The beach of Torre dell'Orso in the first few decades of the last century (from [36]).

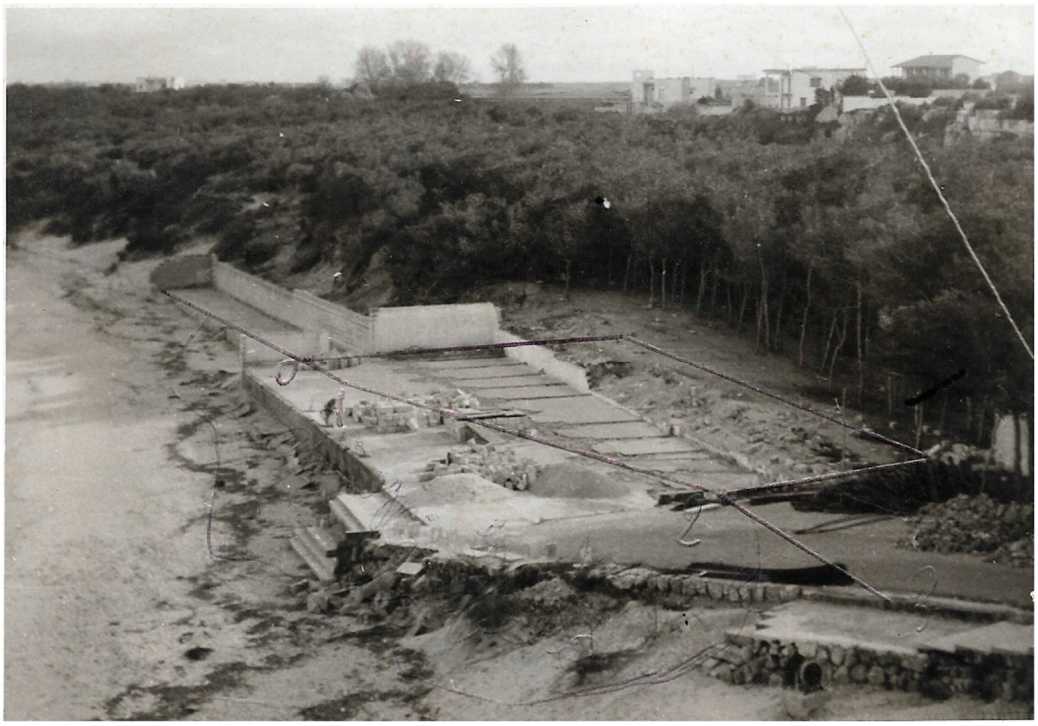


Figure 20. Torre dell'Orso locality. Bathhouses were built during the 1960s at the landward beach border, partly destroying the dune belt.

In the 1970s, a small, urbanized area occupied the northern area of Torre dell'Orso bay, close to the cliff edge, and urbanization spread over a larger area over the following decades such that new rows of houses parallel to the cliff edge were built; an orthogonal pattern

marks the last phases of urban development (Figure 21). The urbanized area grew from about 20 ha in 1972 to about 90 ha in 2006 at a generally constant rate (Figures 22 and 23). The urbanized area/emerged beach surface area ratio peaked in 2006 at about 35 (Figure 23); this resulted in the overcrowding of Torre dell'Orso beach during summer, so bathers would be pushed to occupy the dune belt area. This behavior destroys the pioneering vegetation on the dune surface and the reforestation works recently carried out in the pine forest. Moreover, it poses a threat to public health because the pine trees are prone to falling due to their age and the bad growing conditions due to the high plant density.



Figure 21. Different patterns of urban development recognizable in the Torre dell'Orso urban area. White lines represent roads, orange line marks the cliffed coast, yellow line is a beach.

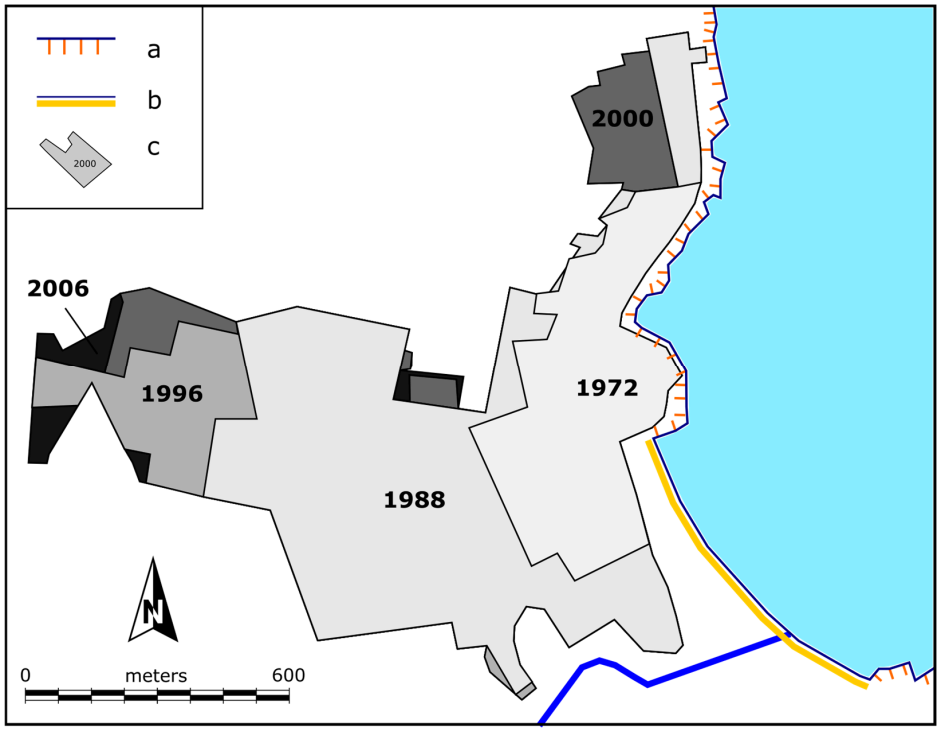


Figure 22. The different phases of Torre dell'Orso urban area development. Legend: a—cliff; b—beach; c—urbanized area (the number is the year of the survey).

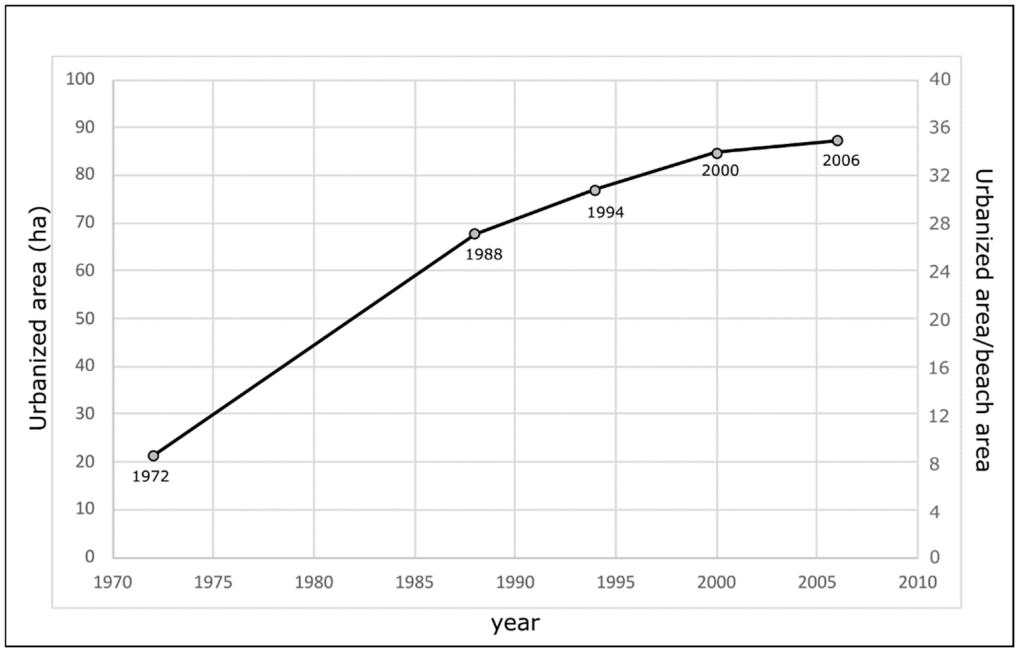


Figure 23. The growth of the urbanized area in the Torre dell'Orso locality from the year 1972 to the year 2006.

The evolutionary trend of Torre dell'Orso beach has been dominated during the last fifty years by erosion due to both natural and anthropic factors. Recent research, in fact, pointed out that this coastal area has been affected during the last 2500 years by active subsidence such that, at present, a relative sea level rise rate of about 1.5 mm/year has been estimated [32]. Furthermore, the carry load of the Ofanto River, the main source of beach nourishment, dramatically decreased after the 1970s due to the numerous dams built in its drainage basin (Figure 24) [37].

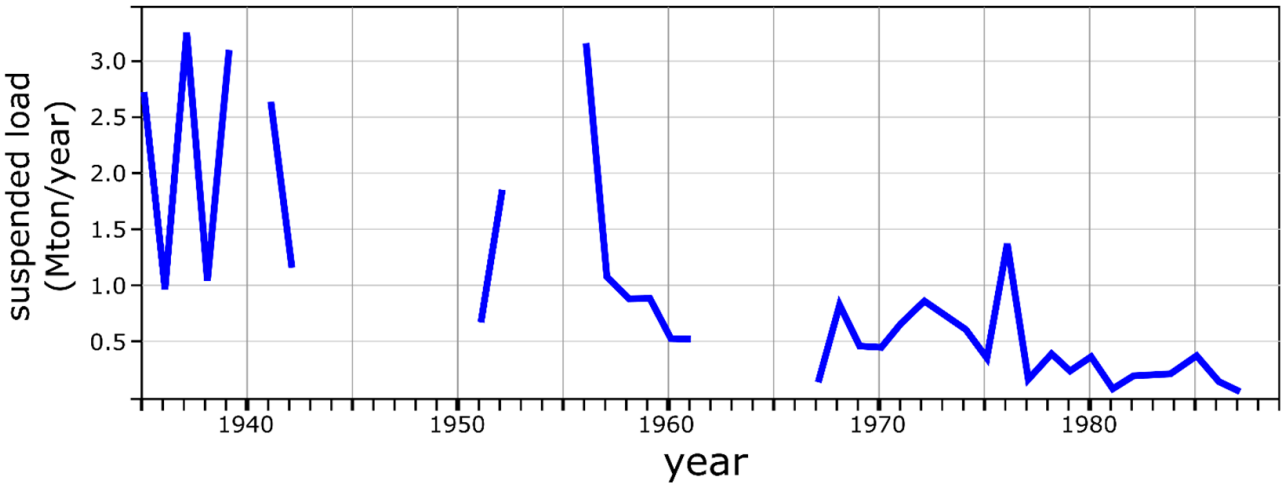


Figure 24. The carry load of the Ofanto River decreased dramatically from the 1960s in response to dam construction within its hydrographic basin (analysis based on data collected at the San Samuele di Cafiero hydrometric station).

The present erosive trend is clearly visible at the foot of structures built just at the beach's inner border, which are actively eroded by storm waves (Figure 25).



Figure 25. The effects of beach erosion on a bathhouse built during the 1960s at the Torre dell'Orso locality.

5.2. Torre Pali (Salve Municipality)

The beach of Torre Pali stretches along the Ionian coast of the Salento Leccese peninsula. It is part of the Torre San Giovanni–Torre Vado physiographic unit composed of beaches of variable length with intervening low rocky platforms. Torre Pali beach is about 2.5 km long and about 24 m wide, and it is bordered landward by a continuous dune belt, up to 6 m high. The beach sediments are medium bioclastic sands mainly composed of calcite (76%), aragonite (10%), quartz (10%), and, to a lesser extent, plagioclases (3%) and dolomites (1%) (Figure 26) [31].

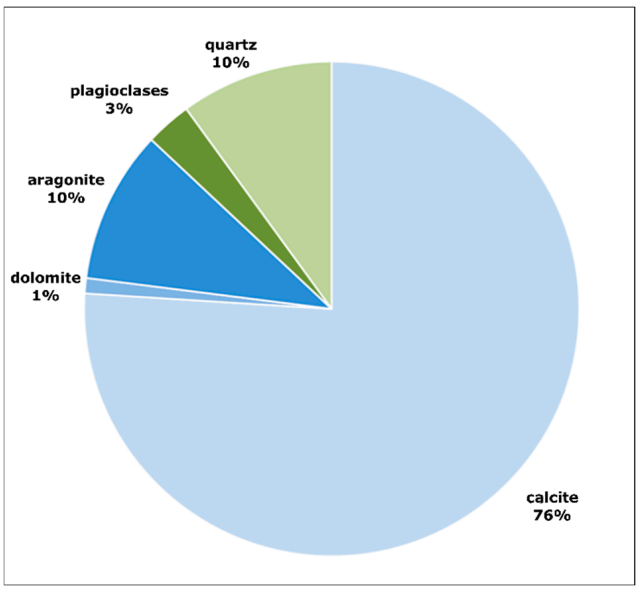


Figure 26. Mineralogical composition of Torre Pali beach sediments (from [31]; mod.).

Coastal erosion at the eastern far end of the beach revealed a rock platform cut across Mesozoic limestones, which showed regular seaward-dipping stratification

(Figures 27 and 28; level a). The limestones are covered by a coarse conglomerate made of well-rounded calcareous pebbles surrounded by a dark red sandy matrix (Figures 27 and 28; level b). The conglomerates rapidly shades upward to purple clayey sands with thin conglomeratic levels (Figures 27 and 28; level c). These clastic deposits are about 1 m thick and can be linked to Canale Fano stream activity during the last interglacial period. The local stratigraphic sequence is terminated upward by loose brownish sands, about 2 m thick, and marked by discontinuous pebble layers (Figures 27 and 28; level d).



Figure 27. Coastal erosion at the eastern far end of Torre Pali beach. (**A**) Mesozoic limestones outcrop at mean sea level; (**B**) a view of continental red conglomerates and continental dark red clay deposits; (**C**) a view of the mid-Holocene aeolian deposits. Legend: a—Mesozoic limestones; b—continental red conglomerates; c—continental dark red clayey sands; d—loose brownish sands; e—mid-Holocene aeolian deposits; f—present aeolian deposits.

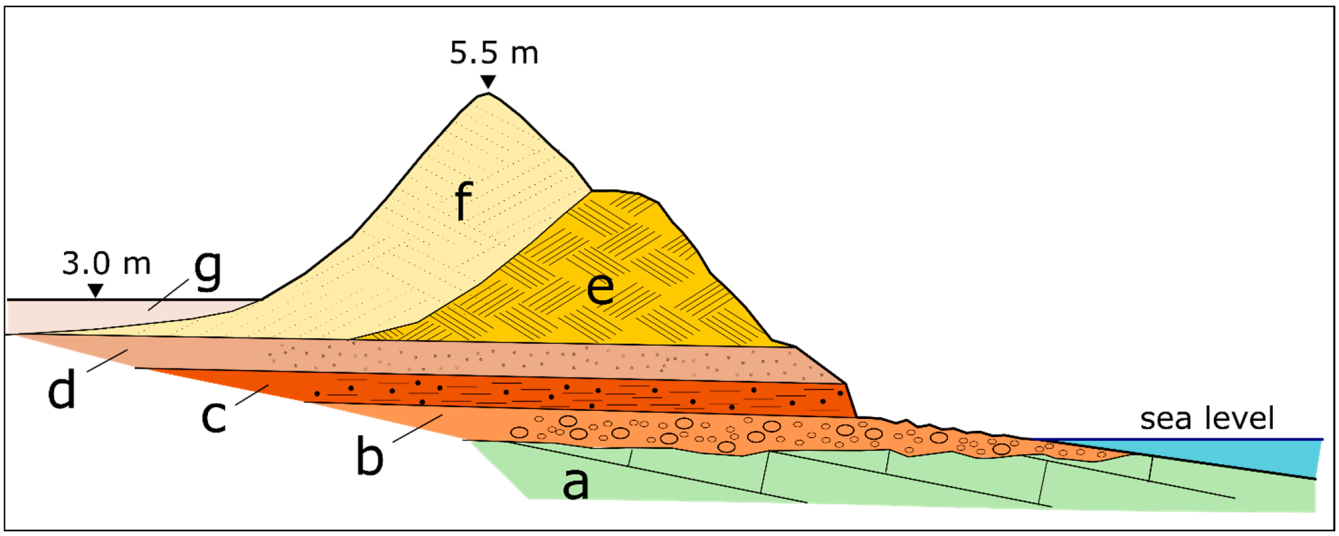


Figure 28. Geomorphological cross-section of Torre Pali coast. Legend: a—Mesozoic limestones; b—continental red conglomerates; c—continental dark red clayey sands; d—loose brownish sands; e—mid-Holocene aeolian deposits; f—present aeolian deposits; g—colluvial deposits.

In the Torre Pali coastal area, two generations of dune belts can be found. The older one is composed of consolidated fine sands marked by high-angle cross-stratification; this unit can be linked to the mid-Holocene (Figures 27 and 28; level e). The younger dune belt is made of brownish loose fine sands (Figures 27 and 28; level f) and is presently strongly impacted by the touristic use of the beach (Figure 29). In fact, notwithstanding the low urbanized area/emerged beach ratio, the occurrence of a network of small roads as well as numerous car parks in the back dune areas leads to the overexploitation of the beach and dune area. The dune belt, in particular, is affected by numerous gaps and is very degraded.

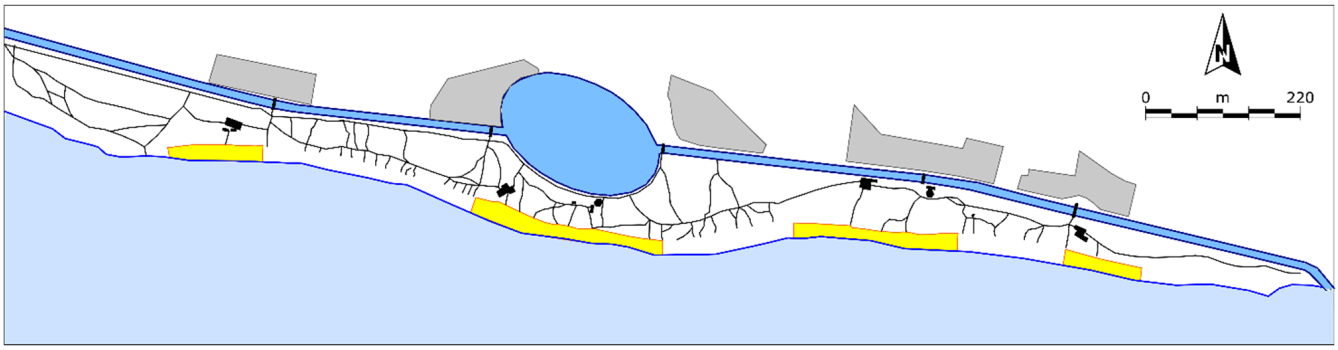


Figure 29. At the Torre Pali locality, numerous paths cut the dune belt. Yellow areas mark the areas occupied by bathhouses, grey areas highlight car parking, and blue areas are canals and ponds.

The main phase of beach development along the Ionian coast of southern Salento was promoted by a local low sea level stand that occurred about 2500–3500 years ago that made available a larger amount of coastal sediments for beach nourishment, along with an increase in the frequency and intensity of southerly winds [9].

As shown by a historical map drawn in 1915 (Figure 30), wide marshes formed behind the dune belt (Palude Sant'Antonio, Palude Chiara and Palude Grande). These areas were reclaimed during the 1930s by constructing a subcircular basin connected to the shoreline using two channels (Figure 31).

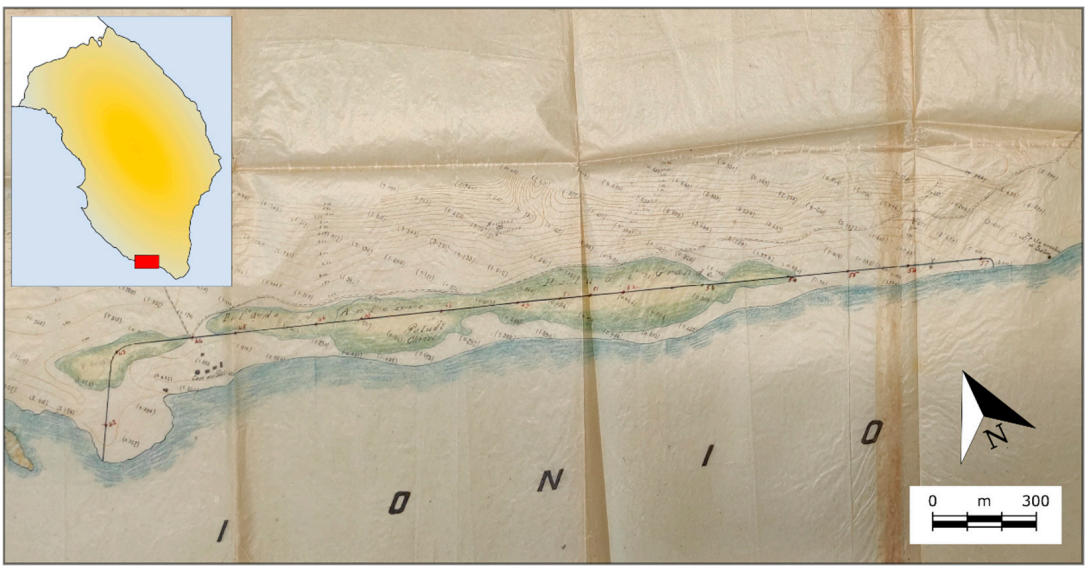


Figure 30. The extension of coastal marshes at the back of the Torre Pali dune belt as reported in a land reclamation plan from 1915. During the 1930s, a subcircular basin was built, connected to the shoreline through a channel (courtesy of Archivio di Stato di Lecce, mod.). The red box marks out the geographical position of the mapped area.



Figure 31. The wide coastal marshes (light blue areas) reported in the map of Figure 30 compared to the present situation. Dark blue lines are channels that link an artificial subcircular basin (dark blue area) to shoreline.

The first phase of urban development occurred in the 1970s and 1980s; it mainly involved the area closest to the shoreline (Figure 32). During the following decades, urban areas grew faster along the coastal road, about 700 m away from the shoreline (Figure 33). The urbanized area/emerged beach surface ratio increased from less than 1 in 1972 up to 3.7 in 2006 (Figure 34).



Figure 32. Present aeolian dune deposits incorporated in a private property at the Torre Pali locality.

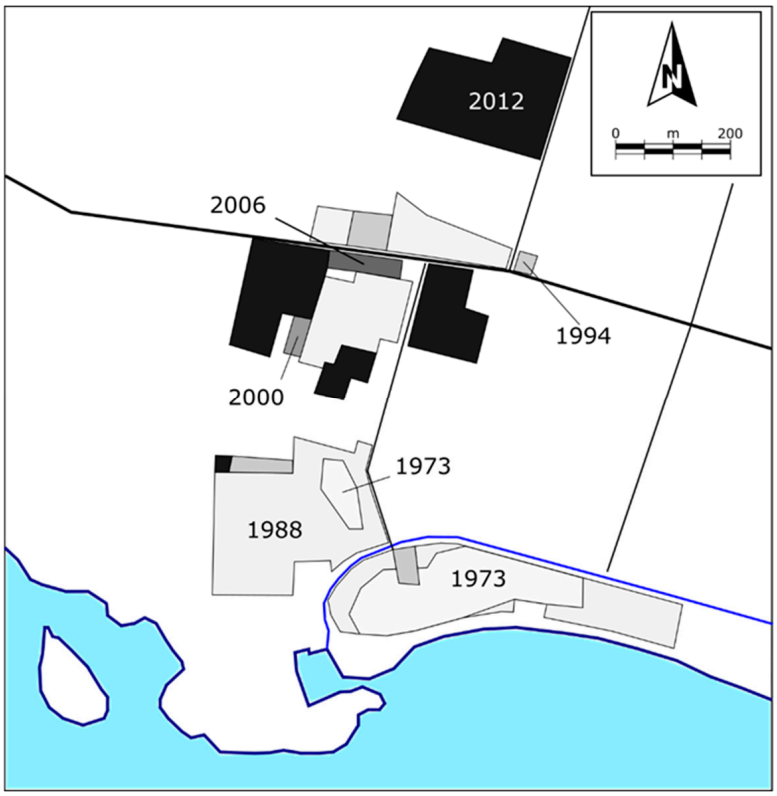


Figure 33. Urban development at Torre Pali locality from 1973 to 2006. Black lines represent roads; blue line is a channel.

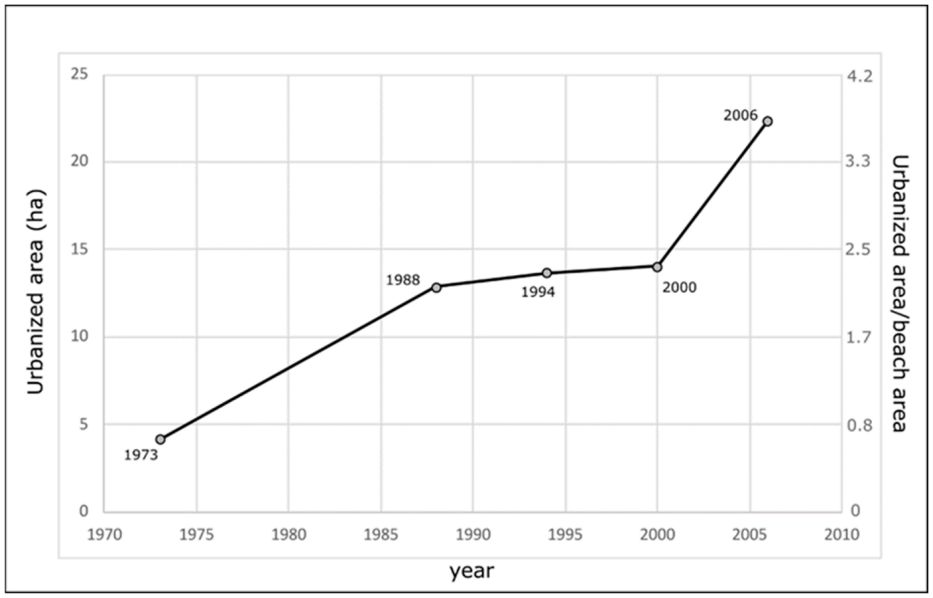


Figure 34. The growth of the Torre Pali urban area from 1973 to 2006.

Over the last 40 years, erosion, driven by both natural processes and human activities, has been the dominant factor shaping the evolution of Torre Pali beach (Figure 35) [38]. This trend is mainly due to the local subsidence of the coastal area coupled with the construction of the Torre San Giovanni and Torre Vado harbors, which constitute two sediment traps. Local subsidence is suggested by the unusual position of the Torre Pali coastal tower (Figure 36), which can be explained by assuming that the mean sea level was 0.6–1.0 m lower than at present when the tower was constructed. This subsidence has been attributed to the doming of the Salento peninsula that occurred over the last four millennia in response

to two geodynamic far-ranging tectonic components that act simultaneously, i.e., the Calabrian arc and the Dinarides–Albanides–Hellenides chain, and the NW–SE Eurasia–Nubia convergence [39].



Figure 35. Severe erosion at Torre Pali beach, with a low cliff incised into the dune foot.



Figure 36. Torre Pali was built during the second half of the 16th century on the coastal platform presently stretching below the mean sea level due to coastal area tectonic subsidence coupled with an eustatic sea level rise that occurred during the last few centuries.

6. Conclusions

The coastal dynamics of the Salento Leccese peninsula are the result of complex relationships among geological characteristics and evolution as well as hydrological, climatic, and wave climate conditions.

The main natural drivers of the Salento Leccese coastal evolution are tectonics, the river sediment input, the relative sea level, and climate change. The Salento Leccese coastal area has been affected during the last few centuries by tectonic subsidence coupled with sea level rises. On the other hand, the sediment budget along the Adriatic side is dominated by the Ofanto River solid load, whereas the Ionian coast's evolution is linked to the production and accumulation of bioclastic sediments enhanced by low sea level stands and prevailing southerly winds.

Historically, these relationships were strongly modified by growing anthropic pressure. Extensive reclamation works in coastal areas were carried out during the last two centuries, whereas during the last few decades, hydraulic works affected all the drainage basins that influence the Apulian coastal area, thus decreasing the sediment load to the coast and inducing a negative beach sediment budget. Harbor structures and defense works have modified the hydrodynamic conditions along the coast, impeding the longshore transport of sediment; the growing urbanization and industrialization have occupied ever wider coastal areas, rendering them vulnerable to even small environmental changes.

The development of wide beaches along the Ionian coast of the Salento Leccese peninsula occurred between 2500 and 3500 years ago, promoted by the availability of bioclastic sediments. On the other hand, beach formation on the Adriatic side occurred during the 18th–19th centuries in response to an increase in the Ofanto River's carry load.

Until the beginning of the last century, the coastal area was deserted; large coastal marshes at the back of the main beach/dune systems or at coastal karst depressions were common. Important reclamation works were carried out between the two World Wars to eradicate malaria and obtain new arable fields. New strong coastal landscape modifications started in the 1960s; a coastal road was constructed, and new coastal agglomerates grew. During the last few decades, the main beaches have attracted ever more tourists, producing a growing impact on beach/dune systems.

The main beaches are currently marked by a negative sedimentary budget, and several coastal tracts are under severe erosion. This is due to an eustatic sea level rise along with local tectonic subsidence, as well as the starvation of coastal sediments due to the building of dams and harbors. On the other hand, beach overcrowding pushes bathers onto the dune belt area, producing a heavy impact, while the increasing urbanization of coastal areas prevents the landward shifting of beach/dune systems, thus worsening the local effects of coastline retreat.

The described case studies illustrate two different models of evolution that will affect the Salento Leccese beaches in future decades. Beaches confined between rocky heads and bordered by nondegraded high dune belts, mainly placed along the Adriatic side, such as Torre dell'Orso beach, will survive in the short term based on the current sea level rise due to dune sediment availability, which now represents the only significant sedimentary source for natural beach nourishment. For this reason, techniques that mitigate beach erosion to make dune sediments more resistant [40] or defense works that protect the dune foot from storm wave action (such as wooden fences) negatively impact the beach sedimentary budget and exacerbate beach erosion. On the contrary, foredune restoration using sands available at nearby places and consolidated through the plantation of local species could mitigate dune erosion, especially if coupled with the implementation of integrated management plans [41].

Beaches along the Ionian side of the peninsula, such as Torre Pali beach, are bordered by low and strongly degraded dune belts that do not significantly influence the beach sedimentary budget. These coastal tracts will be gradually substituted by gently sloping rocky platforms because the current sea level rise will not be accompanied by active nourishment due to a decrease in bioclastic sand production. Finally, coastal erosion will pose severe management problems for the coastal tracts where houses and other anthropic structures have replaced dune belts.

The geomorphological features and history of the Salento Leccese coast along with its evolutionary trend should be carefully considered when devising future National Restoration Plans according to the recent Nature Restoration Law of the European Commission (2024), which aims to restore degraded ecosystems, particularly those with the most potential to capture and store carbon and to prevent and reduce the impact of natural disasters. Among these ecosystems are wetlands and dunes, which are the most impacted environments of the Salento Leccese coastline.

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