Coastal Hazards Along the Ionian Arc of Apulia (Southern Italy)

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Abstract. This study investigates coastal hazards along the Ionian arc coast of the Apulia region (Southern Italy). As the study area was previously classified as a medium-risk sector in a regional-scale assessment, a detailed hazard analysis was conducted to identify the main driving factors and the most affected areas. The shoreline evolution between 1992 and 2023 reveals an overall stable coastal configuration, characterized by alternating phases of progradation and retreat and a slight net shoreline advance. Despite this general stability, the coastal system remains vulnerable to extreme wave storms, sea-level rise, and both riverine and pluvial flooding. In recent years, sea level has increased, with the highest annual mean value recorded in 2023. Estimated wave run-up values indicate a potential risk of temporary flooding on low-lying beaches and dune areas, while riverine and pluvial flooding events have also been documented in recent decades. Overall, coastal risk in the study area is primarily related to the interaction between extreme water levels, low coastal elevations, and the condition of natural and anthropogenic coastal features, highlighting the need to integrate regional-scale assessments with detailed local analyses. Due to the importance of flooding, these processes will be further studied using 2-D numerical models to simulate hydrodynamic and morphodynamic behavior.

Keywords: Coastal Risk · Shoreline evolution · Sea storms · Sea Level · Riverine flood · Pluvial flood

1 Introduction

The increasing pressure of the effects of climate change on coastal areas, combined with the growing exploitation and development of these zones [1], makes it necessary to constantly update the investigations of littoral areas, especially those with the highest risk. In the most vulnerable areas, large-scale assessments

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may be insufficient to accurately identify the most at-risk coastal stretches and to determine, site by site, the predominant hazard factors [2].

Coastal areas along the Mediterranean Sea are particularly vulnerable to ongoing environmental changes, and numerous studies have focused on the various processes and features that characterize these coasts [3,4]. Regional-scale coastal risk assessment along Apulian coastal areas conducted using the Modified EUrosion Model (Mod.E.M.) identified several hotspot areas [5]. Following this approach, the coastline of the Municipality of Castellaneta was classified as presenting a medium level of risk, in contrast to adjacent coastal stretches, along the Ionian sector of the region, which were categorized as low risk. The methodology adopted was based on indicators calculated on the municipal scale, designed to effectively represent the vulnerability and exposure of the coastal zone.

In light of the model results, the Castellaneta coast was subsequently subjected to further in-depth analyses to thoroughly assess both the critical situations that have already occurred and those that may potentially develop in the future. In this study, key factors influencing the assigned risk classification—namely sea level, wave run-up on the emerged beach, shoreline evolution, and flooding events—were analyzed in detail to identify the most vulnerable coastal sectors and the main sources of criticality.

2 Materials and Methods

2.1 Case Study

The coastal area of Castellaneta Marina is located along the Ionian side of the Apulian coast (Gulf of Taranto) and falls within the littoral cell which begins at the multi-sector pier of the Port of Taranto and ends in Basilicata (Sub-Unit 7.3) [5]. This littoral cell is characterized by an extensive sandy beach with a nearly continuous dune system behind it, except near residential settlements. The coastal strip of Castellaneta is characterized by a coastline that extends continuously for about 9 km from the mouth of the Lato River to the boundary with the Municipality of Ginosa (Riva dei Tessali settlement) (Fig. 1). The sandy beach is relatively wide with a gently slope, and is bordered by partially vegetated dunes. Several orders of dune ridges parallel to the coast are present along the entire shoreline, reaching elevations of up to 15 m above sea level. The mouth of the Lato River, which marks the boundary between the Municipality of Palagiano and Castellaneta, remains in a natural state. From the mouth of the Lato River to the beginning of the Castellaneta Marina settlement, the dunes develop almost continuously, interrupted only by a few beach access paths. East of the Castellaneta settlement and westward to the boundary with the Municipality of Ginosa, the dune ridge appears heavily degraded. The total area of the beach within the Municipality of Castellaneta, measured as the area between the 2017 shoreline and anthropogenic structures or the foot of the dune ridge where present, was estimated to be approximately 0.61 km^2 (referred to 2017). The sediments on the emerged beach are classified as medium sand (diameter

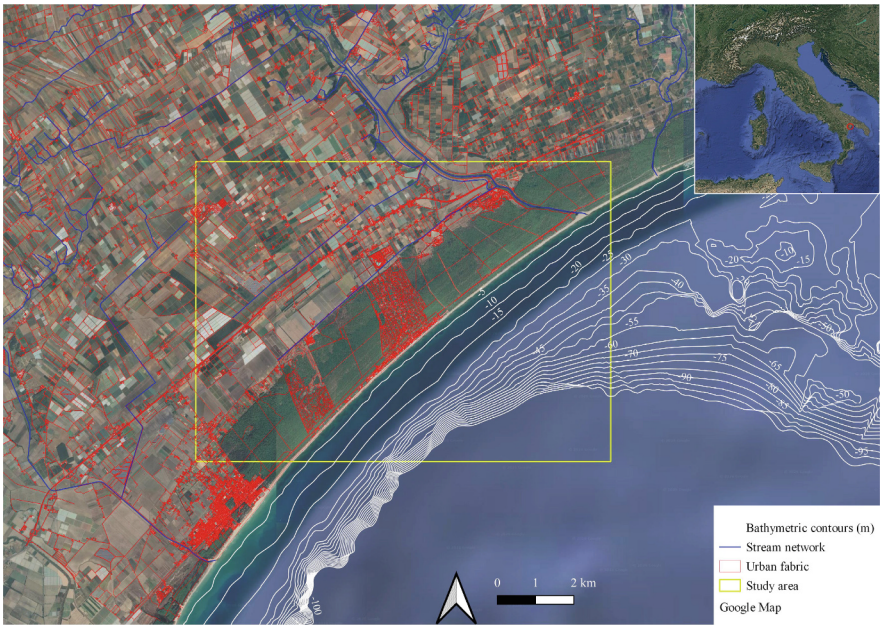

Fig. 1. Study area with stream network (blue lines), bathymetric contours (white lines) and urban fabric (red polygons). (Color figure online)

between 0.25 and 0.5 mm) according to the Udden–Wentworth scale, and quartz is the main mineralogical component (70% of the total).

Rainfall in Castellaneta Marina is typically moderate and seasonal, with most precipitation occurring in autumn and winter and relatively dry summers, consistent with the Mediterranean climate [6]. The hydraulic framework of the area is particularly complex due to the presence of several watercourses, as well as extensive land reclamation and drainage works. In the late 19th century, a railway line was constructed along the coastal belt and, since the 1950 s, numerous concentrated tourist settlements have been developed. These human interventions, together with the construction of numerous reservoirs along the watercourses that flow into the Ionian Sea, have led to a sediment deficit since the 1960s, resulting in widespread erosion phenomena along the Basilicata Ionian coast [7].

Despite the anthropogenic interventions described above, as shown by the diachronic analysis of shoreline positions recorded between 1992 and 2008, the Apulian coastline from Taranto to Ginosa could be considered substantially stable, with some stretches showing a slight progradation trend.

Much of the Castellaneta Marina area is subject to geomorphological constraints, classified as geomorphological hazard areas (low risk-PG1) under the Hydrogeological Plan (PAI) [8], supported by the presence of dune ridges. Moreover, some areas along the Lato River and at its mouth are affected by river

flooding phenomena and fall within areas classified under the PAI as high and medium hydraulic hazard zones.

According to the CNAT – Nature Charter, the municipal coastal area hosts several habitats classified under the European CORINE Biotopes system, ranging from sparsely vegetated sandy shores to more structured dune systems, including native Aleppo pine forests on fossil dunes, many of which have been partially degraded due to human development [9].

Due to the combined occurrence of coastal erosion processes, hydraulic hazard, low elevations above sea level (which contribute to site vulnerability), and the presence of natural areas and residential settlements (constituting the exposure), the Mod.E.M. method classifies the resulting risk level as medium [5]. Specifically, to analyze in detail the hazard indicators affecting the study area, the components attributable to meteo-marine forcing, riverine and pluvial flooding, as well as the evolutionary coastal processes and their temporal variations, have been investigated here.

2.2 Data Sources and Methods

The predisposition of the coast to erosion and/or flood in the Mod.E.M.approach was based on the morphological, geological, hydraulic, and sediment characteristics of the study area, as well as the oscillation of sea level and wave energy approaching the coast [5]. In order to achieve a higher level of characterization, including spatial resolution, these elements were examined in detail by analyzing the evolutionary processes, sea-level fluctuations, wave run-up on the emerged beach, and hydraulic risk phenomena.

To reconstruct the evolution of the sandy shoreline in the examined area, the shoreline positions extracted from aerial and satellite imagery taken at different times were analyzed (1992, 2005, 2019, 2023). The shorelines were digitized and superimposed for comparison. Shoreline evolution was analyzed using DSAS (Digital Shoreline Analysis System), an ArcGIS extension developed by the United States Geological Survey (USGS) [10]. DSAS is based on the tracing of transects, with user-defined length and spacing, perpendicular to a baseline. In this case, 90 transects spaced approximately 10 m apart were drawn from north to south. For each transect, the NSM (Net Shoreline Movement) parameter was calculated, representing the distance between the oldest and most recent shoreline, and the EPR (End Point Rate), representing the annual rate of advance or retreat. The use of EPR values allows for comparison of evolutionary processes without being influenced by different observation period lengths. A high-resolution DTM acquired in 2017 allowed the estimation of the beach slope.

Statistical characterization of meteomarine forcings involved analysis of wave and sea-level events off the investigated area.

Extreme storm event analysis was performed using the ERA5 wave dataset at the grid point located at 40.0°N, 17.5°E, produced by the Copernicus Climate Change Service (C3S) of the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA5 dataset provides, among the more than 200 overall variables, hourly time series of ocean waves on a 0.5° grid [11].

The wave events were then subjected to an analysis of extremes, after employing the POT (Peaks Over Treshold) method in order to consider only the maximum value of significant wave height (peak value) occurring within a single storm event that exceeds the value of a predetermined threshold [12]. The extreme events determined were described by means of the Weibull probability distribution function. In particular, storm events have been analysed with the aim of evaluating their extreme values associated with return periods between 10 and 100 years.

The study of sea-level oscillations in the study area was carried out using data acquired from the Taranto tide gauge station (National Tide Gauge Network managed by ISPRA – Italian Institute for Environmental Protection and Research) [13]. The observed sea level data consist of the sum of contributions from the local mean sea level, the astronomical tide, and the meteorological tide. The annual mean sea level was calculated from the observed data using the Doodson filter [14]. Correcting the observed level with respect to the mean sea level of the reference year makes it possible to remove the influence of the local mean sea level— which varies depending on the reference site—thus allowing a comparison among the results obtained at different stations and, moreover, disregarding the interannual variability of the mean annual sea level.

The probability distribution of extreme events for both the observed level and the corrected level was estimated using a Generalized Pareto Distribution (GPD) applied to two truncated series consisting of the five highest values recorded each year, extracted from the two historical time series [15].

The coastal inundation hazard was assessed using an estimate run-up analysis based on the simplified method proposed by Stockdon [16]:

$$R_{u2\%} = 1.1(0.35\beta_f(H_0L_0)^{0.5} + [H_0L_0(0.563\beta_f^2 + 0.004)]^{0.5}/2) \quad (1)$$

where $R_{u2\%}$ is the run-up level exceeded by two percent of the incoming waves; H_0 is the wave height in deep water; L_0 is the wave length in deep water and β_f is the foreshore slope.

The Stockdon equation estimates wave run-up, defined as the maximum vertical extent of wave uprush on a beach or structure above the Still Water Level (SWL), including also wave setup and requires offshore wave characteristics, so use of this formula is very convenient for cases of application to large areas and where bathymetric data are not available. The probability distribution of extreme events for wave height was estimated using a Weibull Distribution applied to values exceeding a threshold value, extracted from the ERA5 daraset [12]. For each TR return period, run-up values were calculated, allowing the identification of 4 hazard classes (P1 to P4, with increasing hazard level), based on a quartile division of the identified individual samples. The sum of observed sea level and wave run up provides the total storm surge.

Moreover, a targeted search with flood-related keywords has been carried out in local online newspapers following a consolidated approach [17], leading to the detection of other flood events related to extreme rainfall events that caused both river and pluvial flood events [18,19].

3 Results

3.1 Shoreline Evolution Analysis

The diachronic analysis of shoreline positions from 1992 to 2023 shows that the examined coastal stretch is characterized by a variable evolutionary trend depending on the analyzed period (Fig. 2).

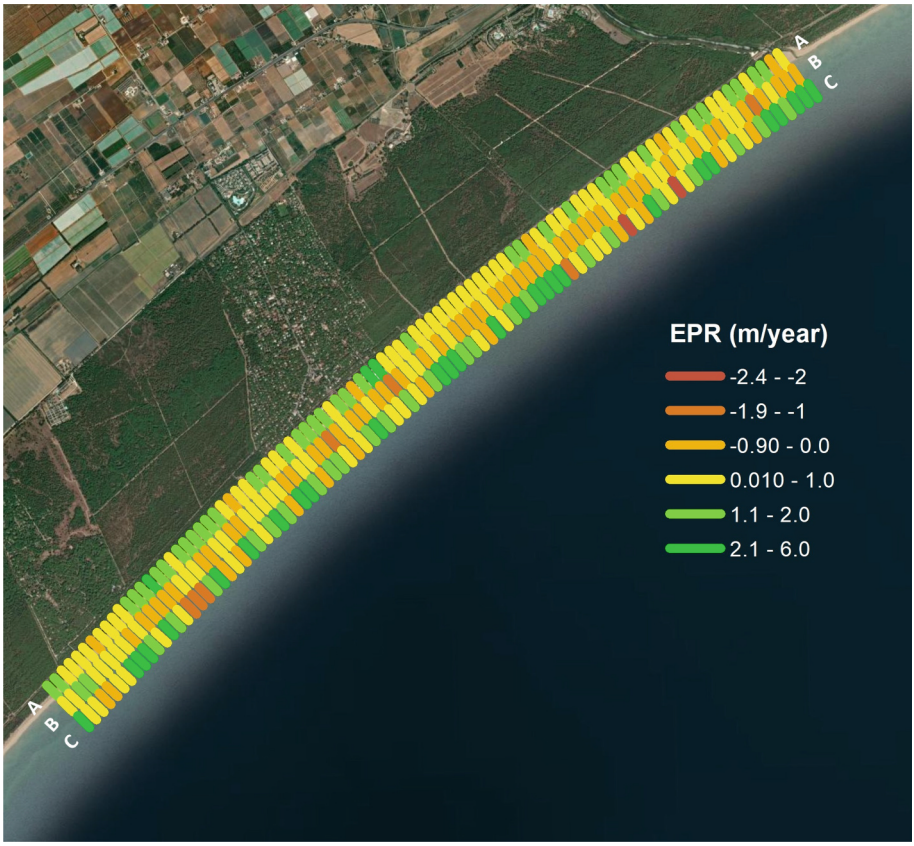

Fig. 2. End Point Rate (EPR) in m/year calculated along 90 transects for three time intervals: A) 1992–2005, B) 2005–2019, and C) 2019–2023.

Between 1992 and 2005, a general positive trend was observed along the entire municipal coastline. Later, in the period 2005–2019, a severe retreat affected approximately 2.8 km of coastline between the mouth of the Lato River and the settlement of Castellaneta Marina, while progradation phenomena were observed along 1.3 km of shoreline, mainly west of the Castellaneta Marina settlement and Riva dei Tessali. The remaining portion of the coast (approximately 50% of the total) remained substantially stable. For the period 2019–2023, based on

satellite imagery retrieved from Google Earth (acquired on 17/09/2023), the EPR analysis shows significant shoreline dynamism, with extensive stretches advancing at rates exceeding 2 m/year.

Overall, despite the alternating phases of retreat and advancement, the analyzed coastal stretch remained largely stable throughout the 1992–2023 period, showing a slight net progradation.

It should be emphasized that the shoreline evolution analyses are based on aerial imagery that captures specific moments in time. Since continuous shoreline monitoring data are not available for the examined stretch, it cannot be excluded that greater advances or retreats occurred during the 1992–2023 period than those reported herein.

3.2 Sea Level Variations

After 2007, a sudden increase in mean sea level was observed in the Mediterranean Sea [20,21], and tide gauges along the Adriatic and Ionian coasts recorded a similar increase, resulting in numerous coastal flooding events. Due to these events, with the aim of checking the current mean levels and extreme events, sea level time series acquired by the nearest tide gauge.

Figure 3 shows the sea level observations collected by the Taranto tide gauge during the period 1999–2024. The variation range is approximately 70 cm: levels vary on average between +0.2 m and −0.50 m. With reference to the hourly dataset, the maximum value of +0.51 m was recorded on 13/11/2019 at 14:00, while the minimum value of −0.71 m was recorded on 10-02-2005 at 21:20.

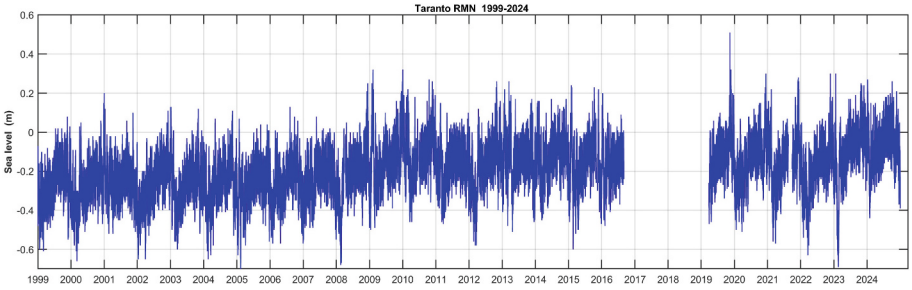

Fig. 3. Sea level recorded by Taranto tide gauge in the period 1999–2024 (hourly dataset).

A strong seasonal variation in mean sea level can be observed, with a marked decrease during the first months of the year. The analysis of annual mean levels at the Taranto station shows a general increase starting from 2008, with differences between 2007 and 2009 on the order of ten centimeters. In 2011, levels decreased to values close to those prior to 2009, followed by a new increase in 2012. It is also observed that in 2023 the highest annual mean sea-level value

was recorded (−0.072 m), with a further increase of approximately 7 cm compared to the previous year. The hourly sea level data was analyzed with the aim of evaluating their extreme values associated with RT between 5 and 100 years. With reference to the results reported in Table 1, it can be observed that the estimated sea levels vary between 0.22 m (5-year return period) and 0.50 m (one-hundred-year return period) through the 50-year value of 0.45 m.

Table 1. Extreme analysis of hourly sea level (observed and corrected with reference to the mean annual level) - GPD distribution.

	RT (years)	Sea level observed (m)	Sea level corrected (m)
	100	0.50	0.78
Years of observation: 22	50	0.45	0.74
Observed max: 0.51 m	10	0.30	0.60
	5	0.22	0.49

3.3 Run-Up Estimation

The wave events were analyzed with the aim of evaluating their extreme values associated with RT between 5 and 100 years. With reference to the results reported in Table 2, it can be observed that the significant wave heights of the sea states coming from the sector 120°- 210° N vary between 4.9 m (10-year return period) and 5.96 m (100-year return period) through the 50-year value of 5.7 m.

Table 2. Extreme analysis of offshore wave heights (sector 120°-210°N) (Weibull distribution).

Sector 120°-210°N	RT (years)	$H_s(m)$
	100	5.96
Threshold: 2. 5 m	50	5.67
Years of observation: 75	10	4.95
Observed max: 5.1 m	5	4.6

Run-up estimation was made using the Stockdon's formula with reference to the extreme values estimated for the offshore wave heights, with associated return periods. For each RT, run-up values were calculated, which allowed the identification of 4 run-up classes (P1 to P4, with increasing level), based on a quartile division of the individual identified samples.

The run-up analysis indicates that the highest values occur in the sector between the mouth of the Lato River and the Castellaneta Marina settlement, due to the steeper slope of the beach, as reported in Fig. 4. The highest level refers to run-up values greater than 1.3 m estimated for a return time of 50-years.



Fig. 4. Run-up estimation for return time RT = 50 years. Run-up classes are based on a quartile division of the individual identified samples. The highest level refers to run-up values greater than 1.1 m.

3.4 Hydraulic Hazard Analysis

The Municipality of Castellaneta is also affected by other types of flood hazards. According to the local flood risk management plan (Fig. 5), the municipal area is interested from river flood prone areas due to the presence of the Lato river, a stream with a catchment of approximately 670 km^2 [22]. The areas surrounding the Lato river have been interested in different flood events, such as those that occurred in October 1966, September 2003, December 2013 and January 2017, which caused relevant damage to infrastructure and rural areas.

The targeted search for flood-related keywords carried out in the local online newspaper has revealed several flooding events. In particular, we mention the events of 2024, 24 July, and 4 August that caused pluvial flooding and road closure of some underpasses of Castellaneta Marina, where the water reached a considerable depth of 0.5 m (Fig. 5). The importance of such events for the city of Castellaneta Marina is motivated by the occurrence of short-duration intense

raifall events, which generally occur in the summer months, when there is a peak of tourists and then a greater risk to people [23].

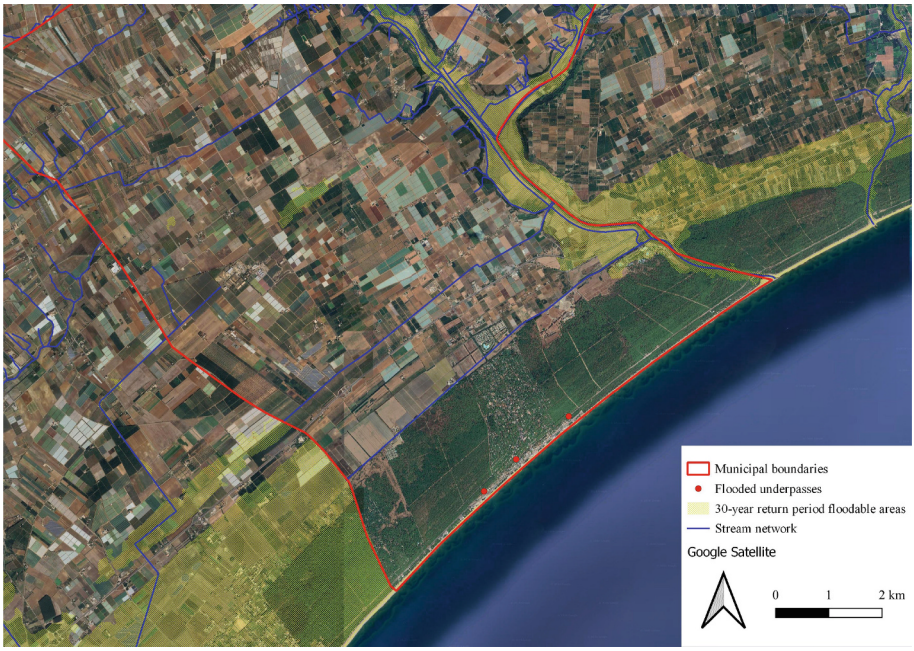

Fig. 5. Floodable area for return time RT = 30 years according to River Basin Plans - PAI (yellow-hatched area). Flooded underpasses after intense rainfall events (red dots). (Color figure online)

4 Discussion and Conclusions

The results of this study provide a clearer understanding of the coastal risk classification for the area examined. This classification comes from a regional-scale assessment using the Mod.E.M. approach. The detailed investigation shows that the coastal system generally has a stable shoreline. However, vulnerability arises mainly from hydrodynamic forces and local landform conditions.

The analysis of shoreline evolution reveals that the coast has gone through cycles of accretion and retreat over the past 30 years. Yet, the overall balance from 1992 to 2023 indicates a mostly stable shoreline configuration with slight advancement. Localized shoreline retreat, especially in the period 2005–2019 between the mouth of the Lato River and Castellaneta Marina, may be related to changes in sediment supply and longshore transport, influenced by dominant wave directions from the S-SSE sector and several severe storms after 2008 in the Ionian Sea [24].

Despite the general stability, the climatic analysis points out the possible exposure of the coastal zone to extreme weather events. Statistical analysis of wave events indicates that significant wave heights could reach nearly 6 m with return periods of 100 years. When these offshore wave conditions reach the nearshore zone, the resulting run-up values exceed 1.1 m in various areas along the coast. This suggests a risk of temporary flooding on low-lying beaches and dune regions.

The sea level analysis further underscores the need to consider long-term changes in mean sea level when assessing coastal vulnerability. Data from the Taranto tide gauge show a general increase in mean sea level since 2008, which is consistent with trends observed throughout the Mediterranean basin [15,25,26]. Specifically, the trend in the annual mean level confirms that the sea level is rising. This suggests that future coastal flooding events may become more frequent and intense, especially when extreme sea levels coincide with storm-induced wave run-up.

The combination of these factors suggests that the current coastal risk is not primarily based on large-scale erosion trends. Instead, it relies on the possible interaction between total water levels, low coastal elevations, and the existence of natural and human-made features. Areas with degraded dune ridges or urbanized coastal zones may be the most vulnerable. The loss of natural dune protection increases the risk of storm impacts in inland areas [27].

Within this framework, it is quite relevant to remark how flood risk management in coastal areas is a complex topic, which requires an in depth analysis of local dynamics arising from the interaction of water with the built environment and people.

In general, the findings highlight the need to integrate regional risk assessments with specific site analyses. Although broad models can identify critical areas, detailed studies of shoreline trends, wave conditions, sea-level changes, and flooding events are essential to understand local processes that affect coastal risk. Given the relevance of flooding phenomena, these processes will be further investigated using 2-D numerical modelling to simulate hydrodynamic and morphodynamic processes.

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