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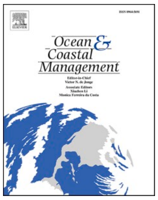

Coastal vulnerability analysis to support strategies for tackling COVID-19 infection

Elvira Armenio[a,*], Michele Mossa[b], Antonio Felice Petrillo[b]

[a] *Regional Agency for the Environmental Prevention and Protection (ARPA Puglia), 70126, Bari, Italy*
[b] *Polytechnic University of Bari, DICATECh, Bari, Italy*

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ABSTRACT

The recent COVID-19 pandemic has constrained world governments to impose measures of restraint and social distancing which also involves coastal areas. One of the most affected activities is tourism due to travel restrictions imposed by precautionary measures. This is also reflected in the recreative use of the coastal strip. Consequently, beaches and coastal stretches of small municipalities can potentially become contagious outbreaks of COVID-19 if adequate control and management measures are not promptly implemented.

During the 20th century, several factors, both natural and human induced, caused alterations to coastal processes and consequently to the services they were providing. Coastal environments are very vulnerable and sensitive to change. This raises the need for careful assessment prior to any intervention or strategy involving the coastal system. Several literature studies have been focused both in the past and in recent years on examining the main factors affecting coastal vulnerability highlighting critical issues and shortcomings.

The present paper, addressing all critical issues from literature review, illustrates a consistent methodology to support coastal management which combines both physical and socio-economic aspects and provides for the quantification of two different coastal vulnerability indices. The approach adopted has led to a distinction of different coastal peculiarities and a mapping of risk levels providing, in addition, the basis for the implementation of strategies risks related to COVID-19. The methodology proposed can be a useful reference in several areas, in demonstrating its effectiveness it has been applied with respect to a coastal area in southern Italy.

1. Introduction

The ongoing COVID-19 pandemic has compelled world governments to impose measures of restraint and social distancing which also involves coastal areas. Some of the major restrictions include: 1) air, sea and road transport limited or totally closed; 2) restaurants, parks, shores, museums, etc. and social activities limited; 3) low consumer demand for products and services except for food and necessities (Campbell et al., 2021; Nghiem et al., 2020; Saadat et al., 2020).

The economy has been severely impacted, and in some places has almost completely disappeared. Among these are economic activities related to marine and coastal environments, such as fishing, aquaculture and coastal tourism. In general, one of the most affected activities is tourism due to travel restrictions imposed by precautionary measures. This is also reflected in the recreative use of the coastal strip: people will tend to move to the coast closer to their residence and avoid large coastal tourist centers. As direct effect, if adequate control and management measures are not promptly implemented, beaches and coastal stretches of small municipalities can potentially become contagious outbreaks of COVID-19. The time pressure and the unpredictable spread of the COVID-19 pandemic require that each small coastal community analyse the possibility of users' contagion and then the appropriate measures to reduce/avoid risks (Loizia et al., 2021a; Neumann et al., 2015; Zambrano-Monserrate et al., 2020).

In addition to the scenario outlined, coastal environments are very vulnerable and sensitive to change. Especially, during the 20th century, several factors caused alterations to coastal processes and consequently to the services they were providing. Some of the most relevant are population growth, urbanization and development activities (Cutter et al., 2003; Petrillo et al., 2010; Postacchini and Romano, 2019; Project PESETA-Coastal Systems study, 2979; Project and 7http). Coastal areas are a small part of the urbanized territory, but they are affected by the continuous impact of different factors, both natural and anthropogenic, operating on different time scales. The most relevant natural factors

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* Corresponding author.
E-mail address: e.armenio@arpa.puglia.it (E. Armenio).

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include wave height and direction, wind, tide, sediment transport, sediment supply from rivers to the sea, subsidence, sea level rise, precipitation, frequency and intensity of extreme weather events, including storms. On the contrary, the main human-induced factors include maritime construction and coastal defence barriers such as ports interfering with sediment dynamics, housing construction, industry, recreational infrastructure, river basin management interventions and regulation of watercourses to provide water resources for drinking water, irrigation and industrial use, which induce vegetation alteration and forest drainage (Ruol et al., 2018; Woodruff et al., 2018). It is worth noticing that a particularly relevant aspect in all the coastal areas of the world, even if with different grades, is climate change (Hoque et al., 2019; Mavromatidi et al., 2018; Pranzini and Wetzel, 2008; Slangen et al., 2014; Snoussi et al., 2010). A direct consequence of climate change is the incidence of extreme meteorological events, such as severe storms, sea swells and floods, which worsens coastal risk situations both in terms of environmental degradation and security for the people living on the coastal zone. In this context, marine flooding can increase beach erosion and saline intrusion, thus causing higher susceptibility of coastal populations and ecosystems (Eurosion, 2004; Framework Directive on st, 2010; 5° Assessment Report, 2014). These consequences could be even more hazardous if associated with a high population concentration and socio-economic activities (Eakin and Luers, 2006; Mavromatidi et al., 2018; Weis et al., 2016; Zorpas et al., 2017).

Typically, coastal vulnerability can be defined as the susceptibility of a coastal area to be influenced by flood or erosive phenomena (Muler and Bonetti, 2014; Papathoma and Dominey-Howes, 2003; Tallman et al., 2019; Thakare and Shitole, 2021; Vogel et al., 2007; Weis et al., 2016), it is a significant problem facing most coastlines worldwide. The present paper refers to the more precise definition provided by Rizzo et al. (2018), which considers coastal susceptibility as strictly related to natural environments such as dunes and beaches sensitive to erosion/-flooding, while coastal vulnerability is concerned with human activities/uses, which is why also the socio-economic aspect should be involved in coastal vulnerability studies. Several literature studies have been focused both in the past and in recent years on examining the main factors affecting coastal vulnerability. A comprehensive review can be found at Anfuso et al. (2021) and Bukvic et al. (2020).

All these studies highlight important observations. Firstly, there are several ways to assess the vulnerability of a coastal zone. From various study by (Alkalay et al., 2007; Anfuso et al., 2021; Aswani et al., 2019; Bukvic et al., 2020; Cogswell et al., 2018; Tate et al., 2010) it can be identified four different approaches to assess coastal vulnerability, which can be clustered as follows: (1) index/indicator-based methods, (2) dynamic computer model-based methods, (3) GIS-based decision support tools, (4) visualisation tools. Of the above methods, the most used to evaluate coastal vulnerability is the Coastal Vulnerability Index (CVI), which considers parameters representative of different coastal characteristics (e.g. mean elevation, geology, coastal landforms, etc.), and external forcing (wave height, tidal range, etc.).

On the contrary, the literary review analysis reveals that, commonly, socio-economic factors are not included in the vulnerability study which are rather based on evaluations involving mostly physical parameters (Koroglu et al., 2019; Zorpas et al., 2017). As argued by McLaughlin et al. (Cutter et al., 2003), there are many useful potential indicators of socio-economic value (e.g. land use, percentage of urbanisation, population density, infrastructure, cultural heritage, tourism, etc.), hence the opportunity to involve a parameter in the CVI calculation must be weighed against the availability of up-to-date data. Because of difficulties in obtaining and classifying the socio-economic data, such parameters are often excluded from the CVI calculation. it is worth noting that the CVI calculation proposed by (Gornitz et al., 1994; Koroglu et al., 2019) has been adopted in several studies to assess coastal vulnerability and that, often, the parameters representative of coastal vulnerability is combined in different types of ICVI (Cogswell et al., 2018; De Serio et al., 2018; Doukakis, 2005; McLaughlin and Cooper, 2010).

One of the main criticalities highlighted is also the difficulty in collecting information on the physical and socio-economic parameters of the coastal stretch and in establishing univocal criteria for assigning different vulnerability values (from low to high). In addition, few studies are still based on methods such as AHP and, more frequently, the assessment of coastal vulnerability is linked merely to the subjective evaluation given by individual experts (De Serio et al., 2018; Islam et al., 2016; Saaty, 1977).

A further issue observed is the inadequate representation of the results, which often takes the form of vulnerability maps that do not include all the characteristic elements of cartography (scale of representation, coordinate system, north arrow, administrative limits, etc.). Finally, a significant issue that emerged from the literature reviewed is that coastal vulnerability studies are more often considered for coastal defence interventions and are rarely relied on supporting social management strategies. Generally, municipalities define criteria for managing coastal zones at the time of COVID, without any assessment of coastal vulnerability (Tallman et al., 2019; Thakare and Shitole, 2021; Tsangas et al., 2019; Weis et al., 2016).

With reference to the above framework, this study, while considering all the critical issues raised by the reviewed literature, considers:

- both physical and socio-economic parameters,
- an accurate description of the data source and the evaluation criteria adopted,
- the application of AHP method,
- both satellite data analysis and statistical data evaluation,
- two of the most widely used indices in the literature,
- the application of coastal vulnerability assessment to a social management case such as Covid-19.

Especially, the present work is aimed to propose a simple but effective methodology to vulnerability degree assessment, based on satellite image, statistical analysis and GIS processing to pursue the principles of sustainable coastal management (MATTM-Regioni, 2018; Jana and Bhattacharya, 2013; MATTM, 2006; Narra et al., 2019; Snoussi et al., 2010; Szlafsztein and Sterr, 2007). The methodology proposed allows collect essential information on coastal environment which to base also pandemic management.

The procedure was applied in with a twofold purpose: first, to analyse the coastal vulnerability, in a comprehensive way that addresses all the critical issues identified in recent literature, and secondly, provide an application example of how such studies can also be used for social management purposes and not only for coastal works and interventions. The approach adopted in this study has a general scope and can thereby provide a useful reference in several areas. In demonstrating its effectiveness, it has been applied with reference to a coastal area in southern Italy which is generally very full of people during summer.

2. Study site

The study area includes the municipalities of Maruggio and Torricella, both in the province of Taranto (Apulian region, south Italy) for a total coastal length of about 15 km (Fig. 1). The study area falls between two distinct main Physiographic Unit (abbreviated U.F. which stands for Unità Fisiografica) called U.F. 6 (Punta del Pizzo (Gallipoli) - Torre dell'Ovo (Maruggio) and U.F. 7 (Torre dell'Ovo (Maruggio) - Capo Spulico (Calabria Region). The coast in question, in particular to the East where there are sandy coasts starting from Porto Cesareo, is part of the very wide coastal dynamic. Contrary to the coastal area located at the West and North West which are characterized mainly by rocky coasts. In particular, the coastline under investigation concerns the sub-unit S.U.F. 6.3, which started in Torre Inserraglio (Nardò) and is 64.92 km long until reaching Torre dell'Ovo (Maruggio), and the Sub Physiographic Units (S.U.F.) 7.1, which has its origin in Torre dell'Ovo (Maruggio) and is 45.55 km until reaching Capo San Vito (Taranto). As regards the sub-

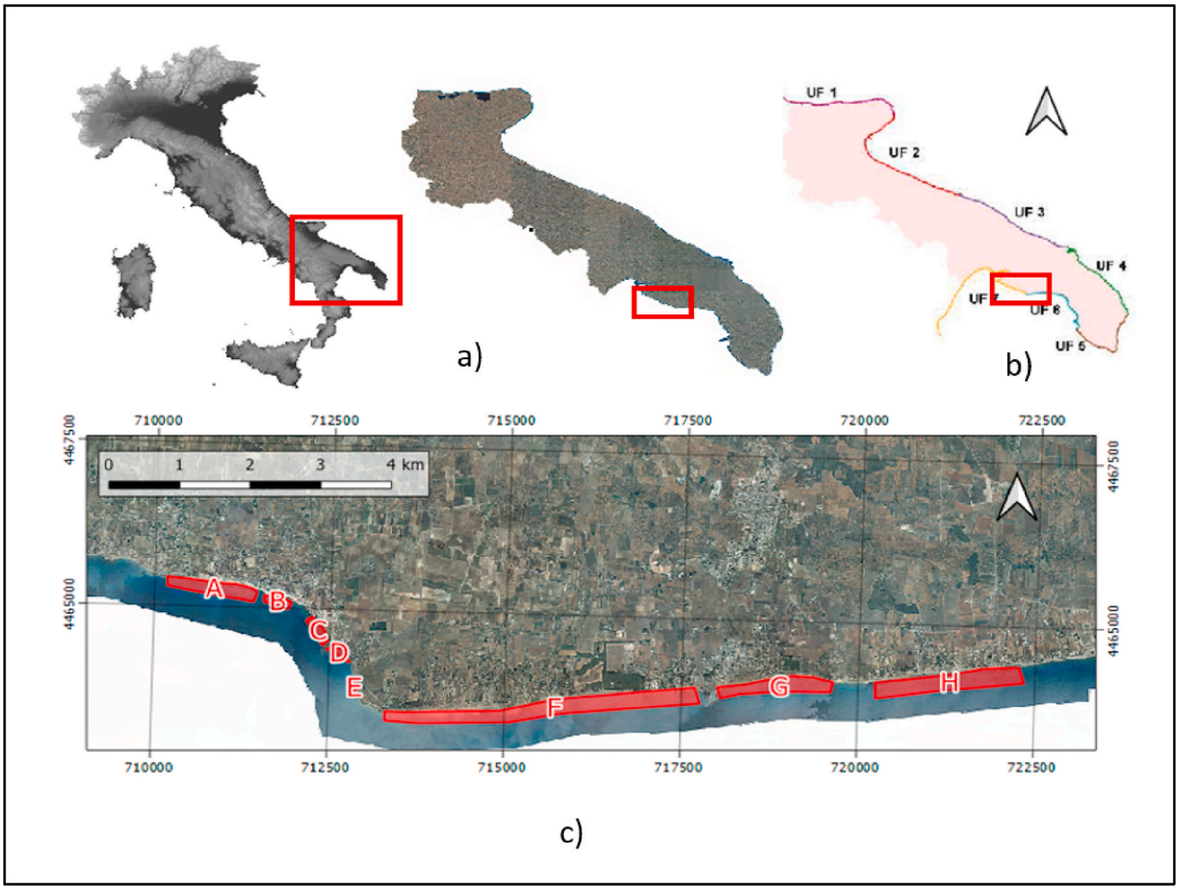

Fig. 1. (a) Location of the target zone; (b) Physiographic units and physiographic subunits; (c) Analysis areas.

unit S.U.F. 6.3, the coast is almost homogeneously characterized by a low sandy or rocky coast with a small cliff. The sandy coastline is often covered by recent dunes and fossils arranged for long stretches in several parallel rows. The dunes and cordons are composed of sands resulting from the disintegration of the outcropping quaternary deposits or from the distribution of marine sediments below the coast. In the areas behind the dunes, swamps and/or marshy areas are often observed. The low rocky coasts are mainly consisting of soft Pleistocene rocks or stratified cretaceous limestone (Festa, 2003; Gornitz, 1991; Parise and Pascali, 2003; Spalluto and Caffau, 2010; Valduga, 1965). In the Torricella area, as early as 2014, there was the complete disappearance of the sand and the emergence of the “Beach Rock”, i.e. old consolidated sands on which the more recent ones were then deposited, symptom that the recent erosive action has taken all the sand away. This phenomenon has been observed in various parts of Italy and the world precisely in the coasts with dunes behind them that no longer feed the littoral. The coastline along the sub-unit S.U.F. 7.1 consists of a low sandy coast that gradually gives way to the low rocky coast composed of soft Pleistocene rocks. The profile is sub-horizontal and generally does not have slopes such as to represent even low cliffs. In the area there are also dune systems. As far as S.U.F. 6.3 is concerned, the coastal area is half sandy; there are, in fact, numerous inlets of different lengths, separated by more or less long rocky parts. The coast, even the rocky one, is generally low and has several marshy areas, with ponds and salt pans. The consistent hydrographic network over time has led to the formation, between Porto Cesareo and Maruggio, of several dune systems separated by rocky conformations (Gornitz, 1991; Parise and Pascali, 2003; Petrillo, 2009). The beauty of the places and coastlines has allowed the tourist exploitation of the coast to develop in recent decades. In the ‘50s on the coastal strip that goes from Torre Colimena (Manduria) to Torre dell’Ovo (Maruggio) was built a coastal road that in very long stretches directly on the dune systems. All the above actions have led to a general sedimentary deficit resulting in a general erosion of sandy coastlines. The coastline included in the sub-unit S.U.F. 7.1 that extends from Torre dell’Ovo (Maruggio) to Capo S. Vito (Taranto), is featured by a rocky coast, also with sandy beach at the foot, and more or less long sandy coves. The coast is strongly anthropized, with urban settlements often close to the shoreline; the dune belt is now compromised and affected by important phenomena of wind transport. Moreover, the coastal road follows the path of the dune belt intersecting it at various points, and due to the intense wind erosion, sandy sediments carried by the wind are deposited on the road surface. In the coastal stretch there are numerous dune systems, mostly in a very poor state of conservation due to the presence of numerous sea passages serving the beaches, and bathing facilities directly built on the sandy strip (Bosellini and Parente, 1994; Festa, 2003). Ultimately, in the coastline described it will be necessary to proceed to restore the dune cordon in correspondence of the not irreparably man-made cordons. The promontory of Torre Ovo identifies a point of divergence of the longitudinal currents that are mainly directed westwards along the western side of the coast in question, and eastwards in the eastern area. The slope of the submerged beach is on average less than 1% in the area north of Torre Ovo, it is around 5% in correspondence with the promontory on which the tower is located, while it is between 1.6% and 1.9% along the east coast (Bosellini and Parente, 1994; Festa, 2003; Petrillo, 2009; Tugend et al., 2019; Valduga, 1965).

3. Materials and methods

3.1. Workflow

The procedure applied in the present study is aimed to evaluate the vulnerability of a coastal area according to the following phases (Fig. 2):

Phase I:

i. to acquire data relating to the area of study both on physical and socioeconomic factors, paying attention to their reliability, and perimeter the areas under study;
ii. to use satellite data to evaluate the coastline evolution;
iii. identification and rating of the parameters that most affect coastal vulnerability;
iv. application of a method based on a multicriteria decision analysis;
v. mapping the vulnerability score by using GIS application;
vi. to determine coastal integrated vulnerability index by applying two of the most relevant formulae and compare the results.

Phase II:

i. to distinguish coastal areas where a higher number of users can reasonably be expected;
ii. to implement emerging practices;
vii. to avoid assemblages in small coastal beaches by adequately equipping other available spaces along the coast.

In particular, the following steps were applied:

1) *Data collection*: this step provides for the collection of all available data related to environmental monitoring, field measures, surveys, high-resolution remote sensing data;
2) *Statistical Analysis*: statistical methods are used for wave climate and tidal analysis, determination of extreme wave events and rate of shoreline change;
3) *Satellite data and GIS processing*: high-resolution remote sensing data pre-processing were carried out for shoreline extraction using visual interpretation method to extracted different historic shorelines based on high-resolution remote sensing data and GIS Software platform;
4) *Vulenrability assessment*: the step consists in rating of the parameters, determination of Integrated Coastal Vulnerability Index and vulnerability mapping by using GIS platform;
5) *COVID-19 risk mapping:* the final step of the methodology proposed provides, on the basis of information already obtained, a classification of coastal areas according to the possibility of contagion.

3.2. Data collection and methodological approach

Awareness of the vulnerability of coastal landscapes to both natural and anthropogenic impacts require monitoring their evolution, adaptation, resilience and developing appropriate coastal defence strategies (Armenio et al., 2020; Armenio and Mossa, 2020; Mossa, 2006; Mossa et al., 2017). Any study related to coastal environments must be based on a detailed and rigorous data collection concerning both physical and socio-economic aspects (De Padova et al., 2017; Guo et al., 2020; Ling, 2009; McLaughlin et al., 2002). It represents a fundamental step to identify coastal areas more susceptible to vulnerability assessment (Hzami et al., 2021; López Royo et al., 2016). Starting from the available data, some key physical parameters were defined (Barman et al., 2016; Loizia et al., 2021b; Ranasinghe, 2016). The physical parameters considered for the vulnerability evaluation are listed in Table 1, together with the sources providing this data and the time period covered by the same data respectively (Papathoma-Köhle et al., 2019). Especially, seven physical parameters were selected among these, sea level rise, significant wave height and mean tidal range (especially exceptional seasonal tides) are those active parameters related to danger, which could potentially cause a negative effect (Vogel et al., 2007; Weis et al., 2016; Woodruff et al., 2018).

On the contrary, the slope and the of the coastline, the elevation of the coastline, the characteristics of the coastline and the rate of change of the coastline are the negative ones related to susceptibility, which

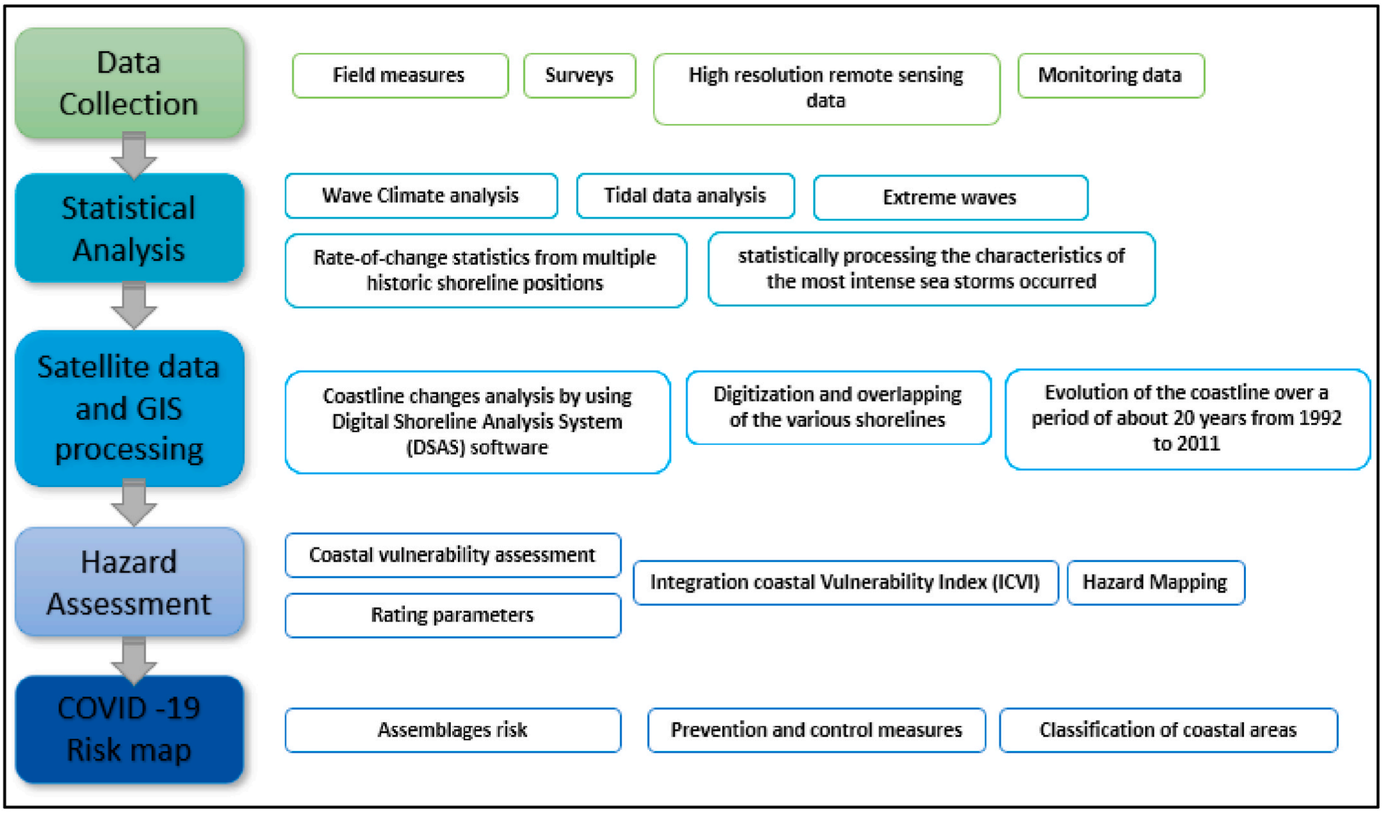

Fig. 2. Workflow of the vulnerability degree assessment.

Table 1
Physical and socio-economic parameters investigated in the study.

	Variables	Data source	Period of reference
Physical	**Coastal slope**	Atlas of Italian beaches Data from Territorial Information Service – Apulian Region (www.sit.puglia.it)	2001
	Coastline landforms/ features	Cartography and orthophoto from National Geoportal (http://www.pcn.minambiente.it)	2005; 2008; 2011
	Significant Wave height	Data analysis	2008–2013
	Shoreline change rate	Aerial photos (spatial), GPS measurements	1992; 1997; 2005; 2008; 2011
	Sea level rise	Literature data about the projections of global mean sea level rise over the 21st century (IPCC, 2014; Galassi and Spada, 2014)	1990–2100
	Tidal data	Tide gauge data from National tide gauge network (https://www.mareografico.it/)	1999–2014
	Coastal elevation	Data from Territorial Information Service – Apulian Region (www.sit.puglia.it)	2015
Socio-economic	**Population**	Census sectors maps and Statistic data from National Institute of Statistics (https://www.istat.it/)	2017
	Road networks	ANAS (http://stradeanas.it/)	2017
	Land use/Land cover	Cartography from Ortho-images from National Geoportal (http://www.pcn.minambiente.it) Data from Territorial Information Service – Apulian Region (www.sit.puglia.it)	2017 2011

make the system tending to the effects of the vulnerability. Changes in coastal systems due to social, economic and environmental variables are frequent and rapid, even more than those due to physical processes, and therefore their contribution cannot be neglected in the assessment of coastal vulnerability (Recommendation 2002/413/, 2002; Szlafsztein and Sterr, 2007). The Socio-economic parameters accounted for the present study are population, road networks and land use/land cover (Table 2).

Even though the physical and socio-economic parameters listed in Table 1 are not exhaustive, they are also indicative of the coastal vulnerability status of the target area.

The methodology adopted for vulnerability assessment consist of the following step:

1 – primarily, key parameters are identified, i.e. those related to vulnerability, which could potentially cause a negative effect, and those related to vulnerability, which make the system susceptible to the effects of the hazard factors (Garozzo, 2007; European Commission, 2004; Mahapatra et al., 2014; Parlagreco et al., 2019). The number and type of key parameters can be changed according to the study area, requirements and available data (Di Paola et al., 2014; Pranzini, 2018; Rizzo et al., 2018; Sherbinin et al., 2017).
2 - the second step is to rate the key parameters, generally based on a semi-quantitative score, from low to high vulnerability and apply the Analytical Hierarchical Process (AHP), a multi-criteria decision analysis method. More detailed can be found in De Serio et al., 2018.
3 - successively, the key parameters are embedded in the single index, which accounts for the general vulnerability of the coastal area.
4 – the vulnerability mapping is implemented in GIS application to identify the most critical hot spot more susceptibility to coastal environmental degradation.
5 – finally, the areas where the highest number of users is expected are identified and adequate control and prevention measures are planned.

A fundamental phase to apply this procedure is the implementation of a GIS System to collect and process all data, through overlapping, graphic display of parameters and, finally, the mapping of results. For this purpose, the available data have been previously converted into vector format to be superimposed and made comparable with each other (Du et al., 2016; Small and Nicholls, 2003; Small and Sohn, 2015; Spalluto and Caffau, 2010).

A relevant aspect is to evaluate the reciprocal influences and interactions between the parameters considered. For these purposes, the adoption of the AHP approach is very useful. Indeed, the mutual influence of the variables is estimated in the procedure, through special comparison matrices. The Analytical Hierarchical Process (AHP) is a multi-criteria decision analysis method that solving decision-making problems, categorising possible alternatives using different criteria (Saaty, 1977; Sekovski et al., 2020). The AHP evaluates the weighting factors by means of a matrix of preferences, in which all the chosen parameters, assumed as relevant to the specific study, are matched against each other. The procedure involves making comparisons in pairs for all the parameters representative of the physical and socio-economic aspects. The matrix is completed using the scores according to their relative importance. To construct the pairwise comparison matrix, each parameter is rated against every other one by assigning a relative dominant value between 1 and 9, according to Saaty rating scale (Saaty, 1977). In this way, qualitative evaluations are transformed into a quantitative assessment. In the present study, referring respectively to physical and socio-economic parameters, a score has been assigned to each couple of compared parameters, following the Saaty scale and two different pairwise comparison matrixes have been derived. In the technique adopted, the coastline was segmented into equally long strips

Table 2
Vulnerability ranking assigned for physical parameters.

Parameter	Description	Coastal vulnerability ranking			
		Very low (1)	Low (2)	High (3)	Very high (4)
Coastal slope (%)	Percentage of coastal slope	>3	2.0 ÷ 3.0	1.0 ÷ 2.0	<1.0
Coastal landforms/ features	Coastal resistance capacity against erodibility and sea level rise	Rocky coast	Protection works	Dunes, estuaries and lagoons	Mudflats, mangroves, beaches, barrier-spits
Significant wave height (m)	Significant wave height can cause severe coastal erosion ($T_p = 50$ yr)	<1.5	1.5 ÷ 3.5	3.5 ÷ 5.5	>5.5
Shoreline change rate (m/yr)	Mobility of the shoreline (positive values mean accretion, negative erosion)	> +10	+5 to 0	0 to −5	< −10
Sea level rise (mm/yr)	Mean sea-level rise per year	1.8	1.8 ÷ 2.6	2.6 ÷ 3.4	>3.4
Tidal range (m)	Difference between yearly mean high tide and low tide	<0.2	0.2 ÷ 0.45	0.45 ÷ 0.7	>0.7
Coastal elevation (m)	Surface elevation to mean sea level	>6	3 ÷ 6	0 ÷ 3	<0

(500 m). For each strip and for each physical parameter considered, a vulnerability ranking from 1 to 4 was assigned, representing respectively a very low, low, high and very high vulnerability (Table 2). The thresholds chosen for the four classes indicated in Table 2 are the same as those already used in previous conventional studies. Consequently, the vulnerability classification map based on socio-economic parameters has been implemented (Lam et al., 2015; Sekovski et al., 2020).

3.3. Physical data evaluation

3.3.1. Statistical analysis, satellite image and GIS processing to analyse wave climate and shoreline evolution

A fundamental parameter in several aspects of coastal evolution is the significant mean wave height, directly related to wave energy. The increase in wave energy means an intensification of coastal processes (more often erosion than accumulation), wave set-up and flooding along the coast, finally causing loss of land (Armenio et al., 2017; Ben Meftah et al., 2020; Bruno et al., 2019; Bruno and Petrillo, 2011).

To assess the susceptibility of the coastline to erosion, a detailed wave analysis was applied with the following aims:

- to evaluate the wave climate;
- to calculate the probability of occurrence of extreme waves.

Several procedures in the literature are referred to the reconstruction of the wave climate, both indirect methods (starting from wind data) and direct methods (starting from wave state measurements). In both cases it is necessary to have rather long time series in to give reliability to the statistical procedures required for the prediction of extreme events and for the reconstruction of the average wave climate (Armenio et al., 2017; Bruno et al., 2014; De Padova et al., 2017).

In the present study the determination of the wave climate was carried out applying the method of geographical transposition from the wave data obtained from the buoy located in Taranto which is part of the Apulia Region's Meteomarine Monitoring Network. The buoy was moored on 16 March 2006 off Capo San Vito in the immediate vicinity of the Port of Taranto on a seabed of approximately 72 m and consists of Datawell Directional Waverider MKIII. It can record the meteo conditions, wave height and direction, and water temperature. The buoy works continuously in telemetry via GSM with a control and data acquisition centre to which it transmits the results of the measurements made at regular intervals, allowing to acquire in real time the meteorological situation and to exercise a constant control of the instrumentation functionality. All the data collected are stored in a database, quality controlled and provided on a semi-annual time. From the buoy data, first were calculated the frequencies of appearance of the sea states classified by direction of origin and intensity. Subsequently, the calculation of extreme waves was carried out by statistically elaborating the parameters of the most intense sea storms occurred. In particular, the determination of extreme events occurring offshore was carried out by applying the geographical transposition method (De Padova et al., 2017; Mossa et al., 2017) which exploits the definition of the $\gamma50$, $\gamma10$ spread parameter. The buoy moored in Taranto belongs to the ionic area where the estimated value of $\gamma50$ is 1.13 (Bruno and Petrillo, 2011; De Padova et al., 2017; Mossa, 2006).

The extreme wave statistics require, as a primary priority, the definition of the independent storm peaks that make up the truncated series. The selection of storm surges was made considering a succession of sea states in which the significant height exceeds a threshold h_{crit}, without falling below it for time intervals of more than 12 hours. The h_{crit} threshold is set at 1.5 times the average significant height. Particular attention has been paid to the identification of independent events. The minimum of the autocorrelation function of the historical series has been identified, obtaining that the independence of the events is verified when the interval between two consecutive swells is at least 48 hours. The wave data were divided into height classes within 0.25 m amplitude ranges. The extreme waves were calculated by applying the POT (Peak Over Threshold - Atlas of the Italian Seas) method to the full dataset recorded from the Taranto buoy.

To characterize the dynamics of the coast under examination, it is useful to know the annual equivalent weather climate, that is the so-called modelling or morphological or equivalent wave.

The equivalent wave climate was assessed by obtaining, for each of the selected directions and for the entire area, the energy-equivalent swell of the time series. The modeling wave is characterized by an H wave height and a T wave period, representative of the energy content for the sector considered. This wave can produce effects on the coast equivalent to those induced by all the waves based on which it has been calculated (Di Luccio et al., 2019; Diez et al., 2007; Eurosion, 2004; Raicich, 2003).

The coastal processes as wave patterns, circulation near the shore, coastal transport and the beach shape are main cause of shoreline changes. Coasts suffering erosion are assumed highly fragile owing to the loss of natural and human resources. The shoreline evolution is caused by the interaction between different natural and anthropic factors. To evaluate an erosive phenomenon, it is necessary to observe the evolution of the coastline for a sufficiently long time period to eliminate the seasonality influence, episodic events (sea storms) and local sedimentary dynamics (Enríquez et al., 2019; Papathoma and Dominey-Howes, 2003).

The present study reconstructs the evolution of the coastline over a period of about 20 years from 1992 to 2011. During this time period there were the major anthropic interventions that had a considerable influence on the alternation of the coastline. Specifically, there were several building and roads constructions along the coast. A series of aerial shots of the coast carried out in different periods were used to investigate on the evolution of the shorelines. In particular, the orthophotos relating to the years 1992, 1997, 2005, 2008, 2011 were digitized, and appropriately superimposed for comparison trying to minimize the approximations due to:

- uncertainty in the georeferencing of aerial images related to errors in the procedure of positioning known reference points;
- uncertainty in the identification of the shoreline from aerial images due to the difficulty in interpreting aerial photos (presence of bathers or boats, presence of waves, Posidonia deposits on the shoreline, etc.);
- lack of information on the tide conditions to which the aerial images refer; depending on the slope of the beach, in fact, small variations in the tide may correspond to significant excursions of the shoreline;
- non-homogeneity between shorelines taken from aerial images of winter beach profiles (e.g. 2005 and 2011 orthophotos) compared to shorelines taken from aerial images taken in summer (1992, 1997 and 2008 orthophotos).

The inevitable presence of such approximations leads to the assumption that there are no significant point differences between two shorelines between −3 and +3 m. The shoreline extraction was performed in the ESRI ArcGIS environment and DSAS, an application of the same ArcGIS software, was used for their analysis.

The Digital Shoreline Analysis System (DSAS), developed by the United States Geological Survey (USGS), works as an extension of ArcGIS software. Its use is based on the tracking of transects, length and spacing chosen by the operator, perpendicular to a reference line, or baseline (Jana and Bhattacharya, 2013; Narra et al., 2019; Snoussi et al., 2010; Szlafsztein and Sterr, 2007).

In the present study a spacing between the transects of 20 meters was adopted, with increasing numbering from North to South. The comparison between the baselines was made only on the sandy stretches, as it was assumed that the rocky coastline stretches remained stable over the period analyzed (1992–2011). Along the sandy shoreline under examination, 8 study areas were identified, as shown in Fig. 4. Areas A, B, C and D are in the Municipality of Torricella, while the other areas are in the Municipality of Manduria. For each transept, the value of the Net Shoreline Movement (NSM) parameter was obtained, representing the distance between the most recent and the oldest of the two coastlines compared. The DSAS model has been applied in five steps referred to the following time frames: 1992–1997; 1997–2005; 2005–2008; 2008–2011; 1992–2011.

Ultimately, for each of the time analyzed, and in correspondence of each identified transept, the shoreline displacement was calculated according to the equation:

$$\Delta Y\ (1, 2) = Y2 - Y1 = NSM$$

where each Yi indicates the position of the shoreline relative to the baseline in the i-th reference year. Positive values of ΔY indicate an advancement of the baseline while negative values represent a setback of the baseline.

Applying the methodology described above, four categories of vulnerability were defined for the rate of change of the coastline, representing high erosion, low erosion, low growth and high growth (Table 2).

3.3.2. Analysis of coastal features

With respect to the Coastal Slope was calculated as the ratio of the change in altitude to the horizontal distance between any two points of the coast perpendicular to the coastline. It is a crucial factor to evaluate the impact of sea level rise on a coastline and to measure the loss of land due to flooding. Coastal areas with a slight slope are highly vulnerable, as they allow considerable seawater penetration, whereby coastal areas with steeper slopes are low vulnerable, providing greater resistance to flooding due to sea level rise and storm surges (Eurosion, 2004; Hzami et al., 2021; Mahapatra et al., 2014; MATTM-Regioni, 2018). The analysis was based on data provided by the Italian Atlas of Beaches and the Territorial Information Service of the Apulia Region (www.sit.puglia.it).

The forms and features of the coastline define the coastal morphology and are determined by marine processes and landscape evolution. Hence, the analysis of coastal landforms/features was based on the consideration that they offer resilience to erosion. Landforms offer resistance to erosion: for example, rocky cliffs and wave-cut benches oppose maximum resistance and are consequently less vulnerable than sandy and muddy forms such as dunes and mudflats. These last, being minimal resistance, are extremely vulnerable to rising sea levels (Bukvic et al., 2020; De Serio et al., 2018; Diez et al., 2007; Petrillo et al., 2009; Torres-Freyermuth et al., 2021).

The average height of the coastline above the mean sea level features the coastline elevation. High elevations make the coast less susceptible, whereas low elevations make it highly vulnerable (Table 2). In this study, data of coastal elevation have been derived from Digital Elevation Models (DEM) of the Territorial Information Service of the Apulia Region (www.sit.puglia.it), from gridded topographic and bathymetric elevation at 1 m vertical resolution for 8 m grid cells.

3.3.3. Analysis sea level rise and tides

Sea level change is one of the most relevant consequences of climate change. Data from the Intergovernmental Panel on Climate Change (5° Assessment Report, 2014; Ranasinghe, 2016) predict a global sea level rise from a minimum of 53 cm to a maximum of 97 cm by 2100.

For sandy coast, the sea level rise has as a direct consequence an increase in ongoing erosion phenomena and the intensification of the effects of sea storms on the coast.

The sea level rise is based on global and local environmental and physical factors, with a strong temporal variation. Its effects are strictly depending on the morphology of the coastal site, lithological composition, hydrodynamic regime and the extent of anthropic pressure and can be mainly: increased erosion of sedimentary coasts; intrusion of salt water into groundwater, with consequent impact on ecosystems; tidal variations, which affect coastal flooding (Bruno et al., 2014; Critchell and Lambrechts, 2016; Diez et al., 2007).

The study of tidal level oscillations in the area was carried out using data acquired from the tide station of Taranto (National Tideographic Network managed by ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale) and the tide station of Porto Cesareo (Rete di Monitoraggio Meteomarino della Regione Puglia realized with POR Puglia, 2000–2006 funds). To verify the consistency of the data recorded in the two stations with the data recorded in the stations located along the regional coast, the analysis was also extended to the stations of the National Mareographic Network present in the lower and middle Adriatic (Ortona, Vieste, Bari, Otranto). The amplitude of the recorded oscillations is of the order of tens of centimetres and is compatible with the sea level variations due to the tide in the Adriatic Sea, which are on average of the order of 30 cm. The acquired data on sea level show a strong seasonal variation in the investigated area; in fact, in the first months of the year there is a sharp drop in the average sea level. The elevation of the sea surface recorded by the tide graphs is the sum of the average sea level (Z_0), the astronomical tide (x) and the meteorological tide (y) induced by winds, storms and atmospheric pressure disturbances (De Serio et al., 2018; Eurosion, 2004; Mahapatra et al., 2014). The hourly level records were subjected to a quality control to identify anomalous data, spikes and timing errors before analysis. The application of harmonic analysis to the time series, conducted using the T-TIDE software (De Serio et al., 2018; Pawlowicz et al., 2002), allowed further quality control of the data with which records for years of observation with inconsistent harmonic constants values for the site were discarded. The annual mean sea level value was calculated from the data observed with the application of numerical filters.

3.4. Socio-economic data evaluation

For the evaluation of the population parameter, it was considered that a high population density usually leads to more residential or industrial construction, with consequent environmental impacts on the coast. Data provided by the National Institute of Statistics (Table 1), were used to evaluate both the population density and the actual distribution of buildings along the coastal strip.

The more developed the road network is, the greater the anthropogenic presence. The spatial layout and aggregation of areas and buildings where people live and move is a crucial factor in determining the damage to human life, services and economies (especially in terms of immediate effects from, for example, floods or surges). It worth noting that road networks are a key element during a natural disaster to tackle emergencies and improve early warning systems. The road network data used in this study were derived from the Ministry of Infrastructure and Transport and local institutions (Table 1). The vulnerability evaluation was made by adopting a buffer within 1.5 km of the coastline.

As regards the analysis of land use/land cover, it was referred to the territorial information system of the Apulian region (www.sit.puglia.it) has provided, since 2011, data on land use together with indications of land covering.

3.5. Integrated coastal vulnerability indexes (ICVI)

The mapping of the most vulnerable coastal zones, where the potential risks may be quite high, has been approached in the literature by applying different methods. Among the widely adopted methods is the index-based one, which provides a Coastal Vulnerability Index (CVI) (Anfuso et al., 2021; Bukvic et al., 2020) usually according to the following steps. In the present study the Analytical Hierarchical Process (AHP) was applied referring the procedures adopted in De Serio et al., 2018).

To get the maximum full vulnerability assessment of the coastline the integrated coastal vulnerability index (ICVI) has been applied following the procedure already applied in De Serio et al., 2018).

Especially, two formulation of ICVI were tested: the first formulation calculated the square root of the product of the estimated contributions of each variable, based on Tables 2 and 3 in our case, divided by the total number of criteria (Bukvic et al., 2020; Cogswell et al., 2018; Loizia et al., 2021b):

$$ICVI_1 = \sqrt{(X_1 \cdot X_2 \cdot \ldots \cdot X_7/7)} \qquad (1)$$

This ICVI represents an average of the numerical values of the criteria (Cogswell et al., 2018; Nguyen et al., 2016) consequently it tends to smooth out single large values of some criteria (damping extreme ranges) and to emphasize cases when most of criteria have above median levels. It is worth noting that this ICVI may be quite susceptible to minor changes in individual factors.

Hence, a second formulation of ICVI has been examined. It considers the average of PVI and SVI consequently, both physical and socio-economic factors have equal contribution in the coastal vulnerability assessment.

$$ICVI_2 = \frac{PVI + SVI}{2} \qquad (2)$$

For each ICVI index, the obtained scores have been equally divided into 4 classes, attributing very low vulnerability to the lowest values class and very high vulnerability to the highest values class. Fig. 8 shows the map of the examined area where both ICVI_1 and ICVI_2 are plotted along the coast, with their corresponding classification.

4. Results

4.1. Waves analysis

Data recorded by the buoy of Taranto were analyzed to identify the most relevant wave directions, frequency and intensity. The analysis of the data recorded by the buoy reveals that the traverse sector of the foreshore consists of the directions between NNO and SSE.

The reconstructed sea storms off the coast of Maruggio - Torricella were ordered by wave height classes of 0.5 m and by sectors of origin of 30°, having considered as calm wave heights lower than 0.25 m. The traverse sector of the study area is concentrated between the 150°N (15.91%) and 300°N (8.47%) directions, with a significant percentage of south swells (24.48%).

Swells with a wave height less than 0.75 m make up 69.71% of the total (calm 24.21%), and only 0.83% of reconstructed swells have a height greater than 3.0 m and come mainly from ESS. The events characterized by a wave height between 0.75 m and 1.75 m represent 25.26% of the total storm surges and come mainly from the South.

The classification of waves according to peak period Tp shows that the highest frequency of occurrence is for waves with a period between 3 and 5 seconds (31.89%) followed by storms with a period in the 5–7 second interval (21.34%); waves with a peak period less than 3s represent 6.47% of the total, while waves with a period greater than 7s represent 16.10%.

The maximum significant offshore heights calculated for the return period of 100, 50 and 25 years are 7.02 m (Tp 11.95 s), 6.54 m (Tp 11.54 s) and 6.07 m (Tp 11.11 s), respectively.

Table 4 shows the maximum significant heights for the 1st transverse sector adopted between the directions 120°N - 180°N and the 2nd transverse sector adopted between the directions 180°N - 330°N.

From the overall processing wave data obtained from the recordings of the Taranto buoy, the values of the equivalent waves shown in shown in Table 5.

The SSE and South directions have the highest energy equivalent wave height of 1.22 m, with an apparition frequency of 20.99% and 32.30% respectively. The characteristic wave height of the entire study area has a height of 1.11 m, period of 5.35s and direction of origin 178°N.

4.2. Shoreline evolution

The net shoreline movement diagram from 1992 to 2011 is shown in Fig. 4 for each area analyzed. In can be noticed a strong variability of the position of the shoreline in the periods examined, the general trend was erosive with an average setback over the whole Area of about 4 meters and a maximum value of 18 meters in some transects of the final part.

In area A (Fig. 4) the strong variability of the position of the shoreline during the periods examined can be seen. From 1992 to 2011 the general trend was erosive with an average setback over the entire section of about 5 m and a maximum of about 11 m. The biggest setback occurred in the period 2008–2011. This is probably since the average sea level has risen significantly and there have also been significant sea storms. In some sites the erosion has been such that the rock formations on which

Table 4

Maximum significant wave heights and peak periods for the 1st transverse sector and 2nd transverse.

I transverse sector *(120°N – 180°N)*			*II* transverse sector *(180°N – 330°N)*		
Return Period (years)	^{H}s max (m)	T_p (s)	Return Period (years)	^{H}s max (m)	T_p (s)
100	6.50	11.50	100	4.22	9.26
75	6.36	11.38	75	4.13	9.17
50	6.17	11.20	50	4.01	9.03
25	5.82	10.88	25	3.80	8.79
20	5.70	10.77	20	3.73	8.71
10	5.33	10.41	10	3.51	8.45
5	4.94	10.03	5	3.28	8.17
1	3.93	8.94	1	2.69	7.40

Table 3

Vulnerability ranking assigned for socioeconomics parameters.

Parameter	Description	Coastal vulnerability ranking			
		Very low (1)	Low (2)	High (3)	Very high (4)
Population on coastal strip	Number of residents on coastal strip (ab/km^2)	0–50	50–150	150–200	>200
Road networks (distance in km)	Presence of roads in coastal areas in terms of distance from the shoreline	>1.0	1.0–0.7	0.7–0.4	<0.40
Land use/Land cover	Land use refers to purposes served by land (i.e., recreation, tourism, agriculture, residence). Land cover refers to surface cover on the ground (i.e., vegetation, urban infrastructure, water, bare soil or other)	Barren land, water bodies, marsh/bog and moor, sparsely vegetated areas, bare rock	Vegetated land or open spaces, Coastal area (tidal flats, mangroves, salt pans, beaches), natural grassland	Agriculture/ fallow land	Urban, ecological sensitive regions. Urban and industrial area

Table 5
Annual equivalent wave height.

Direction (°N)	Hs (m)	Tp (s)	Duration (hours)
0	0.59	2.94	625.0
30	0.43	3.25	102.0
60	0.49	4.08	34.5
90	0.46	2.76	21.0
120	0.81	4.54	253.0
150	1.22	6.68	6606.0
180	1.22	6.08	10165.5
210	1.09	4.99	4007.5
240	0.59	3.57	637.5
270	0.87	4.22	4763.5
300	0.84	4.01	3518.5
330	0.68	3.24	742.5
178	1.11	5.35	31476.5

the sand was placed are emerging. Many times, not rock formations on which sand was placed a sub-layer of Beach Rock.

The situation is alarming because the width of the coastal strip is generally very small. The most critical transept recorded a coastal strip width of 30 meters in 2008, while in 2011 it was 19 meters and the retreat were partly contained by the presence of a dune, although strongly degraded. In other transects, especially in conjunction with the buildings between the coastal road and the shoreline, the width of the coastal strip is much smaller.

In Area B (Fig. 4) the strong variability of the shoreline position in the periods examined is noted. From 1992 to 2011 the general trend is erosive, however, with a small average setback over the entire stretch and a maximum of about 5 m in some transects. The set-back occurred more in the period 2008–2011 for the same reasons reported for Area A. In this area there are only very small remnants of dunes. For this area there is a need for a good management of the beach and in case of need a beach nourishment intervention with the same modalities as those reported for Area A. Also, in this case the coastal road and the houses have limited the dynamic coastal strip.

As far as Area C is concerned, the variability of the position of the shoreline in the periods examined is not very great, except in the first transects, where it may be affected by the passage from a rocky to a sandy coast. For the period examined the general trend is quite stable except in some initial and final transects.

For this area only a good management of the sandy shore is needed and in case of need a beach nourishment intervention with the same modalities exposed for Area A.

In Area D there is a strong variability in the position of the shoreline in the periods examined. The general trend in the period examined is erosive with an average setback of about 15 m that in the initial transects reaches 35 m. It should be noted that there was a greater setback in the period 2008–2011 for the same reasons as those reported for Area A. In this area there are only dune residues. The erosion continued even after the construction of the submerged reef which, even if it attenuates the wave motion, is not able to cope with the rising of the medium sea level, on the contrary, with the breaking on its berm of the waves more determines a consistent wave set-up. In this area, where it is already visible what may happen tomorrow to the other areas examined, urgent intervention is needed, also for Civil Protection purposes. In view of the situation, it would be desirable to carry out an Intervention of Rehabilitation of the whole Area, finding a new solution to the road system and then accompanying this action with a good management of the beach and, in case of need, with a beach nourishment intervention in the same way as for Area A. These interventions would give back part of the naturalness to the coast and to the coastal strip.

Regarding area E it is noted that the variability of the position of the shoreline during the periods examined is not very great. From 1992 to 2011 the general trend is quite stable, although with a minimum of setback. For this Area only a good management of the shoreline is needed together with a monitoring of the shoreline that must be carried out continuously over the years and with more seasonal surveys during the year.

On the contrary, in Area F there is a strong variability in the position of the shoreline during the periods examined with a general slightly erosive trend. However, there is no lack of critical stretches, especially upstream of the Port of Campomarino and in some stretches of sandy coastline between rocky stretches with sandy beach at the foot. A careful analysis of Fig. 4 shows that there was a major setback in the period 2008–2011 when, as mentioned above, the average sea level rose significantly and there were significant sea storms. For the area in question, it is important to protect and regenerate the still existing dune systems and the reconstruction of those demolished or by wave motion or human intervention. The Conservation and Enhancement of undeveloped surfaces and those where the coastal road is located much inland. It is necessary to carry out interventions to retain the sand carried away by the wind and reposition it in the active strip of the coast. It is then necessary to implement a systematic collection of Posidonia; the management of beach Posidonia should be carried out at an intermunicipal level between the municipalities of Torricella (TA); Maruggio (TA); Manduria (LE); Porto Cesareo (LE), although some of these municipalities fall in different Provinces. Posidonia Spiaggiata (Posidonia beach) can be used for dune consolidation/restoration works, as already done in many Italian and Apulian coasts. The irreversible criticality of the stretch west of the Port of Campomarino must be tackled first of all with a Correct Management of the Areniles or with the provision of an artificial beach nourishment, free or at most with foot protection, using suitable sands from other sites and in part could also be taken, in an environmentally compatible way, from the dunes upstream of the coastal road that at present no longer intervene in the coastal dynamics.

In Area G the strong variability of the position of the shoreline in the periods analyzed is observed. From 1992 to 2011 the general trend has been erosive with an average setback over the whole Area of about 6 meters and with a maximum value of 30 meters in some transects. Immediately to the east of the Port of Campo Marino, on the other hand, there is an advancement or stability of the shoreline. Also, in this case, the setback occurred more in the period 2008–2011, coinciding with the significant rise in the average sea level and some significant storm surges. The same actions indicated for Area G are also necessary for Area F.

From a careful analysis of Area H (Fig. 4), also in this case, as highlighted for the other study areas, it can be observed that even in the retreat there was more in the period 2008–2011. Also, for Area G the same actions indicated for Area F and G are necessary.

4.3. Coastal features

With reference to the analysis of coastal slope, data provided by the Italian Atlas of Beaches (Enríquez et al., 2019) and the Territorial Information Service of the Apulia Region (www.sit.puglia.it) demonstrate that the coastline of the study area mainly consists of sandy beaches, with an average slope of the submerged beach of 1%. The west coast is characterized by slopes of less than 0.5%, while along the east and west coast there are variable inclinations in the range between 1.6 and 1.6%. The highest value of slope is in Torre Ovo due to the presence of a promontory with slopes around 5%. In Table 2, with reference to the percentage values of slope, four levels of vulnerability are defined, from high (coastal slope lower than 0.1%, i.e. very gentle) to low vulnerability (coastal slope higher than 3%, i.e. steeper). Because of this classification, the coastal slope vulnerability map has been adopted and is displayed in Fig. 3.

From the analysis of the erosion resistance offered by landforms, as described in the previous section, the vulnerability classes for this physical parameter were defined, as reported in Table 2. The areas under investigation area characterized by beaches, some with short stretches of dunes, and reefs, as can be seen from orthophotos and satellite images

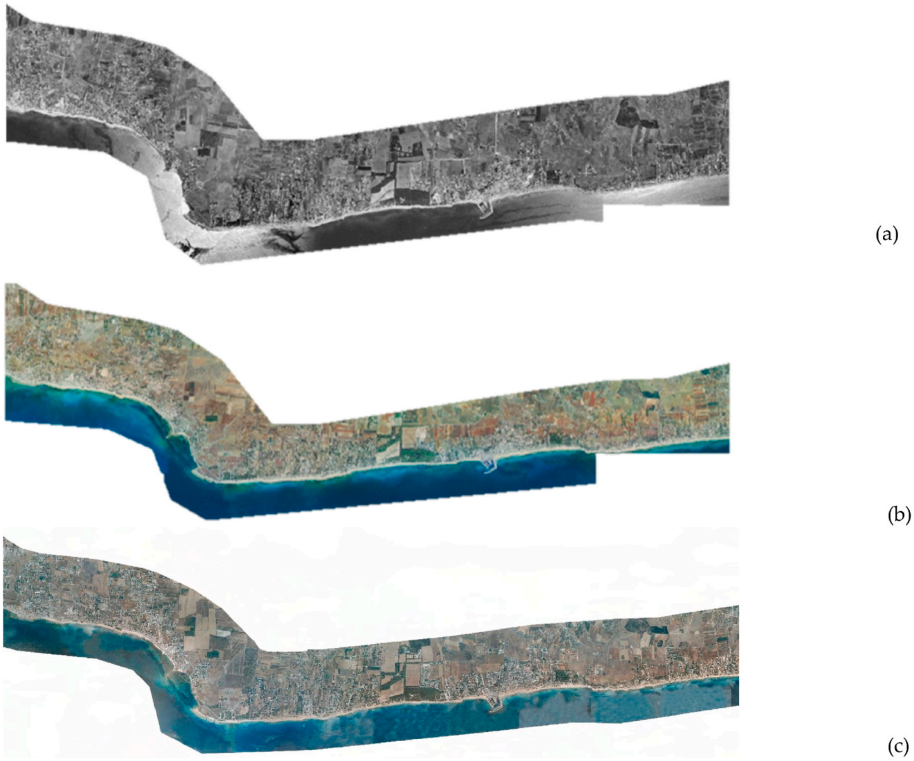

Fig. 3. Aerial photographs of (a) 1997, (b) 2006 and (c) 2008.

(Table 1).

The coastline consists of an alternation of stretches of sandy beach and rocky coastline, with or without the presence of sandy beach at the foot.

From the available data, several dune cords are identified, some of which are located deep inland, almost all of them in erosion. The coast is strongly anthropized mostly in correspondence of the stretches with the presence of dunes. The vulnerability of the entire coast is medium-high except for some stretches where there are the port and the rocky promontory of Torre dell’ Ovo.

The results of the analysis of causal elevation are provided in Fig. 5, where low coasts with sandy beaches are mainly observed, hence being very vulnerable.

4.4. *Significant wave height and shoreline change rate*

The breaking of the highest waves can generate a significant impact on the beach mobilising and transporting coastal sediments. Consequently, coastal areas with higher wave heights are assumed more vulnerable than those exposed to lower wave heights (Cotecchia et al., 1974a; Loizia et al., 2021b). Furthermore, waves action can endanger cultural heritage and infrastructure in low-lying areas (López Royo et al., 2016). Data on significant wave height were acquired from the Taranto buoy.

To assign a vulnerability ranking, the value of significant wave height with a return period of 50 years was estimated. The coast has a very high vulnerability in the easternmost section and an average in the westernmost section. From the Table 4, with reference to a return period of 50 years, the ^{H}s max is equal to 6.17 m and 4.01 m in I and II tranverse sector, respectively.

From Regarding the shoreline change rate, the analysis conducted by using DSAS tool of in ArcGIS© highlights, Fig. 4, the, in the investigated areas, mostly of the shoreline is in strong retreat due to advanced erosion.

4.5. *Sea level rise and tides*

In the Mediterranean and Adriatic Sea, data on historical sea level show large inter-annual and multi-annual variability, mainly due to meteorological conditions (Mavromatidi et al., 2018; McLaughlin and Cooper, 2010; McLaughlin et al., 2002). For the present study, the data on sea level change relate to studies focusing on the Mediterranean Sea (Armenio et al., 2017; Loizia et al., 2021a) indicate a minimum sea level rise of about 2.4–2.5 mm/year. Based on this data a low vulnerability value was attributed to the entire stretch of coastline under review.

The analysis of the annual average tides in all the stations examined exhibits a sea-level increase since 2008 with differences between 2007 and 2009 of the order of 10 cm. The trend for 2011 shows a decrease in levels almost to the level before 2009, followed in 2012 by a further increase in the average sea level which is still ongoing. This agrees with Tsimplis et al. (2013) and Landerer and Volkov (2013); in fact, in both studies, the authors report a sudden increase in the average sea level which has been correlated to the North Atlantic Oscillation (NAO) large scale forcing the entry of large masses of water into the Mediterranean Sea. In the coastal area examined, there were some events of significant tidal excursions locally called “High and Low Sea”, nevertheless for the attribution of the vulnerability level the trend of the average tidal values was considered.

4.6. *Population, coastal road networks and land use/land cover*

By using population density data provided by the National Institute of Statistics (Table 1), it is noticed that the study area has a high population density living along the coast. in some stretches it is noticeable residential buildings located a few tens of meters from the shoreline. The allocation of coastal vulnerability has accordingly considered both the population density and the actual distribution of buildings along the coastal strip.

From the road network data obtained from Ministry of Infrastructure and Transport and local institutions (Table 1), it can be observed that

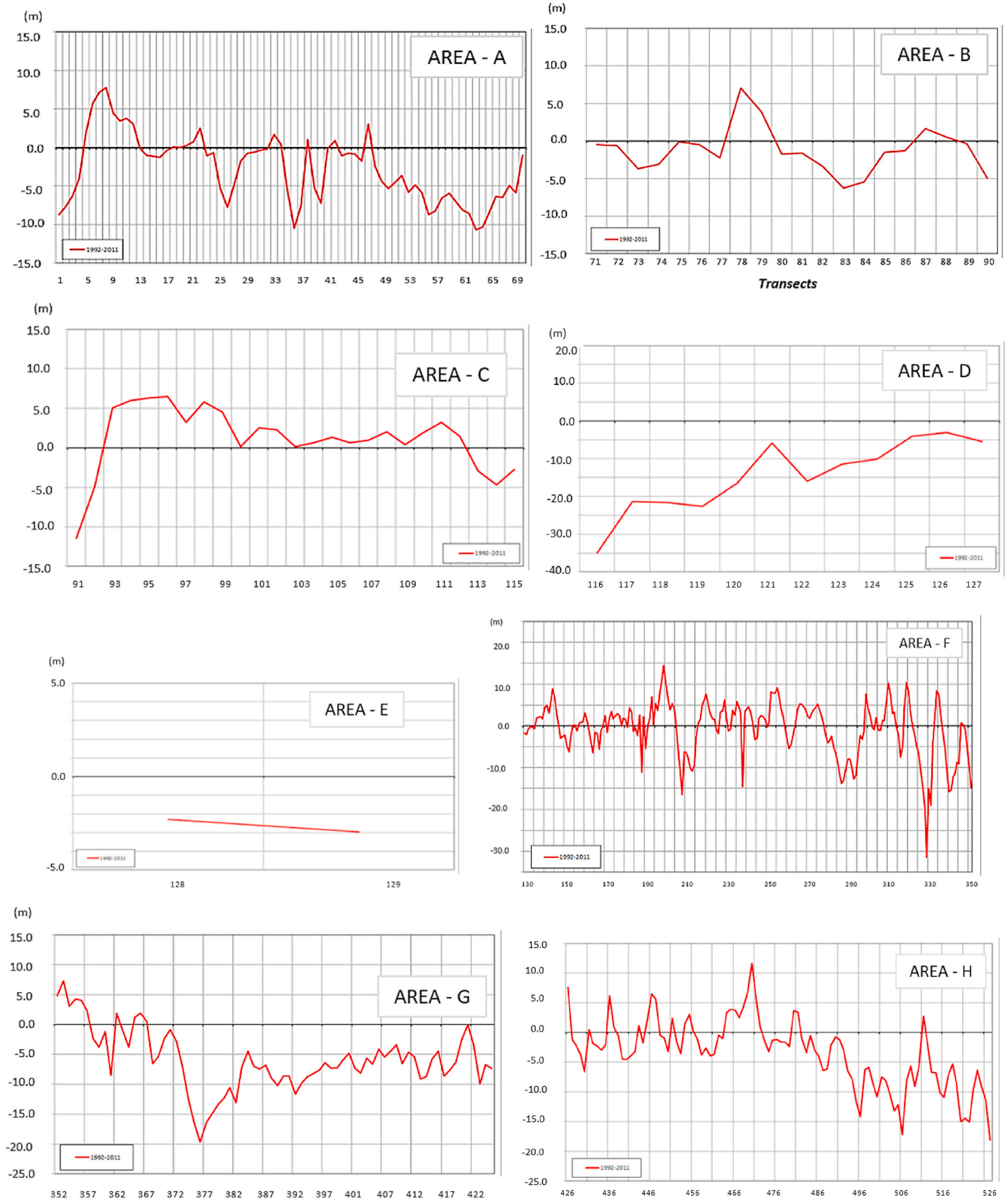

Fig. 4. Net shoreline movement diagram from 1992 to 2011 for each area.

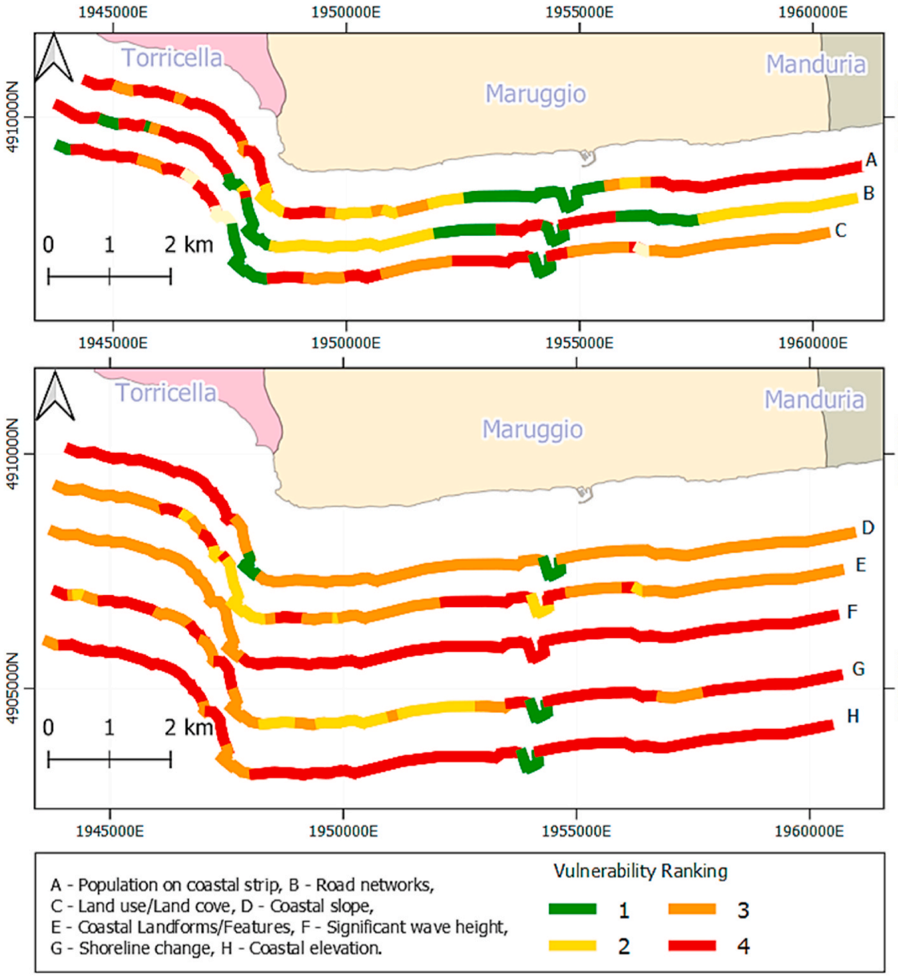

Fig. 5. Vulnerability ranking map of (A) physical and (B) socio-economic parameters (1- Low, 2- Medium, 3 High, 4- Very high).

Provincial roads are detected in several point of the coast. In some stretches the road is reached by the wave motion causing a risk situation.

The analysis of land use/land cover shows that the study area is characterized by beaches and the presence of buildings close to the beach, except for some short stretches. There are no industrial areas close to the coast. It can be assumed a medium-high vulnerability.

4.7. Coastal vulnerability mapping

As a result of the methodology described in the previous section, for each physical and socioeconomic parameter, the corresponding vulnerability values were assigned by referring to Tables 1 and 2

Fig. 5 maps the computed physical and socio-economics vulnerability indexes, where PVI and SVI are displayed for each segmented and examined sector. From the comparison of PVI and SVI (Fig. 6), it can be

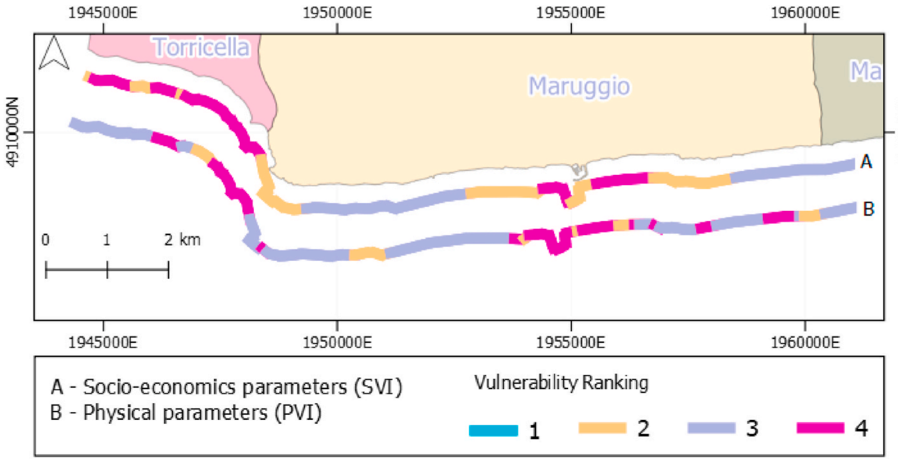

Fig. 6. Physical and socio-economic vulnerability map (1- Low, 2- Medium, 3 High, 4- Very high).

noticed that the coastal stretch of the study area is almost entirely classified as highly vulnerable with reference to both physical and socio-economic features. It can be observed that the stretch of coast in the direction of the town of Torricella is the most vulnerable: the vulnerability ranking of PVI and SVI are in the range 3–4 which means high and very high average vulnerability.

This is also reflected in Fig. 7 which illustrates the Integrated coastal vulnerability indexes (ICVI_1 and ICVI_2), they are representative of both physical and socio-economic vulnerability.

Specifically, in Fig. 6 can be noticed that ICVI_1 is characterized by high/very high vulnerability along mostly of the examined coastline, except for a very limited areas characterized by rocky and sparsely inhabited coast. By the comparison between ICVI 1 and ICVI 2 it can be deduced that ICVI 2 tends to underestimate the real coastal vulnerability, because of the flattening of the higher values due to Equation (5). Conversely, ICVI_1 index seems affected more by physical parameters than by socio-economic ones, when PVI score is higher than SVI one, as resulting along the southern coast. Along the western coast, where both physical and socio-economic effects contribute to high vulnerability, even if with different weights as deduced by AHP, ICVI_1 shows high and very high scores. Thus, we can note that ICV_1 is more sensitive to physical parameters. These considerations agree with what emerged from the study carried out by Armenio et al., 2019.

The ICVI_2 appears more reliably than ICV_1 and it seems to be more appropriate to investigate on target coastal environment, thus resulting in a more accurate and realistic vulnerability assessment. Finally, we note that the ICVI_2 index is also more conservative than the ICVI_1 one.

A validation of this result could be conducted based on the historical behaviour of the costal and on the experience. For instance, a rough validation of ICV_1 approach could be done considering the strong erosion suffered in recent years along the coast and which seems to be consistent with the obtained ICV_1 distribution.

The knowledge of coastal vulnerability is the first step among the actions to be taken at the institutional level to improve the understanding of the "coastal system", increase its resilience and monitor more closely the land use of the coastal zone. Such first step is fundamental for the corresponding coastal planning and design activities. In this regard, Table 6 lists, as an example, the relevant factors and related actions, depending on the critical issues identified.

4.8. Consideration to coastal risks related to COVID-19

The methodology outlined in the previous paragraphs has made possible to collect a lot of data on the study area concerning both physical and socio-economic features. Collected data is also a valuable resource for evaluating the management of coastal uses with respect to the COVID-19 pandemic. Given the rapidly changing nature of the challenge posed by COVID-19, the information collected can be used for a prompt coast risk mapping. The coastal morphology influences the risk connected to COVID-19: flat and sandy beaches are easily accessible by users and therefore attract many more people. In these coasts becomes complicated to ensure the respect of the minimum safety distance especially if the beach is not very wide. On the contrary, in rocky and steeply sloping areas there will be fewer people because they are more uncomfortable and difficult to access coasts. In the first case, it is essential to define measures to access control and to keep the social distance. In the second case, the conditions of access to the coast should be facilitated. For example, removable structures in natural materials (wood) based on natural engineering techniques can be arranged. This solution allows to increase the fruition of all the coast reducing the assemblage in the flat and sandy stretches.

In the urbanized coasts with roads are expected the major users. In these cases, particular attention should be applied to the access points to beaches and car parks avoiding close distance among people. In the beaches facilities it is essential ensuring that the beach and surrounding areas are kept clean of waste that may include potential clinical waste (i.e. discarded face masks), toilets and other shared facilities must have a higher level of cleanliness, commensurate with the risk.

The considerations highlighted were applied to the study area (Fig. 7). The entire coast was classified according to 3 COVID-19 risk levels representative of a low, medium and high-risk level, respectively. The COVID-19 risk is assessed considering the possibility of groupings and therefore non-compliance with the safety distance and potential weak points (shared service areas).

In particular, the Level 1 refers to a low COVID-19 risk level that concerns coastal areas where the presence of people is expected to be low or areas where there is wide space available. The Level 2 corresponds to a medium risk level ant includes coastal areas where a manageable number of people are expected and the sites must be kept under control. Finally, the Level 3 concerns high risk areas characterized of a significant number of people and/or various pinch points. In accordance with the above, in Fig. 8 can be seen that in the study area 7 different zones can be distinguished (for simplicity each zone is identified with a letter). There are two level 3 zones, i.e. zone A and zone C both characterized by flat and sandy beaches where a significant number of people can be expected. It is fundamental maintaining social distancing at 'pinch points', including access points to beaches and car parks the areas B is featured by rocky coast, where generally there are

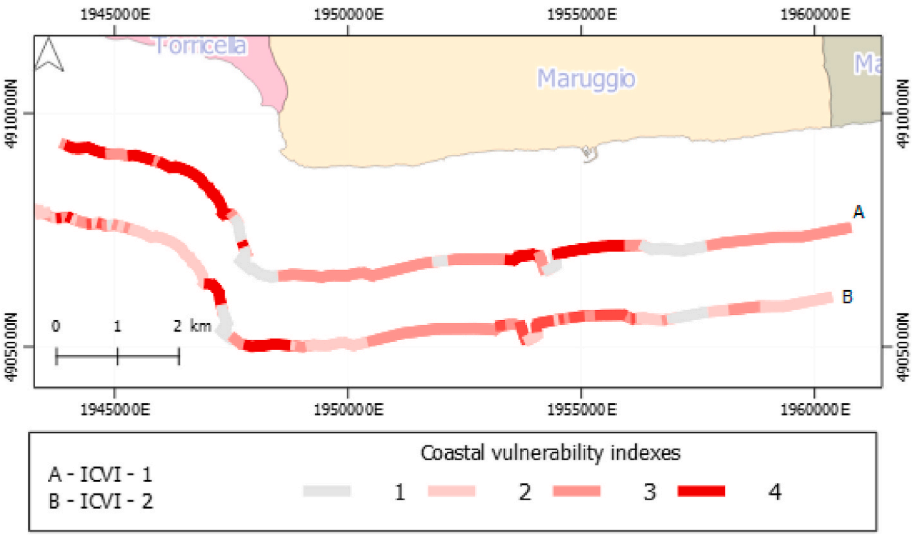

Fig. 7. Comparison of Integrated Coastal vulnerability indexes (1- Low, 2- Medium, 3 High, 4- Very high).

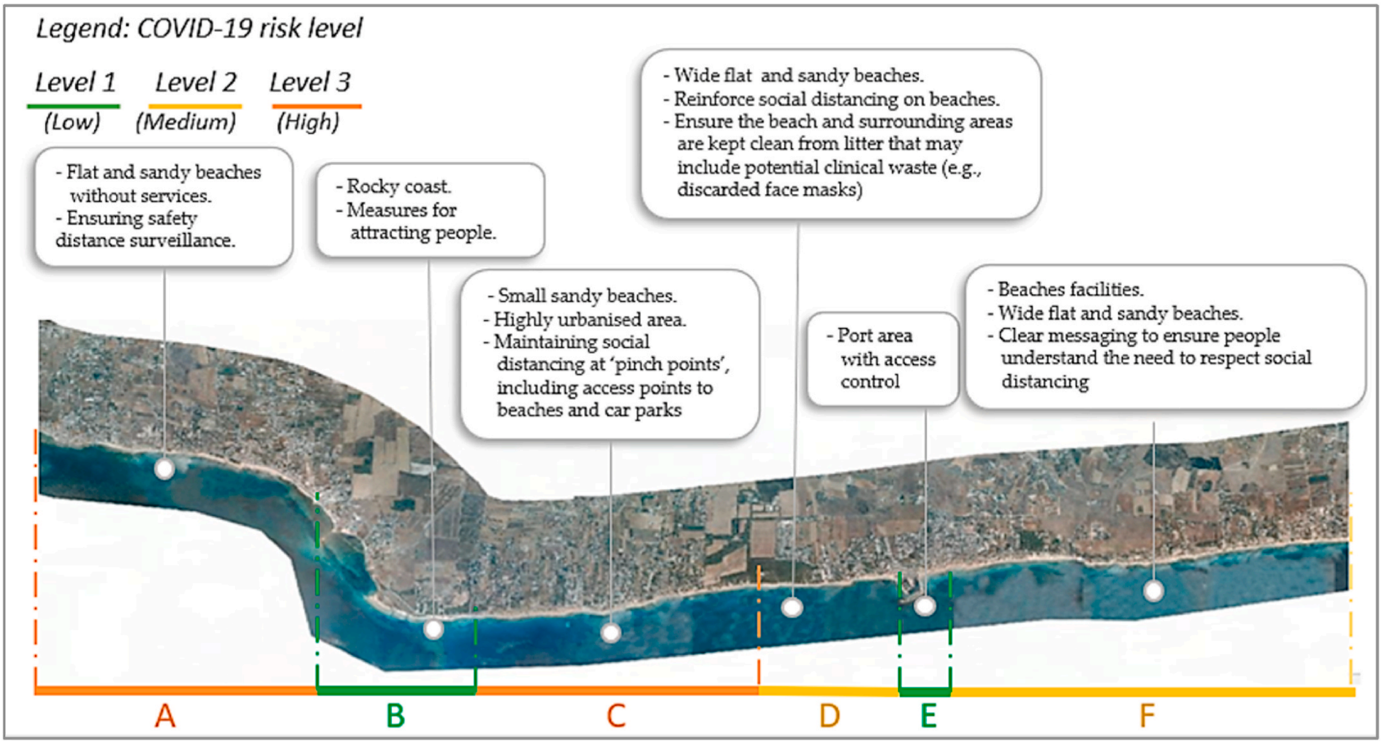

Fig. 8. Coastal areas classification by considering COVID-19 risks (low, medium and high risk).

Table 6
Evaluation actions and relevant factors resulting from vulnerability issues.

Vulnerability issues	Relevant factors	Evaluation Actions
Physical vulnerability	Erosive trend	Sedimentary balance, shoreline variation
	Marine intrusion risk	Floods Directive (2007/60/EC), presence of flood risk areas
	Sediment accumulation	Sediment cycle, evaluation of dredging interventions
	Storm exposure	Interventions to protect the coast and marinas
Socio-economic vulnerability	Relevance of defense interventions	Interventions in recent decades, climate change adaptability
	Environmental value	Presence of Natura 2000 sites, presence of parks or natural oasis
	Tourist presence	Rationalization of the pressure of tourist use
	Productive activities (fishing, agriculture, mussel farming etc.)	Productive usability

few people because of the difficulty of access. In this area, on the contrary, measures can be envisaged to attract people to reduce the assemblage in adjacent areas. Similarly, in area E where there is a marina, a smaller number of people can be expected. It can also be a more easily controlled area. Finally, the areas D and F are small beaches where assemblage of people can be expected. It is fundamental ensuring safety distance surveillance and keeping the beach and surrounding areas clean from litter that may include potential clinical waste (e.g. discarded face masks). The Table 7, referring to the main physical and socio-economic features identified in the study area, the potential risks connected to COVID-19 diffusion and the correlated corrective actions are reported.

Based on the above considerations, it was possible to define a specific protocol for free beaches and coastal areas. The purpose of the protocol is to supply guidelines aimed at increasing the effectiveness of the preventive containment measures adopted to fight the COVID-19 epidemic within coastal areas.

Table 7
Definition of coastal risks related to COVID-19 and prevention actions.

Physical/socio-economic features	Coastal risks related to COVID-19	Prevention Actions
Flat and sandy beaches	High risk of people assemblage.	Maintain social distancing. Increase the possibility of fruition by allowing a more agile access for all users.
Rocky and steeply sloping coast	Low risk due to limited attendance of people.	
Spatial distribution of people	Small coastal strips make less space available for users leading to possible assemblages.	Reinforce social distancing on beaches by delimiting the available spaces on the beach.
Urbanized coasts with roads	More attendance of residents.	Maintaining social distancing at 'pinch points'.
Beaches facilities	Keep the beach and associated facilities clean.	Maintaining physical distancing between the public and staff working at the beach

The protocol consists of the following measures to be applied in all free beaches and coastal areas:

I. Mandatory basic measures
   - The equipment of bathers (umbrellas, sunbeds, deckchairs, etc.), and of all beachgoers must follow the same rules of social distance as those adopted by bathing establishments.
   - Warning panels in multiple languages listing the main prevention measures (keep a distance of at least 1 meter, avoid overcrowding, and any other provisions) must be displayed at the beach entrance.
   - Proper precautions must be adopted for the beach's cleanliness and the hygiene of any common facilities, such as toilets.

II. Advisable additional measures

- Set a limit on the number of people allowed in at any one time: volunteers or special agencies could also be used to provide surveillance staff to avoid overcrowding, provide beachgoers with information on how to prevent the spread of the virus and how to position umbrellas and beach equipment to maintain social distance.
- illustrate to beachgoers how to position their equipment while respecting the rules of social distance.
- define paths for people to go to and from their place/umbrella; place marks on the sand using lines of rope or tape.
- impose control measures could be defined to limit access to the free beaches, once the maximum number has been reached, and to distribute bathers to the adjacent, suitably equipped coasts.

The *Mandatory basic measures* are the minimum required measures to be applied in all coastal areas. On the contrary, the *Advisable additional measures* are a list of possible measures that municipalities, where possible, can take on the most popular and crowded free beaches (see map on Fig. 7).

The above measures can be applied in the Level 3 areas of the map where the highest number of users is expected. It is worth highlighting that ongoing cooperation between the relevant bodies is essential to ensure that all guidelines and protocols, are shared, applied and their application monitored.

5. Conclusion

The present study has illustrated a methodology to assess coastal vulnerability and to extract useful information for the managing of COVID-19 pandemic. The study considers the most recent literature in the field of coastal vulnerability and seeks to overcome the critical issues that have emerged. The methodology proposed has a dual significance: in the first phase it allows an analysis of coastal features and the quantification of its vulnerability; in the second phase, it is shown how the information collected can be used for the management of the pandemic.

The procedure proposed is based on some key parameters, both physical and socio-economic. The method is focused on the application of the analytical hierarchical process (AHP) to get the ranked weights for the investigated parameters. The last step in the procedure proposed consists in combining the obtained weights to compute a physical index and a socio-economic index, successively joined into an integrated coastal vulnerability index. In addition, this study also allows for the evaluation and comparison of two of the most widely used Coastal vulnerability indexes (ICVI) to highlight their differences with respect to the same study area. Many recent coastal studies are examining the application of such methodologies to analyse the vulnerability of a coastal zone aimed to identify priority areas of intervention. Nevertheless, the fundamental aspect to examine is the definition of an integrated coastal vulnerability index capable of well adapting to different types of coastline. In this regard, the study in this article proposed a quite simple approach to pursue this scope. Adjustments may be needed to address relevant characteristics in different regions and/or to make best use of available data. It is a useful tool for "first look" assessment, in need of more detailed investigations, as it allows the identification of priority vulnerable coastal areas. It could be also very useful for communication purposes. If compared with decision support system tools and dynamic models, which are much more complete but also complex to implement and time consuming, this procedure is feasible and telling piece of a system that is satisfactorily illustrated to stakeholders, representing a necessary step in any coastal zone management strategy.

The information collected through the procedure outlined provides a complete framework of coastal areas useful, also, to manage pandemic risks such as the current COVID-19.

The ongoing COVID-19 pandemic has required that everyone adopt precise behavioural norms to reduce the risk of infection with the virus. This has often entailed policymakers establishing specific protocols to ensure the protection of human health. Frequenters of open spaces, such as coastal areas, may make the mistake of underestimating the risk due to a lack of reliable information and no direct experience with the virus. These findings are particularly relevant in the context of public spaces where the risk of contagion is high, such us beaches and touristic coastal areas.

Regarding coastal environments, the time pressure and unpredictable spread of the COVID-19 pandemic require each small coastal community to analyse the possibility of contagion of users and thus appropriate measures to reduce/avoid risks. In addition, it worth noting that coastal environments are very vulnerable and sensitive to change and, therefore, a complete overview of coastal areas vulnerability would also be useful in defining a pandemic risk management strategy. In such contest, the managing of coastal areas should be based on a detailed assessment of the coastal feature in terms of both physical and socio-economic parameters, as starting point to identify the appropriate sanitary behaviors to be followed for the different coastal areas. In the methodology proposed, the coastal vulnerability considerations were used to identify the main features of each coastal zones and appropriately developing a COVID-19 risk map with reference to a coastal zone located in the south of Italy. In addition, to effectively manage infection risks it is necessary to identify the most exposed coastal "hot spots" and focus attention on prevention and control measures to ensure both coastal and human health protection. For this purpose, a specific protocol was defined for free beaches and coastal areas, aimed at increasing the effectiveness of the preventive containment measures adopted to fight the COVID-19 epidemic within coastal areas. The present paper has proven how a consistent coastal vulnerability analysis methodology may serve to collect, analyse and map coastal features and support risk management strategies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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