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Development of a coastal vulnerability index using analytical hierarchy process and application to Ravenna province (Italy)

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Keywords

ABSTRACT

Coastal flooding Low-lying coast Floods directive Flooding impact Multi-criteria analysis

The assessment of coastal vulnerability to natural hazards is a major concern in coastal areas worldwide, particularly in the context of climate change and increased coastal development. In this work an index of physical vulnerability to sea level rise and marine floods was designed and applied over the coast of the Ravenna Province (Italy), a low-lying coastal area historically known as being susceptible to coastal flooding and erosion. The index is intended to be at the same time scientifically sound and easy to apply, so it is composed of five relevant variables (elevation, dunes, artificial protection structures, shoreline change rates, and land cover) that were weighted by using a multi-criteria decision making approach, namely the analytical hierarchy process. The weightings were assigned by experts familiar with coastal processes in the area, and all with background in environmental science. This enabled a transparent approach on integrating established expert knowledge to assign the relative importance of the variables in defining vulnerability scores. The final vulnerability score for each segment along the investigated coast was calculated by applying the weighted sum of all variables. For verification purposes, the obtained vulnerability ranking was compared to existing coastal flood hazard maps developed by regional authorities in the framework of the EU Floods Directive (2007/60/EC), and to real inundation events generated by historical storms. The integration of this framework into geographical information systems resulted in informative maps, useful to a variety of end-users such as coastal managers and decision makers.

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12 1. Introduction

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14 The damage from natural disasters in coastal zones has increased worldwide over the last decades, mainly due to the growth of capital accumulated in flood-prone areas (Filatova et al., 2011). Two 15 major phenomena could contribute to exacerbate such trend in the future. The first one is the expected 16 further sea level rise (SLR) and the increasing extreme sea levels related to global climate change 17 (Church et al., 2013). According to the IPCC SR15 report, "increasing warming amplifies the 18 exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise 19 20 for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure" (Hoegh-Guldberg et al., 2018). The second phenomenon is increasing 21 human susceptibility to coastal flooding and erosion, especially in low-lying floodplains, due to 22 23 higher migration, industrialization and urbanization trends in coastal areas (McGranahan et al., 2007; Wong et al., 2014; Neumann et al., 2015). In 2011 more than 40% of global population lived in areas 24 within 100 km of the coastline (IOC/UNESCO, IMO, FAO and UNDP, 2011), while in the European 25 Union (EU) approximately half of the population lived within just 50 km of the coastline (Ramieri et 26 al., 2011). In the Mediterranean Sea region, about 55% of the total population resides in coastal 27 28 hydrological basins (Martin et al., 2015). As in many other coastal areas worldwide, environmental 29 pressures related to population growth on the Mediterranean coast are further amplified by the development of tourism, which between 1995 and 2014 grew by almost 75% (European Environment
Agency, 2014).

Coastal zones are considered as one of the main climate change hotspots, with major expected impacts such as damage of built environments due to extreme events (e.g. storm surges), permanent inundation of low-lying areas and land loss due to higher erosion rates (Wong et al., 2014). Apart from these direct impacts, wider con- sequences are expected, such as groundwater salinization and impacts on ecosystems and biodiversity, tourism, agriculture, industry, energy production, port activities, health, cultural heritage, among others (Lequeux and Ciavola, 2011; Ramieri et al., 2011; Giambastiani et al., 2017; Reimann et al., 2018).

39 Vulnerability to sea level rise and marine floods is a complex issue influenced by interrelated 40 phenomena of highly dynamic and uncertain nature. High-impact events such as hurricane Katrina in 41 2005 and hurricane Sandy in 2012 in US, or storm Xynthia in France in 2010, raised and renewed the 42 awareness of the population on the vulnerability of coastal areas and dangers of inhabiting coastal 43 zones prone to flooding.

Studies on vulnerability to floods in coastal zones seem to be expanding recently (Roy and 44 Blaschke, 2015; Perini et al., 2016; Seenath et al., 2016; Di Risio et al., 2017; Christie et al., 2018; 45 Zhang et al., 2019, among others). Yet, there is no single standardized way to measure vulnerability 46 (Balica et al., 2012). Satta (2014) distinguished four different categories of methods for assessing 47 coastal vulnerability: (i) index/indicators-based methods; (ii) methods based on dynamic computer 48 models; (iii) GIS-based decision support tools; and (iv) visualization tools. For this research, it has 49 50 been chosen to utilize an index-based approach, after considering the strengths and weaknesses of the above methods. Index-based methods express coastal vulnerability by a one-dimensional, generally 51 52 unitless, vulnerability index. One of the major strengths of index-based methods is that they offer 53 clear comparability of vulnerability between different areas (Balica et al., 2012). In this respect, "vulnerability index" is defined by the IPCC glossary (IPCC, 2014) as a metric characterizing the 54 vulnerability of a system. The general aim is to simplify a number of complex and interacting 55 56 parameters, represented by diverse data types, to a form that is more easily understood and more useful as a management tool (Nguyen et al., 2016). In this way, these indexes are based on the 57 quantitative or semi-quantitative evaluation and combination of several variables (Abuodha and 58 59 Woodroffe, 2010; Ramieri et al., 2011).

60 One of the initial attempts to derive a coastal vulnerability index for assessing sensitivity to SLR 61 was the one by Gornitz (1991), where seven variables related to flooding and erosion hazards (relief, rock type, landform, relative sea level change, shoreline change, tidal range and mean wave height) 62 were combined at a regional scale. Thieler and Hammar-Klose (2000) applied a similar index to study 63 coastal vulnerability of the US Atlantic coast to SLR. Following these studies, many different, 64 modified versions of the Coastal Vulnerability Index (CVI) have been applied to assess coastal 65 vulnerability on different scales (e.g. Pendleton et al., 2005; Abdouha and Woodroffe, 2006; 66 Szlafsztein and Sterr, 2007; Özyurt and Ergin, 2009; McLaughlin and Cooper, 2010; Alexandrakis 67 and Poulos, 2014; Di Risio et al., 2017; and many others). More comprehensive review on different 68 applications of CVI can be found in Abuodha and Woodroffe (2010), Ramieri et al. (2011), Balica et 69 al. (2012), Satta (2014) and Nguyen et al. (2016). 70

The main aim of this study is to propose a method for assessing coastal vulnerability with focus on marine floods that will be at the same time scientifically sound and easy to use. The idea is to derive a replicable framework that could help future planning and decision making in many different fields, such as where to invest in order to improve the level of coastal protection. In this study, a modified version of the CVI is proposed to evaluate vulnerability of different coastal segments to SLR and marine floods. In order to make it widely applicable, the CVI is composed of five essential physical variables: elevation, dunes, artificial protection, shoreline change and land cover.





Prior to estimating a final vulnerability level, the variables were weighted among each other through expert judgement, based on the analytical hierarchy process (AHP) method. In this way, each of the components (variables) was assigned with certain levels of importance in deriving the final vulnerability levels. Therefore, simplistic assumption that all variables equally contribute to the

78 79 80 overall vulnerability was discarded. Finally, index verification was performed by comparing the
obtained results with the outcomes of flood hazard maps from another study, something for which
there are very few examples in similar studies to date (e.g. Del Río and Gracia, 2009).

89 2. Study area

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91 The demonstration site for this study was the 34 km long coastal area within the Ravenna province (Italy), a low-lying coastal sector located along the NW Adriatic Sea (Fig. 1). This area is historically 92 known as being susceptible to coastal flooding and erosion (Perini et al., 2017). The southern part of 93 94 the alluvial plain of Po River, where the study area is located, is characterized by extensive shoreward urbanization. This was driven mainly by the tourism boom that started after World War II, being 95 particularly intense during the 1960s. Beach-related tourism resulted in coastal land occupation by 96 97 second homes and beach establishments known as "bagni" (Cencini, 1998). Such high degree of coastal urban development also caused the flattening of dunes for construction purposes (Sytnik and 98 Stecchi, 2015). Apart from beach- related tourism, land cover change was also driven by the 99 100 development of oil and chemical industries, located particularly in the vicinity of the Ravenna harbour. A great share of land cover corresponds to cropland but there are also natural areas with 101 conservation designation (Sites of Community Importance and Special Protection Areas). 102

The area is characterized by dissipative beaches composed of fine-to-medium sands and with low 103 elevation above mean sea level (MSL) (Perini et al., 2016). It is a microtidal area, with mean neap 104 tidal range of 30-40 cm and mean spring tidal range of 80-90 cm (Armaroli et al., 2012). Along with 105 reduced river sediment supply, mainly due to the land use changes in the river basins, dam 106 construction, flood control works and extensive bed material mining (Preciso et al., 2012), the major 107 causes of coastal erosion are dune destruction, disruption of longshore sediment transport by harbours 108 and piers, land subsidence (Teatini et al., 2005; Taramelli et al., 2015; Perini et al., 2017; Antonellini 109 et al., 2019) and marine storms. Land subsidence along the Ravenna coastline is one of the most 110 significant along the regional coastal area (up to 20mm/yr, Perini et al., 2017). Intense storms mainly 111 originate from Bora (NE) and Scirocco (SE) winds (Ciavola et al., 2007; Perini et al., 2011; Armaroli 112 and Duo, 2018). Storm surge levels are significant: even low return period surges (e.g. a 1-in-10 year 113 event) can reach elevations close to 1 m above MSL (Masina and Ciavola, 2011). Most storms have 114 duration of less than 24h and a maximum significant wave height of about 2.5 m. The wave height is 115 generally low with 91% of occurrences below 1.25 m (Armaroli et al., 2012). The sea level rise 116 component according to IPCC AR5 (Church et al., 2013) in the northern Adriatic area is expected to 117 be between 0.30 0.07 m and 0.45 ± 0.12 (Table 2 of Perini et al., 2017). Because of the high 118 susceptibility to coastal erosion, a great number of artificial protection structures were built along the 119 shoreline starting from the late 1970s, such as emerged breakwaters, groynes and revetments 120 (Armaroli et al., 2009; Perini et al., 2017). These structures are able to protect the coast but can also 121 lead to a high environmental and landscape impact; in the study area, they have also been reported to 122 produce worsening of the water quality and increased sedimentation of silts and clays (Preti et al., 123 2010). 124

125

126 **3. Methodology**

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The workflow of this study includes: (i) preparation of input data and assignation of vulnerability scores to coastal segments in relation to input variables; (ii) determination of the weights based on expert judgment for each input variable; and (iii) deriving the overall score of coastal vulnerability index for each segment considering both vulnerability score related to input variables and associated weights.

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135 *3.1. Input data and assigning of vulnerability scores*

Based on literature review and non-structured discussions with experts, mainly local hydrologists, 136 geologists, and geomorphologists familiar with the area, five variables were chosen as being relevant 137 in reflecting physical vulnerability to SLR and marine floods: elevation, presence/absence of dunes, 138 presence/absence of artificial protection structures, shoreline change rates, and land cover. The choice 139 for five variables was based on the objective of creating a simple, yet relevant, index. Such index 140 could be replicated and exported to different locations within similar environments, i.e. sandy 141 microtidal coastal areas. Values of each variable were assigned with vulnerability scores from 1 to 5, 142 with 1 being the lowest contribution to vulnerability and 5 being the highest (based on Gornitz, 1990) 143 (Table 1). The extraction of values for each variable was performed in ArcGIS 10.1. 144

According to Nguyen et al. (2016), segmentation aimed at ranking different sections of the 145 coastline based on vulnerability (i.e. variables that determine vulnerability) is useful to determine 146 147 high priority areas for vulnerability reduction. In this respect, the study area has been divided into 36 segments ("sectors") for the coastal vulnerability assessment (Fig. 1). These segments have an 148 approximate length of 1 km (or less, if they are disrupted by river mouths), while the landward 149 150 boundary for each segment was chosen to be 1 km from shoreline. We believe that this size of segments is not too large to overshadow the local specificity and variability of receptors, and yet not 151 too small to overlook the true spatial extent of flooding impacts. 152

Elevation values were extracted from the 2012 Digital Terrain Model (DTM) of 1 m horizontal 153 resolution and 20 cm vertical precision, derived from LIDAR surveys and provided by ENI ("Ente 154 155 Nazionale Idrocarburi"), an Italian multinational oil and gas company. Since the elevation in the study area (i.e. 1 km inland from the coastline) ranges to approximately 7 m above MSL, this range was 156 157 split into five equal intervals to which vulnerability scores were assigned, with addition that all 158 elevation values below MSL were automatically considered as having highest vulnerability. For each sector, mean elevation was calculated to assign the vulnerability score. Low elevations were 159 associated with high vulnerability scores; high elevations were given low vulnerability scores (Table 160 161 1).

The layer showing the position and extent of coastal dunes was manually digitized based on 2011 162 163 WorldView-2 multispectral image of 1.84 m horizontal resolution, while the layer showing artificial protection structures was manually digitized using the high-resolution World Imagery Basemap 164 feature (ArcGIS 10.1), based on high resolution satellite images provided by DigitalGlobe®. 165 Vulnerability scores for both variables were assigned based on percentage of shoreline in each 166 segment covered by dunes/artificial protection structures (Table 1). In the latter case both shore-167 normal structures (e.g. groynes, by calculating alongshore length of their base) and shore-parallel 168 169 ones (e.g. breakwaters) were considered.

Historical rates of shoreline change were determined by analyzing shoreline position in 1954 and
2011, using the Digital Shoreline Analysis System (DSAS) extension for ArcGIS provided by the
United States Geological Survey (USGS) (Thieler et al., 2000).

The longest period available between reliable sources for shoreline position was used in order to 173 offset short-term variability due to the dynamic nature of the area. The 1954 shoreline was manually 174 digitized from aerial photos for the study of Sytnik et al. (2018) and kindly provided by the authors. 175 The 2011 shoreline was derived by processing high-resolution multispectral WorldView-2 satellite 176 imagery of 1.84 m resolution, the same that was used for extraction of the position and extent of 177 coastal dunes. The rate of shoreline change was calculated by using the end point rate (EPR) statistical 178 measure. The overall output values of shoreline changes in the area, according to EPR, were divided 179 into five equal segments in order to assign the 1 to 5 vulnerability values. 180

Land cover types were obtained from 2012 CORINE land cover maps (100 m positional accuracy) by the European Environment Agency (EEA), Copernicus Land Monitoring Services, in order to use a general, easily available source of information. CORINE land cover classes were reclassified to seven land cover groups: beaches and dunes, forests, marsh, agriculture, barren soil, built-up areas, and water bodies. Since the focus here is on protection of the landscape from marine floods, the
different land cover types were evaluated on the basis of their relative role in attenuating water flow,
based on their infiltration properties. This way, vulnerability scores were assigned for each land cover
class (Table 1) based on its infiltration properties, i.e. runoff potential (based to some extent on
Hatzopoulos et al., 2010 and Silva et al., 2010). If a certain sector consisted of several land cover
types, the vulnerability score was assigned according to the predominant type.

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Table 1: Designation of vulnerability scores based on range of values for each input variable used to derive the CoastalVulnerability Index.

Elevation Up to 1.4 m 5 $1.4-2.8 \text{ m}$ 4 $2.8-4.2 \text{ m}$ 3 $4.2-5.6 \text{ m}$ 2 $5.6-7.0 \text{ m}$ 1 Dune coverage $0-20\%$ 5 $20-40\%$ 4 $40-60\%$ 3 $60-80\%$ 2 $80-100\%$ 1 Shoreline covered by artificial $0-20\%$ 5 $protection structures$ $20-40\%$ 4 $40-60\%$ 3 60-80\% 2 $80-100\%$ 1 7 5 Recent shoreline change (m/yr) -5 and below 5 -5 to -2.5 4 -2.5 to 0 3 0 to $+2.5$ 2 $+2.5$ and above 1 Land cover Built-up areas, water 5 bodies 8 8 3 Marsh 2 8 8 3	Variables	Range of values	Vulnerability score		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Elevation	Up to 1.4 m	5		
$\begin{array}{cccc} 2.8-4.2 \mbox{ mm} & 3 \\ 4.2-5.6 \mbox{ mm} & 2 \\ 5.6-7.0 \mbox{ mm} & 1 \\ 0-20\% & 5 \\ 20-40\% & 4 \\ 40-60\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ 80-100\% & 1 \\ 80-100\% & 1 \\ 50-20\% & 5 \\ protection structures & 20-40\% & 4 \\ 40-60\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ 40-60\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ 7-5 \mbox{ mm} & 1 \\ 80-100\% & 1 \\ 80-100\% & 1 \\ 7-5 \mbox{ mm} & 1 \\ 80-100\% & 1 \\ 80-100\% & 1 \\ 7-5 \mbox{ mm} & 1 \\ 80-100\% & 1 \\ 7-5 \mbox{ mm} & 1 \\ 80-100\% & 1 \\ 80-10\% & 1 \\$		1.4-2.8 m	4		
$ \begin{array}{cccc} 4.2-5.6 \mbox{ m} & 2 \\ 5.6-7.0 \mbox{ m} & 1 \\ 0-20\% & 5 \\ 20-40\% & 4 \\ 40-60\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ \end{array} \\ \begin{array}{c} 80-100\% & 1 \\ 80-100\% & 1 \\ 80-100\% & 2 \\ 80-100\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ 40-60\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ \end{array} \\ \begin{array}{c} 80-80\% & 2 \\ 80-100\% & 1 \\ 80-90\% & 2 \\ 80-100\% & 1 \\ 80-10\% & 1$		2.8-4.2 m	3		
$ \begin{array}{cccccc} 5.6-7.0 \mbox{ mm} & 1 \\ 0-20\% & 5 \\ 20-40\% & 4 \\ 40-60\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ \end{array} \\ Shoreline covered by artificial & 0-20\% & 5 \\ protection structures & 20-40\% & 4 \\ 40-60\% & 3 \\ 60-80\% & 2 \\ 80-100\% & 1 \\ \end{array} \\ Recent shoreline change (m/yr) & -5 and below & 5 \\ -5 \ to & -2.5 & 4 \\ -2.5 \ to & 0 & 3 \\ 0 \ to & +2.5 & 2 \\ +2.5 \ and above & 1 \\ \end{array} \\ \begin{array}{c} Land cover & Built-up areas, water & 5 \\ bodies \\ Barren soil & 4 \\ Agriculture & 3 \\ Marsh & 2 \\ Beaches and dunes, & 1 \\ \end{array} $		4.2-5.6 m	2		
$ \begin{array}{llllllllllllllllllllllllllllllllllll$		5.6-7.0 m	1		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Dune coverage	0-20%	5		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		20-40%	4		
		40-60%	3		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		60-80%	2		
$ \begin{array}{cccc} \text{Shoreline covered by artificial} & 0-20\% & 5 \\ protection structures & 20-40\% & 4 \\ & 40-60\% & 3 \\ & 60-80\% & 2 \\ 80-100\% & 1 \\ \end{array} \\ \text{Recent shoreline change (m/yr)} & -5 \text{ and below} & 5 \\ & -5 \text{ to} & -2.5 & 4 \\ & -2.5 \text{ to} & 0 & 3 \\ & 0 \text{ to} + 2.5 & 2 \\ & +2.5 \text{ and above} & 1 \\ \end{array} \\ \text{Land cover} & \begin{array}{c} \text{Built-up areas, water} & 5 \\ & \text{bodies} \\ \end{array} \\ \text{Barren soil} & 4 \\ \text{Agriculture} & 3 \\ & \text{Marsh} & 2 \\ & \text{Beaches and dunes,} & 1 \end{array} $		80-100%	1		
$\begin{array}{ccccc} & 20-40\% & 4 \\ & 40-60\% & 3 \\ & 60-80\% & 2 \\ & 80-100\% & 1 \\ \\ \text{Recent shoreline change (m/yr)} & -5 \text{ and below} & 5 \\ & -5 \text{ to} & -2.5 & 4 \\ & -2.5 \text{ to} & 0 & 3 \\ & 0 \text{ to} & +2.5 & 2 \\ & +2.5 \text{ and above} & 1 \\ \\ \text{Land cover} & & & & & \\ & & & & &$	Shoreline covered by artificial	0-20%	5		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	protection structures	20-40%	4		
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		40-60%	3		
$\begin{array}{cccc} 80-100\% & 1 \\ -5 & and & below & 5 \\ -5 & to & -2.5 & 4 \\ -2.5 & to & -2.5 & 2 \\ +2.5 & and & above & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 &$		60-80%	2		
Recent shoreline change (m/yr) -5 and below 5 -5 to -2.5 4 -2.5 to 0 3 0 to $+2.5$ 2 $+2.5$ and above 1 Land coverBuilt-up areas, water 5 bodiesBarren soil 4 Agriculture 3 Marsh 2 Beaches and dunes, 1		80-100%	1		
$ \begin{array}{ccccc} -5 & {\rm to} & -2.5 & 4 \\ -2.5 & {\rm to} & 0 & 3 \\ 0 & {\rm to} & +2.5 & 2 \\ +2.5 & {\rm and} & {\rm above} & 1 \\ \\ {\rm Built-up \ areas, \ water} & 5 \\ {\rm bodies} \\ \\ {\rm Barren \ soil} & 4 \\ {\rm Agriculture} & 3 \\ \\ {\rm Marsh} & 2 \\ \\ {\rm Beaches \ and \ dunes,} & 1 \\ \end{array} $	Recent shoreline change (m/yr)	-5 and below	5		
$\begin{array}{cccc} -2.5 \ \mathrm{to} \ 0 & 3 \\ 0 \ \mathrm{to} \ +2.5 & 2 \\ +2.5 \ \mathrm{and} \ \mathrm{above} & 1 \\ \mathrm{built-up} \ \mathrm{areas}, \ \mathrm{water} & 5 \\ \mathrm{bodies} & & \\ \mathrm{Barren \ soil} & 4 \\ \mathrm{Agriculture} & 3 \\ \mathrm{Marsh} & 2 \\ \mathrm{Beaches \ and \ dunes}, & 1 \end{array}$	ne entre stand het en sense en handeliken de uissen h e uer in het den stadste	-5 to -2.5	4		
0 to +2.5 2 +2.5 and above 1 Built-up areas, water 5 bodies Barren soil 4 Agriculture 3 Marsh 2 Beaches and dunes, 1		-2.5 to 0	3		
+ 2.5 and above 1 Built-up areas, water 5 bodies Barren soil 4 Agriculture 3 Marsh 2 Beaches and dunes, 1		0 to $+2.5$	2		
Land cover Built-up areas, water 5 bodies Barren soil 4 Agriculture 3 Marsh 2 Beaches and dunes, 1		+2.5 and above	1		
bodies Barren soil 4 Agriculture 3 Marsh 2 Beaches and dunes, 1	Land cover	Built-up areas, water	5		
Barren soil 4 Agriculture 3 Marsh 2 Beaches and dunes, 1		bodies			
Agriculture 3 Marsh 2 Beaches and dunes, 1		Barren soil	4		
Marsh 2 Beaches and dunes, 1		Agriculture	3		
Beaches and dunes, 1		Marsh	2		
forests		Beaches and dunes, forests	1		

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196 *3.2. Analytic hierarchy process (AHP)*

The weighting of the variables that contribute to coastal vulnerability is being increasingly 197 implemented in recent vulnerability assessments. The variables are weighted in order to reflect the 198 199 significance of each variable in contributing to overall coastal vulnerability. One of the most common weighting methods is the analytical hierarchy process (AHP), which, although developed in the 1970s 200 (Saaty, 1977, 1980), is lately becoming more frequently used in coastal vulnerability studies (e.g. Yin 201 202 et al., 2012; Le Cozzanet et al., 2013; Mani Murali et al., 2013; Bagdanaviciute et al., 2015). This weighting method is a multi-criteria decision making approach that employs a pair-wise comparison 203 procedure to arrive at a scaled set of preferences among a set of alternatives. The scores are usually 204 205 assigned by experts and a comparison matrix is produced, reflecting the importance of each variable relative to all other variables. Having a comparison matrix, a priority vector, which is basically the 206 normalized eigenvector of the matrix, is computed. This is done by dividing each of the columns in 207 the matrix by the corresponding sum. As the last step, the average values of each row are computed 208 and these are used as weights (Mani Murali et al., 2013). 209

In this study the weightings were done by six experts, all having background in environmental
science (hydrology, geology, geomorphology) and all familiar with coastal processes in the area. The
scores, reflecting to which extent one variable is more (or less) important than another in contributing
to coastal vulnerability in the area, were as- signed using the standard AHP scale (Table 2).

The AHP also provides a mathematical measure to determine the consistency of judgments. The coherence of the pair-wise comparisons is calculated through a consistency ratio (CR) which is utilized to indicate the likelihood that the matrix judgments were assigned randomly:

า	1	7
Z	Т	/

- CR = CI/RI
- 219

Where the RI (random index) stands for the average of resulting consistency index that depends on the order of the matrix by Saaty (1977), and the CI (consistency index) is expressed as:

- 222
- **223** $CI = (\lambda_{max} 1)/(n-1)$
- 224
- 225 Where λ_{max} is the largest or principal eigenvalue of the matrix, and n is the order of the matrix. A 226 CR of the order of 0.1 or less is considered to be a reasonable level of consistency (Saaty, 1980).
- 227

228	Table 2: Pair-wise comparison matrix that reflects preferences among a set of options, commonly used in analytical
229	hierarchy process.

Intensity of importance	Definition			
1/9	Extremely less important			
1/7	Very strongly less important			
1/5	Strongly less important			
1/3	Moderately less important			
1	Equally important			
3	Moderately more important			
5	Strongly more important			
7	Very strongly more important			
9	Extremely more important			

230 231

232 *3.3.* Calculation of final vulnerability scores

The final vulnerability score for each segment was calculated by applying the simple weightedsum of all variables (Eastman et al., 1995), according to the adapted formula:

- 236 $V = \Sigma (W_i X_i)$
- 237

235

Where V stands for vulnerability level, w for weight of variable i and x for the score of variable i (1-5).

240 Vulnerability scores were then normalized to a scale from 1 to 5 following the formula:

241

243

242 N (v_i) = ((V_i Vmin) / (Vmax-Vmin)) * 5

244 Where the N (v_i) is the normalized vulnerability value v_i for variable V, Vmin is the minimum 245 value for variable V, and the Vmax is the maximum value for variable V.

- 246247 4. Results
- 248

249 *4.1. Vulnerability scores based on variables*

The vulnerability scores for each variable were assigned to each of the 36 coastline sectors, based on the vulnerability classification in Table 1.

The whole study area belongs to a wide alluvial plain and is therefore characterized by very low relief. Elevation in the study zone does not exceed 7.7 m above MSL, but even these heights correspond to isolated points and most of the area shows elevations lower than 3.5 m above MSL. By defining vulnerability classes as being separated by increments of 1.4 m, almost all of the study area (Fig. 1) is assigned with the highest possible vulnerability score of 5 since the mean elevation exceeds
1.4 m only at sectors 13 and 15. Vulnerability values for elevation in the area are shown in Fig. 2a.

As for the dunes (Fig. 2b), sectors 1-6 show the highest possible vulnerability score of 5 since there are no dunes present in the area. On the other hand, sectors 30-35, at the southern part of the study zone, were assigned with the lowest vulnerability score of 1 since all of them have over 88% of the coastline protected by dunes. This area, belonging to Lido di Dante pinewood, is known as one of the last remaining coastal stretches with natural dunes in Emilia-Romagna region. Aerial photos of the study area show strong contrasts between urbanized stretches of coast vs. those covered with natural dunes (Fig. 3).

265 Regarding artificial protection structures, almost two thirds of sec- tors are not protected with extensive structures such as groynes, breakwaters and attached rubble mound slopes. These sectors 266 were assigned with vulnerability score of 5. Some other sectors are fully protected by either groynes, 267 268 breakwaters or rubble mound slopes and are assigned the lowest possible vulnerability score of 1. This particularly relates to urbanized stretches such as sectors 15-16 (artificial protection structures 269 in front of Porto Corsini/Marina di Ravenna settlement), sectors 21-26 (in front of Punta Marina and 270 271 Lido Adriano settlements) or sectors 34-36 (in front of Lido di Classe settlement). Fig. 2c shows the vulnerability values considering presence/absence of artificial protection structures in the area. 272

When considering shoreline change, sectors 1, 2, 3 and 4 (north of Reno River mouth) were assigned with the highest level of vulnerability (value = 5), since majority of transects show average erosion rates of over-7 m/yr. The sectors that showed highest accretion trends on average were sectors 14, 15 and 17. These areas, located around the jetties of Porto Corsini/Marina di Ravenna were assigned with the lowest vulnerability score (value=1). The vulnerability classes ac- cording to average shoreline change rates by sectors are shown in Fig. 2d.

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Fig. 2. Map showing vulnerability values for elevation (2a), dunes (2b), artificial protection structures (2c), shoreline
 change (2d) and land cover (2e) for each sector in the study area.

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It is important to mention the areas located in the northern part (sectors 5 to 7, between the Reno river mouth and Casalborsetti - north of the Marina Romea pinewood). These areas are protected by attached rubble mound slopes that were built in the 1990s due to the severe erosion, and therefore
shoreline retreat should be considered here as an indication of a critical stretch of coast, although
since the 1990s the shoreline is in a fixed position. This is reflected in considerably high vulnerability
values assigned to these sectors (value 4) regarding shoreline retreat. Furthermore, the
aforementioned port of Porto Corsini (sectors 15 and 16) reached its present configuration in 1970s.
Both areas are now represented by hard and fixed coastlines that are no longer affected by erosion.
However, sector 15 also includes the beaches adjacent to the port jetties.

As for the land cover (Fig. 2e), the only sector attributed with the highest vulnerability score of 5 was sector 16, but also other sectors (e.g. sectors 23-25) had relatively high vulnerability scores (value = 4) due to a predominantly urban land cover. The southern part of the study area (sectors 30-34) had low vulnerability regarding land cover, since these sectors are predominantly covered with forest.

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298 *4.2. Analytic hierarchy process*

299 Out of the six weightings by the experts (mainly hydrologists and geologists with experience in different kinds of coastal monitoring), two of them were not considered in deriving final weights 300 since the consistency ratio was exceeding the 0.1 threshold (namely 0.12 and 0.15), meaning that the 301 weighting in these two cases was more random than it should be for considering it as consistent. The 302 remaining four weightings showed satisfactory consistency ratios (0.04, 0.06, 0.07 and 0.08) and were 303 304 used to derive average weights. The highest resulting weight was for elevation (0.391), followed by dunes (0.245), shoreline change rates (0.215) and artificial protection (0.167), while the lowest was 305 for land cover (0.135). 306

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Fig. 3. Aerial photos showing natural dune (a) and urbanized coastal stretches (b) in the study area (Photos provided byN. Greggio and B. Giambastaini, University of Bologna).

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312 *4.3. Final vulnerability score*

Final vulnerability scores and the weight value for each variable and for each sector are shown in Table 3 (and visualized in Fig. 4) for all sectors. The final vulnerability values are calculated with two decimal places, since in this way the difference between sectors is more trans- parent than rounding them to integer values.

The highest vulnerability to SLR and marine floods, with a final vulnerability score equal to 4.56, appears in sectors 1, 2 and 4 at the northernmost end of the study area. This area, north of the Reno River mouth, is characterized by a natural barrier beach backed by brackish marshes (Nordstrom et al., 2015). It is known for its erosive trend over the last 50 years, mainly due to the reduced sediment supply, land subsidence and lack of adequate protection systems (Antonellini et al., 2008; Preciso et al., 2012). These sectors are featured by low elevation (0.45-0.8 m mean height), shoreline retreat (around 7 m/yr), no dunes and no artificial protection structures.

It is interesting to note that there are no sectors assigned with very low vulnerability, i.e. with 324 vulnerability score 1. As for the final vulnerability scores of around 2, the lowest in this study, two 325 areas stand out, one of sectors 10 and 11, and another of sector 35. Sectors 10 and 11 represent an 326 area belonging to Marina Romea pinewood, where the coastline is largely protected by natural dunes 327 (71 and 85% respectively) as well as breakwaters and thus minor erosive trends occur (lower than 328 329 -0.5 m/yr in both cases). Furthermore, these sectors are largely covered with coastal forest ("pineta"), contributing to flood attenuation by natural infiltration. As for the sector 35, this part of the coastline 330 is also covered with forests, belonging to Lido di Dante pinewood, and almost fully protected by 331 332 dunes.

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334 5. Discussion

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336 Whenever a composite index that is supposed to reflect vulnerability is designed, the choice of its variables is partly subjective. In this study it was decided to use five variables that could capture the 337 vulnerability to SLR and marine floods in the study area. These variables were chosen as relevant 338 339 based on literature review (e.g. Gornitz, 1991; Abuodha and Woodroffe, 2010; Mahapatra et al., 2015; Nguyen et al., 2016) and the engagement of different experts, so that the chosen variables were 340 significant for the local context and for the processes considered in the vulnerability assessment (i.e. 341 342 flooding and SLR). Balica et al. (2012) argues that an index using few variables is less reliable than a more complex one, since a large variation in one variable can have a strong influence on the overall 343 index. However, since one of the aims of this study was exploring an index that could be widely 344 applicable, the intention was to remain within few relevant variables so that this kind of assessment 345 could also be performed in conditions where there are not many different types of data available. In 346 addition, choosing fewer variables can reduce redundancy (in terms of avoiding closely related 347 variables reflecting the same processes) and help to obtain a simple, feasible index (Del Río and 348 Gracia, 2009). In this case, updating values of chosen variables should be reasonably easy to obtain 349 350 at any given area without requiring extensive surveying (Villa and McLeod, 2002). Consequently, the resulting tool is not only scientifically valid, but also replicable, practical and easy to use and to 351 352 communicate to coastal managers.

Regarding the influence of the different variables in total vulnerability, a weighted CVI method provides more consistent spatial distribution of highly vulnerable sectors than the original, unweighted CVI approach (Bagdanaviciute et al., 2015). This way, in areas with a significant alongshore variability of some of the variables most relevant to determine vulnerability (e.g. dune cover or shoreline change), a weighted index allows to assign the highest vulnerability to those sectors which are actually the most vulnerable ones, while an unweighted approach would under- or overestimate vulnerability.

360 In this work the highest weight resulting from the AHP was assigned to elevation. In this respect, although elevation is very low in the whole study area, it was divided into five vulnerability classes 361 for the purpose of this assessment. However, the question on separation of classes arises: Is the 362 363 elevation of 1.5m really so less vulnerable than the elevation of 1m that they belong to different vulnerability classes? This depends on the properties of forcing, i.e. the height of the water level and 364 its potential to penetrate landward. In this respect, it could occur that a certain height of water level 365 will cause as much damage on locations at 1.5m elevation above MSL (e.g. sector 13 of the study 366 area) as on those at 1m elevation (e.g. sector 14). Therefore, it would be convenient to determine, 367 wherever possible, the threshold elevation above which the potential for inland flooding will be 368 substantial. This would be particularly important in locations characterized by uniformly low 369 topography, as occurs in the study area. In locations where threshold determination is hindered by 370 371 lack of data, the objective procedure of dividing the range of elevations existing in the study area into five equal intervals to assign vulnerability can be considered acceptable. Additionally, the mean 372 elevation is influenced by the chosen landward extension of the sectors. In any case, the sectors where 373

the mean elevation is low represent areas more prone to flooding if the water levels during storms exceed the elevation of the rear part of the beach, leading to water ingression, or if the dunes or other

defences are breached and the water is able to flow landward.

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Fig. 4. Vulnerability scores, number of flooding impacts along the study area between 1946 and 2010 (Perini et al., 2011)
and percentage of flooded surface in each sector for the 1-in-10 years event and calculated by the Regional authorities for
the EU Floods Directive (Perini et al., 2016).

As for the dunes, the variable was chosen because it constitutes a significant natural buffer against 383 384 SLR and marine floods. Inclusion of dunes as a variable should also stress out their importance as a barrier to intruding sea water, especially in areas where they are being removed/ destructed for various 385 purposes, such as in the case of Ravenna province (Sytnik and Stecchi, 2015). An important 386 387 consideration when using dunes as a variable that reflects vulnerability is that the share of coastline occupied by dunes is just a partial factor, as the volume of the dunes, the elevation of the dune base, 388 dune height, dune health, alongshore and cross-shore continuity of dunes, etc. are also essential in 389 390 determining the role of dunes as protection from intruding water (Sallenger, 2000; Armaroli et al., 391 2012). In this respect, in some sectors of the study area the existing dunes are so deteriorated that are no longer able to act as an effective protection against marine ingression, as occurs south of Lido di 392 393 Dante (Armaroli et al., 2013). On the other hand, and regarding the methodological aspect, some areas may have dunes present but if these are not of sufficient height/volume they can be overlooked 394 395 in manual digitization, even from high-resolution imagery. However, and for the above stated reasons (wide replicability, ease of communication), this work was aimed at simplicity when building the 396 composite index, and consequently it was decided to choose only dune presence as a variable. 397

The role of the artificial protection structures should also be taken with care. Perpendicular structures such as groynes can lead to sediment accretion at one side, increasing beach width and, hence, distance that flood waters need to cover to reach a receptor. However, sometimes these

401 structures can even aggravate the erosion at adjacent beaches due to the mentioned sediment retention (Hall and Pilkey, 1991). In addition, improper placement of breakwaters can lead to their sinking into 402 sandy bottoms, which makes them more inefficient in protection (Gerwick, 2007). In fact, according 403 to Sousa et al. (2013) the presence of engineering structures implies a higher vulnerability as they 404 represent areas of instability and have frequent negative impacts on the coastline, although they may 405 provide local short-term protection. In this respect, a special care needs to be given when assigning 406 the highest vulnerability scores to areas without protection structures. It could be that these areas are 407 408 not protected because there are no assets at risk, but it could also be because they are stable, i.e. there is no need for placing defence structures. In that case, the vulnerability of an area without protection 409 structures does not necessarily need to be high, while on the other hand, areas with defence structures 410 are those with a clear erosion trend (which is why the defences were constructed) so they could 411 intrinsically be more vulnerable. This is the case for most part of the study area, where severe erosion 412 occurring around places like Casal Borsetti, Lido Adriano or Lido di Dante led to the building of 413 extensive protection structures (Sytnik et al., 2018). On the other hand, in case of major storms, areas 414 without protection structures would eventually be more vulnerable than the protected ones, as wave 415 416 energy would not be dissipated by any obstacle. This is the main reason why in this work the highest vulnerability was assigned to the sectors without protection structures. 417

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Table 3: Final vulnerability scores and the weight value for each variable for each sector of the study area.

Sector	Elevation	Weight	Dunes	Weight	Artifical protection	Weight	Shoreline Change	Weight	Land Cover	Weight	Final vuln. score
1	5	0.391	5	0.245	5	0.167	5	0.215	2	0.135	4.56
2	5	0.391	5	0.245	5	0.167	5	0.215	2	0.135	4.56
3	5	0.391	5	0.245	5	0.167	5	0.215	1	0.135	4.41
4	5	0.391	5	0.245	5	0.167	5	0.215	2	0.135	4.56
5	5	0.391	5	0.245	1	0.167	4	0.215	3	0.135	3.75
6	5	0.391	5	0.245	1	0.167	4	0.215	3	0.135	3.75
7	5	0.391	1	0.245	1	0.167	4	0.215	3	0.135	2.69
8	5	0.391	2	0.245	1	0.167	3	0.215	3	0.135	2.72
9	5	0.391	3	0.245	1	0.167	2	0.215	3	0.135	2.75
10	5	0.391	2	0.245	1	0.167	3	0.215	2	0.135	2.15
11	5	0.391	1	0.245	1	0.167	3	0.215	2	0.135	2.31
12	5	0.391	3	0.245	5	0.167	2	0.215	3	0.135	3.05
13	4	0.391	5	0.245	5	0.167	2	0.215	3	0.135	4.01
14	5	0.391	2	0.245	5	0.167	1	0.215	2	0.135	2.83
15	4	0.391	5	0.245	1	0.167	1	0.215	4	0.135	3.20
16	5	0.391	5	0.245	1	0.167	2	0.215	5	0.135	3.58
17	5	0.391	4	0.245	5	0.167	1	0.215	2	0.135	3.36
18	5	0.391	4	0.245	5	0.167	2	0.215	1	0.135	3.45
19	5	0.391	2	0.245	4	0.167	2	0.215	3	0.135	3.03
20	5	0.391	4	0.245	4	0.167	2	0.215	2	0.135	3.41
21	5	0.391	5	0.245	1	0.167	2	0.215	3	0.135	3.28
22	5	0.391	5	0.245	1	0.167	3	0.215	3	0.135	3.52
23	5	0.391	2	0.245	1	0.167	4	0.215	4	0.135	3.10
24	5	0.391	4	0.245	1	0.167	3	0.215	4	0.135	3.40
25	5	0.391	4	0.245	1	0.167	3	0.215	4	0.135	3.40
26	5	0.391	2	0.245	1	0.167	4	0.215	3	0.135	2.95
27	5	0.391	3	0.245	5	0.167	4	0.215	3	0.135	3.94
28	5	0.391	3	0.245	2	0.167	3	0.215	3	0.135	3.17
29	5	0.391	1	0.245	5	0.167	3	0.215	3	0.135	3.18
30	5	0.391	1	0.245	5	0.167	2	0.215	2	0.135	2.80
31	5	0.391	1	0.245	5	0.167	2	0.215	1	0.135	2.65
32	5	0.391	1	0.245	5	0.167	2	0.215	2	0.135	2.80
33	5	0.391	1	0.245	5	0.167	2	0.215	1	0.135	2.65
34	5	0.391	1	0.245	5	0.167	3	0.215	1	0.135	2.89
35	5	0.391	1	0.245	1	0.167	3	0.215	3	0.135	2.46
36	5	0.391	5	0.245	1	0.167	3	0.215	4	0.135	3.66

422 Assigning the vulnerability score to certain sectors based on land cover type also raised some questions. The procedure of assigning the vulnerability scores of different land cover types in order 423 to obtain a single value for the entire sector, based on the predominant land cover type, might 424 overshadow the situation at-the-ground. For instance, if a certain asset will be constructed behind a 425 forest zone, its vulnerability regarding floods could be lower than if it was constructed behind a built-426 427 up area, although the distance of this asset from the shoreline is the same in both cases. This is because the infiltration is higher for this land cover type (forest) than for paved impervious surfaces which 428 can transfer flood waters beyond them, if no obstacles exist to dissipate water flow energy. Therefore, 429

it would be important to also consider the land cover type between the receptor and the sea, not only
the predominant land cover type in the sector. In addition, coarse spatial resolution of CORINE land
cover input data (positional accuracy 100 m) can lead to errors when representing land cover on a
local level; nevertheless, the use of CORINE land cover is intended to demonstrate that easily
available databases can be used elsewhere to make a general assessment of vulnerability in a relatively
simple manner.

436 As for shoreline change rates, it is a key variable in determining vulnerability and as such should be carefully evaluated. In this work, obtained rates could have been influenced to some extent by the 437 different methods employed for digitizing the 1954 and 2011 shorelines and by having used different 438 sources of input data with diverse levels of precision. However, shoreline trends in the study zone are 439 440 clear and the results obtained agree with previous works (Sytnik et al., 2018). Regarding the AHP, Youseff et al. (2011), Bagdanaviciute et al. (2015) and Roy and Blaschke (2015) discussed the 441 442 advantages of using this approach in vulnerability analyses: its structured approach of decomposing 443 the analysis problem into hierarchical units and levels; its reliance on expert opinion rather than on completeness of the data; the transparency of the approach; the ability to integrate independent 444 445 opinions and check inconsistencies; and the possibility to involve both experts and stakeholders. 446 Nevertheless, the dependency on the judgment of the experts can also be seen as a limitation of the method since. it can be sensitive to changes in the decision weights associated with criteria 447 (Fernandez and Lutz, 2010). In any case, in this work AHP was found to be a transparent, well-448 structured, and "fit-for-purpose" methodology. One issue in this respect was that two of the 449 weightings had a consistency ratio above 0.1 and, although their values were only slightly higher, it 450 was decided not to include them in the final weighting. One of the experts asked for some 451 clarifications on variables prior to weighting, as he found that the variables were in some cases 452 453 strongly interrelated (e.g. one of the observations was that the dunes can also be viewed as part of the 454 land cover variable). Therefore, the definitions clarifying what each variable stands for should be presented with care to consulted experts in order to avoid any possible confusion. Another concern in 455 456 this work was the relatively low number of experts involved in the weighting. However, this was the 457 case because it was decided to focus not on stakeholders with different backgrounds, but only on environmental scientists with knowledge of the study area, as the CVI is related to the physical 458 459 characteristics of the coastal area. Notably, there was a degree of "diversity" within this group of scientists as they had different backgrounds within environmental science (geography, geology and 460 hydrology). 461

An important issue in studies on composing coastal vulnerability indexes is the possibility of verifying the methodology (Del Río and Gracia, 2009). In this case, the major question would be: is the area assigned with the highest vulnerability level actually the most vulnerable to marine ingression? Although vulnerability is an intrinsic characteristic and hence not suitable for absolute measurement or proper validation (Roy and Blaschke, 2015), a verification via the comparison of the scores with other relevant studies in the area, i.e. previously published flood hazard maps, was considered in this work.

469 In this way, flood hazard maps for the coastal area of Emilia Romagna, issued at the end of 2013 to satisfy the requests of the EU Flood Directive (2007/60/EC), were considered here for 470 "verification" purposes. The maps used were developed by the Geological Service of the Emilia-471 Romagna Region by applying the Cost-Distance tool of ArcGIS®, taking into account three Total 472 Water Level scenarios (10, 100 and > 100 year return periods) and high resolution Digital Terrain 473 Models (DTMs) of the coast (Perini et al., 2012, 2016). More details about the methodology can be 474 475 found in Perini et al. (2016). Although a comparison between a vulnerability index and hazard maps may in principle seem inappropriate from the conceptual point of view, the main factor involved in 476 determining flooded areas in the hazard maps used (namely elevation) is also the most significant 477 variable in the vulnerability index. Therefore, in this work the comparison between both results was 478 performed in order to evaluate the relationship between theoretically vulnerable areas and hazard 479 areas determined by water levels. For this purpose, the 36 sectors of the study zone were overlain by 480

the flood hazard maps and the percentage of flooded area for each sector was evaluated (Fig. 4). The
hazard maps used here were the ones showing the lowest return period floods (1-in-10 years), since
these reflect the highest expected frequency.

There were only four sectors that had more than 40% of the area covered by flood water (Fig. 4). 484 These sectors are assigned with vulnerability scores of 2.65, 3.17, 3.75 and 4.56. It is important to 485 note that one of the sectors assigned with the highest vulnerability score is the one showing the largest 486 percentage of area covered with flood water (i.e. sector 1, with 62.2% of flooded area). Also the sector 487 with lowest percentage of area covered with flood water (sector 11, 1.5%) is assigned with one of the 488 489 lowest vulnerability values (2.31). On the other hand, there were 16 sectors which had less than 10% of their area covered with flood water. Eight of them were assigned with vulnerability scores between 490 491 2 and 3, while eight of them were assigned with vulnerability scores between 3 and 4. However, there are some notable cases in which areas of high vulnerability scores do not correlate with those 492 493 estimated as prone to flooding by flood hazard maps. For example, sector 4 is assigned with 494 vulnerability score 4.56 but "only" 13% of its area is covered with flood water according to the flood hazard maps analysed. It is unrealistic to expect that the results of the vulnerability analysis will 495 strictly correlate those of flood hazard maps, since flood hazard and flood vulnerability are different 496 (although in this case, related) concepts and the two analyses used two different methodologies. The 497 percentage of each sector affected by floods in the 1-in- 10-years storm depends on total water level 498 (determined by waves, tides and storm surge) and land elevation, while the proposed CVI does not 499 consider these hydrodynamic agents but includes the presence of dunes and artificial structures, 500 501 shoreline changes and land use. The lack of wide correspondence between both calculations highlights that these approaches are not mutually excluding but complementary, as they account for 502 different factors in characterizing flood risk. 503

As demonstrated above, the coastline within the Ravenna province is affected by marine storms and by both erosion and inundation. The large impact of energetic events is also reported in the catalogue of historical storms produced by the regional authorities for the period 1946–2010 (Perini et al., 2011). The dataset was used by Armaroli and Duo (2018) to validate the results of the application of the Coastal Storm Risk Assessment Framework - CRAF (Viavattene et al., 2018) along the whole regional coastal area.

The CRAF was developed in the EU Risc-kit project (www.risckit.eu; Van Dongeren et al., 2018). 510 It consists of a framework to identify hotspots of erosion and inundation along regional coastal areas 511 and to apply a storm impact evaluation in selected critical sites (for more information on CRAF 512 methodology and outcomes refer to: Armaroli and Duo, 2018; Christie et al., 2018, De Angeli et al., 513 2018; Ferreira et al., 2018 and Viavattene et al., 2018). Armaroli and Duo (2018) identified the coastal 514 515 area within the Ravenna province as a hotspot of inundation and erosion. The authors also carried out a validation of the results obtained with the CRAF that confirmed the reliability of the results. The 516 517 evaluation of the number of inundation events between 1946 and 2010 (Fig. 3 in Armaroli and Duo, 2018, left panel, reanalysed for the present study and presented in Fig. 4) that affected the coastal area 518 shows that the most critical sites (number≥6 of inundation events that caused an impact) are located 519 in sector 16 (Marina di Ravenna), 24-26 (Lido Adriano), 28 (Lido di Dante) and south of sector 36 520 (Lido di Savio). The sectors 24-26 and 28 are scored 3 in the present work (medium vulnerability, 521 522 Fig. 4) and are protected by defence structures. Sectors 16 and 36 show a better correspondence with 523 the historical information and are scored 4 (high vulnerability). As mentioned above, the reason for the difference between the observed impacts and the CVI is related to the variables included in the 524 CVI, which do not include the hazard component, and the limitations of the method described above. 525 526 As an example related to these limitations, the presence of protection structures is considered to lower the vulnerability while, in the case of the study area, they are located where the coast is more 527 vulnerable. Considering the inundation hazard, it was demonstrated that the coast is primarily exposed 528 to high surge levels (Armaroli et al., 2012), therefore breakwaters are less effective in wave energy 529 dissipation than they would be without high surge levels. 530

An example of the possible application of the CVI for coastal management purposes along the 531 Emilia-Romagna coastline is presented hereafter. As mentioned above, in the framework of the EU 532 533 Floods Directive (2007/60/EC) regional managers carried out the analysis of flooding extension for different return period storms, using simplified inundation models (Perini et al., 2016). The flooding 534 extension was then combined with land use maps to produce risk maps of the coastal area (see Perini 535 et al., 2016 for details on the methodology). For the creation of risk maps, land use typologies were 536 firstly scored by coastal managers, according to their perception, based also on experience, of the 537 degree of susceptibility to be damaged of each land use typology. The scoring can thus be considered 538 a simplified evaluation of the vulnerability of different land use categories in relation to their 539 characteristics (e.g., agricultural area, built-up area, beach, dune, etc.). It is however clear that the 540 "risk" maps produced by regional managers for the Floods Directive do not include a proper 541 vulnerability evaluation of all the elements exposed (located in flood-prone areas). Therefore the CVI 542 presented in this paper could help coastal managers to better define the vulnerability, and 543 consequently define the risk level, of coastal sectors with a more complete and robust methodology. 544 Additionally, a large database of coastal physical characteristics is available for the Emilia-Romagna 545 546 Region (named In Coast1). However, the information stored in the database is used separately for risk evaluations. The CVI could also become a valuable tool for coastal managers because it 547 aggregates relevant (already available) variables to provide a clear indication of vulnerable sites. 548 549 Although regional and local managers are aware of the criticalities of the coastal area, specific and simple tools to define its vulnerability are not used. The CVI developed can thus represent a first step 550 towards a more comprehensive evaluation of coastal vulnerability which can be easily carried out 551 552 also by non-experts of coastal dynamics.

For what concerns the exportability of the methodology, it is important to note that the variables 553 included in the CVI can be retrieved or produced also for data-poor coastal areas. Freely available 554 remote sensing products such as satellite imagery (which can be used to define shoreline trends, 555 identify the presence of dunes and protection structures), land use and land cover maps (already 556 557 available or that can be produced using satellite imagery) and global DEMs can be used to build the 558 CVI, although with different accuracies with respect to the dataset presented in this paper. The forcing components, on the contrary, are more difficult to retrieve or produce. However, many coastal areas 559 560 worldwide are lacking this type of detailed information. For this reason, the CVI does not consider the hydrodynamic forcing, because the proposed method is meant to be replicated also in coastal 561 zones for which there is a lack of long-term research data on hydrodynamic conditions and where 562 coastal managers might not be aware of waves and water levels dynamics. 563

564

565 6. Conclusions

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567 This paper proposes an easy-to-use coastal vulnerability index (CVI) to sea level rise and marine floods that is employed to examine vulnerability of the coastal area in the Ravenna Province (Italy). 568 The index is formulated with five physical variables which are relevant for the intended purpose, yet 569 not difficult to obtain: elevation, dunes, artificial protection structures, shoreline change rates, and 570 land cover. In this way, the index is easy to apply and to communicate to stakeholders, also providing 571 exportability and wide applicability. Each variable was assigned different levels of importance 572 (weights) by experts familiar with the study area, by applying analytic hierarchic process (AHP). In 573 this way quantitative and qualitative data were integrated in a transparent and structured way. This 574 coastal vulnerability index could be replicated to similar (sandy and microtidal) coastal environments, 575 by using AHP to include the local context of the study area where it will be applied. Potential 576 uncertainties in this framework were carefully considered along the different steps of the procedure, 577

¹ available at <u>https://applicazioni.regione.emilia-romagna.it/cartografia_sgss/user/viewer.jsp?service=costa</u>

such as assigning vulnerability scores to input variables, weighting procedure and verification of themethodology.

The verification of the proposed index was one of the key issues in this study. The comparison of 580 the assigned vulnerability scores with flood hazard maps based on water levels yielded inconsistent 581 582 results, showing the complementarity of both approaches to deliver a full risk assessment. Nevertheless, more detailed knowledge on observed floods and their effects in the study area would 583 be convenient to reach a more sound verification. The greatest question arises from the fact that the 584 different variables influencing coastal floods are dynamic and interconnected, so there is a high level 585 of uncertainty regarding their future behaviour. The forcing is changing, since sea level is rising. In 586 many areas, such as the Ravenna province, the coasts are subsiding and sediment input is strongly 587 588 reduced. If these phenomena get jointly exacerbated in the future, this could impact shoreline change rates, which will in turn reduce the flood pathway towards the receptor, i.e. towards built-up areas 589 590 near the coastline which will probably grow even more in the future. Since future changes in forcing 591 and receptors are highly unpredictable, a wide range of uncertainty should be thoroughly considered in future coastal planning. 592

In data-rich coastal areas, the proposed index can be used by coastal managers as a simple tool to 593 aggregate relevant variables in order to obtain a clear identification of sectors that are highly 594 vulnerable to sea level rise and marine floods. In these cases, the use of the CVI could be a first step 595 towards a complete risk assessment that would have to include also the evaluation of the hazard and 596 597 the exposure. In data-poor coastal areas, one of the main advantages of the index for coastal planning and management is the possibility to obtain the relevant variables by freely available remote sensing 598 599 data. In this way, the index provides an easy way to evaluate vulnerability to coastal floods that can be achieved even by non-experts in coastal dynamics. Furthermore, a key potential of this approach 600 lies in its visual component - the integration of the framework into geographical information systems 601 602 results in maps which are highly informative for coastal managers and decision makers, and can also be a powerful public awareness tool. 603

Finally, it must be pointed out that, although the identification of vulnerable sectors can be a solid basis for considering adaptation in the area, any adaptation action should be based on more detailed bottom-up analysis.

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608 Authors contribution

IS and LR conceived and designed the study. IS performed the analysis and wrote the manuscript with contributions from LR. CA provided the Lidar data and contributed to the identification of part of the reference literature. All authors revised the paper and contributed to the interpretation and discussion of the results.

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