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Published Version:
Ivan Sekovski, L.D.R. (2020). Development of a coastal vulnerability index using analytical hierarchy process and application to Ravenna province (Italy). OCEAN & COASTAL MANAGEMENT, 183, 1-11 [10.1016/j.ocecoaman.2019.104982].

Availability:
This version is available at: https://hdl.handle.net/11585/892350 since: 2022-08-13

Published:
DOI: http://doi.org/10.1016/j.ocecoaman.2019.104982

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

Ivan Sekovski[a,b,*], Laura Del Río[b], Clara Armaroli[c]

[a] Department of Biology, Geology and Environmental Science, University of Bologna, 48123, Ravenna, Italy
[b] Department of Earth Sciences, CASEM, University of Cadiz, 11510, Puerto Real, Spain
[c] Scuola Universitaria Superiore IUSS Pavia, Piazza della Vittoria 15, 27100 Pavia, Italy

Keywords

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

ABSTRACT

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.

1. Introduction

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 major phenomena could contribute to exacerbate such trend in the future. The first one is the expected further sea level rise (SLR) and the increasing extreme sea levels related to global climate change (Church et al., 2013). According to the IPCC SR15 report, "increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise 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 human susceptibility to coastal flooding and erosion, especially in low-lying floodplains, due to 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 within 100 km of the coastline (IOC/UNESCO, IMO, FAO and UNDP, 2011), while in the European Union (EU) approximately half of the population lived within just 50 km of the coastline (Ramieri et al., 2011). In the Mediterranean Sea region, about 55% of the total population resides in coastal hydrological basins (Martin et al., 2015). As in many other coastal areas worldwide, environmental 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).

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

Studies on vulnerability to floods in coastal zones seem to be expanding recently (Roy and Blaschke, 2015; Perini et al., 2016; Seenath et al., 2016; Di Risio et al., 2017; Christie et al., 2018; Zhang et al., 2019, among others). Yet, there is no single standardized way to measure vulnerability (Balica et al., 2012). Satta (2014) distinguished four different categories of methods for assessing coastal vulnerability: (i) index/indicators-based methods; (ii) methods based on dynamic computer models; (iii) GIS-based decision support tools; and (iv) visualization tools. For this research, it has 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 unitless, vulnerability index. One of the major strengths of index-based methods is that they offer 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 vulnerability of a system. The general aim is to simplify a number of complex and interacting 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 quantitative or semi-quantitative evaluation and combination of several variables (Abuodha and Woodroffe, 2010; Ramieri et al., 2011).

One of the initial attempts to derive a coastal vulnerability index for assessing sensitivity to SLR 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) were combined at a regional scale. Thieler and Hammar-Klose (2000) applied a similar index to study coastal vulnerability of the US Atlantic coast to SLR. Following these studies, many different, modified versions of the Coastal Vulnerability Index (CVI) have been applied to assess coastal vulnerability on different scales (e.g. Pendleton et al., 2005; Abdouha and Woodroffe, 2006; Szlafsztein and Sterr, 2007; Özyurt and Ergin, 2009; McLaughlin and Cooper, 2010; Alexandrakis and Poulos, 2014; Di Risio et al., 2017; and many others). More comprehensive review on different applications of CVI can be found in Abuodha and Woodroffe (2010), Ramieri et al. (2011), Balica et al. (2012), Satta (2014) and Nguyen et al. (2016).

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.

Fig. 1. Location of the study area within the coastal area of Ravenna province, Italy (NW Adriatic Sea).

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 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).

2. Study area

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 known as being susceptible to coastal flooding and erosion (Perini et al., 2017). The southern part of 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 particularly intense during the 1960s. Beach-related tourism resulted in coastal land occupation by 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 Stecchi, 2015). Apart from beach- related tourism, land cover change was also driven by the 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 conservation designation (Sites of Community Importance and Special Protection Areas).

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

3. Methodology

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.

3.1. Input data and assigning of vulnerability scores

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

According to Nguyen et al. (2016), segmentation aimed at ranking different sections of the coastline based on vulnerability (i.e. variables that determine vulnerability) is useful to determine 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 approximate length of 1 km (or less, if they are disrupted by river mouths), while the landward 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 too small to overlook the true spatial extent of flooding impacts.

Elevation values were extracted from the 2012 Digital Terrain Model (DTM) of 1 m horizontal resolution and 20 cm vertical precision, derived from LIDAR surveys and provided by ENI ("Ente 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 split into five equal intervals to which vulnerability scores were assigned, with addition that all 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 associated with high vulnerability scores; high elevations were given low vulnerability scores (Table 1).

The layer showing the position and extent of coastal dunes was manually digitized based on 2011 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 feature (ArcGIS 10.1), based on high resolution satellite images provided by DigitalGlobe®. Vulnerability scores for both variables were assigned based on percentage of shoreline in each segment covered by dunes/artificial protection structures (Table 1). In the latter case both shore-normal structures (e.g. groynes, by calculating alongshore length of their base) and shore-parallel 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 offset short-term variability due to the dynamic nature of the area. The 1954 shoreline was manually digitized from aerial photos for the study of Sytnik et al. (2018) and kindly provided by the authors. The 2011 shoreline was derived by processing high-resolution multispectral WorldView-2 satellite imagery of 1.84 m resolution, the same that was used for extraction of the position and extent of coastal dunes. The rate of shoreline change was calculated by using the end point rate (EPR) statistical measure. The overall output values of shoreline changes in the area, according to EPR, were divided into five equal segments in order to assign the 1 to 5 vulnerability values.

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.

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

Variables	Range of values	Vulnerability score
Elevation	Up to 1.4 m	5
	1.4–2.8 m	4
	2.8–4.2 m	3
	4.2–5.6 m	2
	5.6–7.0 m	1
Dune coverage	0–20%	5
	20–40%	4
	40–60%	3
	60–80%	2
	80–100%	1
Shoreline covered by artificial protection structures	0–20%	5
	20–40%	4
	40–60%	3
	60–80%	2
	80–100%	1
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 bodies	5
	Barren soil	4
	Agriculture	3
	Marsh	2
	Beaches and dunes, forests	1

3.2. Analytic hierarchy process (AHP)

The weighting of the variables that contribute to coastal vulnerability is being increasingly implemented in recent vulnerability assessments. The variables are weighted in order to reflect the 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 (Saaty, 1977, 1980), is lately becoming more frequently used in coastal vulnerability studies (e.g. Yin 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 procedure to arrive at a scaled set of preferences among a set of alternatives. The scores are usually 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 normalized eigenvector of the matrix, is computed. This is done by dividing each of the columns in the matrix by the corresponding sum. As the last step, the average values of each row are computed and these are used as weights (Mani Murali et al., 2013).

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:

$$CR = CI/RI$$

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:

$$CI = (\lambda_{max} - 1)/(n-1)$$

Where λ_{max} is the largest or principal eigenvalue of the matrix, and n is the order of the matrix. A CR of the order of 0.1 or less is considered to be a reasonable level of consistency (Saaty, 1980).

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

3.3. Calculation of final vulnerability scores

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

$$V = \Sigma (W_i X_i)$$

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

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

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

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

4. Results

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).

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 were assigned with vulnerability score of 5. Some other sectors are fully protected by either groynes, 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 in front of Porto Corsini/Marina di Ravenna settlement), sectors 21-26 (in front of Punta Marina and 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.

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.

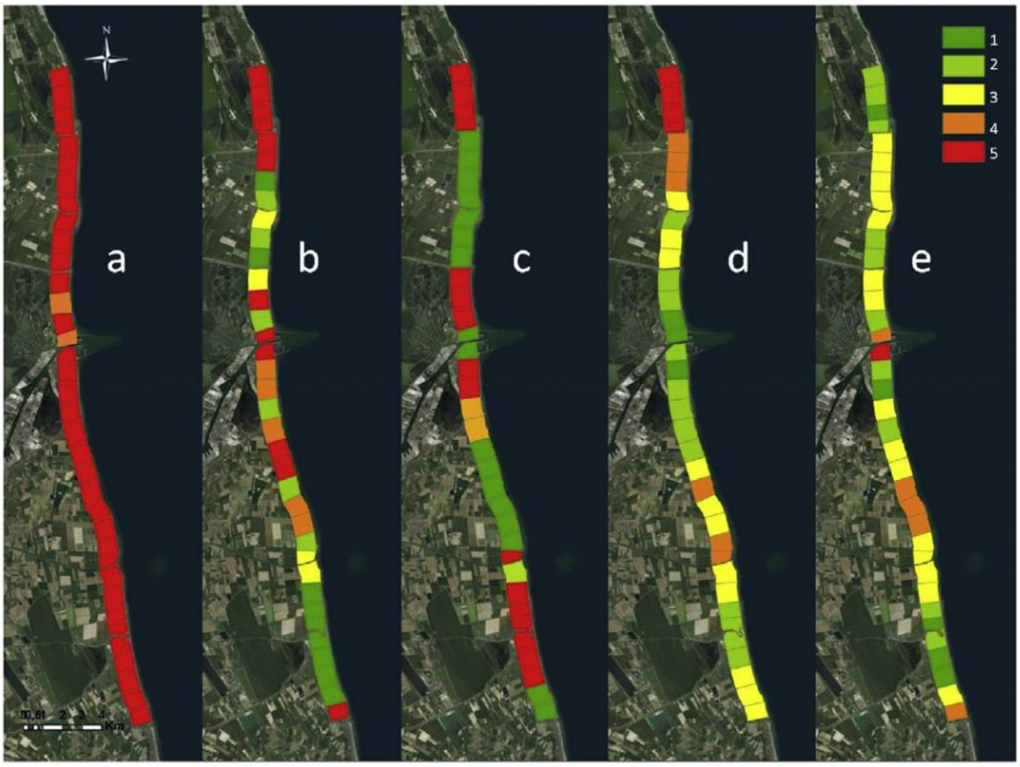

Fig. 2. Map showing vulnerability values for elevation (2a), dunes (2b), artificial protection structures (2c), shoreline change (2d) and land cover (2e) for each sector in the study area.

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.

4.2. Analytic hierarchy process

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 since the consistency ratio was exceeding the 0.1 threshold (namely 0.12 and 0.15), meaning that the weighting in these two cases was more random than it should be for considering it as consistent. The remaining four weightings showed satisfactory consistency ratios (0.04, 0.06, 0.07 and 0.08) and were 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 for land cover (0.135).

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

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 vulnerability score 1. As for the final vulnerability scores of around 2, the lowest in this study, two areas stand out, one of sectors 10 and 11, and another of sector 35. Sectors 10 and 11 represent an area belonging to Marina Romea pinewood, where the coastline is largely protected by natural dunes (71 and 85% respectively) as well as breakwaters and thus minor erosive trends occur (lower than −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 is also covered with forests, belonging to Lido di Dante pinewood, and almost fully protected by dunes.

5. Discussion

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 vulnerability to SLR and marine floods in the study area. These variables were chosen as relevant 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 significant for the local context and for the processes considered in the vulnerability assessment (i.e. 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 index. However, since one of the aims of this study was exploring an index that could be widely applicable, the intention was to remain within few relevant variables so that this kind of assessment could also be performed in conditions where there are not many different types of data available. In addition, choosing fewer variables can reduce redundancy (in terms of avoiding closely related variables reflecting the same processes) and help to obtain a simple, feasible index (Del Río and Gracia, 2009). In this case, updating values of chosen variables should be reasonably easy to obtain 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 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.

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 for the purpose of this assessment. However, the question on separation of classes arises: Is the 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 its potential to penetrate landward. In this respect, it could occur that a certain height of water level will cause as much damage on locations at 1.5m elevation above MSL (e.g. sector 13 of the study area) as on those at 1m elevation (e.g. sector 14). Therefore, it would be convenient to determine, wherever possible, the threshold elevation above which the potential for inland flooding will be substantial. This would be particularly important in locations characterized by uniformly low topography, as occurs in the study area. In locations where threshold determination is hindered by 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 elevation is influenced by the chosen landward extension of the sectors. In any case, the sectors where 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.

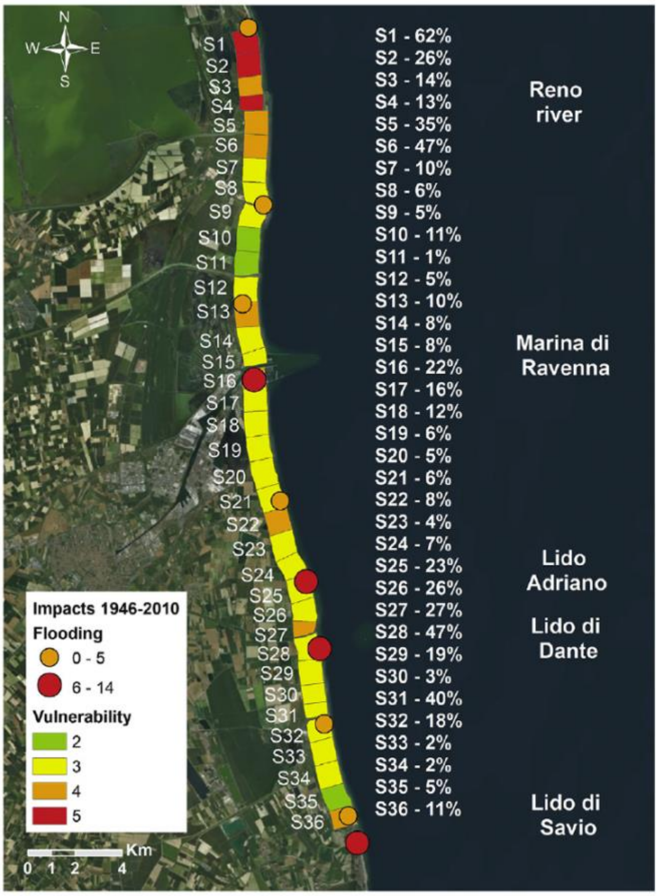

Fig. 4. Vulnerability scores, number of flooding impacts along the study area between 1946 and 2010 (Perini et al., 2011) and percentage of flooded surface in each sector for the 1-in-10 years event and calculated by the Regional authorities for the EU Floods Directive (Perini et al., 2016).

As for the dunes, the variable was chosen because it constitutes a significant natural buffer against 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 purposes, such as in the case of Ravenna province (Sytnik and Stecchi, 2015). An important 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, dune height, dune health, alongshore and cross-shore continuity of dunes, etc. are also essential in determining the role of dunes as protection from intruding water (Sallenger, 2000; Armaroli et al., 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 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 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 composite index, and consequently it was decided to choose only dune presence as a variable.

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 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 sandy bottoms, which makes them more inefficient in protection (Gerwick, 2007). In fact, according to Sousa et al. (2013) the presence of engineering structures implies a higher vulnerability as they represent areas of instability and have frequent negative impacts on the coastline, although they may provide local short-term protection. In this respect, a special care needs to be given when assigning the highest vulnerability scores to areas without protection structures. It could be that these areas are 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 structures does not necessarily need to be high, while on the other hand, areas with defence structures are those with a clear erosion trend (which is why the defences were constructed) so they could intrinsically be more vulnerable. This is the case for most part of the study area, where severe erosion occurring around places like Casal Borsetti, Lido Adriano or Lido di Dante led to the building of extensive protection structures (Sytnik et al., 2018). On the other hand, in case of major storms, areas without protection structures would eventually be more vulnerable than the protected ones, as wave 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.

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

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 to obtain a single value for the entire sector, based on the predominant land cover type, might overshadow the situation at-the-ground. For instance, if a certain asset will be constructed behind a forest zone, its vulnerability regarding floods could be lower than if it was constructed behind a built-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 can transfer flood waters beyond them, if no obstacles exist to dissipate water flow energy. Therefore, 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.

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 different methods employed for digitizing the 1954 and 2011 shorelines and by having used different sources of input data with diverse levels of precision. However, shoreline trends in the study zone are 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 advantages of using this approach in vulnerability analyses: its structured approach of decomposing 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 opinions and check inconsistencies; and the possibility to involve both experts and stakeholders. 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 (Fernandez and Lutz, 2010). In any case, in this work AHP was found to be a transparent, well-structured, and “fit-for-purpose” methodology. One issue in this respect was that two of the weightings had a consistency ratio above 0.1 and, although their values were only slightly higher, it was decided not to include them in the final weighting. One of the experts asked for some clarifications on variables prior to weighting, as he found that the variables were in some cases strongly interrelated (e.g. one of the observations was that the dunes can also be viewed as part of the 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 this work was the relatively low number of experts involved in the weighting. However, this was the 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 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 hydrology).

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.

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 “verification” purposes. The maps used were developed by the Geological Service of the Emilia-Romagna Region by applying the Cost-Distance tool of ArcGIS®, taking into account three Total Water Level scenarios (10, 100 and > 100 year return periods) and high resolution Digital Terrain Models (DTMs) of the coast (Perini et al., 2012, 2016). More details about the methodology can be 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 determining flooded areas in the hazard maps used (namely elevation) is also the most significant variable in the vulnerability index. Therefore, in this work the comparison between both results was performed in order to evaluate the relationship between theoretically vulnerable areas and hazard areas determined by water levels. For this purpose, the 36 sectors of the study zone were overlain by 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). These sectors are assigned with vulnerability scores of 2.65, 3.17, 3.75 and 4.56. It is important to note that one of the sectors assigned with the highest vulnerability score is the one showing the largest percentage of area covered with flood water (i.e. sector 1, with 62.2% of flooded area). Also the sector with lowest percentage of area covered with flood water (sector 11, 1.5%) is assigned with one of the 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 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 estimated as prone to flooding by flood hazard maps. For example, sector 4 is assigned with 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 strictly correlate those of flood hazard maps, since flood hazard and flood vulnerability are different (although in this case, related) concepts and the two analyses used two different methodologies. The percentage of each sector affected by floods in the 1-in- 10-years storm depends on total water level (determined by waves, tides and storm surge) and land elevation, while the proposed CVI does not consider these hydrodynamic agents but includes the presence of dunes and artificial structures, 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 different factors in characterizing flood risk.

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). It consists of a framework to identify hotspots of erosion and inundation along regional coastal areas and to apply a storm impact evaluation in selected critical sites (for more information on CRAF methodology and outcomes refer to: Armaroli and Duo, 2018; Christie et al., 2018, De Angeli et al., 2018; Ferreira et al., 2018 and Viavattene et al., 2018). Armaroli and Duo (2018) identified the coastal 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 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 shows that the most critical sites (number≥6 of inundation events that caused an impact) are located in sector 16 (Marina di Ravenna), 24–26 (Lido Adriano), 28 (Lido di Dante) and south of sector 36 (Lido di Savio). The sectors 24–26 and 28 are scored 3 in the present work (medium vulnerability, Fig. 4) and are protected by defence structures. Sectors 16 and 36 show a better correspondence with 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 CVI, which do not include the hazard component, and the limitations of the method described above. 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 vulnerable. Considering the inundation hazard, it was demonstrated that the coast is primarily exposed to high surge levels (Armaroli et al., 2012), therefore breakwaters are less effective in wave energy dissipation than they would be without high surge levels.

An example of the possible application of the CVI for coastal management purposes along the Emilia-Romagna coastline is presented hereafter. As mentioned above, in the framework of the EU 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 extension was then combined with land use maps to produce risk maps of the coastal area (see Perini et al., 2016 for details on the methodology). For the creation of risk maps, land use typologies were firstly scored by coastal managers, according to their perception, based also on experience, of the degree of susceptibility to be damaged of each land use typology. The scoring can thus be considered a simplified evaluation of the vulnerability of different land use categories in relation to their characteristics (e.g., agricultural area, built-up area, beach, dune, etc.). It is however clear that the "risk" maps produced by regional managers for the Floods Directive do not include a proper vulnerability evaluation of all the elements exposed (located in flood-prone areas). Therefore the CVI presented in this paper could help coastal managers to better define the vulnerability, and consequently define the risk level, of coastal sectors with a more complete and robust methodology. Additionally, a large database of coastal physical characteristics is available for the Emilia-Romagna Region (named In_Coast[1]). 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 aggregates relevant (already available) variables to provide a clear indication of vulnerable sites. 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 towards a more comprehensive evaluation of coastal vulnerability which can be easily carried out also by non-experts of coastal dynamics.

For what concerns the exportability of the methodology, it is important to note that the variables included in the CVI can be retrieved or produced also for data-poor coastal areas. Freely available remote sensing products such as satellite imagery (which can be used to define shoreline trends, identify the presence of dunes and protection structures), land use and land cover maps (already available or that can be produced using satellite imagery) and global DEMs can be used to build the 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 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 zones for which there is a lack of long-term research data on hydrodynamic conditions and where coastal managers might not be aware of waves and water levels dynamics.

6. Conclusions

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). The index is formulated with five physical variables which are relevant for the intended purpose, yet not difficult to obtain: elevation, dunes, artificial protection structures, shoreline change rates, and land cover. In this way, the index is easy to apply and to communicate to stakeholders, also providing exportability and wide applicability. Each variable was assigned different levels of importance (weights) by experts familiar with the study area, by applying analytic hierarchic process (AHP). In this way quantitative and qualitative data were integrated in a transparent and structured way. This coastal vulnerability index could be replicated to similar (sandy and microtidal) coastal environments, by using AHP to include the local context of the study area where it will be applied. Potential uncertainties in this framework were carefully considered along the different steps of the procedure,

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

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

The verification of the proposed index was one of the key issues in this study. The comparison of the assigned vulnerability scores with flood hazard maps based on water levels yielded inconsistent 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 be convenient to reach a more sound verification. The greatest question arises from the fact that the different variables influencing coastal floods are dynamic and interconnected, so there is a high level of uncertainty regarding their future behaviour. The forcing is changing, since sea level is rising. In many areas, such as the Ravenna province, the coasts are subsiding and sediment input is strongly 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 near the coastline which will probably grow even more in the future. Since future changes in forcing and receptors are highly unpredictable, a wide range of uncertainty should be thoroughly considered in future coastal planning.

In data-rich coastal areas, the proposed index can be used by coastal managers as a simple tool to aggregate relevant variables in order to obtain a clear identification of sectors that are highly vulnerable to sea level rise and marine floods. In these cases, the use of the CVI could be a first step towards a complete risk assessment that would have to include also the evaluation of the hazard and 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 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 lies in its visual component - the integration of the framework into geographical information systems results in maps which are highly informative for coastal managers and decision makers, and can also be a powerful public awareness tool.

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.

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.

Funding

Ivan Sekovski was financially supported by the Erasmus Mundus foundation (specific grant agreement number 2011-1614/001-001 EMJD).

Acknowledgements

The authors are very grateful to Dott.sa Luisa Perini, Dr. Lorenzo Calabrese and Dott. Paolo Luciani of Servizio Geologico Sismico e dei Suoli (Regione Emilia-Romagna) for providing data and information, and for their availability. The authors would also like to thank ENI for providing the topographic Lidar data; Dr. Oxana Sytnik for providing historical shorelines; Francesco Stecchi and Francesco Mancini for their advices. This work was a contribution to ADACOSTA research project from the Spanish MINECO (CGL 2014-53153-R) and to the research group RNM-328 of the PAI. The journal editors and three anonymous reviewers are acknowledged for their useful comments and suggestions, that helped improving the paper.

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