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ASSESSMENT OF COASTAL VULNERABILITY TO EROSION: THE CASE OF TIBER RIVER DELTA (TYRRHENIAN SEA, CENTRAL ITALY)

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EXTENDED ABSTRACT

I paesaggi costieri sono il risultato di processi morfogenetici particolarmente vivaci; le rapide modificazioni che essi subiscono determinano, in molti casi, una spiccata vulnerabilità in relazione all'opera aggressiva del mare. Le aree costiere rappresentano, in genere, le zone a più alta densità insediativa e sono spesso minacciate da intensi fenomeni di erosione; pertanto, l'analisi della vulnerabilità costituisce un utile strumento per la mitigazione di tali fenomeni e per una più oculata gestione dell'ambiente costiero.

In questo lavoro si è voluto proporre una metodologia per la Valutazione della Vulnerabilità Locale, che differisce dalle metodologie proposte da diversi autori nel passato, essenzialmente per due aspetti: il primo riguarda la scala di lavoro scelta (di grande dettaglio, con ovvie implicazioni di carattere morfologico e climatico); l'altro consiste nella distinzione fra *vulnerabilità potenziale*, relativa solamente a fattori naturali, e *vulnerabilità effettiva*, che prende in considerazione anche variabili antropiche, il cui contributo può far diminuire o aumentare la vulnerabilità stessa.

La Valutazione della Vulnerabilità Locale (Local Vulnerability Assessment) si fonda sia su una serie di variabili morfometriche e morfodinamiche (quantitative e qualitative) in grado di esprimere la vulnerabilità potenziale (naturale), sia su una serie di variabili connesse all'attività antropica che influiscono sulla vulnerabilità effettiva. La Valutazione della Vulnerabilità Locale è basata sul calcolo di un Indice di Vulnerabilità Costiera attraverso una matrice ove si assegna ad ogni variabile (naturale o antropica) un peso e un punteggio; ciò consente la costruzione di una carta della vulnerabilità costiera, nella quale il litorale risulta suddiviso in settori a diverso Indice di Vulnerabilità Costiera. Tale approccio metodologico consente, dunque, di individuare i settori costieri a maggiore vulnerabilità e che, in priorità assoluta, necessitano di interventi di mitigazione del rischio associato.

L'area oggetto di studio è l'apice deltizio del Fiume Tevere, un litorale di grande pregio storico- ambientale e fortemente urbanizzato; tale paraggio, allungato per circa 12 km, negli ultimi sessanta anni ha subìto fenomeni di erosione così marcati da rendere necessaria la messa in opera di diverse tipologie di protezionedella spiaggia, dell'abitato e delle vie di comunicazione.

Il litorale in esame presenta per circa il 40% valori di *vulnerabilità potenziale* molto elevata (specie in corrispondenza del Canale di Fiumicino) e per il restante 60% valori di *vulnerabilità potenziale* elevata. Le variabili naturali (morfometriche e morfodinamiche) che contribuiscono ad accrescere la vulnerabilità sono essenzialmente: la quota media della spiaggia emersa, la pendenza della spiaggia sommersa e le variazioni della linea di riva storiche e recenti.

Lungo tutto il litorale in studio si rileva una forte pressione antropica: numerose e diffuse sono le strutture insediative, anche a scopo turistico, che negli ultimi decenni sono state minacciate da fenomeni erosivi così cospicui da rendere necessaria la messa in opera di strutture a difesa. I valori di *vulnerabilità effettiva* più elevati si registrano nella parte settentrionale dell'apice deltizio, fra Focene e Fiumicino. Lungo il litorale prospiciente l'abitato di Ostia, nonostante l'intensa urbanizzazione della fascia costiera, la *vulnerabilità effettiva* è relativamente bassa, grazie alla messa in opera di difese di diversa tipologia, prevalentemente caratterizzate da ripetuti interventi di ripascimento della spiaggia, che hanno contribuito ad un significativo decremento della *vulnerabilità effettiva*.

Senza dubbio, la redazione di una carta che descriva il grado di vulnerabilità costiera di un determinato paraggio può essere un utile strumento della pianificazione territoriale, rivolto in particolare agli amministratori locali. A tal fine, la metodologia proposta è estensibile ad altre aree costiere a regime microtidale, come quella considerata in questo lavoro.

ABSTRACT

Coasts are highly sensitive to dynamic geomorphic processes that determine rapid environmental changes and landscape modifications and are potentially vulnerable to accelerated erosion hazard.

Coasts densely inhabited and settled by human infrastructures are threatened by severe erosional processes; therefore the coastal vulnerability analysis may represent an essential tool for hazard mitigation and management purposes.

Tiber River delta has been selected as study area because it has a particularly high vulnerability to sea erosion that has made necessary several protection interventions in recent decades.

The Local Vulnerability Assessment (LVA) methodology proposed differs from the previous ones for two aspects: the working scale (with its morphological and climatic implications), and the distinction between potential (due to natural conditions alone) and effective vulnerability (where the anthropogenic action is present and may contribute to vulnerability mitigation or less).

The LVA takes into account quantitative and qualitative spatial variables that express morphometric and morphodynamic natural factors of vulnerability, as well as selected anthropogenic factors.

Based on a system of numerical weights and scores, the LVA allows the construction of a local vulnerability map in which the Coastal Vulnerability Index (CVI) is represented for different sectors of the study area.

The aim of LVA is to single out he main vulnerable zones that should have priority in the mitigation strategy performed within the study area.

This is the first study finalized to calculate CVI at local scale and its results show that the whole coast strip of the study area has high and very high values of potential vulnerability, while the values of effective vulnerability decrease where suitable defences are present.

Key words: coastal erosion, vulnerability,Tiber River delta, Italy

INTRODUCTION

Coasts are landscape features that undergo deep and fast changes; some morphological modifications can became highly hazardous where marked erosional processes occur. The present high intensity of coastal changes is a problem of worldwide importance that becomes crucial along densely inhabited coastal belts.

Most of the coasts of Italy and of the other European countries - where human settlements exist since long time ago - suffer for particularly marked beach retreat. At present, coastal zones in Europe hostlarge human populations and significant socio-economic activities. One third of the about 450 million of inhabitants of the European Union (EU) is estimated to live within 50 km from the coastline, and the 19% (86 million people) of the total EU population livesin a 10 km wide coastal strip (EEA, 2013). The proportion is as high as 100% in Denmark and it reaches 75% in the United Kingdom and the Netherlands (Nicholls & Klein, 2005). The 75% of the inhabitants of the countries overlooking the Mediterranean Sea lives in coastal areas; in Italy this value is between 60 and 70% (annuario.isprambiente.it).

The urbanisation and rapid growth of coastal cities have been a dominant trend over the last decades that led to the development of numerous megacities in many coastal regions around the world. As a result both demand on coastal resources and people exposure to coastal hazard have been increasing in time (Sterr *et alii*, 2003).

The Italian shores stretches for over 7500 kmand are characterized by landscapes of outstanding natural value; a great deal of the national resources come from the coastal areas, as they host major urban and industrial centres, and continuously growing tourism activities (D'Alessandro *et alii*, 2002).

The recent reports about climate changes over the entire globe (IPCC, 2013) have placed serious problems in the management of coastal resources as well as in the assessment of coastal vulnerability and related risks. To understand the way the coast will evolve is therefore of primary importance.

As Klein & Nicholls (1999) stated, vulnerability to impacts is a multi-dimensional concept, encompassing bio-geophysical, economic, institutional and socio-cultural factors. Owing to the great diversity of natural coastal systems and to the local and regional differences in relative sea-level rise and climatic changes, the occurrence of and response to these impacts will not be uniform around the globe.

Different approaches may be followed to assess coastal vulnerability at different spatial and temporal scales, as well as in different regions and for different policy purposes. Since 1990, a number of major efforts have been made to develop guidelines and methodologies for the assessment of coastal vulnerability to sea-level rise (Gornitz, 1990; Gornitz *et alii*, 1991, 1994).

In the European scientific literature, different procedures are suggested to evaluate coastal vulnerability to climate change at different spatial and temporal scales (Ramieri *et alii*, 2011).These procedures can be categorized into: i) index-based methods that include several variants of the Coastal Vulnerability Index CVI (Gornitz, 1990; Gornitz *et alii*, 1991, 1994); ii) GIS-based decision support systems that helps decision makers in the sustainable management of natural resources and also in the choice of mitigation and adaptation measures (Mocenni *et alii*, 2009; Schirmer *et alii*, 2003); iii) methods based on dynamic computer models that allow to integrate the time dimension in the analysis and mapping of vulnerability and risks of coastal systems to climate change (Hinkel, 2005; Hinkel *et alii*, 2010; Mcleod *et alii*, 2010; Kenny *et alii*, 2000; Warrick *et alii*, 2005; Warrick, 2009; Hsu *et alii*, 2006; Henrotte, 2008; Engelen *et alii*, 1998; Mokrech *et alii*, 2009; Torresan *et alii*, 2012).

The aim of this paper is to propose a methodology for the estimation of the Coastal Vulnerability Index (CVI) at the local scale that is influenced by both natural and human factors. The short term analysis for the evaluation of CVI has been performed in order to support local assessments and to provide information suitable for the identification of areas where vulnerability could be relatively high and for planning preventive adaptation measures (e.g. construction of coastal defences, beach nourishment, planning and zoning of coastal territory). The final outcomes of the analysis are the identification and ranking of homogeneous vulnerable units for each target of interest, the individuation of vulnerable areas and the definition of the priorities of intervention. The Tiber Delta area was selected to test the LVA methodology and the main results of the analysis are presented and discussed in this paper.

CASE STUDY AREA: THE TIBER RIVER DELTA

The Tiber River deltais a wave dominated, cuspate delta (Galloway, 1975) with almost symmetrical wings. Its shoreline extends for about 12.4 km along the central Tyrrhenian coast (Fig. 1). The delta has two distributary channels: the main one (Fiumara Grande) discharges the 80% of the whole liquid and solid load; the secondary one (Canale di Fiumicino) is the evolution of an artificial canal cut in Roman times between 42 and 112 A.D. It was definitively reopened on 1612, after a period of intermittent flow.

Delta progradation began about 6 ky B.P., but the most part of the present cusp developed during the Little Ice Age (LIA), when the four highest floods were recorded (1530, 1557, 1598 and 1606 A.D.). During these events Tiber discharge might have exceeded 3,500 m^3/s (while its mean discharge is about 230 m^3/s).

Cusp growth declined since the end of the XIX century, at the end of the LIA. This change in the evolutionary trend is corroborated by the decrease of both the frequency and magnitude of floods (the last extreme flood was recorded in 1870). In the second half of the XX century a further reduction occurred as a consequence the construction of scattered hydroelectric reservoirs, in the Tiber basin, and of river sedimentdredging.

The backshore inner edge was bounded by dune belts about 5 m high until the half of the XX century. More recently, the emplacement of human settlements along the shore has caused the gradual destruction of the dune system. At present, few and short stretches of dune belts are locally preserved.

Nowadays, westerly prevailing winds produce a littoral drift that is divergent respect to the Tiber River main mouth (Bellotti *et alii*, 1994). Sands are present on the foreshore and shoreface as deep as -5 m; sandy silt prevails on the shoreface between the -5 m and -10 m isobaths (Bellotti & Tortora, 1996).

Boreholes drilled in the foreshore and in shoreface, up to a depth of -10 m, indicate that no significant variations in sediment texture took place in the last 300 years (Bellotti *et alii*, 2007).

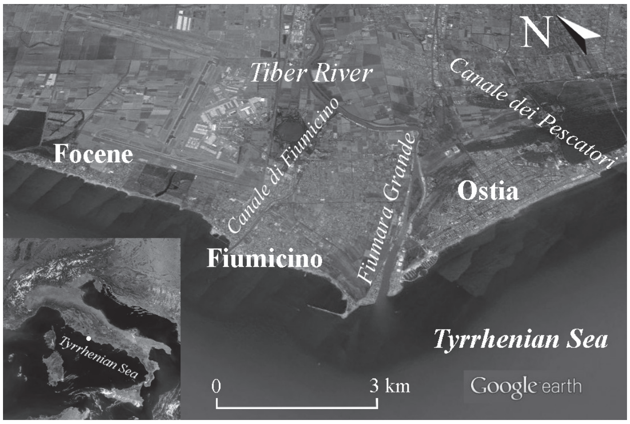


Fig. 1 - Location of the studied area. Latium coast, Tiber River delta. (Google Earth. July, 20, 2014)

Data on solid load by the Tiber River are available in the time interval 1873-1879, and, although discontinuously, for the last 70 years from present time (Bersani & Bencivenga, 2001).

The comparison between solid load and changes in the delta shoreline highlighted the following relationships:

i) the shoreline was in progradation from 1873 to 1879, when the Tiber average solid discharge was about 10.6 x 10^6 t/y;

ii) the shoreline was stable from 1932 to 1938; when the average solid discharge was about 7.6 x 10^6 t/y;

iii) the shoreline suffered a pronounced retreat after the Second World War, when the average solid discharge became lower than 7.6 x 10^6 t/y.

These remarks suggest that flow rates of about 7.6 x 10^6 t/y would ensure delta stability (Bellotti *et alii*, 2012).

The comparison of nautical charts of different periods (Istituto Idrografico della Marina, 1883; 1939; 1984) showed that the delta apex average slope in the depth interval 0-10 m increased from 0.12° to 0.26°, in the period 1883-1939. This suggests that the decrease of the Tiber solid discharge that occurred in the same period had already triggered the erosive phase, albeit only at the shoreface. The subsequent further reduction of solid discharge caused the shoreline retreat and the further increase of average slope to 0.30°.

Several strategies have been followed since 1950 to contrast coastal erosion. Detached breakwaters were constructed along the Ostia coast (close to the Tiber mouth) from the 50's to 80's. Successively, the same protection works were made along the coast between Canale di Fiumicino and Tiber mouth (Fig. 1). In addition, same groynes were built along a part of the Ostia coast during the 80th.

The most important defence intervention is the beach nourishment that was made along the shore between the Pontile and the Canale dei Pescatori in 1990. About 1.360.000 m^3 of sand and gravel were disposed to replenish this coastal stretches that was also protected by detached submerged barriers. Other nourishments were carried out between 1999 and 2005 along the entire Ostia shore. In these cases sands dredged from the sea bottom was used for the replenishment that was only at places coupled with the built of groynes and submerged barriers. (Caputo *et alii*, 1993; Fishhendler *et alii*, 2012).

DATA AND METHODOLOGY

The new methodology proposed for the Local Vulnerability Assessment (LVA) differs from the previous ones for two aspects: the working scale (with its morphological and climatic implications), and the distinction between potential and effective vulnerability. This method takes into account qualitative and quantitative spatial variables that express morphometric and morphodynamic natural factors, as well as the anthropogenic ones, that can affect the coast susceptibility to erosion.

The choice of the working scale is crucial because it strongly influences the selection of the variables. The regional scale studies (Pendleton *et alii*, 2010; Kumar *et alii*, 2010) must take into account variables as, for example, coast typology (i.e. presence of cliff, rocky coast or beach) and wind and sea conditions. Working at the local scale the choice of the variables can be contemporarily easier and more effective. First of all it is possible to assume that wind and sea conditions are homogeneous; secondly coastal morphology is likely to be similar throughout the study area. In particular, only beaches are present in the specific case study of the Tiber delta, which allows very peculiar and detailed morphological features can be considered as variables.

The method, based on the differentiation between potential vulnerability (that neglects the anthropogenic factors) and effective vulnerability (that considers also the anthropogenic action and its possible contribution to vulnerability mitigation or worsening), has been carried out in the framework of metropolitan areas study.

The procedure followed in this work is based on the definition of vulnerability in terms of ranking.

The application of the methodology allows the subdivision of the studied area in sectors (each of them with homogeneous variables) that differ from each other in the value of the Coastal Vulnerability Index (CVI). As a consequence, sectors with the highest CVI value can be identified as priority sites for erosion mitigation practises and management strategies.

The methodology has the following main steps: 1 definition of the matrix; 2 definition of weights to attributes; 3 definition and scoring of classes; 4 aggregation of attributes; 5 classification of vulnerability values and construction of vulnerability maps.

The following paragraphs describe the application of each step of the methodology performed in the study area.

Definition of the local vulnerability matrix

Several factors are involved in the vulnerability analyses; they must be selected taking into account the working scale and the availability of data for the whole case study area. Some variables are expressed by morphometric parameters that are connected to wave dissipation; others are relevant to the morphodynamics of the beach. All variables interact with one another.

According to the vulnerability conceptual framework followed in this paper, two matrixes have been developed and combined: the first one involves natural variables and the second ones anthropic variables (Table 1).

Such matrixes have been already tested (http://www.isc.senshu-u.ac.jp/~thc0456/EAHP/AHPweb.html) in other environmental studies (Simeoni *et alii*, 2007, 2009).They are drawn by using respectively eight and six leading diagonal terms for potential vulnerability (Vp) and anthropic factors (Tab. 1).

Tide amplitude (about 40 cm) has not been considered a significant natural variable: the Tiber delta, in fact, is a wave dominated delta. Sea level rise has also been neglected because CVI has been performed for a short term analysis.

Nourishments not coupled withthe built of detached breakwater protections have also been neglected. They, in fact, although supply new materials to be eroded, are not able to reduce the intensity of erosional processes. Protected nourishments, instead, play a double role: they increase sand supply and lower wave energy. For this reason their effects on coastal dynamics are similar to those produced by detached breakwaters.

Definition of weights to attributes

Calculation of CVI requires the aggregation of single vulnerability variables whose relative importance must be weighted. In this case study, the weight has been expressed as a vector whose magnitude is the relative importance of the factor and its direction is the way it contributes to the vulnerability definition. Variables with positive weight are responsible for the increase of vulnerability (i.e. elevation or slope) and variables with negative weight cause its decrease (i.e. coastal protection measures). The weight assigned to the vulnerability factors used in the Tiber delta case is shown in Table 2.

The consistency of the judgment matrix is then tested. The consistency ratio (CR), is the ratio between Consistency Index (CI) and Random Consistency Index (RI); the lattershould be always <0.1 or <10%, which indicates the overall consistency of the pair wise comparison matrix.

Definition and scoring of classes

A semi-quantitative code has been considered to quantify the different importance of each factor; it ranges from 1 (no importance) to 5 (critical importance). Vulnerability classes represent thresholdsthat reflect variations in the extent the beach may be affected by erosion impact. Classes have been defined in quantitative (e.g. elevation, slope, cover data) and qualitative (e.g. presence/absence or low/medium/high of a particular factor) categories. Quantitative classes have been defined dividing the distribution of data into equal-sized sub-ranges (Zald *et alii*, 2006). All these classification methods establish the vulnerabil-

Natural variables	
Morphometric variables	
Amplitude of backshore (m)	Distance between the shoreline and the dune foot or anthropic structures.
Mean altitude of backshore (m)	The altitude of ordinary berm was taken as the mean altitude of the beach.
Slope of upper shoreface	Calculated between the shoreline and the closure depth.
Dune	Considered taking into account the state of preservation using several attributes (height, slope, vegetation cover, presence of break and presence of fore-dune).
Inland elevation (m)	Altitude of first quartile of inland obtained by considering only the ground elevation and not the building one.
Morpho-dynamic variables	
Evolutionary trend of upper shoreface (m/a)	Calculated comparing two DEM of upper shoreface. The time interval between the data of DEM should not be less than 30-40 years.
Recent evolutionary trend of shoreline (m/a)	Calculated comparing two shorelines. The time interval between the data of shorelines should be between 10-20 years.
Storical evolutionary trend of shoreline (m/a)	Calculated comparing two shorelines. The time interval between the data shorelines should be greater than 35 years.
Anthropogenic variables	
Coast protection measures	
Detached breakwater	By its position related to mean sea level.
Shore breakwater	By its elevation.
Inland defences	By their elevation.
Windbreak structure	By its preservation state.
Nourishment	Protected by breakwater
Other anthropic features	
Tourist pressure	Estimation of sunbathers

Tab. 1 - Vulnerability matrix applied for the assessment of coastal erosion in the Tiber delta

Natural variables	Weight	Sign	Data	Source
Morphometric variables				
Amplitude of emerged beach (m)	0.15	+	LiDAR (2010)	Sapienza University of Rome
Mean altitude of beach (m)	0.15	+	LiDAR (2010)	Sapienza University of Rome
Slope of upper shoreface	0.12	+	Echosounding data	Sapienza University of Rome
Dune (state of preservation)	0.3	-	LiDAR (2010)	Sapienza University of Rome
			Google Earth images (2012)	Google Earth WebSite
Inland elevation (m)	0.2	+	LiDAR (2010)	Sapienza University of Rome
Morpho-dynamic variables				
Evolutive trend of upper shoreface (m/a)	0.27	+	Echosounding data	Sapienza University of Rome
			IIM DEM	Istituto Idrografico della Marina
Recent evolutive trend of shoreline (m/a)	0.07	+	LiDAR (2010)	Sapienza University of Rome
			Aero-photo (1994)	National Cartographic WebSite*
Storical evolutive trend of shoreline (m/a)	0.04	+	LiDAR (2010)	Sapienza University of Rome
			Topographic Map (1954)	Istituto Geografico Militare
Anthropogenic variables				
Coast protection measures				
Detached breakwater	0.5	-	LiDAR (2010)	Sapienza University of Rome
Shore breakwater	0.8	-	LiDAR (2010)	Sapienza University of Rome
Inland defences	0.8	-	LiDAR (2010)	Sapienza University of Rome
Windbreak structure	0.2	-	LiDAR (2010)	Sapienza University of Rome
Other anthropic variables				
Tourist pressure	0.3	+	LiDAR (2010)	Sapienza University of Rome
			Google Earth images (2012)	Google Earth WebSite

*

Tab. 2 - Weight ascribed to the vulnerability factors used to estimate the vulnerability to erosion of the Tiber Delta. CI 6.87%, CR 5.21%
*www.pcn.minambiente.it

ity relative thresholds that are identified considering the distribution of beach data on the Italian territory (Fontolan *et alii*, 2001, 2005; AA.VV., 1995). Qualitative classes have been defined on the basis of information drawn from the specific literature. According to various methodologies internationally known (Gornitz, 1990; Abuodha & Woodroffe, 2006; Pendleton *et alii*, 2010), the assignation of scores to vulnerability classes has been performed using a 1-5 scale. Factors related to the greatest vulnerability (i.e.beach minimum elevation) have the maximum score (5) those that are relevant to the least vulnerability (i.e. beach maximum elevation) have the minimum score (1). Obviously, no class has been assigned to variables missing in the study area.

The highest score has been ascribed to the smallest and lowest values of beach amplitude and inland elevation, respectively that are responsible for the enhancement of the potential vulnerability to erosion. Moreover, potential vulnerability decreases as slope of the upper shoreface decreases (as slope decreases dissipative action increases); for this reason, the maximum score has been assigned to the highest value of the upper shoreface slope. Similarly, the potential susceptibility to coastal erosion increases for decreasing sediment budget, therefore the minimum score has been ascribed to the lowest value of the evolutionary trend of the upper shoreface has been assigned to tourist pressure has the maximum vulnerability score owing to the high density of bathing establishments in this area (Tab. 3); since, the presence of these facilities, in fact, implies the beach profile alteration and loss of sediment due to the continuous cleaning and levelling activities.

The presence of artificial protection and/or dune has been considered a relevant factor decreasing vulnerability of beaches to erosion (Fontolan *et alii*, 2001, 2005; Ozyurt, 2008). From this point of view, the maximum score value have been assigned to the highest coastal protection measures and to the best preserved dunes (McLaughlin & Cooper, 2010).

The state of preservation of the dune is defined by the analysis of five factors (Tab. 4). The maximum score has been ascribed to the variables indicating a well-status (greater height, lower slope, larger vegetation cover, absence of break and presence of fore-dune), and the minimum score has been assigned to the variables indicating a bad-status (Preston *et alii*, 2008).

Concerning recent and storical ytshoreline trend, the highest vulnerability score has been attributed to retreating (Torresan *et alii*, 2008; Abuodha & Woodroffe, 2006).

As to the detached breakwaters, the lowest vulnerability score (1) has been attributed to the lack of structures, the medium (3) to submerged structures and the highest (5) to emerged structures; score 4 has been attributed to the submerged structures combined with nourishment.

Natural variables					
Morphometric variables	1	2	3	4	5
V1 - Amplitude of backshore (m)	>120	120 ↔ 90	90 ↔ 60	60 ↔ 30	< 30
V2 - Mean altitude of backshore (m)	>2.5	2.5 ↔ 2	2 ↔ 1.5	1.5 ↔ 1	<1
V3 - Slope of upper shoreface	<0.004	0.004 ↔ 0.006	0.006 ↔ 0.008	0.008 ↔ 0.01	>0.01
D - Dune (state of preservation)	Very good	good	medium	bad	Very bad
V4 - Inland elevation (m)	<4	4 ↔ 3	< 3 ↔ 2	<2 ↔ 1	<1
Morphodynamic variables	1	2	3	4	5
V5 - Evolutional trend of upper shoreface (m/y)	>5	5 ↔ 1	1 ↔ -1	-1 ↔ -5	< -5
V6 - Recent evolutional trend of shoreline (m/y)	>5	5 ↔ 1	1 ↔ -1	-1 ↔ -5	< -5
V7 - Storical evolutional trend of shoreline (m/y)	>5	5 ↔ 1	1 ↔ -1	-1 ↔ -5	< -5
Anthropogenic variables					
Coast protection measures	1	2	3	4	5
DB - Detached break water			submerged	plus nourishment	emerged
SB - Shore breakwater (m)	< 0.5	0.5 ↔ 2.5	>2.5 ↔ 3	>3 ↔ 4	>4
ID - Inland defences (m)	< 0.5	0.5 ↔ 2.5	>2.5 ↔ 3	>3 ↔ 4	>4
WS - Windbreak structure			discontinuous		continuous
Other anthropic factors	1	2	3	4	5
V8 - Tourist pressure	low		medium		high

Tab. 3 - Classes and scores applied to vulnerability factors used in the Tiber Delta in order to estimate the vulnerability of beach to the coastal erosion. 1: least important class; 2: strongly less important class; 3: rather less important class; 4: weakly less important class; 5: most important class

Dune	very bad	bad	medium	good	very good
	1	2	3	4	5
Height (m)	<2	<3 ↔ 2	<4 ↔ 3	5 ↔ 4	>5
Slope	>0.3	0.22 ↔ 0.3	0.14 ↔ <0.22	0.06 ↔ <0.14	<0.06
Vegetation cover	very poor	poor	discontinuous	profuse	total
Presence of break	>20%		10% ↔ 20%		<10%
Presence of fore-dune	very poor		poor		present

Tab. 4 - Classes and scores applied to vulnerability factors used in the Tiber Delta in order to estimate the vulnerability of beach to the erosion

Aggregation of variables

According to the conceptual framework adopted in this paper, effective vulnerability results from the algebraic sum of the contribute of both natural and anthropogenic factors:

$$CVI = V_n + V_a \qquad (1)$$

where *CVI* = Coastal Vulnerability Index, V_n = Potential Vulnerability and V_a = Sum of anthropogenic factors.

In more details, the assessment of coastal vulnerability to erosion is based on the analysis of multiple morphometric, morpho-dynamic and anthropogenic variables that are aggregated in the *CVI.*

Different approaches have been used for the assessment of CVI (see Ramieri *et alii*, 2011 and references therein). Gornitz & White (1992) and Gornitz*et alii* (1997) proposed and tested (in terms of sensitivity analysis) different equations (considering 7 key variables) for the derivation of a *CVI.*

Many environmental studies (Civita, 1994; Civita & De Maio, 1997; Fontolan *et alii*, 2001, 2005) use multiple regression analysis in which the value of the dependent variable (*V*) changes when any one of the independent variables (*vn*), or relative weight (*kn*), is modified.

$$CVI = \sum_{i=1}^{n} Vn_i kn_i + \sum_{j=1}^{m} Va_j ka_j \qquad (2)$$

In order to integrate different susceptibilities a weighted linear combination has been used according to the following equation: where Vn_i = score related to the natural variable, kn_i = weight associated with the natural variable, Fa_j = score related to the anthropogenic variable and ka_j = weight associated with the anthropogenic variable.The weights have been calculated according to Table 2; the scores used in the assessment of the CVI have been derived from Table 3.

Equation (2) has been applied to all the spatial units, i.e. coastal sectors, of the study area, that have been identified on the basis of an homogeneous distribution of data. As a result, sector size is not constant; anyway all of them have coastline length > 100 m.

Construction of vulnerability maps

To evidence the spatial variability of the Coastal Vulnerability Index, the vulnerability map has been produced.

The first step has been the subdivision of the calculated CVI values into 5 qualitative classes (i.e. very high, high, medium, low and very low); they have been identified by dividing the vulnerability range (CVI_{Max} - CVI_{Min}) into five equal-sized sub-ranges (Zald *et alii*, 2006).

It is to underline two aspects:

- vulnerability values higher than 5 and classified in the highest class (5) are due to high tourist pressure and lack of defensive works; all of them have been included in the maximum score class ("very high") that identifies the sectors that are likely to be the most prone to erosion.
- negative CVI values mark areas affected by redundant defence structures; all of them have been included in the minimum score class ("very low").

0 – 1	>1 - 2	>2 - 3	>3 - 4	>4 - 5
Very low	Low	Medium	High	Very high

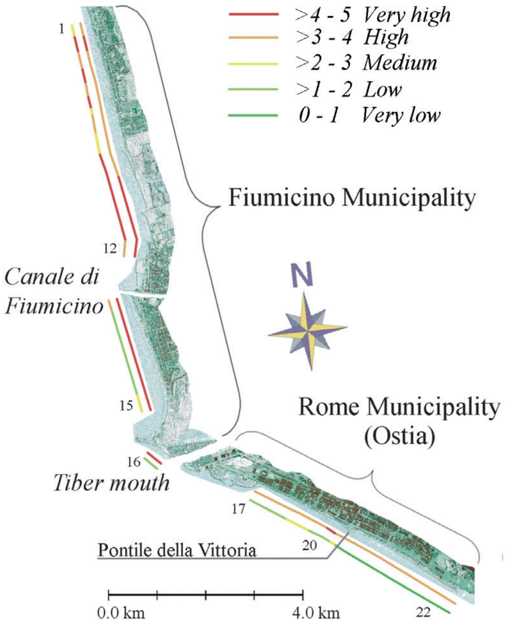
The vulnerability map is the main output of the developed procedure. To represent the areal variability of vulnerability in the studied area, two lines have been drawn parallel to the shoreline. The landwardline indicates the classes of potential vulnerability-while the seaward one shows those of the effective vulnerability. Each line has been divided into segments; each of them corresponds to one or more sectors that have the same *CVI.* Each segment has been coloured according to the *CVI* classes: from green to red passing from minor to greater values.

According to Salman *et alii* (2004), that indicates the Radius of Influence of Coastal Erosion (RICE area) in a buffer of 500 m, the Local Vulnerability Assessment has been performed for the coastal areas located within 500 m from the shoreline (Fig. 2). Obviously only the variables that are strictly related to the beach must be taken into account to evaluate beach and not coastal vulnerability.

RESULTS AND DISCUSSION

The results of the proposed methodology are shown in Fig. 2.

The results attained for the studied area evidence the presence of sectors with potential vulnerability values ranging from 3.1 to 4.4; therefore the whole area has sectors falling in "high" and "very high" classes. This situation is representative of the wide spreading of erosion processes.



			Potential Vulnerability										Anthropic Factors						Effective Vulnerability
	Sector	m	V1	V2	V3	V4	V5	V6	V7	D	Vp	DB	Sb	ID	WS	V8	ΣAF	Ve
Fiumicino Municipality	1	278	0.45	0.75	0.6	0.81	0.28	0.12	0.8	0	3.81	-2.5	0	0	0	1.5	-1	2.81
	2	285	0.75	0.75	0.6	0.81	0.28	0.12	0.8	0	4.11	0	0	0	0	1.5	1.5	5.61
	3	377	0.6	0.75	0.6	0.81	0.21	0.12	0.8	-0.78	3.11	-1.5	0	0	0	1.5	0	3.11
			0.6	0.75	0.6	0.81	0.21	0.12	0.8	0	3.89	-1.5	0	0	0	1.5	0	3.89
	4	244	0.75	0.75	0.6	0.81	0.28	0.12	0.8	-0.18	3.93	0	0	0	0	1.5	1.5	5.43
	5	356	0.6	0.75	0.6	0.81	0.28	0.12	0.8	-0.18	3.78	-1.5	0	0	0	1.5	0	3.78
	6	216	0.45	0.75	0.6	0.81	0.14	0.08	0.8	-0.45	3.18	0	0	0	0	1.5	1.5	4.68
	7	145	0.45	0.75	0.6	0.81	0.14	0.08	0.8	0	3.63	-2.5	0	0	0	1.5	-1	2.63
	8	333	0.6	0.75	0.6	0.81	0.21	0.12	0.8	0	3.89	-1.5	0	0	0	1.5	0	3.89
	9	484	0.6	0.75	0.48	1.08	0.21	0.12	1	-0.59	3.66	-2.5	0	0	0	0.9	-1.6	2.06
	10	515	0.6	0.75	0.48	1.08	0.14	0.12	1	-0.33	3.84	0	0	0	0	0.3	0.3	4.14
			0.6	0.75	0.48	1.08	0.28	0.12	1	-0.33	3.98	0	0	0	0	0.3	0.3	4.28
	11	1337	0.75	0.75	0.48	1.08	0.28	0.16	1	-0.135	4.365	0	0	0	0	0.3	0.3	4.67
			0.75	0.75	0.48	1.08	0.28	0.16	1	0	4.5	0	0	0	0	0.9	0.9	5.40
	12	350	0.6	0.75	0.48	1.08	0.21	0.16	0.8	0	4.08	0	-1.6	0	0	1.5	-0.1	3.98
											Canale di Fiumicino							
	13	206	0.6	0.75	0.6	1.08	0.28	0.12	0.8	0	4.23	-2.5	0	0	0	1.5	-1	3.23
	14	1815	0.45	0.75	0.6	1.08	0.21	0.16	0.8	0	4.05	-2.5	0	-1.6	0	1.5	-2.6	1.45
	15	349	0.6	0.6	0.6	1.08	0.21	0.16	1	0	4.25	0	-1.6	-1.6	0	1.5	-1.7	2.55
	16	347	0.75	0.75	0.6	0.81	0.21	0.2	1	0	4.32	-2.5	0	-1.6	0	1.5	-2.6	1.72
											Tiber mouth							
Rome Municipality	17	875	0.6	0.6	0.6	1.08	0.21	0.12	0.6	0	3.81	-1.5	0	-1.6	-0.3	1.5	-1.9	1.91
			0.45	0.75	0.6	1.08	0.21	0.12	0.6	0	3.81	-1.5	0	-1.6	-0.3	1.5	-1.9	1.91
	18	472	0.6	0.75	0.6	1.08	0.21	0.12	0.6	0	3.96	-1.5	0	-1.6	-0.3	1.5	-1.9	2.06
			0.45	0.6	0.6	1.08	0.28	0.12	0.8	0	3.93	-1.5	0	-1.6	-0.3	1.5	-1.9	2.03
	19	356	0.6	0.6	0.6	1.08	0.28	0.12	0.6	0	3.88	-1.5	0	-1.6	-0.3	1.5	-1.9	1.98
			0.45	0.6	0.6	1.08	0.14	0.12	0.8	0	3.79	-1.5	0	-1.6	-0.3	1.5	-1.9	1.89
	20	184	0.6	0.75	0.6	1.08	0.14	0.12	0.8	0	4.09	-1.5	0	-2.4	-0.3	1.5	-2.7	1.39
	21	100	0.45	0.75	0.6	1.08	0.14	0.12	0.8	0	3.94	-1.5	0	-1.6	-0.3	1.5	-1.9	2.04
	22	2751	0.3	0.75	0.6	0.81	0.14	0.12	0.8	0	3.52	-1.5	0	-3.2	-0.3	1.5	-3.5	0.02
			0.45	0.75	0.6	0.81	0.14	0.12	0.8	0	3.67	-1.5	-2.4	-2.4	-0.3	1.5	-5.1	-1.43
			0.3	0.75	0.6	0.81	0.14	0.12	0.8	0	3.52	-1.5	0	-3.2	-0.3	1.5	-3.5	0.02
			0.45	0.75	0.6	0.81	0.21	0.12	0.6	0	3.54	-1.5	0	-3.2	-0.3	1.5	-3.5	0.04
			0.3	0.75	0.6	0.81	0.21	0.12	0.6	0	3.39	-1.5	0	-3.2	-0.3	1.5	-3.5	-0.11
			0.45	0.75	0.6	0.81	0.21	0.12	0.8	0	3.74	-1.5	0	-3.2	-0.3	1.5	-3.5	0.24
			0.3	0.75	0.6	1.08	0.21	0.12	0.6	0	3.66	-1.5	0	-3.2	-0.3	1.5	-3.5	0.16
			0.3	0.75	0.6	0.81	0.21	0.12	0.8	0	3.59	-1.5	0	-3.2	-0.3	1.5	-3.5	0.09

Fig. 2 - Map of V_p (landward line) and Ve (seaward line) distribution. Table of length of sectors (m), scores for each factors (V_1, V_2, etc.) and potential and effective vulnerability (V_p and V_e).ΣAF is the sum of Anthropic factors (Tab. 3).

The whole area is characterized by low and very low beach altitude (classes 5 and, subordinately, 4), upper shoreface slope (>0.008) and inland elevation (only southern sectors fall in class 3). Sediment budget is another relevant factor. It contributes to the higher vulnerability scores of the shoreline segments characterized by erosional processes: the marked shoreline retreats along the delta apex have been evaluated both during the recent period 1994-2010, and the historical period 1954-2010.

The highest values of potential vulnerability have been obtained near Canale di Fiumicino; they refer to areas characterized by very small and very low beach, erosive upper shoreface (class 4) and very low inland altitude (class 5).

Taking into account anthropogenic factors, the whole area is characterized by high tourist pressure (score 5) and widespread presence of artificial protections that deeply influence the effective vulnerability.The Focene and Fiumicino areas (located to the North of the Canale di Fiumicino) have the highest effective vulnerability; their *CVI* values, in fact, belong to the classes 4 and 5. Moving to the South, the Isola Sacra area, located between the Canale di Fiumicino and the Tiber mouth, has "low", and subordinately "medium"Ve, due to the presence of detached breakwater; the *CVI* values belong mainly to the class 2.

The massive presence of defensive structures in the Rome Municipality contrasts the possible increase of effective vulnerability due to the huge anthropic pressure and determines low values of CVI. As a result, the coastal stretch that extends from the Tiber mouth southward has the lowest vulnerability. More in detail, CVI values are included within class 2 (from the Tiber mouth to Pontile della Vittoria) and 1 (from Pontile della Vittoria to the southern edge of the study area).

Figure 3 shows the percentage of vulnerability classes for the whole studied area and for each municipality; it shows what is the coastal municipality having a higher number of vulnerable sectors.

The first column of Figure 3 shows that about 40% of the total RICE coastline has "very high" potential vulnerability (V_p) and 60% of it has "high" V_p. Taking into account the Ve bar graph (second column in Fig. 3), the percentage of RICE area coastline with "very high" vulnerability decreases from 40% to 21%.

Several sectors that have"high" V_p (from >3 to 4) decrease their vulnerability score: in the Rome Municipality (Fig. 2) that represent the 38% of total studied area, the *CVI* value obtained fall under class 2 (16%) and class 1 (22%).

This statistic clearly indicates that at present the Fiumicino Municipality is the most vulnerable to coastal erosion.

FINAL REMARKS

The vulnerability assessment methodology proposed in this paper can take into account many detailed factors and variables that are connected to beach erosion, as it has been expressly elaborated for the local scale investigations.

For this reason the Local Vulnerability Assessment represent an important and useful tool to single out the most vulnerable

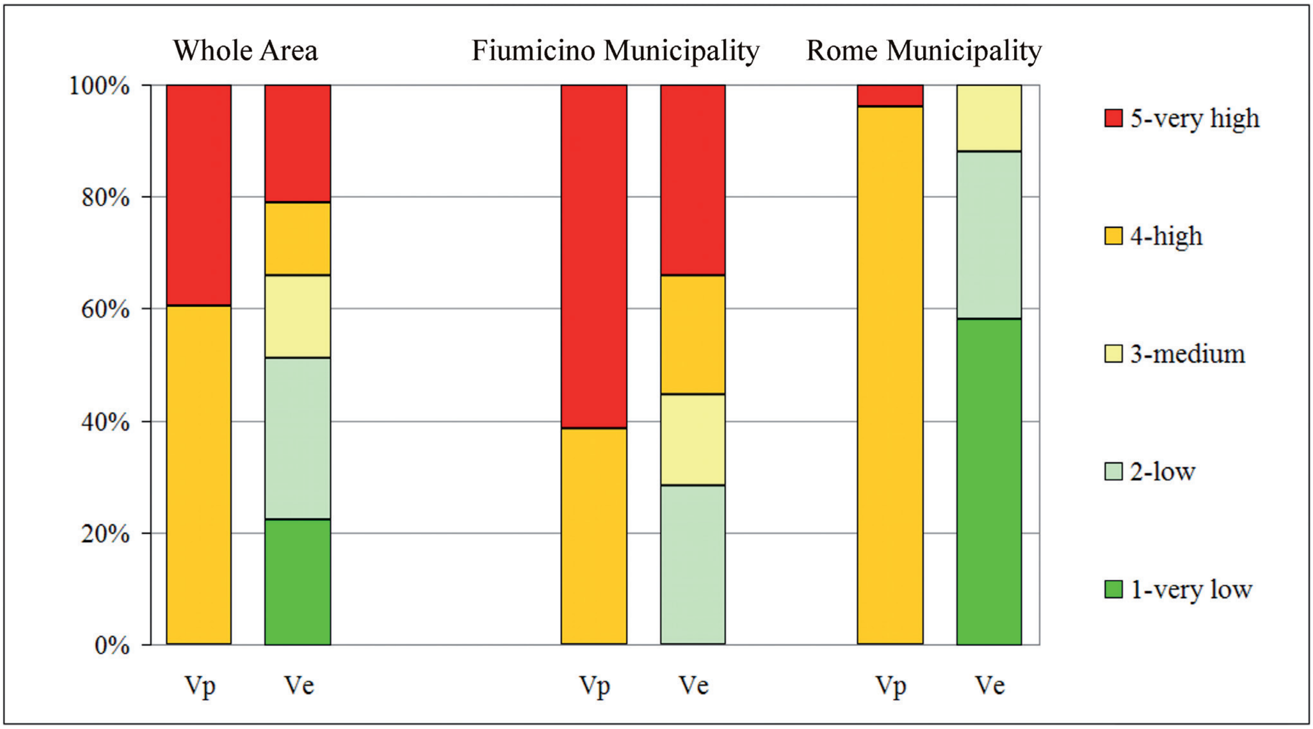


Fig. 3 - Distribution of the percentages of stretches of coast associated with each vulnerability class. Each pair of columns shows the distribution of potential (left) and effective vulnerability (right). On the left, columns show data referred to the whole studied area (12.4 km); moving to the right data referred to Fiumicino Municipality (7.7 km) and Rome municipality (4.7 km) are shown

coastal areas and to support decision makers for territory planning and management.

The Coastal Vulnerability Index (*CVI*) is an outline of weighted linear combination, therefore it allows not only the identification of the most vulnerable coastal stretches but also the variables, and therefore the factors, that most influence the erosional processes they undergo. In other words, this procedure can help the choice of the variables that must be considered in the erosion mitigation programmes.

Considering that the classes of each variable have been defined taking into account the distribution of data on the Italian territory, the proposed *CVI* could be applied in other Italian sandy beach systems, thus allowing the comparison between different areas.

Moreover the values of *CVI* (expressing the effective vulnerability) compared with potential vulnerability (V_p) can evidence the important role of anthropic factors that are able to reduce or enhance the negative effects of coastal erosional processes.

The bi-dimensional visualization of the results in the vulnerability map affords an efficacious tool capable to transfer immediately information to stakeholders and decision makers in order to support them in the planning of appropriate adaptation measures.

If implemented by introducing specific variables that take into account long-term environmental changes (i.e. relative sea level rise) and recalibrating the weights of the variables, this methodology can also be applied for the prediction of future scenarios.

Obviously, the proposed methodology is suitable to be applied to sandy beach coasts in those areas,like the studied one, characterized by microtidal regime.

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