

# The potential vulnerability indices as tools for natural risk reduction. The Volturno coastal plain case study

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Received: 2 February 2017 / Revised: 6 July 2017 / Accepted: 10 July 2017 / Published online: 4 August 2017  
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**Abstract** Coastal areas are exposed to many hazardous events often exacerbated by the sea-level rise with its related effects. The knowledge of vulnerability make possible to plan the actions aimed at reducing the risk and promoting the development of a resilient community. In this frame, the evaluation of potential vulnerability of coastal area only due to the human presence is the topic of the geo-spatial model proposed in this work. At this aim, a dataset of urban areas and population of last 200 years was used to assess the trend of these two factors and four vulnerability indices: urban density, population density, occupied buildings density and buildings surplus. The urban density and population density indices communicate the human pressure due to the presence of men while occupied buildings density and buildings surplus indices identify the zones where accommodation measures, as land use changes, could be applied to improve the coastal system adaptive capacity. This model was implemented at both municipality and censal administrative unit scales and it is well transferable to other areas exposed to hazard, allowing a comparison among regions. The method was applied to the case study of Volturno coastal plain (VCP), located in the north-western zone of Campania Plain (Southern Italy): indeed, the exposure to many natural hazards (coastal erosion, marine inundation,

subsidence, salt water intrusion) coupled with the intense urbanization make the VCP a good test area to validate the methodology here proposed. The model evidenced a low constant value of population growth and the achievement of a sill for the urban development after the nineties, moreover the greatest part of censal districts close to the VCP shoreline have a high percentage of total unoccupied buildings. These conditions make concrete the possibility to change the land use from urban to natural land for wide coastal sectors.

**Keywords** indicator · index · natural risk · urban expansion · population growth · exposure

## Introduction

Coastal zones host a population whose average density is three times major than the global one (Small and Nicholls 2003) in addition, the substantial increase of world population (about 2.75 billion of people by the year 2025) forecasted by Gaffin et al. (2006) suggests a warring scenario in term of exposure for the next future.

In the last decade, these areas were exposed to coastal erosion, marine inundation and storm surges often exacerbated by the global warming (IPCC 2014). The rising of Mediterranean Sea level of about 74 cm for the 2100, forecasted by the IPCC scenario “RCP 8.5” (IPCC, 2014), joined with the subsidence phenomenon (Di Paola et al. 2017 and references therein) could make all these events more dangerous, producing coastal aquifers contamination by salt water, damages to coastal wetlands, loss in term of biodiversity and negative impacts on fishing and coastal tourism (Breil et al. 2007). In these densely populated areas, natural events can cause disasters when their occurrence is not taken into account

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in territorial plans (Alberico and Petrosino, 2014, Alberico and Petrosino, 2015).

Mostly for geophysical risks (Slejko, 1993; Lirer et al. 2001; Glade, 2003; Petrosino et al. 2004; Marzocchi et al. 2008; Pesaresi et al. 2008; Lirer et al. 2010; Grezio et al. 2012; Alberico and Petrosino, 2015), the notation proposed by UNESCO (1972) and Fournier d'Albe (1979)  $\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}$  is adopted. Hazard is the likely frequency of occurrence of a dangerous event in a fixed future time. Exposure measures people, property, systems, or other elements present in hazard zones that are subject to potential losses. Vulnerability is the proportion of lives or goods likely to be lost, and accounts for the characteristics of a system or asset that make it susceptible to the damaging effects of a hazard.

This definition identifies the vulnerability as a characteristic of the element of interest (community, system or asset) and its function of sensitivity and adaptive capacity of system (European Environmental Agency, last connection 31/03/2016). Sensitivity is the degree to which a system is adversely or beneficially affected by a given event (IPCC 2007). Adaptive capacity describes the ability of a system to cope with adverse impacts or adapt to climate changes (IPCC 2007). The ability to adapt indicates the change in a system's exposure or sensitivity to reduce future impacts. These changes can be structural (sea walls, revetments, groynes, breakwaters), non-structural coastal engineering (beach nourishment, dune creation and restoration, wetland restoration and creation, afforestation), accommodation measures (modification of land use, infrastructure, buildings and buildings code) and rules (no new development in vulnerable areas, abandonment of property).

Recent scientific literature and European projects evidenced an uttermost attention to the definition of methods aiming at identify the vulnerability of coastal zones exposed to natural events. A common way to assess the vulnerability is using indicators and indices that are useful to provide a simple representation of complex topic and to make comparisons among regions (Heltberg and Bonch-Osmolovskiy, 2010). In many areas around the world, the Coastal Vulnerability Index (CVI - Gornitz et al. 1994) method, in several cases partially modified, was widely applied to assess the vulnerability of coastal zones exposed to global warming effects (Thieler and Hammer-Klose, 2000a, b; Pendleton et al. 2005; Diez et al. 2007; Torresan et al. 2012; Addo, 2013; Di Paola et al. 2014; Gorokhovich et al. 2014). Moreover, Kunte et al. (2014) highlighted the importance to consider the population density and socio-economic variables especially for coastal zones exposed to intense human pressure.

In this work, the vulnerability was conceived as simple "exposure" (susceptibility to suffer damage), corresponding with the physical fragility or exposure in Cardona (2003). Within this framework, we analysed the territorial transformation of last 200 years to define the trends of urban development

and population growth; both factors allow to identify the exposure system changes to reduce the risk (Alberico and Petrosino, 2014; Alberico and Petrosino, 2015). Moreover, the historical analysis was also used to recognize the natural elements of past landscape characterizing the VCP; these elements could represent a guide to choice correct land-use changes usable as accommodation measures (Alberico et al. 2014 and reference therein).

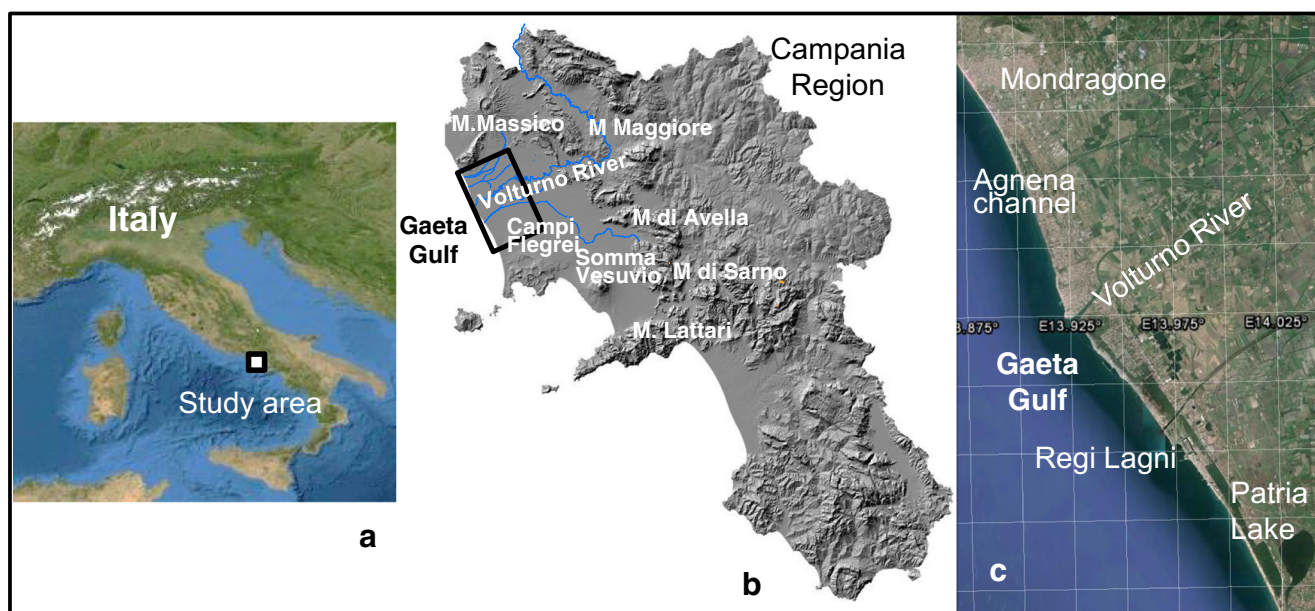
The population and urban data was also used to calculate four indices able to point out the potential vulnerability of territory only due to human presence: urban density, population density, occupied buildings density and buildings surplus. The first two indices, also suggested by several European projects (EUROSION, 2004; THESEUS 2013; CORFU, 2014), identify the geographical distribution of population and of urban environment, emphasising the zones more vulnerable. The occupied buildings and the buildings surplus indices, proposed in this work for the first time, points out the distribution of buildings occupied by residents and the distribution of uninhabited houses, respectively. The latter two indices make possible to identify the areas where land use changes can be easily realized.

The indices were calculated and mapped for the case study of Volturmo coastal plain (Southern Italy), because this area is characterized by the succession of eroded and artificial zones as the whole Campanian coast (Cocco and De Pippo, 1988; Cocco, 2007; Alberico et al. 2012; Di Paola et al. 2017). Moreover, the VCP is also exposed to stream flood (Hydrogeomorphological Setting Plan of Basin Authority of Liri Garigliano Volturmo, 2010), subsidence (Aucelli et al. 2016), coastal aquifers contamination by salt water (ENEA report, 2001; Italian Ministry of the Environment, Land and Sea, 2010). As matter of fact, the absence of planning tools in the Eighties made possible an intense transformation of this coastal zone and the increase of natural risks. The four indices represent useful tools to communicate the territorial status and to improve the collaboration between central and local government and between the latter and population to reduce the natural risk.

## Study area

The study area is located in the north-eastern part of Campania Region; it corresponds with the coastal belt of VCP stretching from Mondragone town to Patria Lake (Figure 1).

The VCP, one of major structural depression formed since the Late Miocene (Patacca and Scandone, 2007), is bounded northward and eastward by carbonate relief (Mt. Massico, Mt. Maggiore, M. Sarno and M. Lattari), southward by the Somma-Vesuvio district and Campi Flegrei volcanic field and westward by the Tyrrhenian Sea. The Meso-Cenozoic Apennine districts actually forming the substratum of the



**Fig. 1** Location of the study area (a), the Volturno Plain with Homonym River and main channels (b) and the coastal zone investigated in this work (c)

plain are overlaid by marine and transitional deposits (Ippolito et al. 1973), in the Late Quaternary the sedimentation of pyroclastic deposits from the volcanic areas prevailed (Romano et al. 1994).

The littoral zone is mainly conditioned by the Volturno River, that has a catchment basin of about 5550 km<sup>2</sup> and a mean discharge of about 40 m<sup>3</sup> s<sup>-1</sup> (Iermano et al. 2012), and by Regi Lagni and Agnena channels with a catchment basin of about 1095 km<sup>2</sup> and of 209 km<sup>2</sup>, respectively.

The Quaternary alluvial deposits host the Mediterranean maquis, pine dune (*Pinus pinea*) and belts of psammophyte and halophyte vegetation. These wetlands are important wintering stations for migratory bird species (pink flamingos, black stork, purple heron, marsh harrier, Montagu's harrier, etc.) while the fluvio-lacustrine environments are particularly important to connect the coastal areas with the inner zones of Campania pre-Apennines (SIC "Volturno Rivers and Calore Beneventano"). These areas, hosting different kinds of amphibians and some species of migratory and nested birds (black kite), require attention because their degradation could expose this wildlife to a drastic reduction. In the last forty years in fact, the intense urbanization promoted the fragmentation process and the consequent loss of naturalness in the coastal zones and countryside (Scorpio et al. 2016).

The first evidence of anthropic modifications at VCP dated back to the 9th B.C., when Opici established at the mouth of the Volturno River and the little maritime fluvial settlement Vulturum (current Castel Volturno) was built, this area assumed the emporium function under Etruscan (Crimaco, 1991; Capasso, 1997).

During the Roman Empire (27 B.C. - 476 A.D.), all the Campanian towns were turned in colonies and the zones near the Volturno River became the core of a rich agricultural resource, called Campania Felix. In this period, a lot of infrastructures were built: the water network that carried water from the Volturno River to the town of Venafro, built under Emperor Augustus; the Domitiana road linking the ancient Appia street with the port of Puteoli and the bridge connecting the sides of Volturno River, constructed under Emperor Domitian in 95 A.D., (Canino, 1981). After the fall of the Western Roman Empire (476 A.D.), the agricultural crisis, the damages triggered by the earthquake of 375 A.D. and the barbarian invasions caused the dispersion of population living in the plain. This dispersion was moderately restrained under the Norman domain (1130–1189 A.D.), when a political and administrative feudal system was in force and the castles of La Rocca and Volturno were fortified to be used as the residence of the feudal lords and militaries.

The latest structures became important military posts under the Swabians (1198–1266 A.D.), the Angevins (1246–1481 A.D.) and the Aragonese (1302–1816 A.D.) (Pistilli, 2003; Giannone, 1723). During the Bourbon domination the Volturno plain was included in Terra di Lavoro Province, the unhealthiness due to the presence of marshes and swamps prevented the development of this area until the vast reclamation works realized from the Bourbon domain to 1954 (Afan de Rivera, 1847; Ciasca, 1928; PTCP, 2012).

The high naturalness of this area is evident in the cartography of 1860; only little villages (Mondragone, S. Nicola, S. Angelo and San Vito) and few houses on right side of Volturno River, the actual Castel Volturno town, are evident. A wide



pine forest is present on both sides of Volturno River mouth while to the north of the Lago Patria Lake the hydraulic structure known as Regi Lagni is visible.

This territorial status is preserved in the cartography of 1957; this map shows a larger Mondragone city, the Cirio factory and a group of buildings at 130 m from the coastline. Single buildings rise along the State road “SS7 Quater”, connecting Mondragone and Castel Volturno (Figure 2). Since ‘70s, the built environment expanded rapidly, disorderly and without rules (Frallicciardi and Cerisano; 2013), the seaside tourist Centre of Pinetamare is the symbol of this uncontrolled territorial transformation.

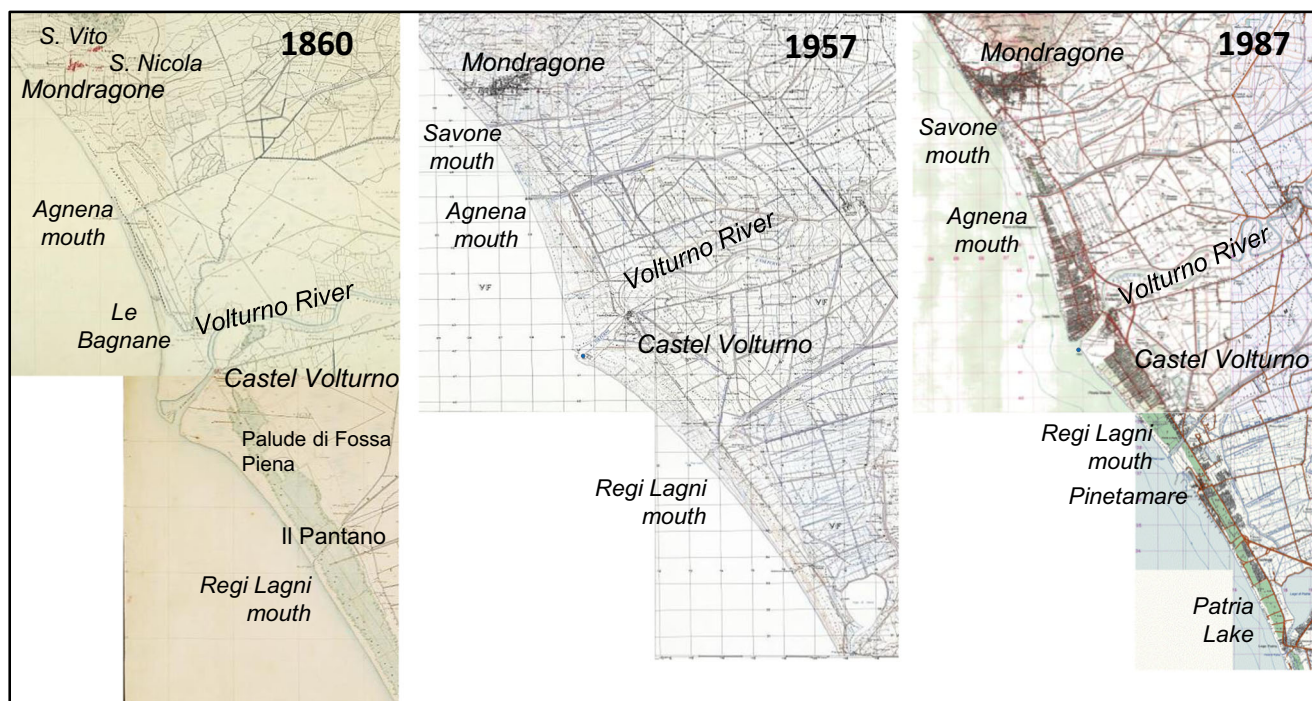
### The planning tool

Until the last decades, the built environment grew without rules along the coastal belt of Volturno River, favoring the increase of vulnerability and at the same time the naturalness loss. This territorial status, which characterizes most of European coastal zones, has led the member states to consider the need of common rules to reduce the vulnerability mainly through nature based solutions aiming at also enhancing the environment too (EEA Technical report; 2014).

Some decrees and plans were focused on the reduction of human activity effects on the environment, bio-diversity preservation, conservation of natural habitats and of wild fauna and flora (Table 1). Other documents were focused on the use of

green infrastructures to mitigate natural and anthropic hazards and favor the growth of naturalness (Table 1). Only very recently, rules for the maritime spatial planning were established by the Directive 2014/89/EU (table 1) while the Integrated Coastal Zone Management (ICZM) dedicated to the protection and the economic development of marine areas is still a recommendation. In the last years also emerged the key role of environmental, economic and societal data integration as a tool to reduce the vulnerability of coastal zones and promote their economic development in the light of naturalness preservation and human well-being (Table 1).

Within this framework, the Territorial Plans actually in force in the study area received several European Union Directives, Legislative Decrees and Regional laws (Table 2). In detail, the Campania Regional Plan (PTR) represents a guide for the Provincial (PTCP) and Municipal (PUC) plans and, in accordance with the Regional law 16/2004, provides the criteria and guidelines for the protection, valorisation and conservation of landscape. The PTCP of Caserta Province (adopted with Provincial deliberation 15/2012) is guided by environmental safeguarding principles as: reduction of soil consumption, protection and improvement of rural land, requalification of urban and rural degraded areas, reduction of zones exposed to flood and erosion, protection of natural landscape and cultural heritage. However, at VCP is still ignored the key role of integrated management of maritime areas as tool supporting the coexistence of economic development and human well-being.



**Fig. 2** Example of historical maps showing the territorial changes occurred at Volturno coastal plain



**Table 1** European directives, recommendations and laws in force in Europe for the protection and preservation of environment and for the coastal management

Date	Document
1972	Stockholm Declaration, it promote the protection of the environmental resources.
1975	Mediterranean Action Plan, it aims to protect the marine environment.
1976	Barcelona Convention, it promote the protection of the Mediterranean Sea Against Pollution.
1976	Directive 79/464/EEC it consider the pollution caused by certain dangerous substances discharged into the aquatic environment of the Community.
1979	Directive 79/409/EEC (Birds Directive),
1987	Report of the World Commission on Environment and Development, it aims to create a United International Community based on shared sustainability strategies.
1992	Council Directive 1992/43/EEC (Habitats Directive), it promotes the conservation of natural habitats and of wild fauna and flora.
1995	Mediterranean Action Plan, it highlights the importance of the marine environment protection.
1999	European Spatial Development Perspective, it works towards a balanced and sustainable development of the territory of the European Union.
2000	Lisbon European Council, it supports the development of a new economy that takes into account the key role of strengthen employment, social cohesion, quality of life and of environment.
2000	Directive 2000/60/EC. of the European Parliament and of the Counsel (Water Framework Directive), it establishes a framework for Community action in the field of water policy. It requires River Management Plans.
2001	Goteborg European Council, it is a document that indicates objectives and measures as general guidance for future policy development in four priority areas: climate change, transport, public health and natural resources, thus complementing decisions on social and economic issues.
2001	European Directive 2001/42/EC, it explains and rules the Strategic Environmental Assessment.
2002	Recommendation 2002/413/EC, it makes recommendations and explain the key role of the Integrated Coastal Zone Management.
2004	Directive 2004/35/CE, it regards the environmental liability with regard to the prevention and remedying of environmental damage.
2007	Directive 2007/60/EC, it regards the assessment and management of flood risks.
2008	2008/56/EC (Marine Strategy Framework Directive), it applies an ecosystem-based approach for the management of human activities while enabling a sustainable use of marine goods and services and highlights priority to achieve or maintain good environmental status in the Community's marine environment, to continuing its protection and preservation, and to preventing subsequent deterioration (transposed in Italy by the Legislative Decree 2010/190).
2008	Directive 2008/1/EC of the European Parliament and of the Council, it concerns integrated pollution prevention and control.
2009	Council Directive 2009/147/EC it regards the conservation of wild birds (Birds Directive)
2011	Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011, it regards the assessment of the effect of certain public and private projects on the environment.
2011	EU's 2020, it identifies a new biodiversity strategy that focus on six measurable targets: (1) enhance the implementation of nature legislation, (2) restore ecosystems and establish the use of green infrastructure, (3) promote sustainable agriculture and forestry, (4) encourage sustainable fisheries, (5) combat alien invasive species, (6) contribute to averting global biodiversity loss.
2014	European Directive 2014/89/EU (Maritime Spatial Planning), it contributes to the effective management of marine activities and the sustainable use of marine and coastal resources, by creating a framework for consistent, transparent, sustainable and evidence- based decision-making. In order to achieve its objectives, this Directive should lay down obligations to establish a maritime planning process, resulting in a maritime spatial plan or plans.
2014	Proposal for a Directive of European Parliament and of the Council, it establishes a framework for the protection of soil and amending Directive 2004/35/EC.

## Methods

The urbanization along the shores was considered by the European Union in the light of rapid disappearance of natural

areas (Environmental pressure indicators, European Commission, 2001), fragmentation of natural and semi-natural areas (Indicator code SEBI 013, biodiversity indicator, Environmental Indicator Report - 2013) and exposure to

**Table 2** Planning tools in force at Castel Volturno coastal plain

Planning tools	Description	Area
Directive “Birds” 79/409/EEC	It promotes the conservation of all wild species living in the territory of the European Member States The area hosting these species are labelled as Special Protection Areas (Zona di Protezione Speciale – ZPS)	Variconi Natural Reserve
Directive “Habitat” 92/43/EEC	It promotes the conservation of natural habitats and of wild fauna and flora establishing Sites of Community Importance (SIC)	- Volturno River, - Volturno Mouth - Variconi - Castel Volturno Pinewood - Patria Pinewood
R. L.89/183 (Campania Region)	It institutes the Basin Authorities. The aims are to protect the landscape, improve the water quality and promote a sustainable economic development. Hydro-geomorphological Setting Plan of Basin Authority of Liri-Garigliano-Volturno. – landslide risk (adopted with the Ministerial Decree of December 12, 2006) – flooding risk (adopted with the Ministerial Decree of December 12, 2006) Plan for environmental protection and wetlands conservation (adopted with the Ministerial Decree of April 27, 2006) Coastal erosion of Domitian coast (adopted with the Ministerial Decree of February 15, 2013)	
Art.5 R. L.33/93 (Campania Region)	It promotes the institution of parks and natural reserves	- Natural Reserve Volturno River Mouth- Licola Coast
L. D. 152/06 and subsequent amendments and additions R.L. 16/2004	It makes mandatory the Strategic Environmental Assessment (VAS) for all plans and programs in order to ensure a high level of environmental protection. It indicates the competences of Institutions, from Regional to local level, that deal with the spatial planning. Moreover, it must ensure the transparency of administrative procedures and the stakeholders involvement in all phases of spatial planning. - Regional Territorial Plan (PTR), 2008 - Provincial Territorial Plan (PTCP), 2012.	

natural hazards (EUROSION, 2004; THESEUS, 2013; CORFU, 2014). The geo-spatial model implemented in this work (Fig. 3a, b), mainly based on the spatial analysis and data integration algorithms available in a Geographic Information System, considers the urban environment and the presence of men as factors influencing the potential vulnerability of areas exposed to natural events. Within this frame, the trend of urban development, the trend of population and four potential vulnerability indices were calculated.

### Historical analysis of territorial transformation

The historical and topographic maps of Italian Geographic Institute for the years 1817–1819, 1834, 1860, 1905–1907, 1936, 1956–1957, 1984 (1:25.000 scale), the technical maps of Campania Region (1998, scale 1:5000) and the ortho-photos of the 2006 and 2012, available on the portal of Italian Ministry of Environment, were used as input data to assess the urban expansion occurred in the last 200 years.

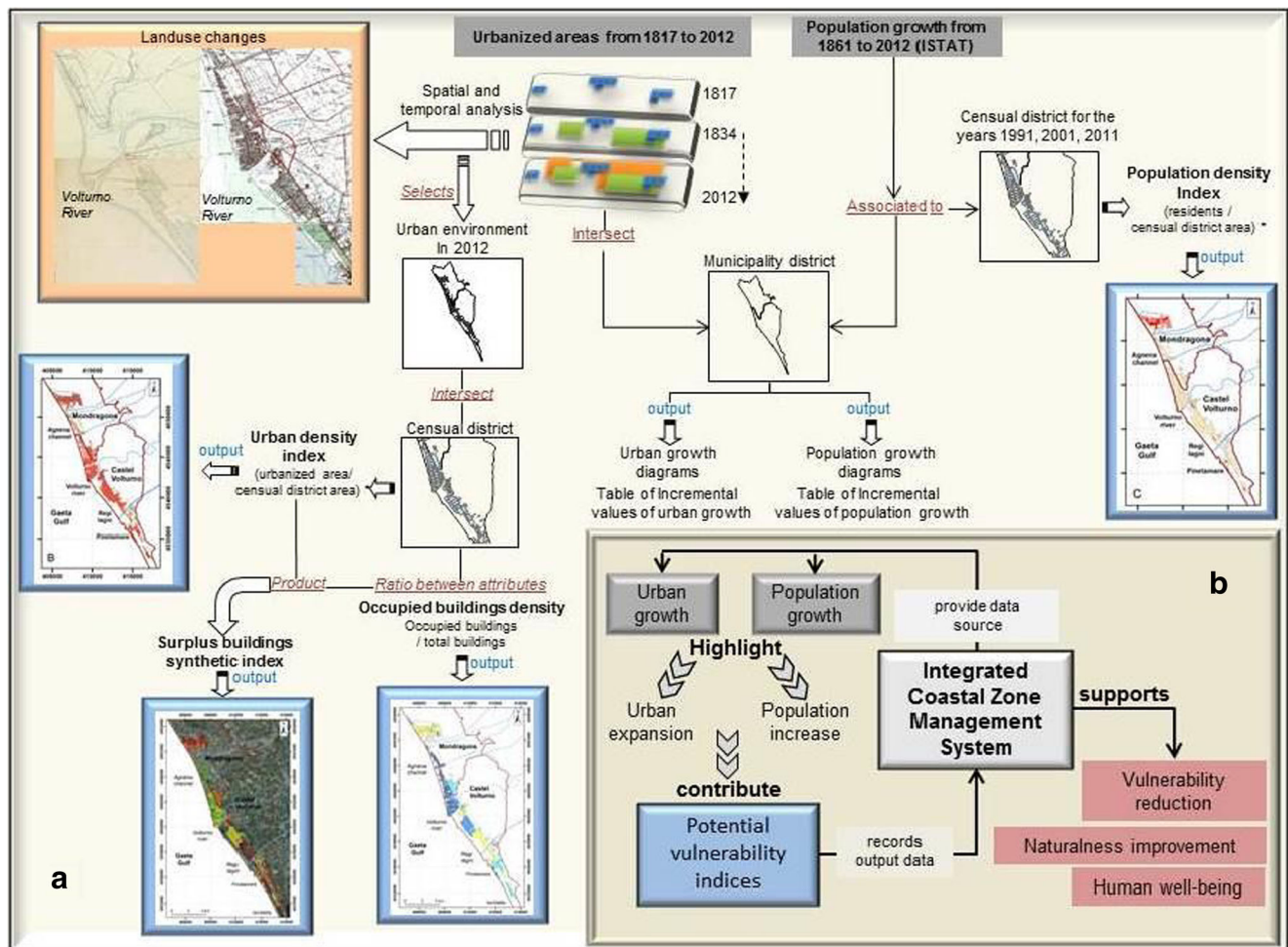
At first, the maps were georeferenced (projection: UTM WGS84 – zone 33 north, datum: ED 50), a process used to assign the real-world coordinates to each geographic element (set of pixels) reported in the maps. After this phase, the

urbanized areas were digitized from the oldest historical map (1817–1819) to the urban zones built in the 2012 (Figure 4). For the single years, the area of urban environment was calculated and expressed as a percentage to rapidly visualize the period with high urbanization growth at VPC (Figure 5a) and municipality scales (Figure 5b). These values were also plotted versus time to evaluate the trend of territorial urbanization for both Castel Volturno and Mondragone municipalities (Figure 6).

The demographic analysis was carried out from 1861 to 2011 using the population data published by Italian National Institute of Statistic (ISTAT 2016). The trend of population growth was assessed by plotting the residents number identified for the single year versus time (Figure 7).

### Potential vulnerability index assessment

The coastal vulnerability due to human presence was calculated with the following four indices: urbanization density, population density, occupied building density, and building surplus. For each one, the focus and type were identified (Table 3) according to DPSIR schema (D - driving, I - impact, P - pressure, S - state, R –response,) and EEA classification (Digest of EEA INDICATORS, 2014) (A - descriptive, B -



**Fig. 3** The flowchart shows the geospatial model implemented for the analysis of territorial evolution and for the assessment of potential vulnerability indices. The role of Integrated Coastal Zone Management is also shown (b)

performance, C - EFFICIENCY, D - policy effectiveness, E - total welfare). The method adopted for the indices assessment slightly changes according to the type of involved data (Giordano et al. 2013).

For data associate to polygon feature, the *index* was calculated following two steps. Firstly, the intersection between the geographical features representing a spatial attribute (e.g. extent of urban environment) and the extent of administrative units (Aau) (e.g. municipality, censal district) was applied. This phase allowed the identification of the area of a generic spatial indicator (Ari) associated to the single administrative units. Secondly, the index was calculated with the following formula:

$$I_{px} = \frac{Ari}{Aau} \tag{1}$$

where:  $I_{px}$  is a generic spatial index derived from polygon features.

For index derived from no-spatial attributes ( $Nx$ ) (e.g. number of residents) and spatial attribute (polygon, lines, point) ( $Aau$ ), the index was calculated as follow:

$$I_{gax} = \frac{Nx}{Aau} \tag{2}$$

where:  $I_{gax}$  is the generic index based on both no-spatial and spatial attributes integration.

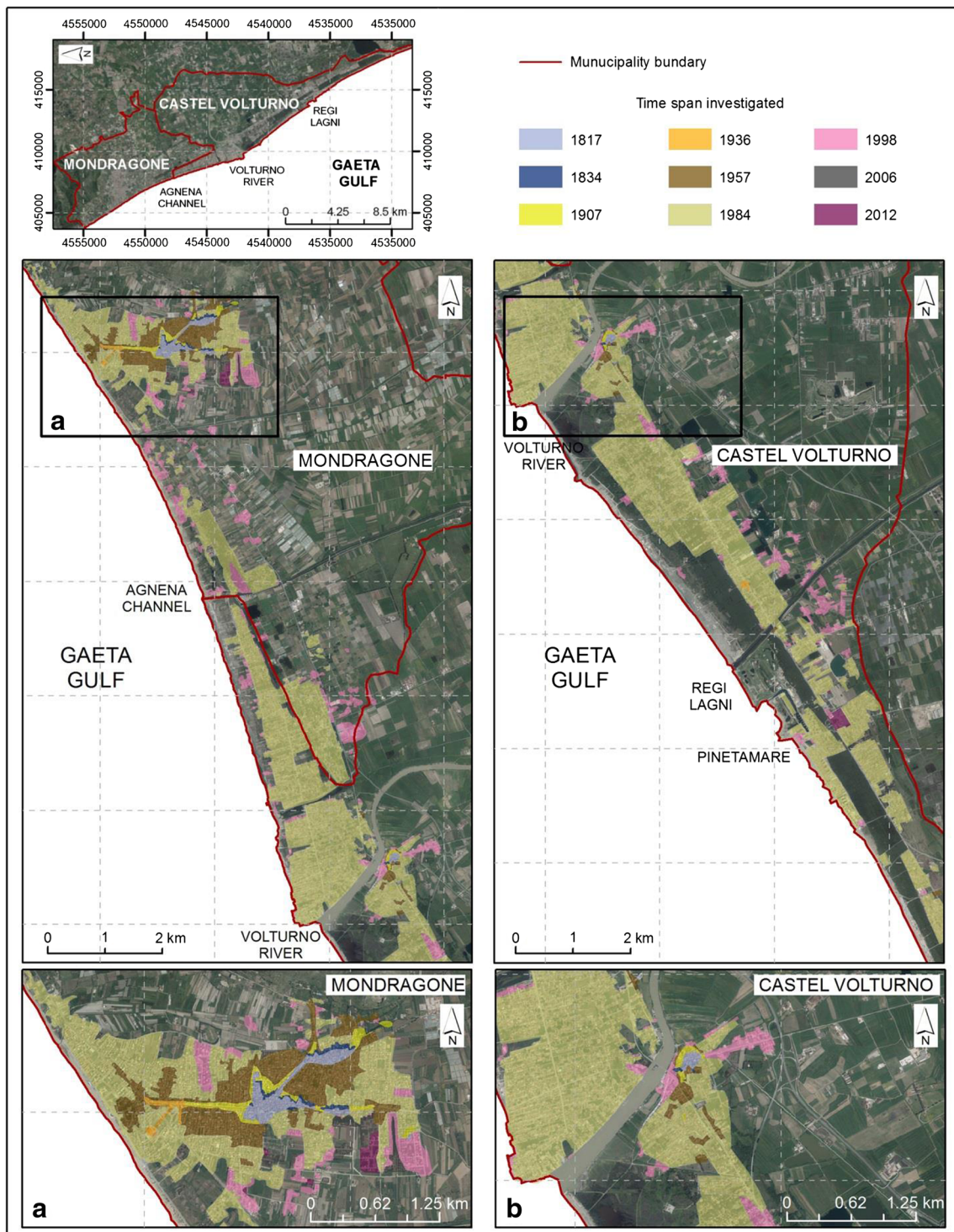
For index calculated only on attributes associated to a specific geographical element (e.g. censal district, municipality, region, state) the following ratio was used:

$$I_{ax} = \frac{Nx}{\sum_{x=1}^n Nx} \tag{3}$$

where:  $I_{ax}$  is the generic attribute index and  $Nx$  is the value of generic attribute.

The values of each index were normalized according to its maximum value recorded over the whole study





**Fig. 4** Urban growth at Volturmo coastal area from 1817 to 2012. The territory falling inside the Castel Volturmo and Mondragone municipality boundaries is illustrated at the top of figure. The urban growth along the

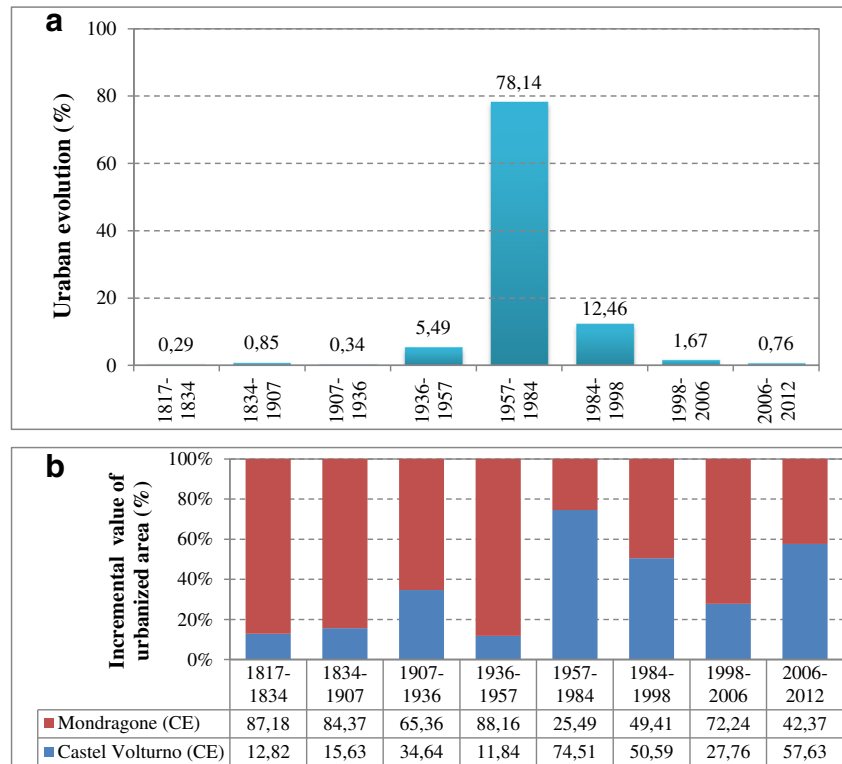
shoreline and a detail on the Centres of the Castel Volturmo and Mondragone are shown in the middle and in the bottom of figure, respectively

area; they range between 0 and 1, the lowest and the highest values, respectively. All the indices were ranked with the natural break method into the same number of classes, these conditions made possible the comparison among indices (Lirer et al. 2010).

#### *The urbanization density index*

The *urbanization density index* identifies the areas potentially exposed to risk in case of new natural events occur but also the natural land consumption tendency.

**Fig. 5** Urban expansion from 1817 to 2012 for the whole investigated area (a) and for Mondragone and Castel Volturno municipalities (b)



This index was calculated, according to the formula (1) as the ratio between the urban environment and the territorial extent (area encircled by censal district or municipality boundaries) indicators. It was assessed at municipality scale from 1817 to 2012 and at censal district scale for the 2011 (the last upgrade data) and for 1991 (first available data) to visualize the urban growth occurred in this elapsed time. The geographical distribution of *urbanization density index* at censal district scale is shown in Fig. 8.

*The population density index*

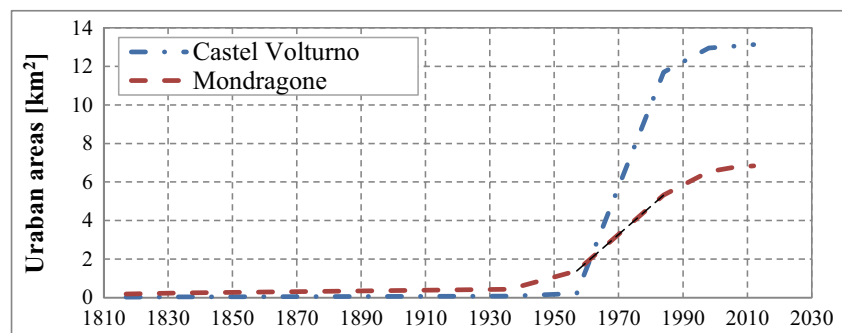
*The population density index* points out the potential vulnerability associated to the presence of people along the coastal belt. It was calculated as the ratio between the total residents and the urban area according to the formula (2) and was

mapped at censal district scale for the years 1991, 2001 and 2011 (Figure 9).

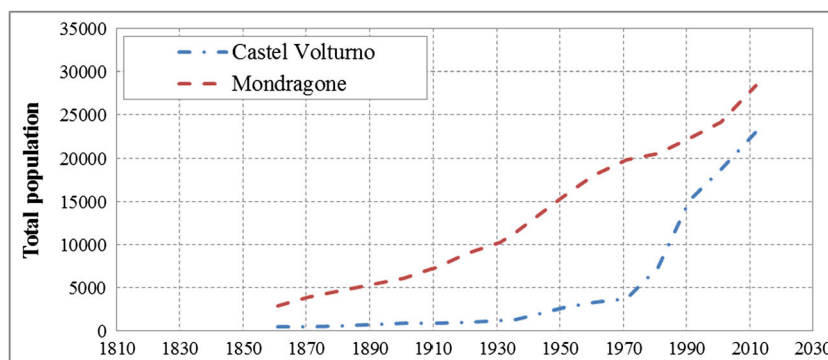
*Occupied buildings density and building surplus indices*

This index identifies the density of building employed as permanent residence (Figure 10); it was defined for the single censal district as the ratio of occupied buildings and total buildings according to the formula (3). Moreover, the different exposure characterizing two zones with same occupied building density but different urbanization density was also taken into account tanks to the assessment of *building surplus index*. It shows the spatial distribution of unoccupied buildings and it is given by the multiplication of *occupied buildings density* and *urbanization density indices*, as reported in the matrix of Fig. 11a.

**Fig. 6** Urban tendency for Mondragone and Castel Volturno municipalities from 1817 to 2012



**Fig. 7** Population tendency for Mondragone and Castel Volturno municipalities from 1861 to 2011



For the *occupied building density index*, the value “0” corresponds to the cases where all the buildings are unoccupied and 1 with opposite condition while for the *urbanization density index* the value “0” indicates no urbanization and 1 total urbanization of censal district. The synthetic index also varies between 0 and 1 as shown in Fig. 11a. In this matrix, the lowest value (equal to 0.04) characterizes the censal districts with low values of urbanization density and a low number of occupied buildings density, it points out the areas with high potential capability to support the land-use changes as measure for risk reduction; opposite condition typifies the censal districts with values 1. The output values of matrix can recur; for example, the value 0.16 is due to three combinations of data entry: a) *urbanization density index* value of 0.2 with occupied building density index value of 0.8 (case labelled with letter C1); b) *urbanization and occupied buildings density indices* values of 0.4 (case labelled with letter E) and c) *urbanization density index* value of 0.8 and *occupied building density index* value of 0.2. The *building surplus index* was also mapped to identify the geographical distribution of censal districts and their distance from the shoreline (Figure 11b).

## Results

### Historical analysis of territorial transformation

Until 1860, a good level of naturalness characterized the VCP, a wide pine forest was present on both sides of Volturno River mouth and several wetlands “Palude di Fossa Piena”, “Pantano di Mondragone” and “il Pantano” depicted the area. Only at Mondragone, S. Nicola, S. Angelo, San Vito and Castel Volturno localities the first sign of modern settlements was evident. From 1817 to 1936, the coastal zone was interested by an urban expansion lower than 1%, this value reached the 5% at the end of 1957 (Figure 5a). The naturalness of coastal area was still preserved, the city of Mondragone became larger, the Cirio factory and a group of houses were built

very close to the shoreline. Single buildings rise along the State road “7 Quater” that connect Mondragone and Castel Volturno (Figure 4).

The huge territorial transformation occurred from 1957 to 1984; the urbanized area increased of about 80% and the seaside tourist Centre of Pinetamare was also built (Figure 5a) in detail, the urban areas increased in the Mondragone and Castel Volturno municipalities of about 26% and 75%, respectively (Figure 5b). The urban environment expanded in the areas close to the Centre of two cities but mainly along the coastal zone (pale yellow in the Figure 4). In the following years, the percentage of new urbanized areas decreased at 12% because of huge urbanization already occurred. After the nineties, the urbanized area increased with very low percentage (lower than 2%) similar to that characterized the VCP before the sixties probably thanks to the entry into force of Campanian Regional Territorial Plan (2008), Caserta Provincial Territorial Plan (2012) and Hydro-geomorphological Setting Plan of Basin Authority of Liri-Garigliano-Volturno (2006) (Figure 5a). Furthermore, Mondragone was constantly grown more than Castel Volturno except for the 1957–1984 time windows (Figure 5b). The transformation of territory started in the sixties and continued until the end of eighties, after this data the urbanized areas reach a sill (Figure 6). In detail, from 1817 to 1957 Mondragone expanded more than Castel Volturno this condition reversed in 1957–1984 time window (Figure 6). The latter represents the time of the highest consumption of natural land due to a strong transformation of the territory that took place in absence of territorial management plans.

As regards the population data analysis, the population growth is dissimilar for Mondragone and Castel Volturno municipalities. For the first municipality, it increased quite constantly over the whole investigated time window while for Castel Volturno a sudden rise of population occurred after 1970’s. In a few years, the population of Castel Volturno reached that of Mondragone. (Figure 7).

The population growth diagram points out an increase of population also after the nineties (Figure 7). This event is due to the increase of foreign residents that passes from



**Table 3** Indicators/indices used in the present work. For the single indicator were reported: category, sub-category, name, focus, type, index and goal. The star indicates the indices defined for the first time in this work

	Category	Sub- category	Name	Focus	Type	Index	Goal
Spatial resolution							
Censal district Municipality	Environmental (vulnerability)	Extent of urban environment	Urban expansion	P, S	A	Urbanization density (urbanized area / territorial extent)	Identify the localities exposed to urbanization
Municipality administrative unit	Environmental (vulnerability)	Number of residents	Population growth	P, S	A	Population density (total population/ urbanized area)	Identify the distribution of population on territory
Censal district	Infrastructural (planning)	Number of buildings	Occupied buildings	P, S	A	Occupied buildings density* (Number of occupied buildings / total buildings)	Define the density of building employed as permanent residence
Censal district	Infrastructural (planning)	-	-	P, S	A	Building surplus index* (occupied buildings Density/l urbanization density) with high number	Identify the zones of unoccupied buildings

155 to about 3000 people for Castel Volturno, and from 37 to about 1700 people for Mondragone (Figure 12a). The increment of Italian resident is constant (about 1500 people) for Mondragone while decreased from about 3000 to 1500 people for Castel Volturno (Fig. 12b, c).

### Maps of potential vulnerability indices

#### The urbanization density index

The *urban density index* maps, drawn at censal district scale for the years 1991 and 2011, were shown in Fig. 4. The first map pointed out the high urban density for the right side of Volturno River mouth and for both Castel Volturno and Mondragone municipalities. In 1991, about 75% of censal districts had an urban density  $\geq 0.6$ . The comparison of this map with that of 2011 pointed out a change of urban density for all the coastal area and particularly for the left side of Volturno River mouth. The percentage of censal districts with high urban density passed to 82% and new urban settlements, sparsely in both municipalities, are evident in Fig. 4.

#### The population density index

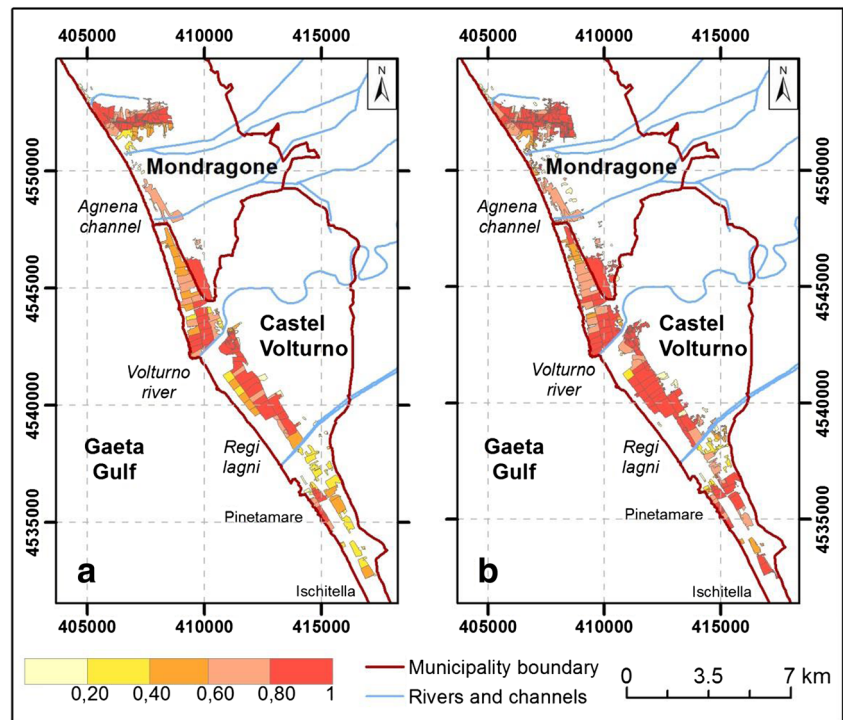
The *population density index* maps showed a value  $\leq 0.20$  for the greatest part of censal district close to the shoreline. In 1991, Mondragone showed a wide urban Centre with censal districts characterized by population density that reached the highest value in the whole study area. Opposite condition typified Castel Volturno in fact, the *population density index* was varied between 0.2 and 0.4. These features unchanged in the following years (2001, 2011) except for the reduction of population density registered in Mondragone Centre (Figure 9).

#### Occupied buildings density and building surplus indices

The high urban density and low population density characterizing the VCP motivated the analysis of geographical distribution of occupied building and the assessment of relative index.

The map of *occupied buildings density index* pointed out a wide distribution of censal districts with the lowest value in the study area ( $\leq 0.4$ ) on the right side of Volturno River and at the left side of Variconi Natural Reserve (Figure 10). Toward Regi Lagni mouth, the buildings density index varies from 0.6 to 0.8, its values slightly decreased in the area between Pinetamare and Ischitella. The highest index values of the study area characterized the urban Centres of Mondragone and of Castel Volturno, as expected for zones inhabited during all the year. The *building surplus index* allowed the identification of areas with same *occupied building density* but

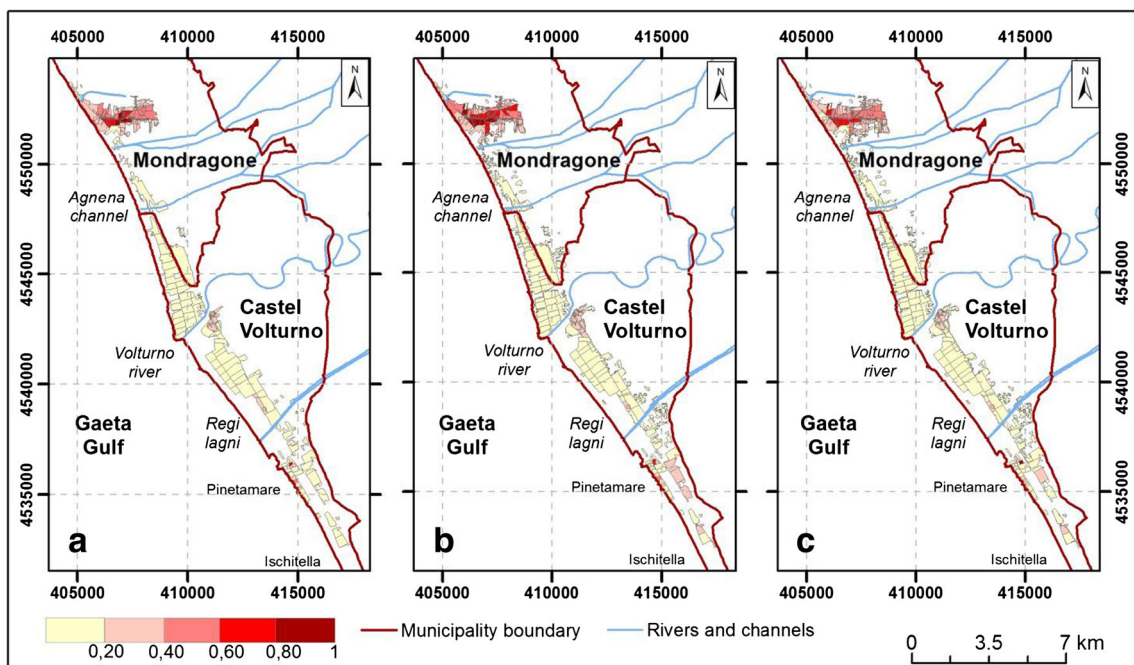
**Fig. 8** Geographical distribution of urban density index at censal district administrative scale for the years 1991 (a) and 2011 (b)



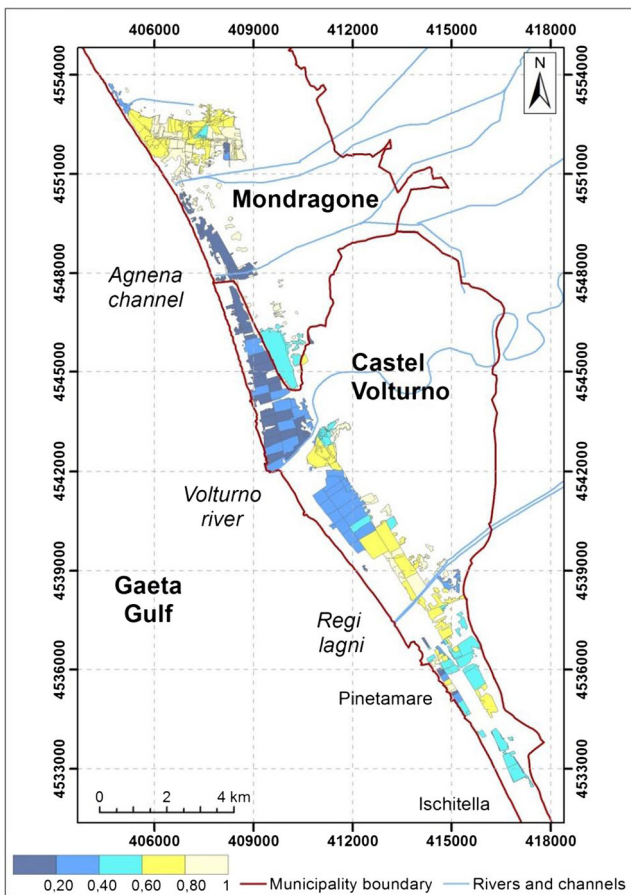
different *urbanization density*, it illustrates the zones able to support the land-use changes as measure for risk reduction (Fig. 11a, b).

The zones with *buildings surplus index*  $\leq 0.24$  (about the 28% of urban environment) are characterized by very high and high potential capability to support the land-use changes,

those with a value  $\geq 0.36$  (about the 50%) were classified as low and very low potential capability to support the land-use changes while the medium vulnerability classes (value range: 0.24–0.36) characterize the 21% of VCP (Fig. 11a, b). In detail, the classes C1 and D1 represent the 65% of those with high potential capability to support the land-use changes



**Fig. 9** Geographical distribution of population density index calculated at censal district scale for the year 1991 (a), 2001 (b) and 2011 (c)



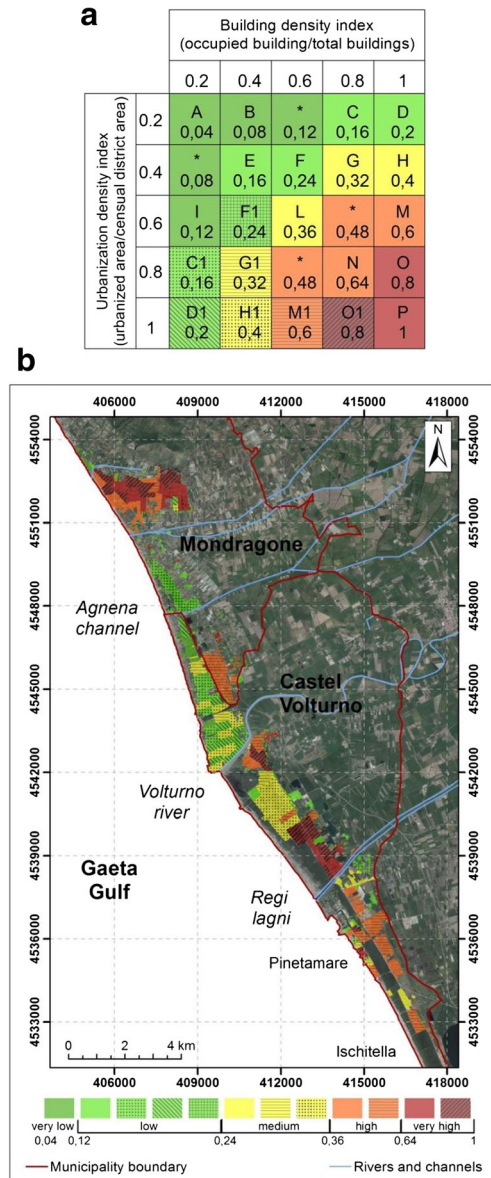
**Fig. 10** Geographical distribution of occupied building density index at censal district administrative scale for the years 2012

(index value  $\leq 0.24$ ) while the classes G1 and H1 the 86% of those with medium capability to support the land-use changes (index value range = 0.24–0.36) (Fig. 11a, b). These four classes characterize the coastal zone placed between the right side of Volturno River mouth to Mondragone urban Centre and the area located to the left side of Variconi Natural Reserve. The classes with low and very low potential capability to support the land-use changes characterize the centre of the Mondragone and the Castel Volturno municipalities.

**Discussion**

This work illustrates the key role of indices as tools to improve resilience and reduce risks in coastal areas. The indices were assessed at VCP, an area exposed to different types of natural hazards and characterized by an urban environment very close to the coastline.

The geospatial model implemented in this work is flexible, and hence many other natural or anthropic factors (land cover, anthropic activities, ecological, social) can be integrated in the scheme to have a complete



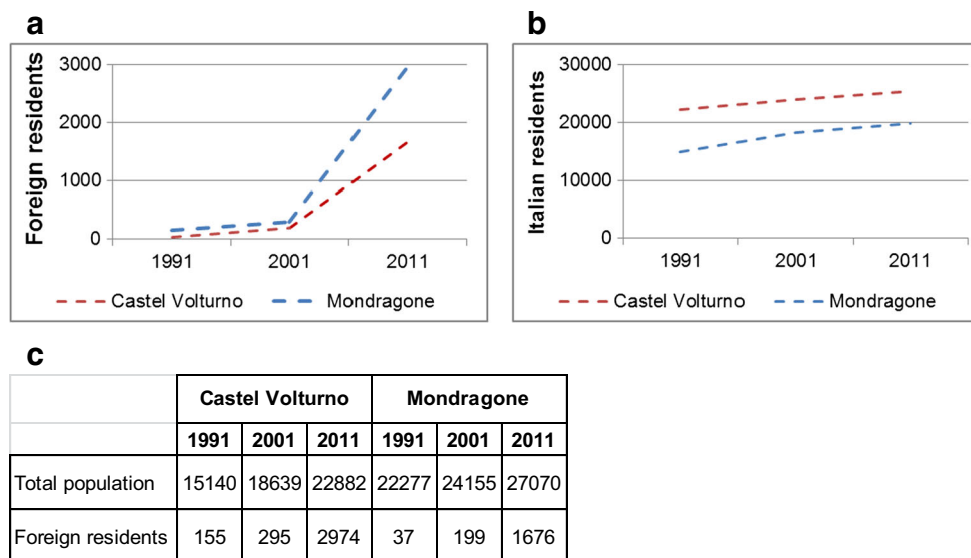
**Fig. 11** Matrix showing the input data used for the building surplus index assessment (a). The symbol star points out the indices absent in the study area, the colours and the line fill symbol are the same used in the building surplus index map (b)

overview of potential vulnerability. This model is well transferable to other areas exposed to hazard and allows also the comparison at regional and national scale.

Starting from the analysis of territorial changes occurred at VCP in the last 200 years, we defined the urban and population trends as a tool to identify the possible future development for this area. Moreover, four indices (*urban density, population density, building density, building surplus*) were calculated to describe the potential vulnerability of study area and to identify the areas where accommodation measure, as land-use changes, can be easily applied to reduce the potential vulnerability. During



**Fig. 12** Foreign residents (a) and Italian resident (b) trends for Castel Volturno and Mondragone municipalities from 1991 to 2011 are drawn. For these years, the total population and the foreign resident values are also reported (c)



the big territorial transformation, started in the sixteen and continued until the 1980, at Castel Volturno the urbanized areas increased about three times higher than Mondragone reaching the apex of urbanization growth (about 80%). In the same years, the population of Mondragone was constantly higher than that of Castel Volturno highlighting for the latter the use of greatest part of new settlements only during the summer. The maps of *population density index* showed high values only for the urban Centre of Mondragone while the lowest typify the zones along the shoreline. For these zones, the *occupied building density index* allowed the recognizing of three classes with different value ( $\leq 0.2$ ;  $0.2-0.4$ ;  $0.4-0.6$ ) of occupied buildings. In addition, the *building surplus index* discriminated between censal districts with the same occupied buildings but different urbanization density. The areas prone to land-use changes are characterized by: a) high *urbanization density index* and very low *occupied building index* and are very close to the shoreline (C1 and D1, Figure 11); b) high *urbanization density* and a building density slightly higher than the previous zones, these areas (G1 and H1, Fig. 11) were located for the greatest part at about 300–600 m from the shoreline. For these zones, the accommodation measures facing to the restoration of natural environments could be applied, they favour not only the potential vulnerability reduction but also the human well-being.

## Conclusions

In the frame of potential vulnerability reduction of coastal zones exposed to natural hazards, the present research proposes four indices to measure the potential vulnerability due

to the presence of man and to identify the area where land-use changes can be easily applied.

The procedure is flexible and then applicable at all scale, it can be extended from censal to municipality to Regional administrative units. Moreover, these indices can also be used to compare zones pertaining different regions because they reflect the local status of anthropic pressure taking into account the extent of investigated territory.

The indices defined in this work are valuable tools to show the potential vulnerability and to identify the areas requiring intervention priorities and to suggest the accommodation measures and rules useful to improve the adaptive system capacity.

The vulnerability indices allowed us to identify for VCP the state of urban density and population density highlighting which of them prevail in the single censal district. In addition, the surplus building density identified the censal district where accommodation measures can be easily applied because characterized by low occupied building density and low urbanization density.

The buildings surplus index map pointed out a medium-low anthropogenic pressure for the greatest part of censal districts close to the shoreline, in the north of Volturno River mouth and at left of Variconi Natural Reserve. For these zones, a land-use change from urban to natural environments would make it possible not only the vulnerability reduction but also the achievement of other benefits as the improvement of resilience, of naturalness and then of human well-being. High anthropogenic pressure characterize the Centre of Mondragone, in this locality high density of both urbanized area and population density prevail.

The maps illustrated in this work provide a vital tool also to involve the stakeholders in all phases of territorial plans construction.

## References

- Addo KA (2013) Assessing coastal vulnerability index to climate change: the case of accra -Ghana. *J Coast Res Spec Issue* 65:1892–1897
- Afan de Rivera C (1847) Memorie intorno al bonificamento del bacino inferiore del Volturno. Stampa del Fibreno, Napoli
- Alberico I, Petrosino P (2014) Territorial evolution and volcanic hazard, Ischia Island (Southern Italy). *J Maps* 10(2):37–41
- Alberico I, Petrosino P (2015) The hazard indices as a tool to support the territorial planning: The case study of Ischia island (Southern Italy). *Eng Geol* 197:225–239
- Alberico I, Amato V, Aucelli PPC, D'Argenio B, Di Paola G, Pappone G (2012) Historical Shoreline Change of the Sele Plain (Southern Italy): The 1870–2009 Time Window. *J Coast Res* 28(6):1638–1647
- Alberico I, Fagnano M, Dal Piaz A, Anzalone E, Barra R, Ferraro L, Giordano L, Di Fiore V, Marsella E (2014) The Land Cover Changes as Tools to Support the Preservation of Naturalness at the Sele Coastal Plain (Southern Italy). IN *Coastal Ecosystems Types, Sustainable Management and Conservation Strategies*. Nova Science Publishers, Inc. New York, 109–128. ISBN: 978–1–63117-236-6
- Aucelli PPC, Di Paola G, Incontri P, Rizzo A, Vilardo G, Benassai G, Buonocore B, Pappone G (2016) Coastal inundation risk assessment due to subsidence and sea level rise in a Mediterranean alluvial plain (Volturno coastal plain, southern Italy). *Estuar Coast Shelf Sci* 1:13 in press
- Breil M, Catenacci M, Traversi C (2007) Impatti del cambiamento climatico sulle zone costiere: Quantificazione economica di impatti e di misure di adattamento – sintesi di risultati e indicazioni metodologiche per la ricerca futura. Apat
- Canino A (1981) Guida d'Italia: Campania. Touring club italiano, Milano
- Capasso S (1997) Gli Osci nella Campania antica. Istituto di studi Atellani
- Cardona OM (2003) The need for rethinking the concepts of vulnerability and Risk from holistic perspective: a necessary review and criticism for effective risk management. In: Bankoff G, Frerks G, Hilhorst D (eds) *Mapping Vulnerability: disasters, development and people*. Earthscan Publishers, London
- Caserta Provincial Territorial Plan (PTCP) (2012) Province of Caserta website. <ftp://ftp.provincia.caserta.it/pub/Ptc%20Caserta/PTCP/>. Accessed 28 July 2016
- Ciasca R (1928) Storia delle Bonifiche del regno di Napoli (Laterza). Bari
- Cocco E. (2007) Le spiagge della Campania. Progetto di gemellaggio tra la Regione Emilia Romagna e la Regione Campania: Sviluppo di un sistema informativo per la gestione della costa della Regione Campania
- Cocco E, De Pippo T (1988) Tendenze evolutive e dinamica delle spiagge della Campania e della Lucania. *Mem Soc Geol Ital* 41:195–204
- CORFU (2014) Collaborative research on flood resilience in urban areas. [www.corfu7.eu](http://www.corfu7.eu)
- Crimaco L (1991) Vitruvium Quasar (collana Studi e ricerche sul Lazio antico)
- Di Paola G, Aucelli PPC, Benassai G, Germàn R (2014) Coastal vulnerability to wave storms of sele littoral plain (southern Italy). *Nat Hazards* 71(3):1795–1819
- Di Paola G, Alberico I, Aucelli PPC, Matano F, Rizzo A, Vilardo G (2017) Coastal subsidence detected by SAR interferometry and its effects coupled with future sea level rise: the case of the Sele plain (southern Italy). *J Flood Risk Manag*. doi:10.1111/jfr3.12308
- Diez PG, Perillo GME, Piccolo MC (2007) Vulnerability to sea-level rise on the coast of the Buenos Aires Province. *J Coast Res* 23:119–142
- Directive 2014/89/EU (2014) Establishing a framework for maritime spatial planning. European Union law website. <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0089&from=EN>. Accessed 28 July 2016
- ENEA (2001) PROT-IDR Progetto Regi Lagni. National Agency for New Technologies, Energy and Sustainable Economic Development website. <http://www.bologna.enea.it/ambtd/regi-lagni/volume-2/0-vol2-index.html> Accessed 28 July 2016
- European Commission (2001) Environmental pressure indicators for the EU. Luxembourg. European Commission website <http://www.uni-mannheim.de/edz/pdf/eurostat/01/KS-36-01-677-EN-I-EN.pdf>. Accessed 28 July 2016
- European Environment Agency (EEA) (2014) Digest of EEA indicators 2014. [http://bookshop.europa.eu/is-bin/INTERSHOP.enfinity/WFS/EU-Bookshop-Site/en\\_GB/-/EUR/ViewPublication-Start?PublicationKey=THAK14008](http://bookshop.europa.eu/is-bin/INTERSHOP.enfinity/WFS/EU-Bookshop-Site/en_GB/-/EUR/ViewPublication-Start?PublicationKey=THAK14008). Accessed 28 July 2016
- European Environment Agency (EEA) (2016) European Environment Agency website <http://www.eea.europa.eu/it>. Accessed 28 July 2016
- EUROSION (2004) Living with Coastal Erosion in Europe: Sediment and Space for Sustainability [www.euroSION.org](http://www.euroSION.org)
- Fournier d'Albe EM (1979) Objectives of volcanic monitoring and prediction. *J Geol Soc* 136(3):321–326
- Frallicciardi AM, Carisano F (2013) La Campania Felix nell'agenda nazionale dei siti di bonifica/The Campania Felix in the national agenda of reclamation sites. *Trials* 6(10):229–238
- Gaffin S, Hachadoorian L, Engelman R (2006) Mapping the future of world population. Population Action International. [http://pai.org/wp-content/uploads/2012/01/Larger\\_file\\_size\\_higher\\_quality\\_image.pdf](http://pai.org/wp-content/uploads/2012/01/Larger_file_size_higher_quality_image.pdf). Accessed 28 July 2016
- Giannone P (1723) Dell' Istoria civile del regno di Napoli, libri XL, tomo II. Noccolò Naso
- Giordano L, Alberico I, Ferraro L, Marsella E, Lirer F, Di Fiore V (2013) A new tool to promote sustainability of coastal zones. The case of Sele plain, southern Italy. *Rendiconti Lincei* 24(2):113–126
- Glade T (2003) Landslide occurrence as a response to land use change: A review of evidence from New Zealand. *Catena* 51:297–314
- Gornitz VM, Daniels RC, White TW, Birdwell KR (1994) The development of a coastal risk assessment database: vulnerability to sea-level rise in the U.S. southeast. *J Coast Res Spec Issue* 12:327–338
- Gorokhovich Y, Leiserowitz A, Dugan D (2014) Integrating coastal vulnerability and community-based subsistence resource mapping in Northwest Alaska. *J Coast Res* 293:158–169
- Grezio A, Gasparini P, Marzocchi W, Patera A, Tinti S (2012) Tsunami risk assessments in Messina, Sicily - Italy. *Nat Hazards Earth Syst Sci* 12(1):151–163
- Heltberg R, Bonch-Osmolovskiy M (2010) Mapping Vulnerability to Climate Change. The World Bank, Washington, D.C.
- Hydro-geomorphological Setting Plan of Basin Authority of Liri Garigliano Volturno (2010) [http://www.autoritadibacino.it/index.php?option=com\\_content&view=article&id=139&Itemid=379](http://www.autoritadibacino.it/index.php?option=com_content&view=article&id=139&Itemid=379). Accessed 28 July 2016
- Iermano I, Liguori G, Iudicone D, Buongiorno Nardelli B, Colella S, Zingone A, Ribera d'Alcalà M (2012) Filament formation and evolution in buoyant coastal waters: Observation and modelling. *Prog Oceanogr* 106:118–137
- IPCC (2007) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) *Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge and New York, p 865 [https://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4\\_wg3\\_full\\_report.pdf](https://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4_wg3_full_report.pdf). Accessed 28 July 2016
- IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In Core Writing Team, Pachauri RK, Meyer LA (eds) *IPCC*, Geneva, pp 151. Intergovernmental Panel on Climate Change. [http://www.climatechange2013.org/images/report/WG1AR5\\_ALL\\_FINAL.pdf](http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf). Accessed 28 July 2016
- Ippolito F, Ortolani F, Russo M (1973) Struttura marginale tirrenica dell'Appennino Campano: Reinterpretazione di dati di antiche ricerche di idrocarburi. *Mem Soc Geol Ital* 7:227–250

- ISTAT - Istituto Nazionale di Statistica (2016) National Institute of Statistics website <http://www.istat.it/it/>. Accessed 28 July 2016
- Italian Ministry of the Environment, Land and Sea (2010) Programmi di azione locale di lotta alla siccità e alla desertificazione. PAL Campania: Valutazione dello stato di salinizzazione dei suoli e potenziale impatto sulla produzione primaria. Ministry of the Environment. <http://www.minambiente.it/pagina/progetti-azione-locale>. Accessed 28 July 2016
- Kunte PD, Jauhari N, Mehrotra U, Kotha M, Hursthouse AS, Gagnon AS (2014) Multi-hazards coastal vulnerability assessment of Goa, India, using geospatial techniques. *Ocean Coast Manag* 95:264–281
- Lirer L, Petrosino P, Alberico I (2001) Hazard assessment at volcanic fields: The Campi Flegrei case history. *J Volcanol Geotherm Res* 112(1–4):53–73
- Lirer L, Petrosino P, Alberico I (2010) Hazard and risk assessment in a complex multi-source volcanic area: The example of the Campania Region, Italy. *Bull Volcanol* 72(4):411–429
- Marzocchi W, Selva J, Sandri L (2008) Probabilistic Volcanic Hazard Assessment and Eruption Forecasting: The Bayesian Event Tree approach. In: Marzocchi W, Zollo A (eds) *Conception, Verification and Application of Innovative Techniques to Study Active Volcanoes* 77–91
- Patacca E, Scandone P (2007) Geology of the Southern Apennines. *Boll Soc geol ital. Special Issue* 7:75–119
- Pendleton EA, Thieler ER, Jeffress SW (2005) Coastal Vulnerability Assessment of Golden Gate National Recreation Area to Sea-Level Rise. United States Geological Survey, Reston
- Pesaresi C, Marta M, Palagiano C, Scandone R (2008) The evaluation of 'social risk' due to volcanic eruptions of Vesuvius. *Nat Hazards* 47:229–243
- Petrosino P, Alberico I, Caiazzo S, Dal Piaz A, Lirer L, Scandone R (2004) Volcanic risk and evolution of the territorial system in the volcanic areas of Campania. *Acta Vulvanologica* 16(1–2):163–178
- Pistilli PF (2003) Castelli normanni e svevi in Terra di Lavoro. In: *Insedimenti fortificati in un territorio di confine*. Libro Co., Italia
- Romano P, Santo A, Voltaggio M (1994) L'evoluzione geomorfologica della piana del fiume Volturno (Campania) durante il tardo Quaternario (Pleistocene medio-superiore-Olocene). *Il Quaternario – Ital J Quat Sci* 7(1):41–56
- Scorpio V, Loy A, Di Febbraro M, Rizzo A, Aucelli PPC (2016) Hydromorphology meets mammal ecology: river morphological quality, recent channel adjustments and otter resilience. *River Res Appl* 32(3):267–279
- Slejko D (1993) Considerations on the seismic risk. *Ann Geophys* 36(1): 169–175
- Small C, Nicholls R (2003) A global analysis of human settlement in coastal zones. *J Coast Res* 19(3):584–599
- THESEUS (2013) Innovative technologies for safer European coasts in a changing climate [www.theseusproject.eu/](http://www.theseusproject.eu/)
- Thieler ER, Hammer-Klose ES (2000a) National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Gulf of Mexico Coast. United States Geological Survey (USGS), Woods Hole, Massachusetts
- Thieler ER, Hammer-Klose ES (2000b) National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Pacific Coast. United States Geological Survey (USGS), Woods Hole, Massachusetts
- Torresan S, Critto A, Rizzi J, Marcomini A (2012) Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. *Nat Hazards Earth Syst Sci* 12: 2347–2368
- UNESCO (1972) Consultative meeting of experts on the statistical study of natural hazards and their consequences, vol SC/WS/500. Paris, France. United Nations Educational, Scientific and Cultural Organization. <http://unesdoc.unesco.org/images/0000/000016/001657EB.pdf>. Accessed 28 July 2016