Land Use Policy 91 (2020) 104413

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Coastal areas and climate change: A decision support tool for implementing adaptation measures

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ARTICLE INFO

Keywords:
Coastal flooding impacts
Urban planning
GIS-based tool

ABSTRACT

Climate change will be one of the main global challenges in the future. In this context cities play a key role. If, on the one hand, cities cause climate change, on the other hand, they are the places where climate change impacts are most evident, as it deeply affects the quality of life of its inhabitants. Climate change impacts are particularly relevant for coastal areas. These are characterized by a higher concentration of buildings and people in comparison to inland areas. In particular, one of the forecasted effects of climate change in these areas is the increase in coastal flooding due to rising sea levels and storm surges. The implementation of strategies and actions for the adaptation of urban areas to the impacts of coastal flooding is essential to ensure the liveability of coastal communities. Urban planning plays a key role in cities' adaptation. However, even though the interest in this topic has been increasing, operative support and tools for planning urban adaptation in cities are in short supply, especially in coastal cities. In light of this, it has become necessary to focus on the definition of new tools responding to the needs of urban planning.

Based on these observations, this paper, starting from the existing literature on coastal vulnerability indices, has developed a new index: the Coastal Resilience Index (CoRI). Thanks to the CoRI and to the use of technological innovations applied to urban planning (in particular, Geographic Information Systems), a decision support tool has been developed to identify adaptation measures aiming to reduce the impacts of coastal flooding, caused by rising sea levels and storm surges.

1. Introduction

Climate change is considered the major global challenge of this century; it is assuming an increasingly important role, not only in orienting scientific research and political strategies, but also in mobilising wide sectors of public opinion, which is witnessed by recent youth demonstrations. As the Intergovernmental Panel on Climate Change (IPCC) has frequently highlighted in the last thirty years, the increase in GHG emissions is causing climate heating with evident consequences on people, the environment, economic activities and cities. In the last report on climate change, the IPCC developed four climate scenarios − the Representative Concentration Pathways (RCPs) − classifying the main climate variability into three main phenomena (IPCC, 2014a):

- increase in the global mean temperature that could vary in ranges of 0.3–1.7 °C (RCP2.6) and 2.6–4.8 °C (RCP8.5) by 2100;
- precipitation variability through an increase in annual mean precipitation at high latitudes and equatorial areas and a decrease at mid-latitude and subtropical dry regions, and more intensity and frequency of extreme precipitation events at the mid-latitude lands;
- rising sea levels in ranges of 0.26 - 0.55 m for RCP2.6 until 0.52 - 0.98 m for RCP8.5.

In this context, cities play a key role in climate action. Indeed, cities can be considered the most blame-worthy with regards to climate change, since they emit 75 % of all carbon dioxide from energy use (IPCC, 2014b; Bulkeley, 2013), which is one of the main drivers of climate change. At the same time, due to climate variability, extreme climate events are more frequent and mainly affect urban areas (Bai et al., 2018). However, thanks to a higher concentration of human and economic capitals, cities represent the perfect place to shape a more effective response to climate change (Kousky and Schneider, 2003; Rosenzweig et al., 2010; Reckien et al., 2018).

Among the effects of climate change, those on coastal areas caused by rising sea levels and flooding are particularly relevant, as many coastal cities are characterized by a higher concentration of people and

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https://doi.org/10.1016/j.landusepol.2019.104413
Received 22 March 2019; Received in revised form 27 November 2019; Accepted 4 December 2019

economic assets that make them more vulnerable to these phenomena (Nicholls, 2004; McGranahan et al., 2007). This makes it important to restructure coastal cities in order to make them less vulnerable to flooding and ensure a better quality of life for local communities. Researchers and urban planners have been increasingly engaged in the analysis of climate change and its impact on cities. In particular, the fight against climate change has been carried out in accordance with two strategies: mitigation, which focuses on climate change drivers, and adaptation, which focuses on climate change impacts (Biesbroek et al., 2009; Laukkonen et al., 2009).

In recent years the concept of "resilience" has been associated with adaptation (Leichenko, 2011; Carter et al., 2015), thus expanding the sets of actions to face the challenges of climate change. Nevertheless, coastal city adaptation is still based on the concept of "vulnerability". The assessment of vulnerability and the definition of urban adaptation actions still represent two separate phases of the urban adaptation process, while their integration can represent an effective support tool in the definition of urban strategies in order to improve the urban resilience level (Goklany, 2007; Swart and Raes, 2011). In light of this, this paper illustrates a methodology to support decision-makers in the definition of urban transformation and its ability to improve the resilience level of the urban coastal system, in the case of coastal flooding.

This paper is structured into four sections. The section 2 provides a literature review on the main coastal vulnerability indices, in order to investigate urban factors affecting cities' response to coastal flooding and the main research gaps from an urban planning perspective. It also provides a framework on how urban adaptation measures are defined in relation to the urban characteristics of the coastal areas, where they should be implemented. This has been investigated through the analysis of some European and American cities' urban adaptation plans. The section 3 introduces a methodology to develop a GIS-based tool to define the Coastal Resilience Index (CoRI) and support the decision-making process in the choice of the most suitable urban adaptation actions for reducing coastal flooding impacts. In the sections 4 there are illustrations of the main results obtained with reference to the classification of urban coastal areas, defined Urban Coastal Units (UCU), considering both their physical and functional characteristics. Furthermore, there are specific Urban Adaptation Actions to implement in the UCU, according to the resilience level expressed by the CoRI. Finally the last section describes the conclusions of this work and future developments of this research.

2. Literature review

Among the different phenomena caused by climate change, rising sea levels and coastal flooding pose a serious risk to cities (Conticelli and Tondelli, 2018) which are located on low-lying coastal areas (Nicholls, 2004; McGranahan et al., 2007). Besides high population density, these areas are also characterized by a high concentration of socio-economic activities.

Due to these factors, in the future these areas will be threatened by coastal flooding, caused by the forecasted rise in sea levels, as well as storm surges. While coastal flooding caused by rising sea levels may result in permanent loss of land, storm surges can cause greater damage in low-lying areas (Kaiser, 2006). Moreover, the forecasted rise in sea levels will exacerbate the impact of coastal flooding caused by storm surges (Wahl, 2017; Nicholls, 2004) estimates that the number of people who will experience flooding will increase 6 times and 14 times given a 0.5- and 1.0-m rise in global levels, respectively. Furthermore, the overlapping of several phenomena (sea level rise, storm floods, tides) must not be underestimated. In this case, in fact, the identification of the most effective intervention measures could be difficult, also because of the interdependencies that are established and which could have opposite effects on the local and regional scale (Wang et al., 2018).

Of the two different and complementary strategies to face climate change effects, mitigation and adaptation, this paper focuses on the second one. According to the EEA's definition (2012, p. 125), adaptation to climate change can be defined as "adjustment in natural or human systems (e.g. urban areas) in response to actual or expected climatic stimuli or their effects. It moderates harm or exploits beneficial opportunities of climate change". Adaptation and vulnerability are strictly linked. Indeed, the adaptive capacity is one of the three dimensions of vulnerability (McCarthy et al., 2001) and reducing vulnerability of a system means to increase the "ability […] to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC, 2014c, p. 118). At the same time, urban adaptation provides opportunities for resilient and sustainable development of cities (IPCC, 2014d; Swart and Raes, 2011). Actually, the concept of resilience is assuming increasing importance in the definition of urban adaptation even if the relationship between resilience and adaptation is not clear. Resilience seems to be a fashionable term that is not used in a defined way (Weichselgartner and Kelman, 2015; Meerow et al., 2016; Galderisi, 2018). Hence, the lack of a clear definition reduces the efficiency of urban adaptation planning towards climate change (Davoudi et al., 2012; Lloyd et al., 2013; Papa et al., 2015). Resilience can be defined as "the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation" (IPCC, 2014c, p. 127). According to Joakim et al. (2015), resilience has several points of contact with vulnerability and both can be considered useful for framing adaptation. In relation to coastal cities, their adaptation is still based on the vulnerability concept and its assessment of these areas (Tyler and Moench, 2012). In this way, coastal vulnerability assessments enable the identification of vulnerability factors influencing adaptation responses. In particular, among vulnerability assessment tools, vulnerability indicators and indices are the most widely used (Table 1). However, some scholars have focused on the role that an integration, among the concepts of vulnerability and resilience, could have in adaptation (including, Joakim et al., 2015). The analysis of vulnerability is often carried out using complex indexes. The study of these indexes is particularly relevant for this work. In fact, our goal is to define a methodology providing a decision support tool that identifies the best adaptation measures at a local scale.

In order to do this, coastal areas are classified using a synthetic index called Coastal Resilience Index (CoRI). To define this index on the basis of the existing literature on vulnerability indexes, urban

Table 1
Vulnerability Indexes selected for the review.

Index Name	Authors
Coastal Vulnerability Index (CVI)	Gornitz, 1991
Sensitivity Index (SI)	Shaw et al., 1998
Coastal Vulnerability Index (CVI)	Thieler and Hammar-Klose, 1999
N.A.	Wu et al., 2002
Social Vulnerability Index (SoVI)	Cutter et al., 2003
Place Vulnerability Index (PVI)	Boruff et al., 2005
N.A.	Kleinosky et al., 2007
N.A.	Preston et al., 2008
Coastal Sensitivity Index (CSI)	Abuodha and Woodroffe, 2010
Coastal Vulnerability Index (CVI)	McLaughlin and Cooper, 2010
N.A.	Tate et al., 2010
Coastal Vulnerability Index (CVI)	Li and Li, 2011
Coastal City Flood Vulnerability Index (CFFVI)	Balica et al., 2012
Coastal Sensitivity Index (CSI)	Karymbalis et al., 2012
Social Vulnerability Index (SoVI)	Guillard- Gonçalves et al., 2015
Socio-Environmental Vulnerability Index for a Coastal Areas (SEVICA)	Zanetti et al., 2016

characteristics influencing "coastal vulnerability" have been pointed out. In this way, the factors affecting cities' response actions to coastal flooding were defined. Despite a high amount of indices in the literature, there seems to be no comprehensive vision of which urban factors can affect the vulnerability and, therefore, the response capacity of urban coastal systems in case of coastal flooding.

Using a holistic-systemic approach, inspired by the General System Theory by von Bertalanffy (1969) applied to the study of urban phenomena (McLoughlin, 1969; Gargiulo, 2009), this work analyses the characteristics of each coastal vulnerability index, classifying them into four categories: (i) socio-economic characteristics; (ii) physical characteristics; (iii) functional characteristics; and, (iv) geo-morphological characteristics. This classification reflects one of the four urban subsystems, which makes up the overall urban subsystem (Papa, 2009): the socio-economic-subsystem (inhabitants and people that conduct activities in the area); the physical subsystem (variables that describe the built environment); the functional subsystem (variables that describe the type, the scale and the localization of urban activities); and, the geomorphological subsystem (variables that describe geographic aspects).

Starting from a research on the Scopus database, several vulnerability indices were detected and among those the most commonly used were chosen (Table 1). The literature review showed that the majority of vulnerability indexes were developed considering the socio-economic and geomorphological factors as main features. The concept of coastal vulnerability, indeed, can be considered as a result of the integration between two other concepts of vulnerability, sensitivity and social vulnerability, which mainly take into account geophysical and socio-economic aspects of coastal areas respectively. However, even if vulnerability indices are based on the integration of socio-economic and geomorphological characteristics, they do not always include other relevant urban characteristics, such as physical and functional characteristics, which may affect the vulnerability levels of the area. The territorial scale of reference of the indices could explain it. Most of the indices, indeed, were developed to be applied to a lower scale than the urban or local one. Therefore, some characteristics, including physical and functional ones, may not be very relevant for vulnerability assessments of coastal regions to coastal flooding.

In this sense, from an urban planning perspective, we believe that, not only little attention has been given to the study of how to assess the vulnerability level of coastal cities, but also that vulnerability indices on a local scale have been defined ignoring the most meaningful characteristics of urban coastal systems. For example, Zanetti et al. (2016) defines a socio-environmental vulnerability index that does not take into account coastal cities' physical characteristics. Instead, a more holistic approach is important to evaluate the vulnerability of coastal areas, since it is not appropriate to exclusively consider specific aspects (Li and Li, 2011). Furthermore, considering that coastal cities have to adapt to future impacts of flooding, vulnerability indices need to have higher spatial resolution, since they should enable the identification of specific phenomena and problems that cannot be studied at a larger scale (Torresan et al., 2008) in order to be more effective.

Finally, another key topic that has emerged from this review is the relationships between vulnerability indices and the adaptation to climate change impacts. Indeed, even if the indices are defined as tools to support the decision-making process in order to implement adaptation measures, the analysed studies show that there is a gap on how vulnerability assessment can be operatively used in the definition and choice of adaptation measures.

In this sense, in order to understand this aspect more deeply, an analysis of some urban adaptation plans[1] (New York; New Orleans, Boston, San Francisco, Rotterdam and Copenhagen) was undertaken. This was useful to understand how vulnerability assessment is integrated into the urban planning process, and which relationships it can acquire in the context of urban adaptation (Mitchell et al., 2015).

As a matter of fact, in recent years, several cities have started to adopt specific adaptation strategies (also called plans) in order to tackle the impacts of climate change. Based on future climate forecasts, these strategies identify a range of adaptation measures for reducing vulnerability at a local level. In particular, in relation to urban adaptation measures, coastal communities' adaptation refers to three main approaches of accommodation, protection and retreat, introduced by the IPCC (2007) and currently used in many adaptation strategies.

From the analysis of case studies, it was noted that two approaches are mainly adopted for urban adaptation in response to coastal flooding impacts. The first approach is based on vulnerability, which is defined and supported by numerous studies in the literature, and, alternatively, while the second one is based on resilience, which it is neither unequivocally defined or operatively codified within the analysed case studies.

Although the strategies of case studies are developed according to two different approaches, a case study showed that adaptation is a two-step process composed of a cognitive phase and a decision-making phase. While the cognitive phase encompasses the study of both future climate forecasts of the city (including future rising sea levels, intensity of storm surges, etc.) and of the urban characteristics, the decision-making phase refers to adaptation measures implemented at the urban and, especially, at the local level.

Applying the systemic-holistic approach to the analysis of urban characteristics used in each strategy for the definition of adaptation measures, it is noted that the majority of case studies adopt a sectoral approach to the study of the city. In particular, mostly physical characteristics are taken into consideration, while only some case studies (Boston and San Francisco) consider functional and/or socio-economic and/or geomorphological characteristics (Table 2). Since most strategies focus on physical characteristics, adaptation measures are mainly related to the physical subsystem of the city, tending to be technical-engineering strategies rather than urban ones. It is important to highlight that adaptation measures are not defined according to the "one-fits-all" principle. Indeed, the measures of the analysed strategies are specific and refer to the physical and functional characteristics of the urban context in which they are implemented, because adaptation is a process whose local scale of implementation is the most effective one, according to Carter et al. (2015) and Füssel (2007).

Based on the research gaps identified in the phases illustrated above, we developed the methodology presented below. Its purpose is defining a tool for supporting the decision-making process in the definition of urban adaptation measures to coastal flooding impacts on a local scale by adopting a holistic-systemic approach.

3. Methodology

As already mentioned, the purpose of this research is to define a methodology to develop a GIS-based tool to support the decision-making process with regards to the urban adaptation measures for reducing coastal flooding impacts in urban areas at a local scale. The methodology is outlined in Fig. 1.

This methodology was developed considering two aspects. The first aspect concerns the adoption of a holistic-systemic approach. In particular, in order to understand the relationships between coastal cities and the impacts of coastal flooding, coastal cities can be interpreted as a system articulated into four subsystems, defined as follows:

- A socio-economic subsystem, including the main socio-economic factors, which characterize the population that lives in the coastal area;
- A physical subsystem, including the spaces and areas where the

[1] The references for the plans are: City of New York, 2015; Waggoner and Ball Architects, 2013a, 2013b for New Orleans; City of Boston, 2016, 2017a, 2017b; City and County of San Francisco, 2016; Rotterdam Climate Initiative, 2013; City of Copenaghen, 2011.

Table 2
Urban characteristics introduced in the analyzed adaptation strategies.

Case study	Urban characteristics			
	Socio-economic	Physical	Functional	Geomorphological
New York	–	Building	Land use	–
New Orleans	–	Infrastructure network Urban fabric	–	Soil types Water and biodiversity
Boston	Population	Housing stock	Facilities and assets	–
San Francisco	Population	Building Shoreline protection Parks open space and natural ecosystems	Solid and hazardous waste Transportation Public facilities and utilities	–
Rotterdam	–	Consumer pressure Open space	–	–
Copenhagen[a]	–	–	–	–

[a] Copenhagen's strategy does not introduce an explicit correlation between urban features and adaptation measures, but considers the potential floodable areas and monetizes the potential economic losses due to climate events by adopting a more risk-oriented approach rather than vulnerability-based one.

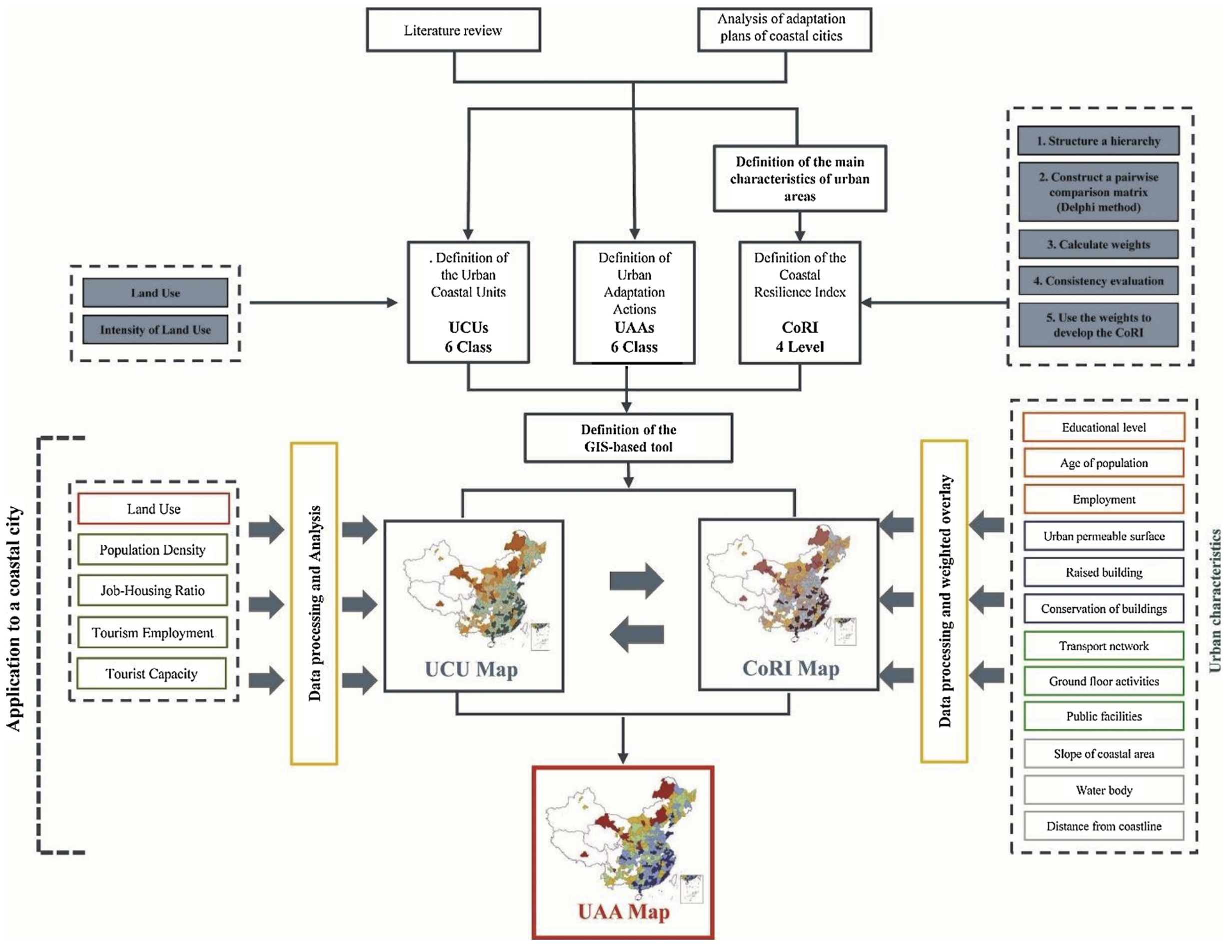

Fig. 1. Methodology to develop a GIS-based tool defining urban adaptation measures to reduce impacts of coastal flooding.

urban activities of the coastal area take place;

- A functional subsystem, including features referring to the type and the localization of urban activities and concerns accessibility;
- A geomorphological subsystem, including geographical coastal characteristics, such as the topography and morphology of the coastal area.

The second aspect refers to the use of Geographic Information Systems (GIS). According to Stillwell et al. (1999), GIS can contribute to the analysis of spatial complexity of real urban contexts and support decision-making processes in urban planning. Furthermore, the technological innovations of GIS, as well as the increasing availability of new data sources (especially, open data), represent a relevant input for the development of new instruments in the urban planning practice (Fistola and Costa, 2009; Murgante et al., 2009).

Moreover, as for climate change, the use of complex GIS models involves the use of user-friendly products, representing scenarios related to risk exposure (i.e. maps of areas exposed to significant flood risk), easily accessible to non-expert users, to sensitize public opinion and decision-makers, who could avail with the use of appropriate adaptation measures (Erikson et al., 2018).

Based on this approach, we used a GIS-based tool to define:

- the Coastal Resilience Index (CoRI), a composite index for

Table 3
Selected urban characteristics with categorical classes for the variables.

Category	Characteristic	Description	Class 1	Class 2	Class 3	Class 4
Socio-economic	SE1. Education level	Number of inhabitants for each level of education	Elementary school or less	High School	College	University or higher
	SE2. Age of population	Number of inhabitants by age bracket	0-5 years old and more than 65 years old	5-25 years old and 50–65 years old	35-50 years old	25-35 years old
	SE3. Employment	Percentage of population in employment	0-25 %	25-50 %	50-75 %	> 75 %
Physical	P1. Urban permeable surface	Degree of permeability	0-30 %	20-50 %	50-75 %	> 75 %
	P2. Raised buildings	Number of buildings in each category based on their degree of elevation above the ground floor	With ground floor	Raised from the ground (below 1.5 m)	Raised from the ground (above 1.5 m)	On pilotis
	P3. Conservation of buildings	Number of buildings for each level of maintenance	Bad	Medium	Good	Excellent
Functional	F1. Transport network proximity	Presence of main roads and railways from the coastline	Present			Absent
	F2. Ground floor activities	Number of buildings for classes according to the use and occupancy of their ground floors	Residential	Tertiary and industrial	Storages	None
	F3. Public facilities	Presence of public facilities from the coastline	Present			Absent
Geo-morphological	G1. Slope of coastal area	Slope of coastal area	0-20 %	20-40 %	40-60 %	> 60 %
	G2. Water body proximity	Water body	Present			Absent
	G3. Distance from coastline	Distance from coastline	< 50 m			> 1000 m

measuring the urban resilience of coastal cities;

- the urban coastal areas – named Urban Coastal Units (UCU) – in relation to their physical and functional characteristics;
- the classes of urban adaptation measures, defined as Urban Adaptation Actions (UAA).

The CoRI aims to measure, at a local level, the urban coastal resilience level as previously defined (IPCC, 2014c). In particular, the CoRI measures the endogenous ability of the urban coastal system to cope with hazardous events such as coastal flooding in relation to its socio-economic, physical, functional, and geomorphological characteristics. In this perspective, the CoRI is based on the key role of spatial planning in the prevention and preparation stages (Etinay et al., 2018; van Dongeren et al., 2018) to reduce the impact of coastal flooding on these areas.

To define the CoRI, using the results of the literature review, we selected twelve urban characteristics, with their variables, and classified them into four categories according to the holistic-systemic approach (Table 3). In particular, the characteristics were chosen considering site-specific datasets, having high spatial resolution, which is more appropriate for the territorial scale of interest, i.e. local scale.

As for the socio-economic characteristics of the population, these have a close relationship with urban coastal resilience (Nicholls et al., 2008). In fact, the population's educational level can affect access to the information necessary for the management of the urban system during coastal flooding (Tate et al., 2010; Rufat et al., 2015; Cimellaro et al., 2016). Hence, the higher the level of education, the greater the resilience of the system. Another important aspect is the age of the population; in particular, children and the elderly might experience greater mobility constraints during an exceptional event (Cutter et al., 2003; Koks et al., 2015). Finally, the economic capacity of the population also influences the system's ability to reduce the externalities of coastal flooding. Above all, high-income people, as well as a high percentage of employees, experience faster post-event recovery (Tapsell et al., 2002; Braun and Aßheuer, 2011; Li and Li, 2011; Guillard- Gonçalves et al., 2015).

From the physical perspective, urban coastal resilience is also affected by the characteristics of the built environment. The presence of permeable areas (e.g., wetlands and floodable areas) can reduce runoff due to coastal flooding. Likewise, if the existing or new building stock is built according to specific construction standards (e.g. buildings elevated above the forecasted sea-level rise), interruptions in the provision of services necessary in citizens and city users' urban life can be significantly reduced. Finally, according to Cutter et al. (2003), good quality building maintenance reduces the chances of buildings being damaged during coastal flooding and, therefore, makes them more resilient.

Functional characteristics include those related to the localization of urban activities within and along coastal areas, the accessibility to the coastal area and its functions in relation to the impacts of coastal flooding. In particular, in order to ensure that the urban system is resilient to coastal flooding, it is important to take into account all the urban activities that are carried out daily by citizens and city users, but also the public services, whose delivery has to be continuous, especially during coastal flooding. Furthermore, transport infrastructure has also to be designed and localized in order to guarantee accessibility to urban activities located in the area during coastal flooding.

Geomorphological aspects also influence the resilience of coastal cities. The slope, as highlighted by Karymbalis et al. (2012) and Preston et al. (2008), is one of the main factors to estimate the impacts of coastal flooding. Indeed, it allows the identification of coastal areas where water is most likely to runoff or accumulate. Although less widely discussed in the literature, the distance from the shoreline also plays a key role in the definition of coastal areas' resilience level, since the areas that are nearest to the coastline are more exposed to coastal flooding. Finally, the proximity to the coastline of water bodies can magnify the extension of flooded areas and, consequently, lead to a reduction in urban coastal resilience.

After the definition of urban characteristics and their variables, a definition of normalization methods is required since it allows an aggregation of datasets with different measurement units (JRC, 2008).

Since the selected variables are spatial data available in two main typologies, aggregated data referring to spatial units (e.g. in Italy they are named "census sections" in the US "census blocks"), named vector data, or data associated to a matrix of cells, named raster data, it was necessary to use specific normalization methods. Among the different methods to avoid loss of information, starting from a categorical normalization of the selected variables, the indicators were normalized according to the techniques described below.

In particular, each variable was rescaled into a range of [0,4], where the "0" is assigned when the urban characteristic provides poor contribution to the urban coastal resilience, while "4" is assigned when a characteristic substantially contributes to it. The majority of variables are vector data that were rescaled by calculating a weighted arithmetic mean of the classes' values recorded by each spatial units. In particular, the formula is the following one:

$$\bar{x}_i = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} x_i} \ (n = 4)$$

where $\bar{x}_i$ is the rescaled variable, x_i is the variable value for the i class and w_i is the relative weight referred to such *i* class. This method was applied for normalizing the SE1, SE2, P2, P3 and F3 variables. In the case of SE3, according to the brackets of the four categorical classes, the *Min-Max* method was used with the following formula:

$$\bar{x}_i = 4\frac{x_i - x_{min}}{x_{max} - x_{min}}$$

where $\bar{x}_i$ is the normalized value of the indicator in *i*-th census block, x_i is the indicator's value, and x_{min} x_{max} and x_{min} x_{max} are respectively the maximum (100 %) and minimum (0 %) values of reference for the indicator.

For the P1, G1, and G3 variables, it was necessary to use a different method from those aforementioned. In particular, these variables are mainly available as raster datasets. For this reason, in GIS applications, normalization by categorical classes is often used. However, this normalization method has its limitations. In order to solve these issues, we used the Rescale by Function tool, in order to transform categorical classes for each variable into a continuous function. In particular, categorical classes' brackets were used as data points to find the "best fit" line or curve for each variable. This process enables the construction of a curve which has the best fit of the classes' brackets, represented as data points. In particular, the "Distance from the coastline" brackets are defined according to McLaughlin and Cooper (2010) and Palmer et al. (2011). For the "Urban permeable surface" brackets, we used the data points introduced by Akan and Houghtalen (2003), also used in several other studies (e.g. Giugni and De Paola, 2011; Saraswat et al., 2016). Instead, in literature, the D "Slope of coastal area" brackets are not unequivocally defined. Definitions depend on both the territorial scale of interest (mainly, the regional one) and the analyzed phenomenon. In this perspective, Zanetti et al. (2016) was chosen as the reference source for the definition of classes' brackets since their index was developed and applied to the local level. Therefore, according to CoRI's purpose, it could be used for the development of the new index. Starting from the categorical classes derived from literature, power functions were used to model the relationships between each selected variables and the CoRI. Finally, F1, F3 and G2's categorical classes were univocally normalized since "0" corresponds to the absence of transport infrastructure or water body in the analyzed area, while "4" is assigned when these elements are present.

The last step was the weighting and aggregation of multiple variables for measuring urban coastal resilience. The choice of methods had to be made along the lines of the basic concept expressed by the composite index (JRC, 2008).

Considering the most common aggregation methods used to develop the vulnerability index, the linear aggregation technique was used and the indicator weights were calculated using the Analytic Hierarchy Process (AHP), developed by Thomas Saaty (1980). Thanks to the AHP, we were able to define the weight of each indicator, which quantifies its relative importance in relation to the level of urban coastal resilience.

The AHP was developed in five main steps. The first step was to structure a hierarchy by breaking down the issue into its component and considering "goals, criteria and alternative" (Mu and Pereyra-Rojas, 2017). In this case, the holistic-systemic approach was useful to determine such a hierarchy, whose "goal" is to assess the level of urban coastal resilience, the "criteria" corresponding to the four subsystems composing the urban coastal system, while the "alternatives" are represented by the identified indicators. In the second step, the relative weights for each indicator were calculated through the development of a pairwise comparison matrix.

In order to understand the importance of each pair of indicators, it was necessary to adopt a Delphi study (Skulmoski et al., 2007). In light of existing literature (Rowe, 1994; Delbecq et al., 1975), the Delphi study was carried out by an international panel of 135 experts, composed of academics and researchers addressing the topic, professionals and technical experts working in public administration with experience on the issue of coastal flooding.

All the experts were invited to fill in an electronic questionnaire that was sent to the panel by email. The survey was filled in by 68 experts (about 50 % of the whole panel) and their opinions were collected in order to define each cell value of the pairwise comparison matrix (for a detailed description of the survey, see Annex 1).

Having developed the pairwise comparison matrix using the Delphi results, it was possible to calculate the weights of each indicator (wi). The calculation was obtained by using the *eigenvalue* method. According to this method, the weights can be calculated by setting the mathematical problem of the **P**-matrix, the pairwise comparison matrix eigenvalues with eigenvector w (the weights). In particular, the vector **w** is a normalized component of the eigenvector corresponding to the largest eigenvalue λ_{max}:

$$Pw = \lambda_{max} w \tag{1}$$

In order to solve this problem, one of the most commonly used approaches is the geometrical method of the products of the row elements of the **P**-matrix (Podvezko, 2009). For each row of the **P**-matrix, the product of the elements was calculated, according to the following formula:

$$\Pi_i = \prod_{j=1}^{m} p_{ij} \ (i = 1, 2, \ \ldots, m) \tag{2}$$

where *m* is the order of the matrix.

After that, the *m*-th degree root was extracted from each product Π_i. Hence, the weights w_i were obtained by dividing each root by the sum of all the roots, as follows:

$$w_i = \frac{\sqrt[m]{\Pi_i}}{\sum_{i=1}^{m} \sqrt[m]{\Pi_i}} \tag{3}$$

Table 4
Weights' indicators.

Category	Indicator	Weight
Socio-economic	SE1. Education level	*0.074*
	SE2. Age of population	*0.055*
	SE3. Employment	*0.051*
Physical	P1. Urban permeable surface	*0.081*
	P2. Raised buildings	*0.088*
	P3. Conservation of buildings	*0.076*
Functional	F1. Transport network proximity	*0.081*
	F2. Ground floor activities	*0.074*
	F3. Presence of public facilities	*0.085*
Geomorphological	G1. Slope of coastal area	*0.128*
	G2. Water body proximity	*0.088*
	G3. Distance from coastline	*0.121*

In this way, the sum of components is normalized to unity (Formula 4).

$$\sum_{i=1}^{n} w_i = 1 \tag{4}$$

The last step of the AHP consisted in checking the consistency matrix. This phase is fundamental for evaluating the consistency of the experts' opinions, starting from the expectation of a specific inconsistency amount from the AHP analysis (Mu and Pereyra-Rojas, 2017). In particular, the consistency is judged by the Consistency Ratio (CR), defined as follows:

$$CR = \frac{CI}{RI} \tag{5}$$

where CI expresses the Consistency Index of the matrix and RI (called Random Index) expresses the Consistency Index for random-like matrices, calculated by Saaty (2012). As argued by Saaty (2012), the AHP analysis is valid if the CR is less than or equal to 0.10. In this case, since the Consistency Ratio is equal to 0.04, the AHP weights are acceptable and they can be used for formulating the CoRI as follows:

$$CoRI = \sum_{i=1}^{n} w_{se_i} se_i + \sum_{i=1}^{n} w_{p_i} p_i + \sum_{i=1}^{n} w_{f_i} f_i + \sum_{i=1}^{n} w_{g_i} g_i \tag{6}$$

where:

n is the number of indicators for each subsystem category;

w_{se_i}, w_{p_i}, w_{f_i} and w_{g_i} represent the social-economic, physical, functional and geo-morphological weights respectively; and se_i, p_i, f_i and g_i represent the corresponding indicator.

In Table 4 the indicators' weights are reported. In particular, the geomorphological indicators affect mainly the urban coastal resilience levels. Furthermore, physical and functional indicators play an important role in the definition of the CoRI, while socio-economic variables influence less than other ones the overall evaluation.

4. Results and discussion

4.1. Definition of urban coastal units

As already stated, the purpose of this paper is to develop a GIS-based tool to support the decision-making process with regards to the urban adaptation measures for reducing coastal flooding impacts in urban areas at a local scale. But the adaptation measures to be implemented at local scale depend both on the level of resilience and on the specific characteristics of the coastal areas. As for the first aspect, the methodology for defining the CoRI was illustrated. Regarding the second aspect, it is necessary to define a classification system for coastal areas.

In general, scientific studies distinguish coastal areas in relation to geomorphological characteristics. This classification is useful to define the varying degrees of vulnerability (or sensitivity) in coastal zones to seaward hazards, among them the rising sea level (e.g. Torresan et al., 2008). However, some studies have also started to introduce land-use characteristics in their classification (e.g. Wu et al., 2002). For example, Zanetti et al. (2016) introduced five land-use classes that are: (1) environmental protection area or natural habitat, (2) rural area, (3) residential area, (4) commercial area and (5) industrial area.

However, as highlighted by the study of some adaptation strategies (e.g. New York and New Orleans), physical urban features are also meaningful characteristics to take into account in the definition of urban adaptation actions. Hence, in urban planning and in urban adaptation it is important to consider both physical and functional characteristics (Young, 2016). In light of this, a new classification that considers both physical and functional characteristics was defined. The urban coastal area typologies were called Urban Coastal Units (UCUs). The UCUs represent homogeneous urban areas with specific physical and functional features. In particular, the objective of this classification is to be a point of reference for a better definition of urban adaptation measures in coastal areas.

In relation to the physical and functional urban characteristics, coastal cities can be articulated into six classes that are:

- Class 1. Compact Urban Areas: urban areas characterized by high population density, high dense urban fabric, and a high functional stratification. Historic centres and consolidated urban areas belong to this category;
- Class 2. Monofunctional and Facility Urban Areas: urban areas characterized by a highly specialized function and a specific physical configuration. In particular, this class includes both industrial and commercial areas and water-waste systems, harbours, airports, stations and other kinds of transport infrastructure (railways, motorways and so on);
- Class 3. Medium and Low-density Residential Areas: residential areas characterized by medium and low population density. Suburban areas belong to this class;
- Class 4. Tourist Facility Areas: urban areas characterized by a variable population density and by the presence of several accommodation facilities and activities related to different types of tourism (e.g. cultural tourism, seaside tourism, etc.). Well-equipped beaches for seaside tourism and areas with tourist accommodations can be included in this class;
- Class 5. Potential Redevelopment Areas: abandoned urban areas that can be planned for redevelopment. For example, brownfield sites belong to this category;
- Class 6. Natural Coastal Areas: coastal areas not urbanized and characterized by the presence of coastal ecosystems, such as wetlands, sand dunes, and freshwater ponds.

A set of five indicators were defined to spatially identify the UCUs. These indicators express the land use and the land-use intensity of each UCU class.

As for land-use intensity, the indicators are:

- Population Density: expressed as the number of inhabitants per square kilometre. This indicator is mainly used to evaluate not only the attractiveness of the coastal areas compared to inland territories, but also to measure the number of people potentially exposed to a flooding event (Neumann et al., 2015). According to Eurostat (European Commission, 2012) and OECD (2012, 2013), European urban areas are categorized as high population density areas when

they have more than 1500 inhabitants per square kilometre (ISTAT, 2017);
- Job-Housing Ratio (or Employment to Housing Ratio): it's the ratio between the number of employees and the number of inhabitants in the area. A ratio of more than 1, representing the Job-Housing Balance, indicates that there are more workers than residents in the area;
- Tourism Employment: percentage of workers in the tourism industry in relation to the total number of workers in the area, where the tourism industry includes accommodation services, food and beverage serving activities, travel agencies and tour operators and recreational, cultural and sporting activities (UNWTO, 1994).
- Tourist Capacity: ratio of the total number of accommodation beds and the total of inhabitants in the area.

To identify the Class 4 areas, we used two complementary indicators (Tourism Employment and Tourist Capacity). This is useful to classify with greater precision areas that present specific characteristics that make them different from other areas (areas with a high concentration of hotels, low-density private residencies), such as a great variability in the number of users in different periods of the year (Graham et al., 2014).

In relation to their definition, for each indicator a benchmark value was set in order to define a first-level binary articulation of the urban area.

To assess whether the benchmark values set for the indicators are able to correctly identify the classes of areas, a test was carried out on a sample coastal area in the city of Naples (Italy). For this purpose, we used the Urban Atlas classification, as it provides detailed mapping of urban areas, besides higher solution land use data, for example, Corine Land Cover (Prastacos et al., 2011). This difference is particularly relevant if the land-use data have to be used at local level.

The application to the study area has shown the accuracy of the benchmark values in relation to the use of the land and the intensity of land use. In this way, the set of actions to be applied to different urban typologies can be identified appropriately.

4.2. Definition of classes of urban adaptation actions

In the absence of adaptation, coastal areas will continue to be exposed to the impacts of climate change, especially coastal flooding due to sea level rise and those associated with storm surges. Furthermore, future population growth, economic development, and urbanization of these areas will increase the exposure of people and assets to these events. Therefore, the adaptation of urban coastal areas is necessary to reduce the impacts of coastal flooding on coastal communities, and at the same time, to provide an opportunity for increasing the quality of life in those areas. As introduced by IPCC (2007), the possible adaptation approaches available for coastal communities are threefold:

- Accommodation: it considers urban layout modifications and organization in relation to the flooding exposure. This approach includes measures about land use change, retrofitting buildings, development of more accessible routes for pedestrians and for the transit of safety means;
- Protection: it includes the placement of physical barriers in an exposed area in order to reduce the impacts of flooding. In general, protection measures can be distinguished in 'hard' measures (e.g. dams, dikes, seawalls, storm surge barriers) and 'soft' measures (e.g. the realization of green infrastructure or the beach and dune nourishment);

Table 5
Connections between adaptation approaches and system relationships.

Adaptation approach	Land Use	Land-Use Intensity	Urban Form
Accommodation	x	x	x
Protection		x	x
Retreat	x		

- Retreat: it concerns the delocalization of activities and communities from high-risk areas to low-risk areas. This approach is adopted when no other option is available and requires a careful decision-making and governance process.

In different ways, these approaches can refer to urban transformations according to the General System Theory applied in the analysis of urban phenomena. Indeed, if the coastal city is an urban system, in order to define its future urban layout and organization it is necessary to take into account the relationships among the four subsystems that compose it. In this perspective, in order to be effective, urban adaptation actions have to be defined considering which relationships are expressed by the (i) land use, the (ii) land-use intensity, and (iii) urban form.

Land use is defined as "the functional dimension of land for different human purposes or economic activities" (OECD, 2007).

It expresses the relationships between urban activities localized in an area and the adapted urban space (Gargiulo, 2009). Land-use intensity is the extent of land being used, including that for agriculture, and indicates the amount and degree of urbanization in an area (Wellmann et al., 2018). Eventually, the concept of urban form is used to describe the urban physical characteristics that range from housing type, street type and their spatial arrangement (Dempsey et al., 2010). It is important to highlight that these relationships are hierarchical. In particular, the main relationship among the urban subsystems is expressed by land use, which defines the kind of urban activity on the territory and, consequently, the amount of urban activity that can be settled in an area (land-use intensity) and the type of urban layout (urban form). Hence, land use is predominant on the land-use intensity and urban form, while land-use intensity is predominant on urban form.

From this viewpoint, adaptation actions are influenced by the specific characteristics of each urban system.

Accommodation, Protection and Retreat can be associated with these systemic relationships, as it is shown in Table 5.

In particular, it is noted that Accommodation refers to all the relationships since accommodation measures refer to different objects of intervention (i.e. building, infrastructure, urban area). Protection and Retreat include measures that are more specific and refer to the urban form and land-use intensity and land use respectively.

Considering these connections, it was possible to define four categories of Urban Adaptation Actions, as follows:

- Maintaining the land use (1);
- Reducing land-use intensity and maintaining urban form (2);
- Reducing land-use intensity and modifying urban form (3);
- Changing land use (4).

While the first and the second categories are related to the Accommodation approach (A), the third and fourth categories refer to the Protection (P) and the Retreat (R) approaches respectively. This articulation highlights the importance of land use in urban planning.

With regards to the first category, it mainly includes actions at building scale and on infrastructure. In particular, those actions are

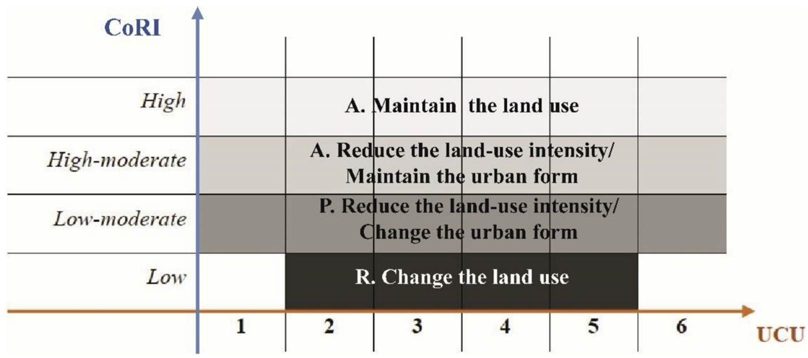

Fig. 2. Relationship among Urban Adaptation Actions, CoRI levels and UCU. (Source: by authors).

referred to: (i) retrofitting existing buildings and building new ones that are either wet-floodproofed or dry-floodproofed; (ii) integrating infrastructure and public facilities with coastal defense solutions, and; (iii) maintaining existing permeable areas in order to guarantee good drainage and storage of water during flooding events.

The reduction of land-use intensity without changing urban form includes the measures of the previous category, but also: (i) supporting alternative uses of ground floor spaces, mainly for storage, parking and also access to building amenities or commercial spaces; (ii) avoiding high-crowding urban activities in the area; (iii) inserting recreational areas and maritime uses along the waterfront; (iv) adopting strict land-use regulations in hazard zones.

The third category includes the measures aforementioned and a further set of protection measures that could be integrated with accommodation measures in order to be more effective. In particular, those actions refer to: (i) compartmentalize the area in order to reduce the flooded zone and designing new developable spaces; (ii) reinforcing the existing "hard" infrastructure (dikes, levees and seawalls) and/or building new ones in order to protect strategic urban activities; (iii) adopting "soft" solutions such as a periodic beach nourishment, dune restoration, wetland creation, littoral drift replenishment and afforestation.

The category related to land-use change refers to the retreat approach, that is considered to be a form of time-consuming and expensive adaptation (Lee, 2014). Beyond the previous actions' categories, this category includes: (i) moving coastal settlements, infrastructure, productive activities, and public facilities to inland low-risk areas, choosing among vacant lands and redeveloping abandoned areas in natural ecosystems in order to allow tourism or leisure activities; (ii) avoiding new developments in the coastal area, incorporating land-use changes in urban plans and in other instruments for regulating urban transformations.

Considering this articulation, each category refers to a resilience level measured by the CoRI. In particular, the distribution of Urban Adaptation Actions follows a specific principle: the higher CoRI, the fewer Urban Adaptation Actions, and vice versa.

In order to define the most effective actions to implement in each kind of urban coastal area, the categories of Urban Adaptation Actions were associated with each category of Urban Coastal Units, in relation to their physical and functional characteristics (Fig. 2).

The diagram shows that all the UCUs can implement Urban Adaptation Actions in relation to the four identified categories. There are only two exceptions, Category 1 and 2, because of their low resilience level for CoRI. Indeed, the UCU Class 1 corresponds to the most populated and urbanized areas of a coastal city. Therefore, using retreat measures in these areas is very expensive and problematic. Hence, it is necessary to operate with urban measures according to the protection and accommodation approaches. At the same time, adopting retreat measures for the UCU Class 6 is not relevant, since green and natural areas are already linked to coherent land uses for protecting coastal areas from the impacts of coastal flooding.

5. Conclusions

The purpose of this paper is to illustrate the methodology developed to define a GIS-based tool for supporting the decision-making process of urban adaptation in cities in relation to the coastal flooding impacts. In fact, GIS, thanks to a balance between the capacity to develop complex operations and the efficiency of the visual communication, can offer an important opportunity for spatial analysis and its popularization (Cowen, 1988; Goodchild, 2000). The tool synthesizes the spatial-analysis process composed of all the methodological phases illustrated above.

Since the tool has to mainly support public administrations and technicians in planning more resilient urban coastal areas, it was developed using input data that is readily available and ArcGIS, one of the most common GIS environments.

Furthermore, since the tool has to measure the Coastal Resilience Index and support other mathematical calculations, the spatial analysis tool was implemented by adopting a raster-based approach. Using raster data, indeed, allows spatial analysis to have richer modelling environments and more operators. This is also the most suitable and common form of representing the continuous spatial distribution of indexes and modelling spatial phenomena.

Finally, the raster data structure is more convenient than that of vector data because it allows intense spatial analyses to be performed by the application of Map Algebra[2] and Matrix Algebra.

The tool works in three phases: the first one is to map the Coastal Resilience Index; the second phase is to map the Urban Coastal Units, and; the last one maps the Urban Adaptation Actions for each Urban Coastal Unit in relation to its CoRI level (Fig. 3).

In conclusion, in this work by adopting a holistic-systemic approach and using GIS, the methodology provides the definition of a new composite index – the Coastal Resilience Index – for measuring the urban resilience of coastal cities, the definition of homogeneous urban coastal areas – the Urban Coastal Units – and the definition of a set of Urban Adaptation Actions. According to those methodological phases, a design workflow was defined for developing the GIS-based tool.

The main innovation of the methodology proposed by this research is not only represented by the use of GIS technology, but also by the adoption of the holistic-systemic approach according to an urban planning perspective. In particular, the use of such an approach was fundamental for the definition of the CoRI. This index, indeed, represents the "core business" of the developed methodology, because it links the types of coastal urban area with adaptation actions, which should be implemented at local level. Furthermore, the same CoRI

[2] Map Algebra is a cell-by-cell combination of raster data layers.

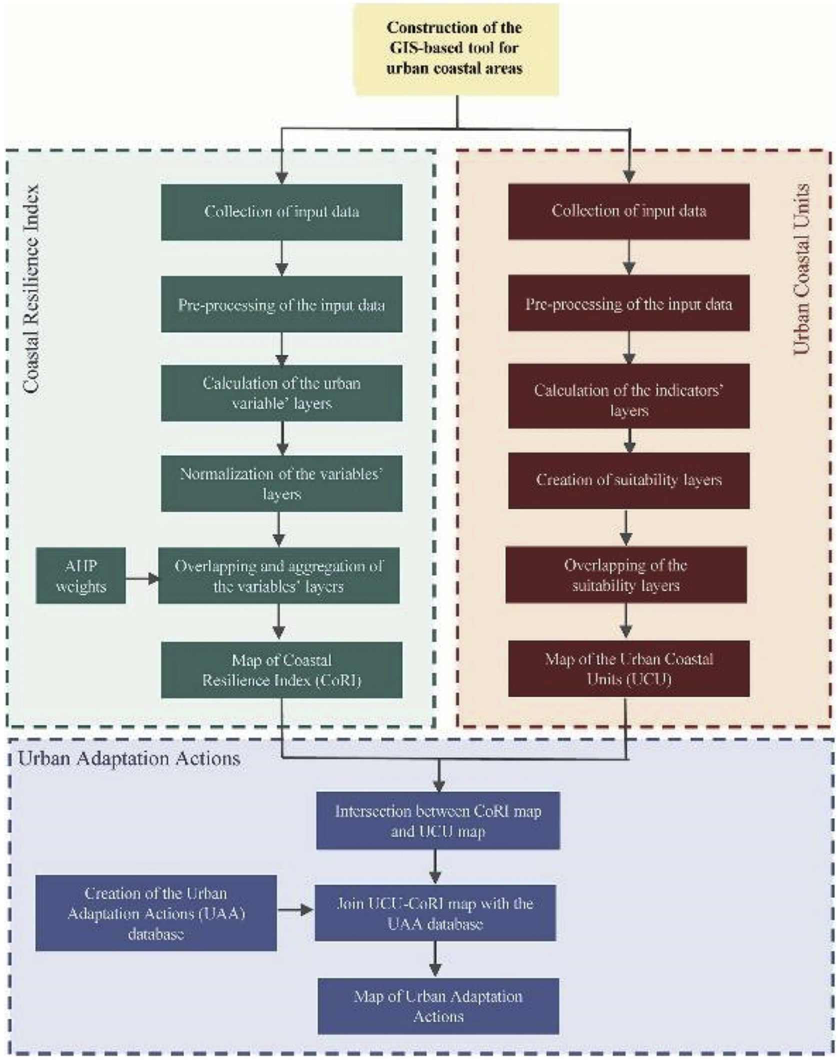

Fig. 3. Design workflow of the GIS-based tool (Source: by author).

could be also used to evaluate the effectiveness of implemented adaptation measures.

The subsequent research developments will concern the application of the illustrated methodology to a sample area to verify the reliability of the methodology and, eventually, improve and/or correct it.

The validity of the proposed methodology is confirmed by an application for a coastal area in Naples, the results of which, still under analysis, seem to show the correctness of the indicators selected to define the CoRI. As soon as possible these results will be presented to the scientific community.

CRediT authorship contribution statement

Carmela Gargiulo: Supervision, Methodology, Validation. **Rosaria Battarra:** Methodology, Writing - original draft, Writing - review & editing. **Maria Rosa Tremiterra:** Conceptualization, Methodology, Investigation, Data curation, Writing - original draft.

Acknowledgment

The authors would like to thank the referees for their comments which helped to improve the paper.

Annex A The Delphi study

As stated in the literature, a Delphi study is used when “there is incomplete knowledge about a problem or phenomenon” (Skulmoski et al., 2007) and can be successfully applied in the field of social sciences (Landeta, 2006). According to Delbecq et al. (1975) and Rowe (1994), a heterogeneous panel, characterized by experts with different perspectives on the problem, produce proportionately higher quality results and more acceptable solutions than homogeneous groups. In particular, Rowe (1994) suggests that experts for the Delphi study should have different backgrounds in order to ensure a greater knowledge base.

In light of this, the Delphi study was carried out on an international panel of 135 experts, composed of academics and researchers of the topic and professionals and technical experts working in public administration with experience on the issue of coastal flooding (Figs. A1 and A2).

In order to select the most representative stakeholders from public administrations and professional technicians, the Climate-ADAPT platform was used. In particular, the platform collects adaptation initiatives in different fields, among which coastal flooding. Starting from a list of all the funded projects on this topic, it was possible to identify corresponding project managers for the construction of the panel.

As for the geographical distribution of the expert panel in the survey (Figs. A3 and A4), we tried to engage experts according to a well-balanced

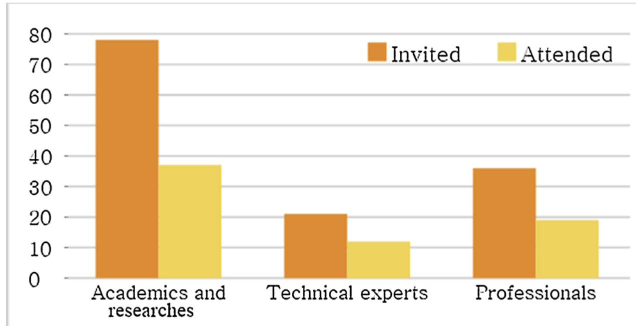

Fig. A1. Composition of the experts' panel in relation to the profession.

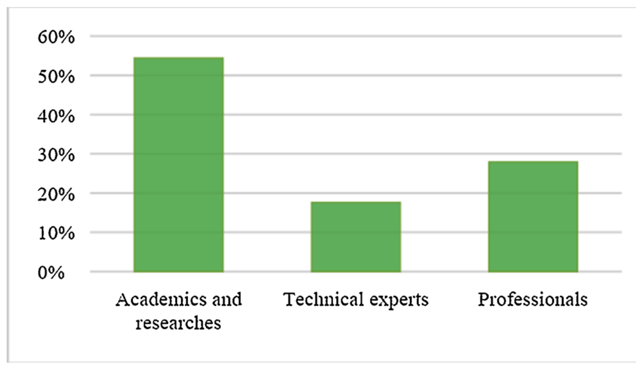

Fig. A2. Distribution % of the attended experts' panel in relation to the profession.

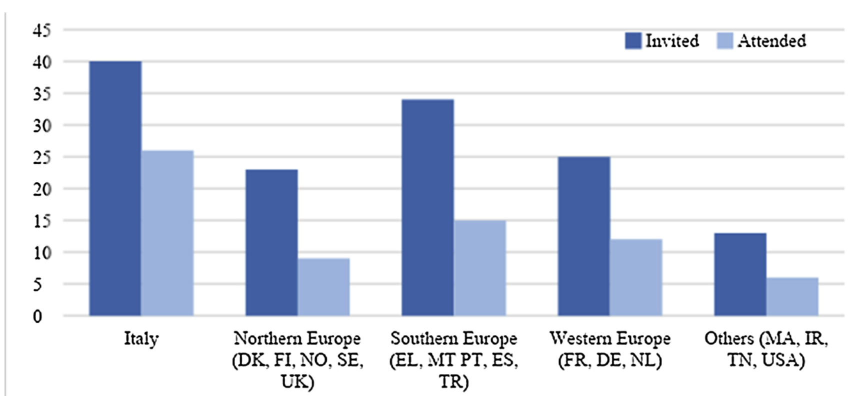

Fig. A3. Composition of the experts' panel in relation to the geographical area.

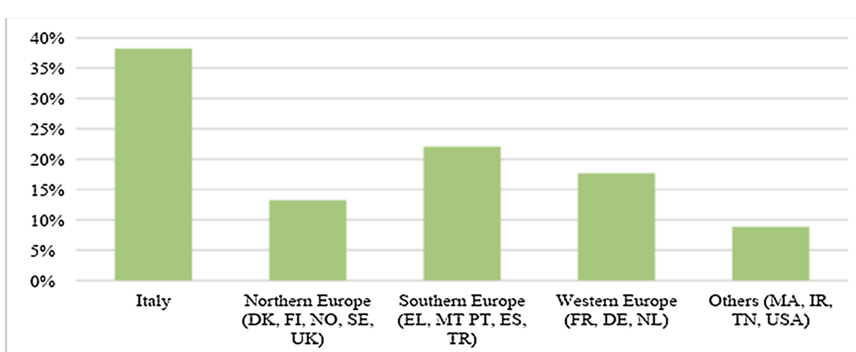

Fig. A4. Distribution % of the attended experts' panel in relation to the geographical area.

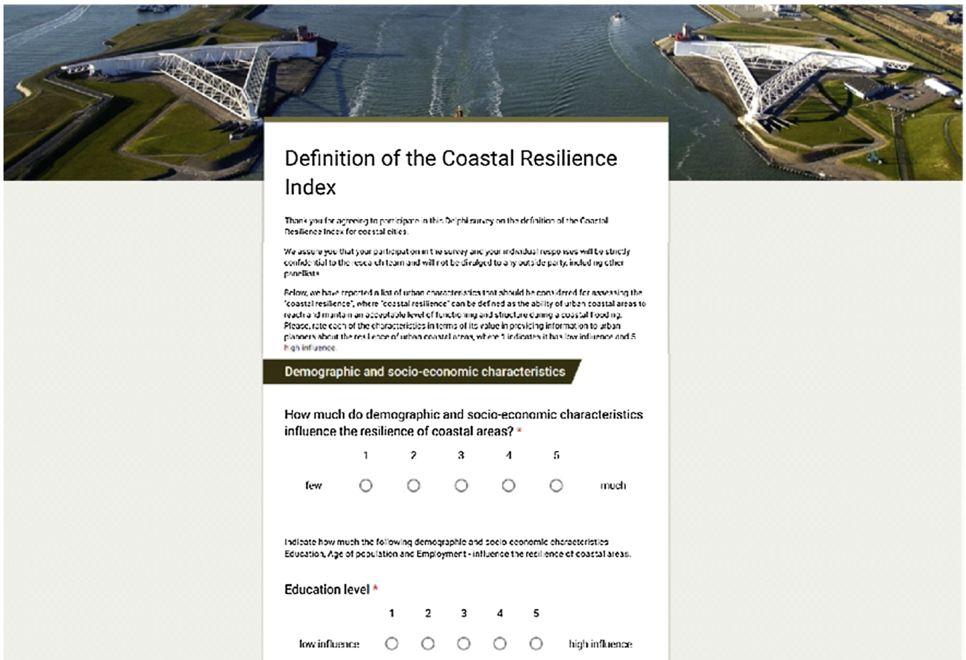

Fig. A5. Screenshot of the first page of the survey.

geographical distribution, however, about 60 % of these experts came from Mediterranean countries. We considered that, in relation to an experimentation of this methodology in an Italian coastal city, it was more appropriate to balance the panel by employing experts who had addressed the topic of Sea Level Rise in this geographical area.

The questionnaire, devised through Google Survey (Fig. A5), included 18 questions. It was presented to experts in the period December 2017-March 2018. It was preceded by a short description of our research objectives.

We also explained that the questionnaire mentioned a set of urban characteristics to consider for assessing “coastal resilience”, where “costal resilience” can be defined as the ability of urban coastal areas to reach and maintain an acceptable level of functioning and structure during coastal flooding.

In the questionnaire, experts were asked to rate each of the characteristics in terms of its value in providing information to urban planners about the resilience of urban coastal areas (where 1 indicates it has low influence and 5 high influence). The characteristics the experts had to rate were those previously defined through the study of related scientific literature and adaptation plans. (see Table 3 of the paper).

Moreover, experts were also asked to point out other important urban characteristics that had not been included in the questionnaire, explaining why they should be included. They were also asked to indicate the characteristics they would eliminate.

The data collected through the questionnaire were developed using the pairwise comparison matrix to calculate the weights of each indicator (see Section 2 of the paper).

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