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Urban Coastal Systems and Coastal Flooding
A GIS-based tool for planning climate-sensitive cities

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To Who struggle every day to do what they believe in,
To "Strangers" who gave me confidence and self-esteem,
To Who sincerely believed and believe in me,
To Eyes of me who know.

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Section 1. Executive summary

1.1 Executive summary

Climate change is one of the main future global challenges and in this context cities play a key role. If, on the one hand, cities cause climate change, then the other hand, they are the places where the impacts of climate change principally appear and affect the quality of life of its inhabitants.

In 2013, the "EU Strategy in adaptation to climate change" adopted by the European Commission (2013a) highlighted the importance of adaptation to climate impacts and has supported it through the promotion of initiatives on urban scale, including the Covenant of Mayors for Climate and Energy. In particular, among several topics, EU Strategy paid attention to the issue of the protection and adaptation of coastal areas. In fact, these areas are characterized by a higher concentration of buildings and people in comparison to inland areas. Therefore, these characteristics make coastal cities more vulnerable to the impacts of climate change. In particular, one of the forecasted impacts of climate change in these areas is the increase of coastal floods due to rising sea level and storm surges.

According to the Staff Working Document (SWD), named "Climate change adaptation, marine and coastal issues, attached to the EU Strategy", no-adaptation of coastal areas could cost an average of €25 billion per year to the European Union (European Commission, 2013b). Therefore, the implementation of strategies and actions for the adaptation of urban areas to the impacts of coastal flooding is essential for guaranteeing the liveability of coastal communities.

In this context, urban planning plays a key role in urban adaptation. However, even though the interest in this topic is increasing, operative support and tools for planning urban adaptation for cities are in short supply, especially for coastal cities. In light of this, it seems necessary to focus attention on the definition of new tools that can respond to the needs of urban planning. Moreover, the adoption of new technologies and the availability of new free data sources in urban planning can enhance the opportunity to support decision-making processes.

From the literature review, it arises that urban adaptation has been mainly based on the concept of vulnerability, so far. Indeed, several vulnerability indices have been developed for supporting decision makers in the adaptation of coastal areas to coastal floods, especially on the territorial level. However, the vulnerability concept concerns specific territorial and urban aspects, mainly geomorphological and social ones. Therefore, the use of vulnerability indices could not provide valid support for the definition of urban adaptation measures to implement in a coastal area from an urban planning perspective.

Even the analysis of the urban practices (i.e. adaptation strategies/plans) highlights that a sectoral approach has been used for the definition of urban adaptation measures on the urban level. Indeed, due to the adoption of this approach, urban adaptation measures mainly refer to the physical features (buildings, infrastructure, etc.) of urban coastal areas.

Based on these observations, the purpose of this research work has been to the develop a new decision support tool for increasing resilience of coastal cities. In particular, by using the main technological innovations applied to urban planning (in particular, the Geographic Information Systems), this tool aims to support the decision-making process through the definition of the urban measures for reducing the impacts of coastal flooding due to rising sea levels and storm surges. From an urban planning perspective, it was necessary to adopt a holistic-system approach. Therefore, according to McLoughlin (1969), the coastal city was interpreted as a system that is composed of four subsystems: socio-economic, physical, functional and geomorphological.

For what concerns the development of the GIS-based tool, a four-phase methodology was defined. The first step was the definition and development of a new composite index for evaluating "urban coastal resilience" on the local level, named Coastal Resilience Index (or CoRI). It is the weighted linear combination of twelve urban variables, which were defined according to the holistic-system approach. Furthermore, in order to calculate the variables' weights, the Analytic Hierarchy Process (AHP), supported by the Delphi Method, was used. In particular, from the definition of the CoRI, it is highlighted that the geomorphological, physical and functional indicators play an important role in the definition of the composite index, while socio-economic variables influence the overall evaluation less than other ones. In the second step, since the urban adaptation measures should be defined in relation to physical and functional characteristics of the urban context, a classification of urban coastal areas was introduced, by specifying Urban Coastal Units (UCUs). According to this classification, the identified urban coastal typologies are six: Compact Urban Areas (e.g. historic centres), Mono-functional and Facility Urban Areas (e.g. harbours), Medium and low-density Residential Areas, Tourist Facility Areas, Potential Development Areas (e.g. brownfields), Natural Coastal Areas (e.g. wetlands). Considering the CoRI levels and the UCU classification, in the third phase, the four classes of Urban Adaptation Actions have been defined. Starting from the coastal adaptation approaches defined by the IPCC (Nicholls et al., 2007), a matrix that puts in relation the Urban Adaptation Actions classes with UCUs and CoRI levels has been developed. In particular, the definition of this matrix is based on a specific principle: "the higher CoRI the fewer are the Urban Adaptation Actions, and vice versa". In relation to these three main phases and considering the potentialities of GIS applications in urban planning, in the last phase, a design workflow for developing the GIS-based tool was defined.

Based on this workflow, the GIS-based tool was implemented and applied to a study area in the city of Naples. In particular, the identification of the potential coastal floodplains of Naples was useful for selecting the study area, localized in the eastern part of the city. Hence, the data input of the area chosen for the tool's implementation were collected. According to the methodology, the GIS-based tool was developed in three parts. In the first part, the Coastal Resilience Index Tools toolbox was implemented for mapping the CoRI of the study area. After that, the Urban Coastal Units Tools toolbox was constructed for the classification of the study area in UCUs. Finally, the CoRI and UCUs' maps were used for identifying the four classes of Urban Adaptation Actions by the Urban Adaptation Actions Tools toolbox. From the application of the tool to the study area, the main findings were the following ones. About the CoRI map, the study area is characterized by the presence of urban areas with medium-low resilience levels (61% of the study area) and by the absence of urban areas with high resilience levels. About the UCU map, a high physical and functional complexity of the urban area and the absence of natural areas (or UCU 6) are noted. Regarding the Urban Adaptation Actions map, due to the absence of urban areas characterized by high resilience levels, all the UCUs need to enhance their resilience level through the implementation of fitting urban measures. In particular, in the majority of the area (about 61%), urban transformations should be addressed towards the realization/improvement of protection infrastructure systems, the use of resilient design standards at building scale and the reduction of land-use intensity through the delocalization of critical facilities in the proximity of the coastline.

Finally, thanks to the use of open data sources, the developed tool could also be used in other urban coastal contexts. Furthermore, decision-makers could use it for both monitoring the resilience status of urban coastal areas, but also for programming and monetizing future urban transformations and evaluating the synergies among the different interventions on the territory in order to minimize the use of (economic) resources for their implementation.

1.2 Dissertation structure

The dissertation is structured into five sections. The first part provides a review of the main researches on this topic and, specifically, on the tools developed for urban adaptation and the analysis of the main urban adaptation measures, which are possible to implement in coastal cities to reduce the impacts of coastal flooding. In particular, Section 2 provides a review of the main coastal vulnerability indices in order to investigate which urban factors affect the response action of cities to coastal flooding and which are the main research gaps from an urban planning perspective. In order to study the relationships between urban coastal characteristics and the adaptation measures in depth, Section 3 illustrates the most innovative adaptation strategies/plans provided by six coastal cities. It also provides a framework on how urban adaptation measures are defined in relation to the urban characteristics of the coastal area where they should be implemented.

Based on the findings from the literature review and the analysis of urban adaptation strategies/plans, Section 4 introduces the research aim. In particular, in the section, the methodology developed for the development of the tool is illustrated. As such, the methodology is articulated into four phases: (1) definition of a new composite index for measuring the urban resilience of coastal cities; (2) classification of urban coastal areas in relation to their physical and functional characteristics; (3) definition of classes of urban adaptation measures; and, (4) definition of a design workflow for the implementation of the GIS-based tool.

In Section 5, the defined methodology is used to develop the GIS-based tool. In particular, the tool is applied to a coastal zone in the city of Naples (Italy). Hence, the obtained results are discussed in light of both the direct knowledge of the study area, as well as the developed methodology and the technical limitations of the developed tool.

Finally, Section 6 illustrates a summary of the main results obtained and provides some concluding remarks about the research works. Furthermore, the section highlights also the main limitations of the research work and introduces some potential directions for future research developments.

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Section 2. Coastal Cities and Coastal Flooding:
a literature review

2.1 Introduction

Climate change is considered the major global challenge of this century. It is assuming an increasingly key role both at academic and institutional level. As highlighted in the last thirty years by the Intergovernmental Panel on Climate Change (IPCC), the increase of GHG emissions is causing a heating of the climate system with evident consequences on people, the environment, economic activities and on cities. In the last report on climate change, the IPCC developed four climate scenarios - the Representative Concentration Pathways (RCPs) - that are RCP2.6, RCP4.5, RCP6 and RCP8.5. Starting from the evaluation of a wide range of scientific and socio-economic data, such as population growth, GDP, land use, energy sources, etc., these scenarios identify GHG concentration trajectories and the future climate variability. However, their goal is not to "predict the future", but to better understand uncertainties and alternative futures in order to take into account a range of possible effective decisions for a better management of climate impacts on Earth and human systems (Stocker et al., 2013). According to the four RCPs, it is possible to articulate the main climate variability into three main phenomena that are:

- increase of 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 of annual mean precipitation at the 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 for climate action. Indeed, cities can be considered the most blameworthy with regards to climate change, since they emit 75% of all carbon dioxide from energy use (Edenhofer et al., 2014), that is one of the drivers of climate change. At the same time, due to the climate variability, extreme climate events are more frequent and hit mainly urbanized areas (Bai et al., 2018). However, thanks to the high concentration of human and economic capitals, cities represent the places where to organize a more effective answer for fighting climate change (Kousky & Schneider, 2003; Rosenzweig et al., 2010; Reckien et al., 2018).

Therefore, researchers and urban planners have started to increase their interest in the analysis of climate change and its impact on the city. In particular, the fight against climate change has been tackled in accordance with two strategies: mitigation[1], which is focused on the climate change

[1] The IPCC defines "mitigation" (of climate change) as "a human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs)", and "[human interventions] to reduce the sources of other substances which may contribute directly

drivers, and adaptation[2], which concerns the impacts of climate change. In the beginning, urban studies were addressed to the first strategy. Indeed, also thanks to the pushing effect of the Rio Agreements (1992) and the Kyoto Protocol (1997), urban studies were mainly focused on the analysis of relationships between urban characteristics and drivers of global GHG emissions in order to identify the most suitable urban solutions to implement.

Nevertheless, when it was clear that despite mitigation the impacts of climate change would have increased due to delayed effects of the preceding GHG emissions, researchers also started to analyse the relationships between urban characteristics and climate impacts on the city according to the adaptation concept. In particular, urban planning research has focused mainly on the relationship between urbanized areas and increases in temperature at local level (urban heat island), as highlighted by the several reviews of the topic (e.g. Berardi et al., 2014; Lo & Quattrochi, 2003), as well as the impacts of increased intensity and frequency of precipitation in cities (Huong & Pathirana, 2013).

Instead, the effects of rising sea levels and, in general, coastal flooding in urban areas have not been deeply investigated thus far. In comparison to the other climate effects, coastal flooding represents a serious risk for cities (Conticelli & Tondelli, 2018). Major cities, indeed, are settled on low-lying coastal areas (Nicholls, 2004) and about two-thirds of the world's major cities are located in these zones (McGranahan et al., 2007). Because of their high accessibility and the presence of several resources, besides high population density, these areas are characterized also by a high concentration of socio-economic activities. According to some studies (i.e. Jongman et al., 2012; Neumann et al., 2015), it estimates that population and economic activities in these areas will go on to increase in the future. In light of this, because of these factors, in the future these areas are particularly threatened by forthcoming coastal flooding due to both the forecasted rise in sea levels, as well as storm surges. While coastal flooding due to rising sea levels may cause permanent land losses, storm surges can cause more damage in low-lying areas (Kaiser, 2006). Moreover, the forecatsed rise in sea levels will contribute to increase the coastal flooding impacts due to storm surges (Wahl, 2007). 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. In this sense, adaptation planning of coastal cities for reducing externalities due to coastal flooding gains a strategic meaning for the future liveability and quality of life in these zones (Hunt & Watkiss,

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or indirectly to limiting climate change, including, for example, the reduction of particulate matter emissions that can directly alter is the radiation balance (e.g., black carbon) or measures that control emissions of carbon monoxide, nitrogen oxides, Volatile Organic Compounds and other pollutants that can alter the concentration of tropospheric ozone which has an indirect effect on the climate".

[2] According to IPCC (2014), "adaptation" is "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects".

2011). However, as highlighted by Hurlimann et al. (2014), urban planning has yet to face a more complex challenge for the adaptation of urban coastal areas since its aim will be to take into account the urban needs of growth, equity and sustainability despite a lack of habitable land.

Until now, the literature concerning the urban adaptation to coastal flooding has been interpreted from an economic point of view by evaluating the convenience of limited adaptation options (including protection infrastructure, land use changes or retreatment) (Hinkel & Klein, 2007; Nicholls et al., 2007; Vafeidis et al., 2008). Over the last thirty years, several indices were developed to assess the vulnerability of coastal systems to natural hazards, including coastal flooding. Indeed, the use of vulnerability indices is one of the possible "means" for understanding possible risks and defining the relative adaptation strategies and measures (Carter et al., 2015).

According to Füssel (2007), there are two main approaches for the development of adaptation to climate change impacts and they are based on the concepts of hazard and vulnerability. On one hand, the adaptation developed according to the hazard-based approach is mainly focused on the use of climate models and does not consider non-climatic factors, in particular social and economic aspects. The vulnerability-based approach, indeed, has a strong focus on the social factors and it can be useful in absence of reliable impact projections (Füssel, 2007). In relation to their characteristics, these two approaches can be considered complementary, even if the most common approach used for the urban adaptation is the vulnerability-based one, which takes into account several factors for reducing the climate risks. In order to face the climate challenge in a more effective way, in recent years the "resilience" concept has been associated to adaptation (Leichenko, 2011; Carter et al., 2015). Although the use of the term resilience has increased, the description of what it means is often lacking. 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" (Mach et al., 2014). 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 with coastal cities, their adaptation is still based on the vulnerability concept and its assessment of these areas. In this way, coastal vulnerability assessments enable one to identify which vulnerability factors influence adaptation response. With regards to resilience, this concept is mainly taken into account for the identification of adaptation solutions (see Section 3).

With regard to the vulnerability assessment, several tools were developed, including Decision Support Systems (DIVA by DINAS COAST Consortium, 2006), spatial mappings, etc. In particular, among the vulnerability assessment tools, the vulnerability indicators and indices are the most widely used. As highlighted by some authors (i.e. McLaughlin & Cooper, 2010), vulnerability indices aim to simplify a number of complex and interacting parameters to a synthetic form that is more readily understood. Therefore, vulnerability indices have a great utility as management tools. In particular, the parameters defined by each index allows one to identify which characteristics affect mainly the "coastal vulnerability". However, vulnerability indices have a restricted use in urban planning due both to their purpose not always being suitable with the urban practice, but also for the territorial scale to which they refer. In this sense, as well as providing an interesting picture of how the "coastal vulnerability" topic has evolved, the analysis of these indices represents an interesting knowledge basis for developing new decision-making tools in urban planning in order to support the adaptation of urban coastal areas to storm-surge flooding events.

In this sense, starting from the complexity of urban coastal systems and the uncertainty of future climate impacts, this section provides a review of the main coastal vulnerability indices in order to investigate which urban factors affect the response action of cities to coastal flooding and which are the main research gaps from an urban planning perspective.

This section is structured as follows: paragraph 2.2 presents the methodology used for the review; paragraph 2.3 describes the analysis conducted on the selected studies according to the methodology; finally, paragraph 2.4 illustrates the main findings of the literature review and lists the main research gaps of the topic in the field of urban planning.

2.2 Methodology of the literature review

Nowadays, in the literature several studies are focused on the definition of methodologies and tools for assessing the coastal vulnerability. An interesting review about it can be find in Nguyen et al. (2016). Despite the 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. In order to understand this topic more deeply, it is necessary to take into account the complexity of urban coastal systems. Indeed, coastal cities are characterized by the complexity and dynamism of both urban systems (Batty, 2008; Papa, 2009) and coastal systems (Balica et al., 2012; Hopkins et al., 2011; Nicholls et al., 2007). In general, due to their numerous interactions (including, land-sea interaction) and overlapping scales, coastal zones can be considered examples of stressed complex systems. In particular, since urban areas settled along coastline produce an abnormal burden on the surroundings natural systems, the study of these areas on a local scale could offer "an experimental microcosm" for the development of methods for improving sustainability in strongly open systems (Hopkins et al., 2011), among which it is also possible to consider coastal cities.

Therefore, adopting an urban system perspective for the study of coastal cities could allow the consideration for not only its double nature system, but also all those elements that influence this system and continue to operate it even if subjected to shocks or stresses (da Silva et al., 2012).

Based on these considerations, this review combines the developed vulnerability indices in order to investigate which are the most relevant coastal characteristics that can have implications on an urban scale. Using a holistic-system approach, in the review the characteristics of each coastal vulnerability index were classified into four categories that are: (i) socio-economic characteristics; (ii) physical characteristics; (iii) functional characteristics; and, (iv) geomorphological characteristics. Such classification is inspired by the General System Theory by von Bertalanffy (1969) applied to the study of urban phenomena (Gargiulo & Papa, 1993). In particular, each group of characteristics reflect one of the four urban subsystems, which composes the overall urban subsystem (Papa, 2009): socio-economic-subsystem; physical subsystem; functional subsystem; and, geomorphological subsystem. In particular, socio-economic characteristics refer to inhabitants and people that conduct activities in the area including all the factors that describe both social and economic aspects of the system.

The second category of physical characteristics include all the elements that compose the built environment (buildings, open spaces, etc.) which are accommodated in order to host all the different types of human activities. Functional characteristics refer to those variables that describe the type, the scale and the localization of urban activities on the territory in order to also guarantee their accessibility. Finally, the last category –geomorphological characteristics – includes all the factors that allow describing geographic aspects of the system.

In this review, according to this approach, the most widespread and used vulnerability indices for coastal areas were analysed. In particular, starting from a research on the Scopus database, several vulnerability indices were detected. The majority of these indices represent an adaptation of already existing vulnerability indices. Those indices are applied and/or adapted to different territorial contexts in comparison with the original application. Therefore, this review is focused on the analysis of a selection among the detected vulnerability indices. In detail, they were chosen among ones that are the main references used for the development of other vulnerability indices in the literature (Table 1).

After their selection, each index was analysed according to the following criteria: (i) analysis of indices' parameters according to the aforementioned approach; (ii) analysis of the weighting and aggregation method of parameters; and, (iii) analysis of the territorial scale of interest. Since this study is focused on analysing the relationships between coastal cities and coastal flooding, the analysed coastal vulnerability indices have been further classified with respect to the vulnerability approach and according to the hazard driver of coastal flooding.

Index Name	Authors
Coastal Vulnerability Index (CVI)	Gornitz et al., 1991
Sensitivity Index (SI)	Shaw et al., 1998
Coastal Vulnerability Index (CVI)	Thieler & 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 & Woodroffe, 2010
Coastal Vulnerability Index (CVI)	McLaughlin & Cooper, 2010
N.A.	Tate et al., 2010
Coastal Vulnerability Index (CVI)	Li & 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-Gonclaves et al., 2014
Socio-Environmental Vulnerability Index for a Coastal Areas (SEVICA)	Zanetti et al., 2016

Table 1. Vulnerability indices selected for the review

Moreover, this study is dealt with from an urban planning perspective. Hence, in this review the climate variables taken into account in the vulnerability indices have been excluded from the analysis.

According to Wu et al. (2002) and Zanetti et al. (2016), it is possible to distinguish three main approaches to vulnerability. The first one – named geophysical-vulnerability approach - identifies vulnerability with the exposure to a hazard. Therefore, vulnerability is assessed by the measurement of physical and geomorphological variables, (e.g. proximity to the source of hazard, incident frequency/probability, magnitude, etc.).

The second perspective – named social-vulnerability approach - is focused on potential coping ability of individuals and communities. In this case, social features assume a key role in the definition of vulnerability. Finally, based on the model by Cutter et al. (2000), the last approach integrates the previous ones. It is known as place-vulnerability (or socio-environmental) approach and considers both geomorphological and social characteristics that can influence the vulnerability of a geographic context. A further interpretation based on this last approach is the concept of "contextual vulnerability" by O'Brien et al. (2007), and takes into account not only the biophysical and socio-economic conditions but also the political and institutional ones, in the context of where to operate.

Since the analysed indices do not consider the same coastal hazard, another classification of studies is introduced. In general, it is possible to distinguish coastal flooding in relation to two main drivers, storm surges that are episodic inundation events, and rising sea levels that can cause a permanent inundation of coastal areas. Actually, these drivers are interconnected since the forecasted rising sea levels inevitably increase the frequency and intensity of storm surges, and, consequently, of coastal flooding. In light of this, the selected indices are classified into three groups, referring to coastal flooding due to (i) sea-level rise, (ii) storm surges and (iii) both drivers.
In Table 2, the analysed indices are classified according the three vulnerability approaches and the hazard drivers of coastal flooding.

Hazard Driver / **Vulnerability Approach**	**Sea-Level Rise**	**Storm Surges**	**Sea-Level Rise and Storm Surges**
Geophysical	Karymbalis et al., 2012		Gornitz et al., 1991 Shaw et al., 1998 Thieler & Hammar-Klose, 1999 Abuodha & Woodroffe, 2010
Social			Cutter et al., 2003 Guillard-Gonçalves et al., 2014 Tate et al., 2010
Socio-environmental	Zanetti et al., 2016	Li & Li, 2011	Wu et al., 2002 Boruff et al., 2005 Kleinosky et al., 2007 Preston et al., 2008 McLaughlin & Cooper, 2010 Balica et al., 2012

Table 2. Studies of the coastal vulnerability indices categorized by vulnerability approach and hazard driver

2.3 Results and discussion

Before describing the review results carried out on the coastal vulnerability indices, it is useful to highlight how the analysed studies define the vulnerability concept, and which definition of vulnerability they adopt. The definition of vulnerability, indeed, has meaningful implications for the structure of the indices. Therefore, it is necessary to understand this aspect more deeply.

An interesting analysis can be carried out starting from the three vulnerability approaches aforementioned. In particular, in relation to the geophysical approach, it is noted that the concept of sensitivity is replaced by one of vulnerability in some cases (i.e. Abuodha & Woodroffe, 2010; Karymbalis et al., 2012; Shaw et al., 1998). Sensitivity specifically refers to the susceptibility of coastal areas to seaward hazards, in particular to the action of rising sea levels. The use of the sensitivity concept is useful in distinguishing the aim of the index, since vulnerability-based assessments concern the socio-economic factors of coastal areas, while sensitivity-based ones on the geophysical ones (Abuodha & Woodroffe, 2010). Other researches (i.e. Gornitz et al., 1991; Thieler & Hammar-Klose, 1999) do not consider a specific vulnerability concept, even if vulnerability assessment can be related to the identification of coastal areas at risk to future sea-level changes.

With regard to the socio-vulnerability approach, Cutter et al. (2003) examined it in depth. In particular, they define the social vulnerability as *"a multidimensional concept that helps to identify those characteristics and experiences of communities (and individuals) that enable them to respond to and recover from environmental hazards"*. According to this definition, since the definition of social vulnerability is independent from the geography of areas and from the type of hazard, it was applied for different purposes and to different territorial contexts, including coastal areas (i.e. Guillard-Gonçalves et al., 2014; Tate et al., 2010).

Regarding the approach based on the socio-economic vulnerability, with the exception of the studies by Wu et al. (2002) and Zanetti et al. (2016), the analysed research focus their attention on the definition of coastal vulnerability with respect to specific hazards (for example, storms, climate change, etc.). Such a definition, indeed, provides a sound conceptual reference for the construction of the vulnerability indices of coastal areas. In particular, Preston et al. (2008) introduces a definition of coastal vulnerability to climate change. In detail, it is defined as a function of changes in sea levels combined with the inherent variability of dynamic coastlines caused by tidal ranges and weather patterns. In particular, according to IPCC's 2001 definition (McCarthy et al., 2001), the coastal vulnerability model is characterized by three factors, exposure, sensitivity, and adaptive capacity.

While exposure is driven by interactions between the climate system and the coastal topography, sensitivity is a function of assets and infrastructure within the area. Finally, adaptive capacity depends on material and social capitals. In addition, Kleinosky et al. (2007) adopt the same definition and state that assessing vulnerability means exterminating a "system" under stress and its ability to respond to such stress. Balica et al. (2012) also consider a systemic approach. In particular, in their study vulnerability is defined as "the extent of harm" and is a function not only of exposure but also of susceptibility and resilience in comparison to the IPCC's definition.

McLaughlin & Cooper (2010) define coastal vulnerability as a function of three components that are coastal characteristics, coastal forcing and socio-economic factors. In particular, coastal characteristics represent the physical nature of the coast, while coastal forcing expresses the frequency and magnitude of perturbation. Finally, the last component refers to the degree of impact on human activities due to coastal morphological changes. Concerning storm surges, Li & Li (2011) propose a definition of coastal vulnerability as the "*capacity to be wounded*"; the degree to which a system is likely to experience harm due to exposure to storm surges. From this definition, it arises that the study assumes a systemic approach to the vulnerability assessment, taking into account five components: socio-economic, land use, eco-environmental, coastal construction and disaster-bearing capability.

As aforementioned, Wu et al. (2002) and Zanetti et al. (2016) do not consider a specific definition of vulnerability. However, they state to adopt a socio-environmental-vulnerability approach. In particular, while Zanetti et al. (2016) try to provide an integrated perspective to vulnerability studies in relation to rising sea levels, Wu et al. (2002) combine physical and social vulnerability for understanding how the overall vulnerability of a coastal area may change in relation to the future coastal flooding intensified by climate change.

2.3.1 Analysis of indices' parameters

According to the aforementioned approach, characteristics that vulnerability indices take into account can be articulated into four categories - socio-economic, physical, functional and geomorphological.

Socio-economic characteristics

Except for geophysical vulnerability indices, in general, coastal vulnerability indices take into account socio-economic characteristics of coastal communities. As aforementioned, for a long time, the vulnerability assessment has been interpreted from a socio-economic perspective. Despite the vulnerability indices currently being developed by adopting a greater integration between geophysical and social components of coastal areas, socio-economic characteristics are numerous and they play a key role in the definition of vulnerability indices.

The basic parameters for measuring the socio-economic characteristics of coastal areas are total population (i.e. Balica et al., 2012; McLaughlin & Cooper, 2010; Wu et al., 2002) and population density (i.e. Li & Li, 2011; Preston et al., 2008). In particular, according to Zanetti et al. (2016), a higher population density corresponds to a higher level of vulnerability in the area. High population density, naturally, complicates evacuation during a hazard (Cutter et al., 2003). A similar parameter to population density is future population growth. Measuring population growth enables the consideration and magnitude of future challenges for coastal management and hazard mitigation (Preston et al., 2008). However, the most common socio-economic characteristics that vulnerability indices take into account refer to other population structure features, in particular, age, ethnicity, education and gender.

The analysed study considers the population age as a characteristic that highly influences the vulnerability of coastal areas. According to Cutter et al., (2003), young and old people may have mobility issues during a hazardous event and may affect the movement of other people out of harm's way. However, even if children and elders are considered the most vulnerable part in a population, the researchers do not agree on which are the most exposed age groups to hazard. In detail, the vulnerable elderly population varies between over 60 (Wu et al., 2002; Zanetti et al., 2016) and over 65 (Balica et al., 2012; Boruff et al., 2005; Cutter et al., 2003; Guillard-Gonçalves et al., 2014) years old, while the young population varies between under 5 (Boruff et al., 2005; Cutter et al., 2003; Zanetti et al., 2016) and under 12 years (Balica et al., 2012; Preston at al., 2008) until 18 years (Wu et al., 2002). Sometimes, in some studies (e.g. Kleinosky et al., 2007), the elderly population is associated or identified with people with disabilities or special needs, since this population category may find particular difficulties during disasters, especially during recovery. The presence of different races may negatively influence the vulnerability of a community because there are language and cultural barriers that reduce the effectiveness of awareness-and-preparedness policies to disaster, especially if these people live in areas at-risk (Cutter et al., 2003). However, according to some studies (i.e. Boruff et al., 2005; Cutter et al., 2003; Kleinosky et al., 2007) the age composition of a population affects the vulnerability of an area more than its ethnicity composition.

The opportunity of preparing and informing people is strictly linked to their education level. If population is characterized by a high education level, it has more capacity to understand warning information and access to recovery information. In several studies (i.e. Boruff et al., 2005; Cutter et al., 2003; Guillard-Gonçalves et al., 2014) it arises that education levels do not seem to meaningfully influence the vulnerability levels of territory. On the other hand, Tate et al. (2010) highlight that education level is a factor that can positively influence the reduction of vulnerability levels. In some studies, another characteristic that can influence the vulnerability of a community is gender. In particular, this characteristic is taken into account in terms of gender differences among men and women. The female population, indeed, is considered more vulnerable than the male one. Despite being more responsible, especially in the family care, women tend to have lower incomes. However, not all studies agree on how and if such a characteristic can influence vulnerability assessment. In addition, while Guillard-Gonçalves et al. (2014) highlight that the female population influences vulnerability and is positively correlated to it, according to Cutter et al. (2003) it does not appear to be particularly significant.

In addition to the characteristics of population structure, coastal vulnerability indices also pay particular attention to the economic characteristics of communities. In particular, considering the parameters of the analysed indices, it is possible to distinguish three types of characteristics: income, community wealth, and employment. The indices adopt several parameters for measuring the population income. Some of them refer to the ownership of a home (Preston et al., 2008) or its rent (Wu et al., 2002). They also consider the dependence of people to social services for survival (including, Cutter et al., 2003; Guillard-Gonçalves et al., 2014; Preston et al., 2008; Tate et al., 2010), as well as the population income (Cutter et al., 2003; Li & Li, 2011; Zanetti et al., 2016). As highlighted by Cutter et al. (2003) and Guillard-Conclaves et al. (2014), personal wealth negatively affects the overall vulnerability since it enables communities to better cope and recover from losses. Concerning the wealth characteristic, it refers to the gross value generated by economic activities that are located on the territory. It is mainly measured as output value per capita of a specific economic activity (i.e. agriculture, industry, commerce, etc.) (Li & Li, 2011; Preston et al., 2008). In particular, the most vulnerable economic activity in the case of natural hazards is agriculture, since it is strictly correlated to climate conditions (Cutter et al., 2003). Finally, employment (or occupation) is considered an important component of vulnerability in literature. In particular, as highlighted by Cutter et al. (2003) and Guillard-Concalves et al. (2014), even if these studies consider both percentages of the unemployed and employed within a population, the employed population is considered as the parameter, which principally affect vulnerability of a community, in particular, slowing the recovery phase from a disaster.

Physical characteristics

Among the analysed indices, physical characteristics of coastal areas are not always taken into consideration. In particular, considering the three approaches to vulnerability, indices based on social and socio-environmental vulnerability are much more focused on these aspects, while physical characteristics are completely absent in the definition of geophysical vulnerability (and sensitivity) indices. According to Preston et al. (2008), a great accumulation of buildings, infrastructure and wealth in close proximity to coastline corresponds to a greater risk of being affected by future seawards hazards, including coastal flooding. In this sense, a first characterization is to distinguish urban areas from rural areas. Some vulnerability indices introduce a land use variable that enables the identification of urbanized zones (i.e. McLaughlin & Cooper, 2010; Preston et al., 2008; Wu et al., 2002).

In order to measure the degree of urbanization, specific variables are considered in some pieces of research. For example, some vulnerability indices take into account the concentration (including Boruff et al., 2005; Wu et al., 2011) and the quality of housing units (Cutter et al., 2003; Guillard-

Concalves et al., 2014; Tate et al., 2010) as variables. In particular, a lower housing quality corresponds to a higher vulnerability of analysed areas. Li & Li (2011) and Preston et al. (2008) introduce also road density as a physical variable that is associated with a greater degree of urbanization degree in coastal regions.

Besides the degree of urbanization in coastal areas, some of the analysed studies also consider the coastal protection degree provided by the presence of specific infrastructure. In particular, Li & Li (2011) identify specific variables that refer to tide-prevention engineering structures, including seawalls. Besides the presence of flood protection infrastructure along the coastline, Balica et al. (2012) introduce the density of drainage canals considering that a higher drainage density and presence of coastal protection infrastructure reduce the vulnerability of coastal areas.

Functional characteristics

As for the physical characteristics, also the functional ones are mainly considered by social and social-environmental vulnerability indices. In particular, from the analysis of vulnerability indices, it is possible to identify three main functional characteristics: the first one refers to land use type, the second one to the transport network, and the last one to the presence of critical facilities and public utilities in the area.

Concerning the land use type, many of the analysed studies shows that vulnerability assumes a different degree in relation to the activities established in the area. The analysis of the land use is based on an economic evaluation, since the damage to an economic activity can influence the economy of a community. In general, since several land-use types characterize cities, they represent the most vulnerable areas of coastal zones. In particular, according to Cutter et al. (2003) and Boruff et al. (2005), a higher presence of commercial establishments increases the social vulnerability, while Zanetti et al. (2016) consider industrial areas as the most vulnerable land-use type. Another aspect that can be linked to the land use of a coastal area is the presence of areas, especially natural ones, subjected to specific protection conditions that can increase coastal vulnerability at regional level (McLaughlin & Cooper, 2010; Preston et al., 2008).

Another characteristic that influence the coastal vulnerability is the presence of transport infrastructures. In detail, roads and railways can be considered as vital lines of communication and the main medium transport in a coastal area (Cutter et al., 2003; McLaughlin & Cooper, 2010). Therefore, transport infrastructure should be well located, in relation to its proximity to the coastline, to ensure that the right localization of this infrastructure allows an at-risk area to function even in the event of flooding and, thus, to reduce its vulnerability levels.

With regard to the last characteristic, some vulnerability indices also pay attention to the presence of specific urban functions on the territory. In particular, a high concentration of critical facilities and public utilities increases vulnerability levels in the area where these functions are localized. In particular, vulnerability indices take into account critical facilities that are useful for the emergency management. For example, Cutter et al. (2003), Guillard-Gonçalves et al. (2014) and Tate et al. (2010) identify only one type of critical facility, which is medical services, while Kleinosky et al. (2007) consider more categories of facilities (schools, fire and rescue stations, solid waste facilities, water treatment facilities, etc.). Besides these facilities, McLaughlin & Cooper (2010) impose cultural heritage as a factor that can affect negatively vulnerability levels in a coastal areas. However, unlike other facilities mentioned above, cultural heritage assumes an economic value that can be lost in the case of a coastal hazard.

Geomorphological characteristics

As well as socio-economic, geophysical characteristics are also a relevant component in the development of the coastal vulnerability indices. As aforementioned, for a long time coastal vulnerability has been quantified through variables related to the geophysical and geomorphological aspects of coastal areas and aggregated to climatic variables that measured the frequency and magnitude of a specific coastal hazard. However, since this analysis is carried out from an urban planning perspective, in these paragraphs the main geomorphological characteristics introduced in the geophysical and socio-environmental vulnerabilities indices will be analysed.

In most of the analysed indices, it is noted that geometric characteristics of coastal areas take on particular importance. Indeed, even though Gornitz et al. (1991) introduced the relief (or coastal elevation), subsequently this parameter has been replaced by the coastal slope, which is one of the most frequent parameters in the analysed indices, including Abuodha & Woodroffe, (2010), Karymbalis et al. (2012), Thieler & Hammar-Klose (1999) for the geophysical vulnerability indices, and Balica et al. (2012), Preston et al. (2008) and Zanetti et al. (2016) for the socio-environmental ones. In particular, all the studies agree that the lower the coastal slope is, the greater its vulnerability. However, they do not agree on the definition of specific reference values (or of a function) for measuring vulnerability in relation to this parameter. Furthermore, these considerations are also applicable to the elevation parameter.

An important role is also assumed by the coastal geomorphological and morphodynamic characteristics. In particular, unlike the socio-environmental vulnerability indices, sensitivity indices always take into account geomorphology. Since geomorphology is measured as a qualitative variable, all the researchers, except Shaw et al. (1998), agree that beaches are more vulnerable than rocky and cliffed coasts. Some indices also take into account the shoreline orientation (Abuodha & Woodroffe, 2010; McLaughlin & Cooper, 2010), while only sensitivity indices consider the shoreline change parameter that assumes values in a range from -1,0 (e.g. Shaw et al., 1998) to -2,0 m/year (e.g. Abuodha & Woodroffe, 2010; Gornitz et al, 1991) of coastal erosion for high vulnerability. Furthermore, Gornitz et al. (1991) and Balica et al. (2012) identify two other parameters in relation to coastal morphodynamic characteristics related to shoreline vertical movement and soil subsidence respectively. Concerning the rock type, it refers to the geological characteristics of the coast and represents an important parameter for both sensitivity and vulnerability indices. As for the geomorphology, it is also expressed as a qualitative variable and the majority of analysed studies (i.e. Gornitz et al., 1991) agree that the most vulnerable kind of geological stratification is composed of fine unconsolidated sediments.

It is interesting to note that the socio-environmental vulnerability indices have introduced new parameters in comparison to the sensitivity indices. One of these is the distance to the coastline. In particular, a buffer distance from the coastline is set to identify the most vulnerable areas. This buffer is 500 m as a reference value for coastal vulnerability at the regional scale (McLaughlin & Cooper, 2010) and 10 m as a reference value at the local scale (Zanetti et al., 2016). Another parameter concerns the presence of rivers along the coastal area. In particular, the presence of water bodies can increase the vulnerability of coastal areas. In particular, McLaughlin & Cooper (2010) evaluate this aspect by adopting a dichotomous variable (absence/presence), while Zanetti et al. (2016) defines a reference value equal to a distance not over 10 m.

2.3.2 Analysis of weighting and aggregation methods of vulnerability indices

In relation to their theoretical framework, each vulnerability index adopts an aggregated and weighted method.

With regards to the weighting methods, they express the contribution and the relative importance of individual indicators/parameters in a system (Nguyen at al., 2016). One of the weighting techniques is to give the same weight to all the variables (*equal weighting*). It can be used if there is an insufficient knowledge of the relationships among the variables. Applying this method, indeed, could generate an unbalanced structure in the composite index (JRC, 2008). Other techniques are derived from *statistical models* (e.g. factor analysis) or from *participatory methods* (e.g. Budget Allocation Process or BAP). In particular, participatory methods are the most common since they are easy to carry out (Parker, 1991). One of the main used methods is the Analytic Hierarchy Process (AHP), a multi-attribute decision-making method developed by Thomas Saaty (1987). For each weighting method, it is possible to associate the most suitable aggregation method. In particular, there are three kinds of aggregation methods (JRC, 2008):

- *linear aggregation*: it is useful when all the indicators have the same measurement unit and it is the most common method;

- *geometric aggregation*: it is used when the modeller wants "some degree of non-compensability" (JRC, 2008) between indicators because this type of aggregation compensability is lower than the linear aggregation;
- *the multi-criteria approach*: it is a non-compensatory method and it permits a consideration of the advantages (or disadvantages) for each indicator.

Generally, the linear method matches with all the weighting methods. While on the other hand, geometric methods cannot be used with some statistical models, such as the "benefit of the doubt" (BOD) approach. In the same way, the multi-criteria approach does not support the same weighting methods supported by the geometric method and, furthermore, some participatory methods, such as the AHP.

According to the aforementioned weighting and aggregation methods, analysed vulnerability indices were categorized as shown in Table 3. From their analysis, it highlights that the majority of them are aggregated using the geometric method, while socio-environmental ones use mainly an equal-weighted linear combination.

Aggregation method / **Weighting method**	**Linear**	**Geometric**	**Multi-criteria**
Statistical model	Cutter et al., 2003 Guillard-Gonçalves et al., 2014 Tate et al., 2010		Kleinosky et al., 2007
Participatory method	Zanetti et al., 2016		
Equal weighting	Balica et al., 2012 Boruff et al., 2005 McLaughlin & Cooper, 2010 Preston et al., 2008	Abuodha & Woodroffe, 2010 Gornitz et al., 1991 Karymbalis et al., 2012 Li & Li, 2011 Wu et al., 2002 Shaw et al., 1998 Thieler & Hammar-Klose, 1999	

Table 3. Vulnerability indices categorized according to weighting and aggregation method

On the contrary, the vulnerability indices provided by Kleinosky et al. (2007) and Zanetti et al. (2016) use different techniques in comparison to the other socio-environmental indices. Indeed, while Kleinosky et al. (2007) introduce the Pareto ranking technique for guaranteeing a correct combination of components obtained by PCA, Zanetti et al. (2016) combine parameters by using the weighted linear combination.

Finally, social vulnerability indices are developed by using statistical methods and, in particular, the Principal Component Analysis. The employment of this method can be explained by considering that such method warrant a reduction of several variables that are taken into account by social vulnerability indices (Beccari et al., 2016).

2.3.3 Analysis of territorial scale of vulnerability indices

In relation to the territorial scale, the analysed vulnerability indices can refer to four levels: regional, urban, local and, multiple (Table 4). From their analysis, it is noted that the majority of coastal vulnerability indices have been mainly developed for their application on a regional scale. In particular, Gornitz et al. (1991) develop their index to be applied at regional level, specifically, to the US Atlantic coast. Kleinosky et al. (2007), Karymbalis et al. (2012), Li & Li (2011), Shaw et al. (1998), Tate et al. (2010), and Thieler & Hammar-Klose (1999) conduct a similar application to Gornitz et al.'s research. In particular, Kleinosky et al. (2007) and Li & Li (2011) extend their vulnerability assessments to the whole coastal region, also taking into account the inland areas that are adjacent to the coastline. Abouodha & Woodroffe (2010) specify that their index is applied to a coastal area mapped as cells with a dimension of 1.5x1.5 km.

Territorial level			
Regional	**Urban**	**Local**	**Multiple**
Gornitz et al., 1991	Balica et al., 2012	Guillard-Gonçalves et al., 2014	McLaughlin & Cooper, 2010
Shaw et al., 1998		Zanetti et al., 2016	
Thieler & Hammar-Klose, 1999			
Abuodha & Woodroffe, 2010			
Karymbalis et al. (2012)			
Cutter et al., 2003			
Tate et al., 2010			
Li & Li, 2011			
Wu et al., 2002			
Boruff et al., 2005			
Kleinosky et al., 2007			
Preston et al., 2008			

Table 4. Classification of vulnerability indices for territorial level

Instead, at the same scale, Preston et al. (2008) use data of census districts for measuring their index. In the same way, Boruff et al. (2005) and Cutter et al. (2003) apply their vulnerability indices to each of the US counties, while Wu et al. (2002) conduct their evaluation on a county.

However, there are also indices that refer to more detailed territorial scales. Balica et al. (2012) have developed one of these indices to be applied at urban level, while Zanetti et al. (2016) have constructed another index for applications on a local scale. Guillard-Gonçalves et al. (2014) have also developed a local-scale index. Even if their index is applied to the metropolitan area of Lisbon, it is measured for each sub-urban district of the metropolitan area. Finally, among the analysed indices, Mc Laughlin & Cooper (2010) have developed the only multi-level one. In particular, starting from the analysis of each vulnerability characteristics, they define three forms of the same index to apply at national, regional and local levels.

2.4 Conclusions

The aim of the literature review described in this section was to identify the main characteristics of a urban coastal system that can influence its ability to respond during a coastal flooding event. In particular, in order to identify these characteristics, the main coastal vulnerability indices developed in the literature were analysed in relation to two of the main drivers of coastal flooding: rising sea levels and storm surges. Vulnerability indices, indeed, represent the most widespread "tools" for assessing vulnerability to natural hazards and climate change impacts. In particular, by adopting a holistic-system approach for analysing the selected indices, the review showed that the majority of them have developed considering the socio-economic and geomorphological factors as main features. The concept of coastal vulnerability, indeed, can be considered as the result of an integration between two other concepts of vulnerability, the sensitivity and the social vulnerability, which mainly take into account respectively geophysical and socio-economic aspects of coastal areas. However, even if vulnerability indices are based on the integration of socio-economic and geomorphological characteristics, they do not always include in their framework other relevant urban characteristics, such as physical and functional ones, which may affect vulnerability levels of the area. The territorial scale of reference of the indices could explain it. Most of indices, indeed, are 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 assessment of coastal regions to coastal flooding.

In this sense, from an urban planning perspective it is noted that not only little attention has been given to the study of how to assess vulnerability of coastal cities, but also that the vulnerability indices on a local scale have been defined ignoring the most meaningful characteristics of urban coastal systems (e.g. Zanetti et al. (2016) defines a socio-environmental vulnerability index that does not take into account physical characteristics of coastal cities). Instead, a more holistic approach is necessary to evaluate the vulnerability of coastal areas, since it is not appropriate to consider only specific aspects (Li & Li, 2011). Furthermore, considering that coastal cities have to adapt to future impacts of coastal flooding, the coastal vulnerability indices need to be at a higher spatial resolution since they enable the identification of peculiar 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 refers to the relationships that vulnerability indices have with the adaptation to impacts of climate change. Indeed, even if the indices are defined as tools to support decision-making process in order to implement adaptation measures, the analysed studies show that there is a gap on how vulnerability assessments 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 the main urban adaptation strategies and plans can be useful for understanding how vulnerability assessment is integrated into the urban planning process, and which relationships it can acquire in the context of the urban adaptation.

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Section 3. Coastal Cities and Adaptation tools: *strategies, plans and measures*

3.1 Introduction

Climate change is one of the most important challenges at international level, and adaptation is one of the policy strategies to deal with it. In 2010 the Cancun Adaptation Framework and in 2015 the Paris Agreement stated that adaptation to impacts of climate change is a priority as mitigation for reducing GHG emissions in the atmosphere. In 2013, through the EU Adaptation Strategy (European Commission, 2013), the European Union started to promote adaptation in cities thanks to the Covenant of Mayors for Climate and Energy initiative. Indeed, in order to be effective, adaptation should implement at the local level considering that the impacts of climate change are experienced locally (Carter et al., 2015; Füssel, 2007). Hence, international and European agreements have pushed the promotion of adaptation at city level considering the key role of cities in the fight to climate change. In this context, urban adaptation represents a new important mission for urban planning.

According to the IPCC's definition (IPCC, 2014), EEA (2012) and Carter et al. (2015), urban adaptation can be interpreted as a process for increasing the adaptive capacity of cities to cope with the climate impact and reduce vulnerability. Adaptation and vulnerability are strictly linked. Indeed, the adaptive capacity is one of the three dimensions of vulnerability (McCharty et al., 2001) and reducing vulnerability of a system means to increase this *"ability […] to adjust to potential damage, to take advantage of opportunities, or to respond to consequences"* (IPCC, 2014). At the same time, urban adaptation provides opportunities for a resilient and sustainable development of cities (Revi et al., 2014). Actually, the concept of resilience is assuming an 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. Hence, the lack of a shared definition reduces efficiency planning for urban adaptation to climate change (Davoudi et al., 2012; Papa et al., 2015). However, some scholars have focused their attention of the opportunities that an integration among the concepts of vulnerability and resilience could have in the adaptation (including, Joakim et al., 2015).

Even though theoretical concepts of vulnerability and resilience have not been agreed until now to support the development and implementation of urban adaptation, and any legal framework does not codify them, in the practice urban adaptation plans and/or strategies have been already realized. In recent years, as a matter of fact, several cities have started to adopt specific adaptation strategies (also named plans) in order to tackle the impacts of climate change. Indeed, since climate impacts on cities represent a threat for local communities in relation to social and economic consequences, cities have started to invest in urban adaptation as an opportunity for improving urban quality and increasing urban resilience. Grounding on future climate forecasts, these strategies identify a range of adaptation measures for reducing their vulnerability at local level. In particular, relative to the urban adaptation measures, the adaptation of coastal communities can refer to three main approaches of accommodation, protection and retreat, introduced by the IPCC (Nicholls et al., 2007) and currently used in many adaptation strategies. In particular, *"protection aims at advancing or holding existing defense lines by means of different options such as land claim; beach and dune nourishment; the construction of artificial dunes and hard structures such as seawalls, sea dikes, and storm surge barriers; or removing invasive and restoring native species. Accommodation is achieved by increasing flexibility, flood proofing, flood-resistant agriculture, lood hazard mapping, the implementation of flood warning systems, or replacing armored with living shorelines. Retreat options include allowing wetlands to migrate inland, shoreline setbacks, and managed realignment by, for example, breaching coastal defenses allowing the creation of an intertidal habitat"* (Wong et al., 2014).

However, from a preliminary evaluation of urban adaptation measures, it has arose that there is a poor attention to the study of the relationships between coastal cities' characteristics and adaptation measures to implement.

In light of this, this section provides a framework on how urban adaptation measures are defined in adaptation strategies by six coastal cities. In particular, such frameworks describe the relationships between the defined adaptation measures and the urban characteristics of the area where they should be implemented.

Section 3 is articulated into four paragraphs. Paragraph 3.2 illustrates the methodology used for the case study analysis. While in Paragraph 3.3 each case study and the main adaptation actions identified for coastal flooding are described, in Paragraph 3.4 the main results derived from the case study analysis are reported. In the last paragraph, some reflections on the conducted analysis conclude the section.

3.2 Methodology of case study analysis

The analysis of urban adaptation strategies (or plans) was carried out on six coastal cities. In particular, the selected case studies are New York, New Orleans, Boston and San Francisco in America, and Rotterdam and Copenhagen in Europe.

There were two selection criteria for the strategies. They were selected among ones adopted by cities that are historically subjected to accommodating themselves to the presence of the sea or were hit by extreme climate events (e.g. hurricane and storm surges) in recent years. In addition, the strategies introduce innovative adaptation measures in relation to the impacts of coastal flooding due to rising sea levels and/or storm surges.

The analysis of the case studies was conducted in two stages. In the first one, the main information included in the strategies was collected. In particular, besides to the approach used by each strategy, the urban characteristics considered for the definition of adaptation measures were identified for each case study. Hence, the main urban areas where the adaptation measures should be carried out were identified and for each of them, the set of adaptation measures defined by the strategy was described.

In the second stage, the information collected by the strategies was further systematized, in order to further study in depth the literature review, illustrated in the previous section. In particular, according to the holistic-system approach illustrated in the previous chapter (see Paragraph 2.2) the urban characteristics detected in each plan were articulated into the four subsystems - socio-economic, physical, functional and geomorphological -, which compose the urban coastal system. With regard to adaptation measures, they were grouped into different measures categories according to their object of intervention, urban subsystems and the adaptation approaches of accommodation, protection and retreat. In particular, after classifying the urban coastal areas specified in the plan based on their physical and functional attributes, the adaptation measures categories were associated with each urban typology. In this way, it was possible to develop an operative framework that can be useful in the choice of urban adaptation measures to implement in an urban area for reducing impacts due to coastal flooding.

3.3 Analysis of Adaptation Plans

As shown in Table 5, the cities that have taken up a strategy (or plan) of adaptation have different demographic dimensions. New York is the most populated city among those analysed and it is one of the most densely populated cities together with Rotterdam. Considering the population density of all the analysed cities, it is noted that, except New Orleans and Copenhagen, they have a population density higher than the urban density of the coastal areas defined by McGranhan et al.[3] (2005). New York, New Orleans, and Boston have developed their strategies after that an extreme event hits them. With regards to Rotterdam, since it lies on the sea level, the adaptation strategy is an opportunity both to reinforce its urban structure and to guarantee a resilient future economic development and a good standard quality of life of citizens and city users also considering the future climate change. Although San Francisco and Copenhagen have not been recently affected by coastal flooding, their strategies are the result of political and cultural contexts where risk management and environmental issues are key topics.

[3] The reference value for urban areas of coastal zones is equal to 1,119 people per sq. km.

City	Population [inhabitants]	Total Area [sq.km]	Population density [inhab./sq.km]	Elevation above sea level[4] [m]	Coastal flooding event
New York	8,622,698	1,213.37	7,106	22	Hurricane Sandy (2012)
New Orleans	391,495	906.10	432	0	Hurricane Katrina (2005)
Boston	685,094	232.14	2,951	63	Winter storm (2018)
San Francisco	884,363	600,59	1,472	78	-
Rotterdam	635,389	125.79	5,051	0	-
Copenaghen	613,288	897.24	683	1	-

Table 5. Data collection of the analysed case studies

3.3.1 New York

In 2007 New York City adopted the "PlaNYC 2030", a long-term sustainability plan that aimed at reducing the urban carbon footprint and also included measures for realising protections against eventual storms.

In 2012, the impacts of the destructive Hurricane Sandy pointed out limitations of the "PlaNYC 2030". Hence, the City of New York decided to develop a new plan to provide additional protection to the community from future increasing impacts of climate change. In 2013 the City launched a new PlaNYC, named "A stronger, More Resilient New York – a roadmap for producing a truly sustainable 21st century New York". This plan contained a set of recommendations for both rebuilding the community after the Hurricane Sandy and increasing the resilience of the city. In particular, in the plan particular attention was focused on adaptation and protection of New York from coastal flooding events.

In 2015, considering the multiple challenges of New York (economic growth, social inclusion, fight against climate change and its impacts), a new plan, named "OneNYC: The Plan for a Strong and Just City" was adopted. Such a plan, taking into account past progress, articulates the vision for New York into four points (City of New York, 2015):

- *Our Growing, Thriving City: "New York City will continue to be the world's most dynamic urban economy where families, businesses, and neighbourhoods thrive";*
- *Our Just and Equitable City: "New York City will have an inclusive, equitable economy that offers well-paying jobs and opportunity for all to live with dignity and security";*

[4] This data are available at the USGS database (https://geonames.usgs.gov/apex/f?p=138:1:0).

- *Our Sustainable City: "New York City will be the most sustainable big city in the world and a global leader in the fight against climate change";*
- *Our Resilient City: "Our neighbourhoods, economy, and public services are ready to withstand and emerge stronger from the impacts of climate change and other 21st century threats".*

These four visions refer to four principles that are growth, equity, sustainability and resiliency. About urban adaptation and coastal flooding events, the plan identifies a number of initiatives especially in the fourth vision. Some of the vision goals include:

- upgrading buildings against changing climate impacts (e.g. promotion and realisation of resiliency retrofit measures at building scale);
- adapting infrastructure systems for maintaining continued services (e.g. elevation or dry-proofing of facilities and systems, realization of green infrastructure for storm water management, etc.);
- in addition, strengthening coastal protection against flooding and rising sea levels.

Since 2013 the city has implemented many projects to improve the protection system of coastal areas, including beach nourishment, construction of large-scale storm surge barriers, flood-proofing basements, realization of storm water detention ponds, and restoration of wetlands, but also insurance, better forecasting and development of special evacuation plans for reducing risks against flooding events. In particular, the Department of City Planning developed many initiatives, including the "Resilient Neighbourhoods" (New York City – Department City Planning, n.d.). Such initiative was launched in 2013 and aims at analysing zoning and land use of floodplain communities and evaluating opportunities for improving urban resilience. In particular, the initiative goals are:

- reducing flood risks;
- planning for adaptation over time;
- developing resilient and vibrant neighbourhoods.

The main adaptation measures, provided by this initiative, refer to different urban areas in New York (Figure 1), which were heavily affected by Hurricane Sandy's impacts. These interventions are defined considering some specific context characteristics, including the floodplain area, the building and lot typologies, the land use and the zoning analysis. Below the urban characteristics of each area and the relative urban adaptation measures are described.

Edgewater Park

The Edgewater Park was originally developed as campground. Progressively, it was transformed into a residential neighbourhood. The main initiatives provided for this area are referred to a parameter, the Design Flood Elevation (DFE) defined as the elevation of the expected 1% annual chance flood, and include mainly the construction of new buildings elevated above DFE and the retrofits of the existing ones through the use of wet-flood proof[5] or dry-flood proof[6] techniques.

Harding Park

Harding Park is a little residential neighbourhood, characterized by low population density and large coastal natural areas. In order to increase its resilience against future climate impacts, the main initiatives provided for this area are:

- retrofitting of existing buildings through the elevation of the existing structure on new foundation systems and above the DFE line;
- installation of bioswales or planted strips along streets, increasing of permeable and vegetated areas, and installation of underground drains for collecting and transporting runoff;
- repaving of parking surfaces with permeable pavement and increasing of green coverage on site;
- reconversion of vacant lands and City-owned waterfront areas in gardens, bioswales or retention ponds with the insertion of neighbourhood amenities such as benched, pergolas or other site furnishings;
- enhancement of breakwaters by increasing their height to reduce wave impacts and widening them to accommodate pedestrian circulation;
- maintenance of the three saltwater marsh lagoons.

Figure 1. Study areas of Resilience Neighbourhoods initiative

[5] Wet-floodproof buildings are floodable under the DFE line and the possible ground-floor uses are parking and storage.
[6] Dry-floodproof buildings are protected by floods and the possible ground-floor uses are parking, storage and other non-residential utilizations.

West Chelsea

West Chelsea is mixed-use neighbourhood. It comprises a wide range of building types and has a distinctive concentration of arts and cultural uses and economic vitality.

In order to both preserve the neighbourhood's active streetscapes and historic character and meet the resilient requirements for facing coastal flooding events, the main adaptation measures for this area are:

- retrofitting of existing buildings according to flood proofing standards with reconversion of ground floor sub-BFE spaces to alternative uses, including storage, parking and access to building amenities or commercial spaces and, eventually, addition of a new floor on the rooftop;
- realization of new developments with resilient standards (e.g. buildings elevated above the floodplain).

East Village - Lower East Side - Two Bridges

East Village, Lower East Side and Two Bridges are urban compact areas characterized by mixed-land use.

These three neighbourhoods are served by bus transit, with subway service available further west and ferry service to the south.

Furthermore, the Williamsburg, Manhattan, and Brooklyn Bridges provide important multi-modal connectivity for these neighbourhoods along with the FDR Drive, which flanks Manhattan's eastern side and connects to the Bronx, Queens, and Brooklyn.

Finally, these three areas are characterized by a waterfront that includes large open spaces, including East River Park, with recreational and social functions. Considering these urban characteristics, the main resilient measures provided for these areas are the following ones:

- integration of coastal protection with the shoreline parkland;
- retrofitting of existing buildings according to flood proofing standards with reconversion of ground floor sub-BFE spaces to alternative uses, including storage, parking and access to building amenities or commercial spaces and, eventually, addition of a new floor on the rooftop;
- retrofitting of existing towers by redesigning the site slope in relation to the DFE line or inserting continuous flood shields around the building perimeter;
- definition of an operational preparedness planning for implementing mitigation strategies to support property owners and managers.

Old Howard Beach – Hamilton Beach – Broad Channel

Old Howard Beach and Hamilton Beach are two residential neighbourhoods and are characterized by the presence of two canals. Broad Channel is an island and is connected to the two neighbourhoods by only one road and the railway line. Also in Broad Channel the majority of its buildings are for residential uses.

Considering the urban adaptation to coastal flooding events, the main measures for the Broad Channel and the Hamilton Beach can be summarized as follows:

- zoning changes to limit vulnerability to sea level rise and to promote retrofitting of existing buildings and construct new ones with resilience standards;
- promotion of programme for increasing awareness of small businesses about resilience opportunities and benefits;
- reconversion of City-owned vacant lots in wetlands and native landscapes.

Instead, the main measures provided for Old Howards Beach are the following ones:

- zoning changes to limit vulnerability to sea level rise and to promote retrofitting of existing buildings and construct new ones with resilience standards;
- waterfront rezoning for improving local accessibility and increasing its adaptive capacity (e.g. insertion of public parks for reducing the impervious surfaces and enhancing the drainage capacity during a flooding event);
- maintenance and realisation of street end bulkheads as protection against coastal inundations;
- promotion of programme for increasing awareness of small businesses about resilience opportunities and benefits;
- realisation of specific infrastructure for coastal protection (hurricane barrier).

Canarsie

Canarsie is a residential neighbourhood in Brooklyn, characterized by a heterogeneous housing stock, a well-equipped waterfront and several open spaces that surround the urbanized area.

In order to reduce the flooding impacts also due to storm surges and sea level rise, the resilience framework proposes the following measures:

- retrofitting of existing buildings, relocation of their lost spaces below the DFE line through the realization of a vertical addition, and retention of ground floor space for storage and parking;
- revitalization of commercial corridors that are not located in the floodplain as resiliency assets;
- utilisation of parklands for coastal protection;
- realization of specific infrastructure for coastal protection (hurricane barrier).

Gerritsen Beach

Gerritsen Beach is a residential neighbourhood. This urban area is mainly characterized by the presence of single-family detached homes and one commercial corridor.

Furthermore, the channels in this neighbourhood are used for recreational boating and fishing. In order to mitigate the future risks due to sea level rise, the resilience measures for this area are related to:

- retrofitting of existing buildings according to flood-resistant standards;
- realization of new developments with resilient standards (e.g. buildings elevated above the floodplain);
- retrofitting of commercial buildings through relocation both of commercial spaces and mechanical systems on a second story, adoption of dry-flood proofing solutions at the ground floor and installation of deployable flood gates;
- limitation of residential development, and construction of new buildings according to floodproofing design standards along the waterfront;
- relocation of maritime and commercial uses along the waterfront;
- elevation of streets and storm sewers and realization of green infrastructure for reducing the impacts of sea level rise in proximity of the shoreline;
- maintenance of bulkheads for protecting from minor and frequent storms;
- realization of specific infrastructure for coastal protection (hurricane barrier).

Rockaway Park – Rockaway Beach

Rockaway Park and Rockaway Beach are two mixed-land use areas and are characterized by an attractive waterfront. Considering the heterogeneity of building stock, the presence of active commercial areas and the beachfront, the resilience measures for facing coastal flooding events are focused on:

- retrofitting of existing residential and commercial buildings and realization of additional floors for wet-flood proofing buildings to balance the loss of usable spaces below the DFE;
- promotion of education programs for increasing awareness of homeowners about benefits and opportunities of investing in solutions for improving the resilience of housing stock;
- improvement of the waterfront accessibility and resilience through the realization of recreational spaces and implementation of flood mitigation solutions;
- implementation of shoreline protection measures (groins, dunes, berms, reinforced dunes), realisation of specific infrastructure for coastal protection (hurricane barrier) and for monitoring sea level rise;
- improvement of transportation systems, maintenance of transportation infrastructure and development of solutions for their flooding protection (i.e. installation of floodwalls along the railway lines).

Sheepshead Bay

The Sheepshead Bay is a mixed-use area that includes different typologies of buildings (from small bungalows to multi-family apartment buildings), commercial corridors, and a working and recreational waterfront. Considering the future flooding impacts on this area, the main measures are related to:

- retrofitting of existing buildings and construction of new ones according to flood proofing standards;
- recovering and retrofitting of bungalows through the use of floodproofing techniques;
- redevelopment of the Special Sheepshead Bay District on the waterfront for facing coastal floods;
- implementation of shoreline protection measures (groins, dunes, berms, reinforced dunes), and realization of specific infrastructure for coastal protection (hurricane barrier).

East Shore

The East Shore is an area of Staten Island. This neighbourhood is a low-density residential area characterized by beach destinations, natural areas, including wetlands, bluebelts and parks, few commercial corridors, and some utilities and public facilities (e.g. Staten Island University Hospital). Considering its high exposure to flooding due to rains and coastal storms, the main adaptation measures of the East Shore are:

- realization of seawalls and armored levees;
- expansion of the Mid-Island Bluebelt;
- promotion of new constructions without increasing overall density;
- limitation of residential growth;
- creation of beachfront commercial areas and beachfront improvements through the use of flood proofing methods;
- improvement of the open space network intended for recreational and educational uses;
- limitation of future growth in State Buyout Areas and their reservation as open space;
- conservation and improvement of wetlands.

3.3.3 New Orleans

In 2005, the Hurricane Katrina invested New Orleans, submerging about 80% of the city. In 2010, the State of Lousiana's Office of Community Development – Disaster Recovery Unit funded Greater New Orleans, Inc. to develop a plan for urban water management. The outcome was the Greater New Orleans Urban Water Plan, developed by Waggonner & Ball Architects and a team of local and international water management experts. Such plans provide a vision for long-term urban water management at regional level, also developing urban design solutions. In particular, it includes measures for improving management of flood and subsidence threats and, at the same time, creating economic value and enhancing quality of life (Waggoner & Ball Architects, 2013a).
The Plan is the answer to the future challenge of climate change. Indeed, even if the region of New Orleans possesses a century-old hurricane protection system, it is insufficient for facing growing risks posed by climate change, especially by hurricanes and floods. Hence, the Urban Water Plan tries to faces this problem and integrate innovations in engineering with urban planning and design.
In particular, the Plan is inspired by six principles that are:

- *Live with Water*: it refers to making space for water and using it as an asset for the region;
- *Slow and Store*: it refers mainly to stormwater and to the need to make sure that it flows slowly across the landscape and stores for infiltration or other uses;
- *Circulate and Recharge*: it refers to the incorporation of surface water flows and higher water levels into water management in order to improve groundwater balance, water quality, and the region's ecological health;
- *Work with nature*: it refers to the integration of natural processes for water management (storing, filtering, etc.) with mechanical systems for enhancing function, beauty and resilience of the region's water infrastructure and landscape;
- *Design for Adaptation*: it refers to the designing of systems for dynamic conditions in order to support diverse uses, economic development and environmental restoration;
- *Work Together*: it refers to support an effective (cultural, political) collaboration at different territorial levels for a better development of effective solutions.

For better water management, regional planning and urban design, the plan considers three characteristics: the soil types, water and biodiversity; the infrastructure networks; and finally, the urban fabric.
Considering these factors, the Plan proposes the development of an integrated living water system for the three "hydrological basins" of the region that are the Jefferson-Orleans Basin, Orleans East Basin, and St. Bernard Basin. In particular, this system will be implemented through the retrofits of the existing systems (e.g. streets, parks, squares, etc.), the insertion of new pumps and waterways, and the strengthening of connections between lakes, canals and wetlands.

Concerning the adaptation measures, the Plan does not distinguish them considering climate events (e.g. rainfall, hurricanes, etc.) and characteristics of the urban area. In particular, the Plan describes the urban "opportunities" that are possible to implement in each basin. Therefore, in order to provide a meaningful framework of the adaptation measures proposed by the Plan in relation to coastal flooding events, the description of the Water Plan measures is limited to those ones to implement in the coastal area. In particular, since the Plan selects seven demonstration projects within the three basins, the analysis is focused on the actions provided for the Jefferson-Orleans and Orleans East basins (Waggoner & Ball Architects, 2013b).

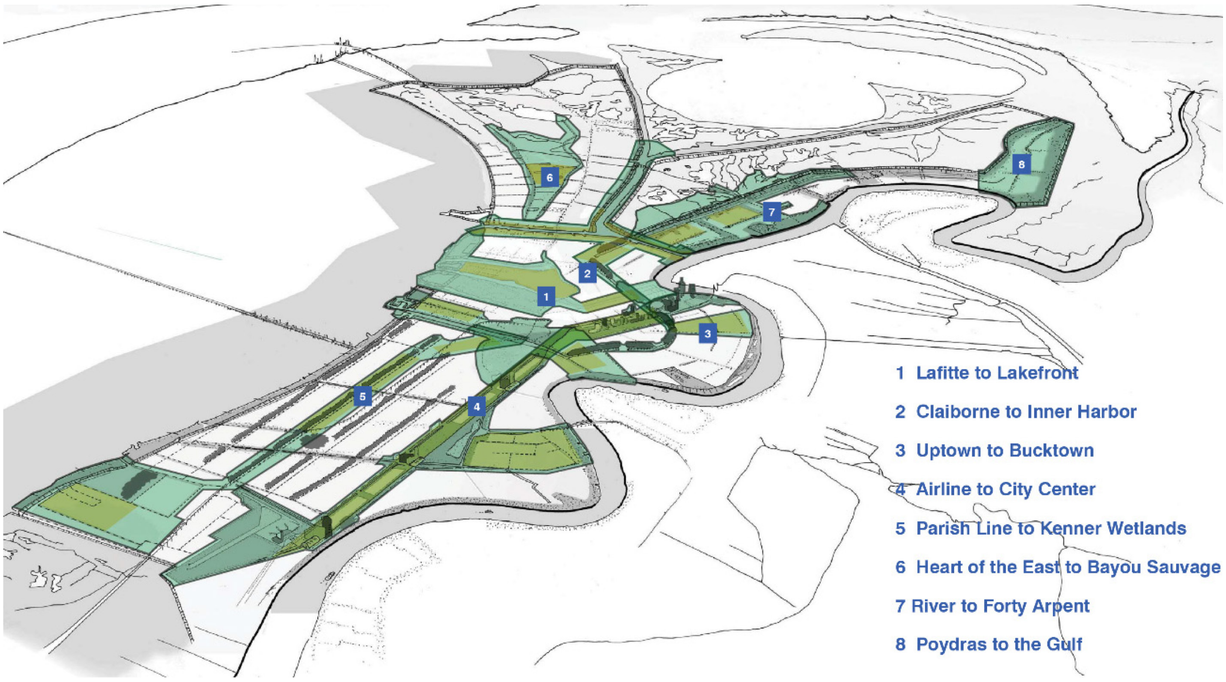

Figure 2. The Demonstration projects described by the Urban Water Plan

Lafitte to Lakefront

The objective of the urban measures in this low-lying area (Figure 2- Point 1) is to re-establish the historic connection between the Missisipi River and the Lake Pontshartrain and, at the same time, to revitalize the entire city. The main interventions are:

- the redevelopment of the Lafitte Blueway for improving the existing drainage system and upgrading the surrounding areas with recreational and educational opportunities for residents and visitors;
- the realization of waterfront retail, restaurant, recreational and residential spaces in the vacant and blighted lots localized along the Orleans Avenue and London Avenue Outfall Canals for making attractive and publicly accessible lowland neighbourhoods;
- the use of the vacant lots and underutilized neutral grounds in the Filmore District for creating a network of pocket parks and corridors and lessening street flooding;
- the design of a large parcel for memorialization, education, filtration and recreation at the Mirabeau Water Garden in the Filmore neighbourhood.

Claiborne to Inner Harbor

The objective of the interventions in this zone (Figure 2 – Point 2) is to modify the configuration of its drainage system, diverting the water flows towards a broad open area, the Desire Parkland, able to store and filter thousands of acre-feet of runoff. In particular, the interventions in this zone are:

- the reconnection of the Desire District to the rest of the city through streetscape improvements, new crossing over utilities and drainage canals, and the widening of the Florida Avenue Canal for improving the storage capacity of the area and realizing infrastructure and open space to revitalize the surrounding neighbourhoods;
- the redesign of the Inner Harbor as an opportunity for the improvement of regional hydrology and economy, considering the existing port facilities, infrastructure, industrial installation and nearby wetland restoration efforts and also the new flood protection structures.

Uptown to Bucktown

This zone (Figure 2 – Point 3) is characterized by a complex drainage system of canals. The objective of the defined measures for this area is to realize small retrofits and storage features for reducing flooding and improving groundwater balance. The interventions provided for this area can be summarized as follows:

- the realization of a range of retrofits (rain gardens along both street sides, pervious pavers) for strengthening the storage capacity of the Uptown District;
- the redevelopment of the Hollygrove District through the promotion of access to water, improved street design, increased vegetation, and pedestrian amenities, the design of the Monticello Canal Park for reducing the flooding risk and the revitalization of the area along the Airline Highway and the Monticello Canal;
- the realization of "floating streets" to store and infiltrate storm water and the development of the West End Canal Boulevard as a critical component of the water system in the Lakeview District;
- the widening of the 17th Street Canal to increase the water storage capacity and the redesign of its waterfront for building a new mixed-use and residential development.

Parish Line to Kenner Wetlands

The interventions in this lowland (Figure 2 – Point 5) aims at redesigning its drainage system in order to reduce the subsidence phenomenon and enhance urban quality. In particular, the drainage system of this zone is composed of three elements, the Canal Street Canal, the Jefferson Lowland Canals, and the Kenner Wetlands, where water collected by canals is filtered before to empty out into the wetlands on the western side of the basin. Thus, the main interventions are referred to these three system components and are:

- the redesign of the Canal Street Canal and its banks for reducing street flooding events, soil subsidence, and improving the urban quality of the area;
- the provision of an additional storage for the Jefferson Lowland Canals, improving vegetation along the canal edges to make them more attractive and design them for improving the accessibility of pedestrians and cyclists;

- the improvement of the filtering surface of the Kenner Wetlands to reduce floods, realising also a mixed residential and commercial development (the Kenner Parklands) for spurring the economic development of the area.

3.3.3 Boston

Climate Ready Boston is the strategy, developed by the City of Boston and the Green Ribbon Commission, which Boston has adopted in 2016 for adapting the city to the climate change impacts (City of Boston, Green Ribbon Commission, 2016). This strategy is coordinated with a wider strategy, called Imagine Boston 2030 and 100 Resilient Cities in order to address Boston towards "a more affordable, equitable, connected and resilient future". As reported in the strategy, *"Since 1991, Boston has experienced 21 events"*. The city experienced mainly high winds and coastal flooding and *"as the climate changes, the likelihood of coastal and riverine flooding—as well as other hazards, like stormwater flooding and extreme heat—will increase"*. Hence, the city decided to reinforce its adaptive capacity in order to create a "resilient, climate-ready" Boston and improve the city and quality of life for all its citizens.

The strategy is composed by 4 parts: the first part illustrates a set of updated projections for 4 climate factors (extreme temperatures, rising sea levels, extreme precipitation and storms); the second one contains a vulnerability assessment for three climate hazards (extreme heat, storm water flooding, and coastal and riverine flooding); in the third part, climate resilience initiatives are applied to 8 Boston areas; finally, the last part describes the roadmap to implement the resilience initiatives.

With regards to the future sea level rise, the strategy highlights that it may be three times faster: *"by 2050, sea levels may be as much as 1.5 feet higher than they were in 2000, and by 2070, they may be as much as 3 feet higher than in 2000"*. This phenomenon will cause more flooding with the increasing of intensity and frequency of storm surges. Indeed, with higher seas, the storm surge action may produce the same amount of flooding as a powerful storm when the seas are lower.

Considering the climate resilience initiatives, they are organized into 4 layers and 11 strategies (Table 6).

While the layers represent an approach for realizing resilience purpose in relation with community, shoreline, infrastructure assets and buildings, strategies are referred to each layer and they are the references for the clustering of initiatives.

After the definition of the resilience initiatives, the strategy illustrates the applications of them to eight Boston areas that will be primarily exposed to coastal and riverine flooding risks according to the future climate forecasts.

These areas are Charlestown, Charles River, Dorchester, Downtown, East Boston, Roxbury, South Boston and South End (Figure 3).

Layer	Strategy	Initiative
Updated Climate Projections	1. Maintain up-to-date information on future climate conditions in Boston	1.1 Update Boston-area climate projections periodically
		1.2 Create future flood maps to support planning, policy and regulation
Prepare and Connected Communities	2. Expand education and engagement of Bostonians about climate hazards	2.1 Expand citywide climate readiness education and engagement campaign
		2.2 Launch a climate ready buildings education program for property owners and users
		2.3 Conduct outreach to facilities that serve vulnerable populations to support preparedness and adaptation
		2.4 Update the city's heat emergency action plan
		2.5 Expand Boston's small business preparedness program
	3. Leverage climate adaptation as a tool for economic development	3.1 Identify resilience-focused workforce-development pathways
		3.2 Pursue inclusive hiring and living wages for resilience projects
		3.3 Prioritize use of minority- and women-owned businesses for resilience projects
Protected Shores	4. Develop local climate resilience plans to coordinate adaptation efforts	4.1 Develop local climate resilience plans to support district-scale climate adaptation
		4.2 Establish local climate resilience committees to serve as long-term community partners for climate adaptation
	5. Create a coastal protection system	5.1 Establish flood protection overlay districts and require potential integration with flood protection
		5.2 Determine a consistent evaluation framework for flood protection prioritization
		5.3 Prioritize and study the feasibility of district-scale flood protection
		5.4 Launch a harbour-wide flood protection system feasibility study
Resilient Infrastructure	6. Coordinate investments to adapt infrastructure to future climate conditions	6.1 Establish an infrastructure coordination committee
		6.2 Continue to collect important asset and hazard data for planning purposes
		6.3 Provide guidance on priority evacuation and service road infrastructure to the ICC
	7. Develop district-scale energy solutions to increase decentralization and redundancy	7.1 Conduct feasibility studies for community energy solutions
	8. Expand the use of green infrastructure and other natural systems to manage stormwater, mitigate heat, and provide additional benefits.	8.1 Develop a green infrastructure location plan for public land and rights-of-way
		8.2 Develop a sustainable operating model for green infrastructure on public land and rights-of-way
		8.3 Evaluate incentives and other tools to support green infrastructure
		8.4 Develop design guidelines for green infrastructure on private property to support co-benefits
		8.5 Develop an action plan to expand Boston's urban tree canopy
		8.6 Prepare outdoor facilities for climate change
		8.7 Conduct a comprehensive wetlands inventory and develop a wetlands protection action plan

Layer	Strategy	Initiative
Adapted Buildings	9. Update zoning and building regulations to support climate readiness	9.1 Establish a planning flood elevation to support zoning regulations in the future floodplain
		9.2 Revise the zoning code to support climate-ready mechanical systems
		9.3 Promote climate readiness for projects
		9.4 Pursue state building code amendments to promote climate readiness
		9.5 Incorporate future climate conditions into area plans
	10. Retrofit existing buildings	10.1 Establish a resilience audit program for private property owners
		10.2 Prepare municipal facilities for climate change
		10.3 Expand backup power at private buildings that serve vulnerable populations
		10.4 Develop toolkit of building retrofit financing strategies
	11. Insure buildings against flood damage	11.1 Evaluate the current flood insurance landscape
		11.2 Join the national flood insurance program community rating system
		11.3 Advocate for reform in the national flood program

Table 6. Collection of layers, strategies and initiatives defined by the Boston strategy

For each area, the strategy illustrates the urban features, three flood scenarios (2030, 2050 and 2070), the asset exposure to three sea level rise scenario, the population and infrastructure vulnerabilities, and, finally, the possible consequence on the built environment and the local economy. With regards to the vulnerability assessment, the factors taken into account are related to socio-economic characteristics of the population (including elderly, children, immigrants, low-income residents, disabled people, sick people), to those of the housing stock (location, use, size, type of structure, etc..), to those of facilities and assets (critical facilities, transportation infrastructures, essential facilities and public facilities). About resilience interventions, the strategy does not define specific actions at the local scale and for the different climate events. Instead, it suggests for each Boston area which interventions should be designed and, therefore, implemented. Currently, there are projects for the East Boston, the Charlestown, the South Boston and the Moakley Park in Dorchester. Below, the main features of the focus areas and the main actions defined for each area are illustrated.

Charlestown

Charlestown is the oldest neighbourhood in Boston and is surrounded by water on three sides. It is a thriving residential community and hosts the largest public housing development in the city. This neighbourhood has some commercial corridors and some strategic infrastructure (e.g. hospital and autoport). Furthermore, Charlestown has also different industrial areas. Considering the layers and the strategy, the resilience initiatives referred to the flooding events are the following ones:

- realize new Flood Protection Overlay Districts in those areas that are strategically important for protecting infrastructure;
- conducted an outreach campaign to private facilities that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area;
- locate emergency micorgrids along the main street corridor and the main square of the area not exposed to coastal flooding for guaranteeing the continuous functioning of the facilities in the neighbourhood;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;
- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale;
- retrofit municipal facilities (e.g. EMS Station, Charlestown Navy Yard) that have high levels of vulnerability.

Furthermore, other measures including in the project for the area are (City of Boston, 2017a):

- elevate Main Street by about 2 feet for reducing the flooding impacts;
- relocate or redesign the fire station at the intersection of Medford Street and Main Street;
- renovate and raise the most vulnerable structures of the Ryan Playground in order to reduce the negative effects due to floods;
- redevelop the Schrafft's Center waterfront with elevated parks, nature-based features and mixed-used buildings.

Charles River Neighbourhoods

The Charles River area is composed of neighbourhoods that lie along the Charles River. These neighbourhoods have different land uses. The Back Bay and the Beacon Hill are expensive residential neighbourhoods; the Fenway/Kenmore has a mixed-land uses (residential, cultural and educational); the Allston/Brighton is a mixed-use district with commercial, residential and institutional uses (e.g. site of the recent Harvard University expansion). The Charles River area is characterized by the presence of the urban park Charles River Esplanade, and some commercial corridors. With regards to the flooding events, the main interventions are to:

- construct a district-scale flood protection at the primary flood entry points for the area;
- conducted an outreach campaign to private facilities (e.g. the Bright Horizons Family Centre) that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area;
- locate emergency microgrids in the low-exposed areas to flooding events for guaranteeing the continuous functioning of the facilities in the neighbourhood;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;

- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale.

Figure 3. Focus Areas of the Boston strategy

Dorchester

Dorchester is the largest neighbourhood in Boston in terms of population and geographic area. It is mainly a residential area, anchored by commercial districts (i.e. Uphams Corner, Fields Corner and Codman Square). The neighbourhood is characterized by the presence of the Fairmount Line along that the City is planning transit-oriented development. The main measures adopted in this area for reducing the coastal flooding impacts are:

- realize new Flood Protection Overlay Districts in those areas that are strategically important for protecting infrastructure;

- conducted an outreach campaign to private facilities (e.g. the Harbor Point and Columbia Point Infant Toddler Daycare) that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area, especially the three main street districts of Upha's Corner, Bowdoin/Geneva and Field's Corner;
- locate emergency microgrids in the low-exposed areas to flooding events (e.g. the intersections of Gallivan Boulevard and Neponset Avenue) for guaranteeing the continuous functioning of the facilities in the neighbourhood;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;
- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale;
- retrofit municipal facilities that have high levels of vulnerability, in particular the public school facilities and the fire station.

Downtown

The Downtown includes several neighbourhoods: the West End hosts residential and commercial uses and the Massachusetts General Hospital and other facilities; the North End is a vibrant mixed-use neighbourhood with residential areas and commercial corridors; the Financial District is a commercial centre with high-rise buildings, a retail, a recreational hub, commercial and cultural areas, and the Government Center; Chinatown is a densely populated mixed-use district; finally, the Leather District contents residential and commercial uses. Furthermore, Downtown hosts a significant part of the transportation infrastructure that is critical for the whole territorial accessibility. With regards to the intervention for facing the future coastal flooding events, they are:

- realize new Flood Protection Overlay Districts in those areas that are strategically important for protecting infrastructure;
- conducted an outreach campaign to private facilities (e.g. the Kinder Care Learning Center) that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area, especially the Chinatown main street district;
- locate emergency microgrids in the low-exposed areas to flooding events for guaranteeing the continuous functioning of the facilities in the neighbourhoods;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;
- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale;
- retrofit municipal facilities that have high levels of vulnerability, in particular the EMS Station Ambulance 8 and the South Postal Station.

East Boston

The East Boston is composed of five islands connected by fill. This area is home to a mix of residential neighbourhoods, commercial areas (Maverick Square, Central Square, Day Square and Orient Heights) and major regional transportation, including the Route 1A/McClellan Highway, the Interstate 90 and the Logan Airport. Furthermore, this area includes also some industrial areas along the waterfront (e.g. the Chelsea Creek) and important recreational and natural areas (East Boston Greenway, Constitution Beach and Belle Isle Marsh). In particular, the waterfront area is evolving into a mixed-use environment with residential and open-space development. According to the strategy, the main resilience actions to implement are:

- realize new Flood Protection Overlay Districts in those areas that are strategically important for protecting infrastructure;
- conducted an outreach campaign to private facilities (e.g. the East Boston YMCA, the East Boston Head Start/Elbow child care facility and the East Boston Neighbourhood Health) that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area, especially in its four main commercial districts;
- locate emergency microgrids in the low-exposed areas to flooding events and eventually strength the solar power capacity at Logan Airport for guaranteeing the continuous functioning of the facilities in the neighbourhoods;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;
- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale;
- retrofit municipal facilities that have high levels of vulnerability, in particular the Fire Department Engine 9, the Boston Police Department District A-7, the Mario Umana Academy the BHA's Heritage housing complex and the Boston Centers for Youth and Family.

Furthermore, other measures including in the project for the area are (City of Boston, 2017b):

- installation of a seven-foot-high flood walls across the Greenway under Sumner Street for providing protection to the flooding impacts;
- elevation and redesigning of the Greenway entrance and Piers Park II as protection against the Marginal Street flood pathway;
- elevation of the Harborwalk in combination with the installation of flood walls across the Lewis Street;
- redevelopment of the waterfront area in order to reduce the flooding impacts on the Border Street.

Roxbury

Roxbury is at the centre of Boston and hosts a high concentration of people of colour, low- and no-income residents and people with disabilities. Dudley Square is the commercial hub of the area and is a transit hub for several buses and for the Silver Line, a bus rapid transit system. Furthermore, in some parts, the area hosts also some parks, including the Franklin Park. The main climate issues in this area are connected to the effect of the urban heat island, but with regards to coastal flooding, the initiatives are:

- realize new Flood Protection Overlay Districts in those areas that are strategically important for protecting infrastructure;
- conducted an outreach campaign to private facilities (e.g. the American Red Cross/Boston Pantry, the Sojourner House Food Pantry, and Tartt 's Day Care Center) that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area, especially along the Melnea Cass Boulevard;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;
- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale.

South Boston

The South Boston area is characterized by a mixed-land use. In particular, the waterfront is a recreational and cultural hub and will become a mixed-use neighbourhood. In some areas, there are still industrial uses, including the Port, the Raymond L- Flynn Industrial Park and the Fish Pier. The main measures for this areas are:

- realize new Flood Protection Overlay Districts in those areas that are strategically important for protecting infrastructure;
- conducted an outreach campaign to private facilities (e.g. the Tiny Tots daycare facility, the Harborview Children's Center, the Bright Horizons and the South Boston Head Start) that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area, especially in City Point, Telegraph Hill and the South Boston Waterfront;
- locate emergency microgrids in the East Broadway and the Ray Flynn Marine Park;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;
- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale;
- retrofit municipal facilities that have high levels of vulnerability, in particular the EMS Harbour Unit, the Police Department Harbour Patrol Unit, the Boston Marine Industrial Park and the Boston Housing Authority Old Colony, Mary Ellen McCormack, and West Ninth Street housing developments.

South End

The South End is a residential neighbourhood and is characterized by historic brick row houses, public housing developments and some infill. It presents the commercial corridors of Tremont Street, Columbus Avenue and Washington Street. Furthermore, the area hosts the Boston Medical Center and the Boston University School of Medicine. The main transportation corridors are the Orange Line and the Silver Line. The main resilience interventions for this area are:

- realize new Flood Protection Overlay Districts in those areas that are strategically important for protecting infrastructure;
- conducted an outreach campaign to private facilities (e.g. the Ellis Memorial Early Education and Care Program, Eagle's Nest Learning Center, and Pine Village Preschool) that serve vulnerable populations to support preparedness and adaptation;
- develop a business preparedness program that includes physical adaptation solutions for small businesses located in the area, especially along Tremont Street and Massachusetts Avenue and in the Washington Gateway Main Street District;
- locate emergency microgrids along Massachusetts Avenue, Tremont Street and Public Alley 706;
- amend the zoning code to support climate readiness (e.g. elevating first-floor ceilings) for projects in the development pipeline;
- develop a climate ready buildings education program and a resilience audit program to inform property owners about their current and future climate risks and actions that they can undertake to address these risks at building scale;
- retrofit municipal facilities that have high levels of vulnerability, in particular the Boston Housing Authority developments.

3.3.4 San Francisco

In December 2014, San Francisco was hit by a storm that interrupted transportation and other services of the city. Climate events and the future forecasts of the climate variability were the main reasons of the creation of the Sea Level Rise Coordinating Committee in 2015. The Committee's first task was the development of the Sea Level Rise Action Plan, published in 2016 (City and County of San Francisco, 2016). This Action Plan defines a vision for making the city more resilient for facing future sea level rise and relative coastal flooding. In particular, the Action Plan aims at:

- establishing an overarching vision, goals, and a set of guiding principles for the adaptation planning of San Francisco;
- summarizing current climate science, relevant policies and regulations, and vulnerability and risk assessments for the city;
- identifying data gaps and establishing a framework for further assessment, adaptation planning, and implementation;
- providing the foundation and guidance to develop a citywide Adaptation Plan for rising sea levels.

Even if this Plan represents a first step for the development of a citywide adaptation plan, it represent an effective guidance for urban adaptation. Except for the Plan's introduction and its future developments, it is articulated into four main parts.

- the first one illustrates the existing and future impacts of rising sea levels on the city, for which the sea level rise forecast is 36-66 inches (91-168 cm) for 2100;

- the second part includes the possible adaptation approaches and measures in an urban planning perspective;
- the third part considers the possible barriers related to the implementation of adaptation measures and the importance of the community engagement;
- in the last part, the elements of vulnerability and risk assessments are described.

In particular, about vulnerability and risk assessments, the Plan identifies as specific assets in these evaluation population, buildings, water and wastewater utilities, shoreline protection, solid and hazardous waste, energy, transportation, parks, open space and natural ecosystems, public health facilities, communications, and community facilities.

Starting from of different inundation maps, the Action Plan identifies the most vulnerable areas of the city to rising sea levels. The majority are already interested by waterfront projects. Therefore, besides the description of those projects, the Plan illustrates also the main adaptation actions to implement in these areas.

Downtown to Central Bayshore

The coastline area from Downtown to Central Bayshore is characterized by different land use. Downtown is a mixed-land use area with high building density, Central Bayshore is characterized by the presence of the harbour, commercial and industrial activities and abandoned areas. According to the projects related to Mission Rock and Mission Bay, Crane Cove Park, Pier 70 Sud and NRG, the main adaptation interventions concern to redevelop abandoned urban areas and realize parks and open spaces for recreational uses along the waterfront.

San Francisco Airport Shoreline

San Francisco Airport Shoreline hosts various assets, including runways, taxiways, terminal buildings, emergency facilities and tenant operation centers, beyond the City Airport. Considering the projects of the India Basin, Hunter's Point Shipyard and Candlestick Point, the main adaptation actions are referred to:

- realize new developments with extensive parks and open space along the waterfront;
- create a better connection for pedestrians, cyclists, improve traffic circulation, and introduce amenities and vegetation for a more attractive space;
- design streets to support walking, the use of bicycles and public transportation;
- enhance natural ecosystems along the shoreline.

With regards to the Airport, along the shoreline, it is protected by seawalls, berms and sheet piles. For reducing flood risks, a Shoreline Protection Program will be promoted in order to develop further protection infrastructure.

Southern Pacific Coast

The Pacific Coast of San Francisco is particularly exposed to wave action and future sea level rise. It is mainly characterized by the presence of beaches and natural coastal ecosystems and in parallel to the shoreline it is crossed by the Great Highway. In relation to the urban adaptation of this area, the main interventions are incorporated in the Ocean Beach Masterplan, which is promoted by a non-profit organization, the San Francisco Bay Area Planning and Urban Research Association (SPUR). The main actions proposed by the Masterplan can be summarized as follows:

- reroute the Great Highway behind the zoo and replace it with a coastal trail;
- protect the existing wastewater system localized along the shoreline with low-profile hard structure;
- restore and revegetate the Great Highway area to allow recreational and ecological functions;
- reduce the width of the Great Highway to provide amenities and facilitate managed retreat;
- restore the dunes along the shoreline;
- create a better connection for pedestrians, cyclists, improve traffic circulation, and introduce amenities and vegetation for a more attractive space.

3.3.5 Rotterdam

The Rotterdam Climate Change Adaptation Strategy is one of the main results of the Rotterdam Climate Initiative programme[7], designed to implement both mitigation and adaptation's actions. Indeed, the Strategy is a part of the Rotterdam Climate Proof (RCP) programme (2009), developed to make the city of Rotterdam climate proof by the year 2025 (Rotterdam Climate Initiative, 2009). In particular, the focus of the RCP programme is *"on creating additional opportunities to enhance the attractiveness of the city in terms of living, recreation, working and investments"*. Rotterdam is one of the largest European ports, and the future climate change can represent an opportunity for the future growth of the city.

In this perspective, in 2013 the Rotterdam Climate Change Adaptation Strategy was published (Rotterdam Climate Initiative, 2013). The goal of the Strategy is not only to create a "climate-proof city" for the inhabitants of Rotterdam and the future generations but also *"a city that is both attractive and economically prosperous"*.

Thanks to its geographical and urban history, Rotterdam has collected a broad knowledge about the concept of adaptation. Adaptation is defined as *"the process whereby society reduces its vulnerability to climate change or whereby it profits from the opportunities provided by a changing climate"*. Thanks to its awareness, Rotterdam has already taken many measures against the climate change effects, but considering also the uncertainty of the future changing of climate, the city needs to continue to adapt.

The Strategy defines four main aims that are:

- maintaining and strengthening its system of storm surge barriers and dikes, canals and lakes, outlets, sewer and pumping stations;

[7] The Rotterdam Climate Initiative programme is a collaboration of the Port of Rotterdam Authority, Deltalinqs, DCMR Environmental Protection Agency Rijnmond (hereafter: DCMR) and the City of Rotterdam.

- making use of the entire urban environment since adaptation solutions have to involve all the aspects of the urban environment in order to alleviate the urban system and make it more resilient;
- improving cooperation with the national government and the water boards, but also with other partners who are active in the city and linking with other projects;
- using the climate change adaptation as an opportunity for strengthening the economy of the city; improving the living environment of neighbourhoods and districts, increasing biodiversity and encouraging the people to actively participate in society.

In general, the adaptation actions of the Strategy responds to the following objectives:

- the city and its inhabitants are protected from the rivers and the sea;
- the city and its inhabitants experience minimal disruption from too much or too little rainfall;
- the Port of Rotterdam remains safe and accessible;
- the inhabitants of Rotterdam are aware of the effects of climate change and know what they themselves can do;
- climate change adaptation contributes to a comfortable, pleasant and attractive city in which to live and work;
- climate change adaptation strengthens the economy of Rotterdam and its image.

The Strategy states that Rotterdam is a delta city. Indeed, the city is located in the delta of the rivers Rhine and Meuse and has open links to the sea and is influenced by the tide. The city is characterized by an ingenious system of dikes. Therefore, in the city it is possible to distinguish between inner-dike areas and outer-dike areas (Figure 4). Much of Rotterdam, including the main port, lies in outer-dike areas.

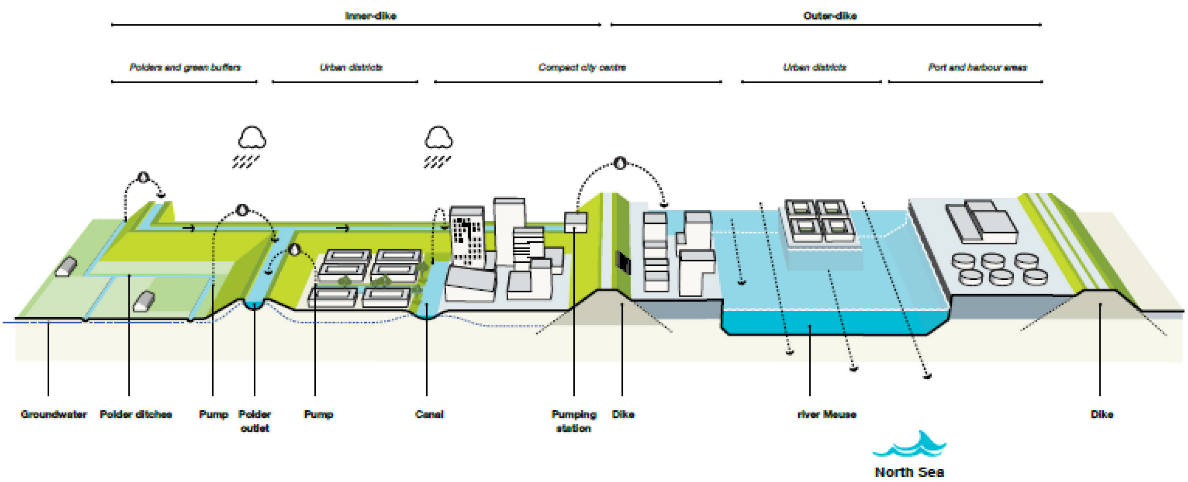

Figure 4. Scheme of the inner-dike and outer-dike areas in Rotterdam

Within the dikes, the inner-dike city of Rotterdam is mostly well below sea level, with the lowest point being as much as 6.67 metres below NAP[8] in the Alexanderpolder district. According to the strategy, the historic outer-dike areas are the most vulnerable to damage by flooding.

In particular, *"the low-lying historic outer–dike areas such as the Noordereiland, the Scheepvaartkwartier, the Kop van Feijenoord and Heijplaat are the most vulnerable to the effects of high water levels. If sea levels rise by 60 cm, the frequency of flooding of these areas will increase from once every 50 years to an average of once every year. Moreover, much larger areas will be affected. Recently developed areas such as Katendrecht, the Wilhelmina Pier, the Lloyd Pier and the Muller Pier will also suffer the consequences of higher water levels. A rise in sea level of 60 cm will increase the risk of water damage from 1 x 10,000 to 1 x 1,000. This is the probability of the areas flooding in any particular year and can be seen as a frequency. The risk of floods affecting Stadshavens (Merwe-Vierhavens), which are in the process of transformation, will also increase. The new port areas including the Botlek, Europoort and the Maasvlakte have been constructed at such high elevations that for many years to come, far into the 21st century, the risk of flooding will remain extremely low. The main port of Rotterdam is, and will remain, one of the safest ports in the world as far as flood protection is concerned".*

With regards to the inner-dike areas, Rotterdam has a primary flood defense system consisting of dunes along the coast and dike along the rivers. Furthermore, there are also storm surge barriers that are Maeslant, Hartel and Hollandsche Ijssel. Within these barriers there is another defense system composed of polders and outlet systems. The primary defense system of dikes plays an important role not only for the protection of the city, but in some places dikes are green and recreational, whilst elsewhere, they are an integral part of the urban infrastructure (see the Boompjes) such as roads or recreational cycle routes. Even if there is the need to reinforce and maintain the current defense systems of the city and to monitor eventually changes in the position of the storm surge barriers in relation to the future climate change, the inner-dike areas are well protected from flooding. Indeed, *"the primary dikes provide a high level of protection from flooding. Nevertheless, there is always a chance, however small, that the dikes will be breached or collapse".*

Considering the specific characteristics of Rotterdam, the Strategy provides solutions for each kind of climate change events. In particular, the adaptation solutions are described in relation to the kind of climate event and to the type of urban area where they have to be implemented.

Generally, in order to prevent flooding events due to the rising of sea and river levels, the main measures, described by the Strategy, are the following ones:

for the outer-dike areas:

- optimising the protection provided by the storm surge barriers;

[8] NAP the National Amsterdam Level, is an agreed ordnance measurement that is almost equal to mean sea level.

- realising flood-proofing buildings and flood-proof design of public areas (e.g. incorporating local flood walls);
- guaranteeing the continuum function of essential infrastructures;
- informing inhabitants and businesses about the likelihood risks and giving to them specific details of safety measures;

for the inner-dike areas:

- optimising the storm surge barriers;
- reinforcing the current system of dikes also as an opportunity for improving the attractiveness of the city and realising multi-functional structures;
- realising regional dikes (e.g. compartment dikes);
- improving the crisis management (e.g. reassessing the evacuation plans).

The Strategy identifies the main factors for implementing adaptation measures as the availability of spaces in the city and the consumer pressure. For example, consumer pressure is high in the compact city centre and in the high-densely urban districts. From this viewpoint, robust adaptation measures are possible where there is more space in the city, while in the more compact areas of the city it will be possible to realize “sponge functions” that don’t require particular space or consistent urban transformations (e.g. replacing paving stones with plants in streets and neighbourhoods, constructing infiltration zoned within existing infrastructure, etc.).

Finally, considering all the climate change effects, the Strategy describes the specific adaptation measures to implement for 6 types of urban areas (Figure 5), that are the port, Stadshavens, the outer-dike urban districts, the compact city centre, the inner-dike urban districts and the post-war suburbs with their parks and gardens.

The port

The port (Figure 5.1) has a key role in the economic life of Rotterdam. It stretches out over forty kilometres and encompasses one third of the total land area in the city. It is situated in the outer-dike area and for its position it is very vulnerable both the high river levels and storm surges. While the new area of the port was arose than the water level, the older harbour is more exposed to flooding events. In relation to the flooding events, for this area the adaptation forecasts are:

- realization of rising platforms for the storage of goods;
- realization of wet-proof constructions, characterized by floodable ground floor and where it is possible to move goods to higher floors;
- compartmentalization of sensitive infrastructure in the area;
- elevation of the road infrastructure for guaranteeing accessibility and safe evacuation routes;
- realization of dry-proof construction and floodwalls in order to protect essential function whose continual operation must be guaranteed.

Stadshavens

This area (Figure 5.2) links the city and the port in order to strengthen the economy and to create an attractive city. Indeed, this area will host transport companies, innovative enterprises and knowledge institutes but also residential environments and cultural facilities. As the port, Stadshavens is located in the outer-dike area and near the inner-dike area and is part of the old harbour complex. The transformation of this area represents an opportunity for improving the resilience and the environmental quality of the city. The main adaptation actions proposed for the area are the following ones:

- realizing "adaptive developments" that are safe living and working environments (e.g. floating houses);
- realizing "climate dike" linking dike reinforcements with real estate developments, in order to create more attractive environments where to live and work;
- realizing dike reinforcements also for recreational functions (e.g. cycle routes);
- improving recreational facilities, such as tidal park, also for realising wave breaker in order to protect dikes and transform dike in public areas.

The outer-dike urban districts

These districts (Figure 5.3) are central and linked to the river Meuse. They are characterized by the presence of old buildings and limited availability of spaces. There are two possible type of flood protection for these areas. One is to realise floodwalls in combination with the construction of parks along the Meuse river. In other places where the contact with the water is important, local waterproof thresholds at the entrances to houses and car parks are possible solutions. The main measures for these urban districts are:

- realization of flood walls for protecting neighbourhoods and districts linked to the water but also areas where are settle recreational functions;
- realization of dry-proof construction;
- realization of floodable quays that are functional in relation to shipping.

The inner-dike urban districts

The inner-dike urban districts (Figure 5.4) are located around the city centre and represent the densely built-up areas. Considering those physical characteristics, it is possible to realize mainly small-scale interventions. The adaptation actions have as main objectives improvements in the water system and an increasing of the storage capacity in order to increase their resilience, quality of life and property values.

In relation to river and coastal flooding events, the Strategy does not propose solutions.

The compact city centre

This part of the city (Figure 5.5) is a consolidated urban area, reconstructed after the Second World War. Even if in this area there is more space rather than other Dutch cities, the consumer pressure is high. The city centre, indeed, is characterized by the presence of modern high-rise buildings and many paved surfaces. The adaptation actions aims at reinforcing protection systems and reducing the imperviousness of urban surfaces although the considerable consumer pressure makes more difficult the incorporation of green areas in the city centre. The main adaptation measure for facing coastal flooding is the creation of multi-functional dike reinforcement as further urban development, especially for improving recreational facilities and green areas.

The post-war districts and surrounding areas

These districts (Figure 5.6) are located on the outskirts of Rotterdam and many of them are in the process of being restructured and improved. It represents an opportunity for inserting vegetated areas in the excess space reinforcing the features of the city and providing recreational spaces. The measures of adaptation for these areas are the following ones:

- strengthening of wetlands not only for recreational uses but also for increasing the value of the nature in the area and the water storage capacity;
- realization of green-blue ribbons that have both an ecological and a social value for these areas.

Figure 5. Six types of urban areas identified in the Rotterdam Strategy

3.3.6 Copenaghen

In 2011, Copenaghen was subjected to heavy rainfall that caused considerable damage. In response to this experience, in the same year, Copenaghen decided to prepare itself for the future extreme climate events by adopting of the Copenaghen Climate Adaptation Plan (City of Copenaghen, 2011). The Plan is a strategy for promoting the climate adaptation of the city to various climate events, primarily heavy rainfalls and rising sea levels. According to such aim, the strategy identifies three levels of adaptation:

- *Level 1* – Reduce the likelihood of the event happening: at this level, the main adaptation measures concern establishment of dike, building above sea level, local adaptation of sewer capacity, local management of stormwater, etc.;
- *Level 2* – Reduce the scale of the event: if the only measures at level 1 are not effective, it is necessary to implement further adaptation actions, including establishment of watertight basements, presence of sandbags, adaptation of public spaces;
- *Level 3* – Reduce the city's vulnerability to the event: this level is adopted when realizing prevention measures are easier and cheaper than interventions to clear up after an event.

Besides the three adaptation levels, the strategy highlights how much the effectiveness of urban adaptation measures is linked to its territorial scale of implementation. In the strategy, a diagram shows the various adaptation measures articulated in relation to both the adaptation levels and the geographical scale (Figure 6). The strategy also highlights that the adaptation planning is an opportunity for improving quality of life for people and measures have to be effective and economically justifiable.

	Level 1	Level 2	Level 3
Geography/Measure	Reduce likelihood	Reduce scale	Reduce vulnerability
Region	Delay of quantities of rain in catchment, pumping of water to sea	Delaying of volumes of rain in catchment, pumping of water to sea	
Municipality	Dikes, raised building elevations, increased sewer capacity, pumping of water to sea	Emergency preparedness Warning Securing of infrastructure	Information, moving of vulnerable functions to safe places
District	Dikes, "plan B", raised building elevation/ threshold	"Plan B" securing of infrastructure	Moving of vulnerable functions to safe places
Street	Control of stormwater runoff, raised building elevation/threshold, local management of stormwater	Control of stormwater runoff, raised building elevation/threshold, sandbag	Moving of vulnerable functions to safe places
Building	Backwater valve, raised building elevation/ threshold	Sandbags	Moving of vulnerable functions to safe places

Figure 6. Measures in relation to the adaptation levels and geographical scale

In this perspective, the adaptation measures have to be selected in relation to further gains from the social and economic perspective for the city, e.g. more recreational opportunities, new jobs, and improvement of local environment with more green elements.

After the description of its approach, the strategy illustrates the main city challenges resulting from climate change. For each of them, a set of measures and recommendations are proposed. Finally, the strategy comments on the adaptation opportunities to various perspective (green growth, buildings and roads, legislation and planning, emergency preparedness, and financing).

Concerning the rising sea level forecasts, Copenhagen may be hit by severe coastal floods. Indeed, in recent years, also due to economic growth, the urban density increased in the areas at flood risk. According to the Danish Meteorological Institute assessment based on the latest calculations, the sea level in Copenaghen will rise up to over 1 meter for 2100. Obviously, there is a lot of uncertainty about these projections, but they show that coastal floods can damage heavily the city, more than flooding events from rain (City of Copenaghen, 2011). Therefore, the strategy suggests investing in protection facilities.

This option is economically more advantageous than realizing no form of protection. In particular, in relation to the three adaptation levels and the territorial scale, the main adaptation actions to implement are shown. For example, at local level and building scale, the urban adaptation of low-lying areas is characterized by the following measures:

- raised building elevation, realization of dikes (for reducing the probability of coastal floods);
- preparedness, sandbags, installation of backwater valves, sealed basements (for reducing the scale of coastal floods);
- moving of vulnerable functions and installation in areas at low risk (for reducing the vulnerability to coastal floods).

Finally, the strategy does not illustrate applicative examples for the adaptation implementation in Copenaghen. However, a summary of the overall projects for protection against high water is reported. In particular:

- for the West and South Amager, there is a project for raising the dike along the area;
- in the Nordhavn, a barrier out towards the Øresund could be realized for reducing the risk of high water for the areas close to the harbour;
- in the south, the realization of a movable gate at the south of Kalveboderne can provide protection.

3.4 Results and discussion

After the analysis of case studies, the collected information of each case was further systematized. A first reflection concerns the urban characteristics used for defining the adaptation measures. It is noted that urban characteristics have not always been introduced and explicated in the case studies, as shown in Table 7. For example, Copenhagen's strategy does not introduce any urban characteristics but considers only 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. With regard to the other case studies, urban characteristics do not always refer to all the subsystems identified for a coastal city. In particular, the analysis shows that a lot of attention is given to the physical characteristics and, in some cases, to the functional ones for the definition of adaptation measures. The recurring physical characteristics refer to building stock, considering mainly their typology, and open spaces, which include recreational spaces, parks and natural areas.

Urban characteristic Case study	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	-	-
Copenaghen	-	-	-	-

Table 7. Urban characteristics introduced in the analysed adaptation strategies

Moreover, New Orleans's strategy introduces also the presence of the network infrastructures among the physical features while the San Francisco's one also the presence of shoreline protection systems.

Finally, it is interesting to note that Rotterdam introduces a new characteristic named "consumer pressure". It may be a useful "indicator" to establish the extent of the interventions to carry out in urbanized areas. As for the functional characteristics, these are taken into account only in three cases: New York, which considers only the land use, and Boston and San Francisco, which consider the presence facilities and assets in the coastal areas. Moreover, Boston and San Francisco are also the only cases that introduce socio-economic characteristics (age, ethnicity, income, etc.), referred to the identification of the vulnerable population. Finally, only New Orleans introduces the geomorphological features. In particular, it considers the analysis of the soil type (geomorphology) and the biodiversity of the area as key factors for defining the design choices contained in the Urban Water Plan.

With regard to the adaptation measures identified for each case studies, they can be articulated according to their object of intervention into four categories, such as: (i) localized interventions which concern the building scale; (ii) network interventions, which concern infrastructure, including coastal protection; (iii) land interventions, which affect portions of natural or urban coastal areas; (iv) awareness-raising interventions, which concern the population and urban actors (for example, companies). In relation to these four categories, the adaptation measures collected by the analysed case studies have been redefined as follows:

1. *Localized interventions* (4 measures):
   - Realization of new buildings according to resilient design standards (i.e. wet-proofing buildings, dry-proofing buildings, buildings raised from the ground over the rising sea-level threshold, etc.)
   - Retrofit of existing buildings according to resilient design standards (i.e. wet-proofing buildings, dry-proofing buildings);
   - Alternative uses for ground floors and basements of existing buildings;
   - Relocation of critical facilities and assets in safe areas;
2. *Network interventions* (6 measures):
   - Elevating of critical infrastructure localized in proximity of coastline;
   - Relocation of infrastructure in low-risk areas;
   - Integration of infrastructure networks (including one for transportation, energy, wastewater, etc.) with coastal defence structures (e.g. floodwalls);
   - Realization of coastal protection infrastructure (floodwalls, dikes, storm-surge barriers, etc.);
   - Reinforcement of existing coastal protection systems (dikes, breakwaters, bulkheads, etc.);
   - Realization or reinforcement of multi-functional dikes;
3. *Land interventions* (7 measures):
   - Compartmentalization;
   - Conservation and improvement of the natural coastal ecosystem (e.g. wetlands, saltwater marsh lagoons, dunes, etc.);
   - Creation of wetlands, waterways and floodable spaces from vacant land reconversion;
   - Localization of recreational areas and maritime uses;
   - Design of new developments and redevelopments according to resilient design standards;
   - Promotion of strict regulations in hazard zones;

- Ban of new developments in areas susceptible to flooding.

4. *Awareness-raising interventions* (2 measures):

- Development of preparedness programs for supporting population, businesses and other urban actors in case of coastal flooding;
- Promotion of awareness programmes on climate change and its effects.

Furthermore, each measure has been associated with the urban subsystems on which it affects. In particular, as shown in Table 8, most of the adaptation measures proposed by the case studies mainly affect the physical subsystem.

Among the most widespread measures, there are the realization and strengthening of coastal defence systems, but also the interventions on buildings and network infrastructures according to resilient design standards. Sometimes, the proposed adaptation measures also concern the functional subsystem and refer both to the location of the relevant activities and infrastructures and to the land use of areas in proximity to the coastline.

Some interventions affect both the physical subsystem and the geomorphological subsystem. They are frequent in the analysed case studies but result to be limited to a few interventions (e.g. compartmentalization[9] and measures related to the natural coastal ecosystem). Finally, with regard to the socio-economic system, there are two main measures. In particular, both New York and Copenhagen consider the development of programs for the preparedness of the population and urban actors in case of exceptional events. Furthermore, New York and Boston also introduce measures to aware the population to the climate change issue. The measures have been further classified according to the three adaptation approaches, provided by the IPCC, - accommodation, protection, and retreat. This classification shows that most of the introduced measures refer to accommodation. In particular, the localized interventions are mainly classifiable as accommodation measures, while for the categories of network interventions and land interventions there is a greater balance between the two approaches.

Moreover, with respect to urban subsystems, it is noted that the protection measures affect the physical subsystem and, in some cases also the geomorphological one, while accommodation measures can relate to the physical and/or functional subsystem. Finally, retreat measures concern, at the same time, both the physical and functional subsystems and refer to the relocation of public facilities and infrastructures or even coastal communities from at-flood-risk zones.

[9] The compartmentalization is an adaptation measure that is used to reduce the consequences of floods. Such a measure consists in upgrading old dikes, roads, railways and other "line elements" that are present in the area in flood protection elements. When these structures have a height over the forecasted sea-level rise, indeed, they can be used for creating enclosed compartments of the coastal area (Koks et al., 2014).

Intervention's category	Adaptation Measures	Socio-economic subsystem	Physical subsystem	Functional subsystem	Geomorphological subsystem	IPCC's adaptation approach
1. Localized	1.1 Realization of new resilient buildings		•			Accommodation
	1.2 Retrofit of existing buildings		•			Accommodation
	1.3 Alternative uses for ground floors and basements			•		Accommodation
	1.4 Relocation of critical facilities and assets		•	•		Retreat
2. Network	2.1. Elevating of critical infrastructure		•			Accommodation
	2.2 Relocation of infrastructure		•	•		Retreat
	2.3 Integration of infrastructure networks with coastal defense structures		•			Protection
	2.4 Realization of coastal protection infrastructure		•			Protection
	2.5 Realization or reinforcement of multi-functional dikes		•	•		Protection
	2.6 Reinforcement of existing coastal protection systems		•			Protection
3. Land	3.1 Compartimentalization		•		•	Protection
	3.2 Conservation and improvement of the natural coastal ecosystem				•	Protection
	3.3 Creation of wetlands, waterways and floodable spaces		•		•	Protection
	3.4 Localization of recreational areas and maritime uses		•	•		Accommodation
	3.5 Design of adaptive developments and redevelopments		•	•		Accommodation
	3.6 Promotion of strict regulations in hazard zones		•	•		Accommodation
	3.7 Ban of new developments in areas susceptible to flooding		•	•		Retreat
4. Awareness-raising	4.1 Development of preparedness programs	•				Accommodation
	4.2 Promotion of awareness programmes	•				Accommodation

Table 8. Adaptation measures classified for urban coastal subsystems

As illustrated in the previous paragraph, with the exception of Copenhagen, the adaptation measures refer to urban districts or neighbourhoods with specific physical and functional characteristics. In particular, the urban districts identified in the case studies can be articulated into eight types of urban areas, defined as follows:

- *Type 1*. High-density and mixed-use urban areas;
- *Type 2*. High-density residential areas;
- *Type 3*. Medium-low residential areas;
- *Type 4*. Low-density touristic areas;
- *Type 5*. Industrial and commercial areas;
- *Type 6*. Transport infrastructure and public facilities;
- *Type 7*. Natural and recreational areas;
- *Type 8*. Redevelopment areas.

Starting from the analysis of the case studies, a set of adaptation measures has been defined for each type of identified area (Table 9). In this way, it was possible to get a framework of adaptation measures to implement in urban coastal areas according to their urban characteristics for reducing impacts due to coastal flooding.

In particular, the creation of wetlands, waterways and floodable spaces within coastal areas, using vacant lands in case of high-density areas, the integration of infrastructure networks with coastal defense structures for the network interventions, and, finally, all the accommodation measures at building scale can be implemented for all the urban types (except for *Type 8*). With regards to the awareness-raising initiatives, they are provided for areas where there is a high concentration of urban actors (inhabitants, employees, city users, etc.).

If the classification referred to the IPCC's adaptation approaches is considered, the most used measures in the urban areas are the accommodation and protection ones. The most innovative measures among the analysed ones is the realization or reinforcement of multi-functional dikes, as it represent an attempt to integrate the accommodation and protection approaches. The accommodation and protection measures have been identified for the urban areas characterized by high urban density, and for those ones by high functional specialization or by the presence of infrastructure. For what concern retreat measures, they are provided for *Types 1*, *2*, *3*, *4* and *7* and concern the delocalization of activities, infrastructure or whole coastal community from an at-risk area. In particul*ar, a localized measure of retreat is provided for Types 1, Type 2, Type 3 and Type 4*, while a network intervention concern *Types 3* and *Type 7*. Finally, a land intervention of retreat is introduced for *Types 3* and *4* and they are related to the new development in flood-risk areas. In summary, technical and engineering measures of accommodation and protection are more adopted in urbanized and infrastructure areas. Instead, the retreat measures concern mainly areas exposed to the coastal flood risk but characterized by low-population density and low-building density. Indeed, retreat measures are particularly expensive (Lee, 2014) and intervening in low-density contexts ensures a greater balance in the cost-benefit relationship.

Adaptation Measures	**Type 1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**	**Type 6**	**Type 7**	**Type 8**	**IPCC's adaptation approach**
1.1 Realization of new resilient buildings	•	•	•	•	•	•			Accommodation
1.2 Retrofit of existing buildings	•	•	•	•	•	•			Accommodation
1.3 Alternative uses for ground floors and basements	•	•	•	•	•	•			Accommodation
1.4 Relocation of critical facilities and assets	•	•	•	•					Retreat
2.1 Elevating of critical infrastructure			•	•					Accommodation
2.2 Relocation of infrastructure			•				•		Retreat
2.3 Integration of infrastructure networks with coastal defense structures	•	•	•	•	•	•	•		Protection
2.4 Realization of coastal protection infrastructure	•	•	•	•	•	•		•	Protection
2.5 Reinforcement of existing coastal protection systems	•	•	•					•	Protection
2.6 Realization or reinforcement of multi-functional dikes	•	•			•	•			Protection
3.1 Compartimentalization					•	•			Protection
3.2 Conservation and improvement of the natural coastal ecosystem	•		•				•	•	Protection
3.3 Creation of wetlands, waterways and floodable spaces	•	•	•	•	•	•	•		Protection
3.4 Localization of recreational areas and maritime uses		•	•	•		•		•	Accommodation
3.5 Design of adaptive developments and redevelopments	•	•		•			•	•	Accommodation
3.6 Promotion of strict regulations in hazard zones	•	•	•	•					Accommodation
3.7 Ban of new developments in areas susceptible to flooding			•	•					Retreat
4.1 Development of preparedness programmes	•	•	•	•					Accommodation
4.2 Promotion of awareness programmes	•	•	•	•					Accommodation

Table 9. Adaptation measures for types of urban coastal areas

3.5 Conclusions

Urban adaptation to the impacts of climate change is a topic of growing interest in urban planning. Despite the need to plan climate-proof cities, the scientific literature seems to be lacking a theoretical model that allows operating on the urban layout and its functional organization in order to reduce the impacts of climate change and, in particular, of coastal flooding at local level.

In order to understand how the adaptation of coastal cities to the impact of coastal flooding is really implemented, in this section the strategies and measures adopted by six international case studies were analysed.

From the analysis of the case studies, it arose that two approaches are mainly adopted for urban adaptation to the impacts of the coastal flooding. The first approach is based on the vulnerability, which is defined and supported by numerous studies in the literature, and, alternatively, while the second one is based on the 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, the case study analysis shows that adaptation is a two-step process composed of a cognitive phase and decision-making phase. While the cognitive phase concerns the study both of future climate forecasts for the city (among which there are the future rising sea level, the intensity of storm surges, etc.) and of the urban characteristics, the decision-making phase refers to adaptation measures to implement at the urban and, especially, at the local level.

According to the application of 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, physical characteristics are mainly taken into consideration, while only some case studies consider those functional and/or socio-economic and/or geomorphological.

Since strategies consider mainly physical characteristics, adaptation measures are also related to the physical subsystem of the city and they are technical-engineering rather than urban ones.

It is important to highlight that adaptation measures are not defined according to the "one fits all" principle. Indeed, 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 of adaptation is a process whose local scale of implementation is the most effective, according to Carter et al., (2015) and Füssel (2007). Furthermore, the adoption of a sectoral approach to the study of the urban system and the definition of adaptation measures may not take into account other likewise important aspects, including those related to the organization and liveability of the city.

In this context, the General System Theory applied to the urban planning, theorized by McLoughlin (1969) seems to be a well-grounded theoretical approach for analysing the whole urban system and the complexity of the relationships between urban coastal systems and coastal flooding. Moreover, this theory offers more guarantees in supporting the choice of integrated and effective solutions for the city in relation to its present challenges (Papa, 2009; Papa et al., 2015), including climate change, which further increases the complexity of the urban system, mainly due to uncertainty related to future weather forecasts (da Silva et al., 2012).

Based on the research gaps identified in the cognitive phases illustrated in this Section and in Section 2, the next section presents the methodology developed for the construction of a tool for supporting the decision-making process in the definition of urban adaptation measures to impacts of coastal flooding on a local scale by adopting a holistic-system approach.

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Section 4. Methodology

4.1 Introduction

The purpose of this research is to develop a GIS-based tool to support the decision-making process with regards to the urban adaptation measures for reducing impacts of coastal flooding in urban areas at local scale.

In the previous Sections, it arises that urban adaptation of coastal cities to coastal flooding is a process that adopts a sectoral approach and it is a limitation to understand on how to plan coastal areas for reducing impacts due to sea-level rise and storm surges. Hence, in this Section the methodology for developing the GIS-tool is illustrated. This methodology has been developed considering two aspects. The first aspect concerns the adoption of a holistic-system approach according to the General System Theory applied to the analysis of urban phenomena (Gargiulo & Papa, 1993). In particular, in order to understand the relationships between coastal city and impacts of coastal flooding, coastal cities can be interpreted as a system articulated into four subsystems, defined as follows:

- *Socio-economic subsystem*: it includes the main socio-economic factors, which characterize the population that lives in the coastal area;
- *Physical subsystem*: it includes spaces and areas where the urban activities of the coastal area take place;
- *Functional subsystem*: it includes features referring to the type and the localization of urban activities and concerns accessibility;
- *Geomorphological subsystem*: it includes 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 proceses 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 & Costa, 2009; Murgante et al., 2009).

Based on this holistic-system approach and thanks to the use of GIS, the methodology for the development of the GIS-based tool has been articulated into four phases:

- definition of a new composite index for measuring the urban resilience of coastal cities, defined as the Coastal Resilience Index;

- classification of urban coastal areas – named Urban Coastal Units - in relation to their physical and functional characteristics;
- definition of classes of urban adaptation measures, defined as Urban Adaptation Actions;
- definition of a design workflow for the implementation of the GIS-based tool.

In particular, Section 4 is articulated in five paragraphs. Paragraphs 4.2 describes the criteria, indicators, and techniques used for the development of the composite index. Paragraph 4.3 defines Urban Coastal Units and illustrates their main features and indicators introduced for identifying them. Paragraph 4.4 specifies how Urban Adaptation Actions have been set. Paragraph 4.5 introduces the main features and the workflow process of the GIS-based tool. Section 4 concludes by summarizing the main findings of the developed methodology and illustrating the next steps of this research.

4.2 Construction of the Coastal Resilience Index

The literature review (illustrated in Section 2) and the case study analysis (illustrated in Section 3) represented the starting point for developing a new composite index, named the Coastal Resilience Index (CoRI).

According to the JRC (2008), the construction of the CoRI can be articulated into four main steps:

- Defining the CoRI;
- Selecting the urban parameters and the relative variables to develop the composite index;
- Defining the normalization technique of the data;
- Choosing the aggregation method of the data for constructing the CoRI.

4.2.1 Definition of the Coastal Resilience Index

To date, vulnerability indices are the main tools developed for the definition of adaptation strategies. However, from a semantic point of view, the comparison between the concept of vulnerability and that of resilience highlights that vulnerability refers to the pre-event characteristics of a system that create the potential for harm, while resilience considers the capacities that a system has to absorb and cope with an event, as well as post-event (Cutter et al., 2008). From this point of view, the urban adaptation process is more strictly linked to the resilience concept rather than the vulnerability one. In this perspective, it was decided to introduce the concept of resilience for the development of a new index.

With regards to its definition, the CoRI aims at measuring at local level the "urban coastal resilience". According to the definitions of the Hyogo Framework for Action (UNISDR, 2005) and the IPCC (Mach et al. 2014), urban coastal resilience is defined as the capacity of an urban coastal system to reach and maintain an acceptable level of functioning and structure during a coastal flooding. In particular, starting from such a definition, the CoRI measures the endogenous ability of the urban coastal system in relation to its socio-economic, physical, functional, and geomorphological characteristics to cope with hazardous events such as coastal flooding. 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) for reducing the impacts of coastal flooding on these areas.

4.2.2 Selection of urban indicators

In this second step, in relation to the literature review and the case study analysis, twelve urban characteristics and the relative variables were selected and classified into four categories according to the holistic-system approach (Table 10): three socio-economic characteristics; three physical variables; three functional characteristics; three geomorphological characteristics. In particular, this set of characteristics has been chosen considering site-specific datasets characterized by a high spatial resolution appropriate for the territorial scale of interest, i.e. local scale.

Category	**Characteristic**	**Description**
Socio-economic	SE1. Education level	*Number of inhabitants for each level of education*
	SE2. Age of population	*Number of inhabitants by age bracket*
	SE3. Employment	*Percentage of population in employment*
Physical	P1. Urban permeable surface	*Degree of permeability*
	P2. Raised buildings	*Number of buildings in each category based on their degree of elevation above the ground floor*
	P3. Conservation of buildings	*Number of buildings for level of maintenance*
Functional	F1. Transport network	*Presence of main roads and railways close to the coastline*
	F2. Ground floor activities	*Number of buildings for classes according to the use and occupancy of their ground floors*
	F3. Public facilities	*Presence of public facilities close to the coastline*
Geomorphological	G1. Slope of coastal area	*Slope in percentage*
	G2. Water body	*Presence of water bodies close to the coastline*
	G3. Distance from coastline	*Distance from coastline*

Table 10. Selected urban characteristics

Urban coastal resilience is closely linked to the socio-economic characteristics of the population. In particular, as highlighted in Section 2, the education level of the population can affect access to the information necessary for the management of the urban system during a coastal flooding. Hence, the higher the level of education, the greater the resilience of the system. Another important aspect concerns the age of the population. In particular, the elderly and children can have greater mobility constraints during an exceptional event. Finally, the economic capacity of the population also influences the system's ability to reduce the externalities of coastal flooding. Above all, people with a high income, as well as a high percentage of employees, can guarantee a faster post-event recovery. In this perspective, the socio-economic characteristics identified were as follows: (1) education level, calculated as number of inhabitants for each level of education; (2) age of population, calculated as the number of inhabitants by age bracket; (3) employment, calculated as the percentage of population in employment.

From the physical perspective, urban coastal resilience is also affected by the characteristics of the built environment. In particular, as highlighted in Section 3, 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 realized according to specific construction standards (e.g. buildings elevated above the forecasted sea-level rise) it can reduce any interruptions in the provision of services that are necessary for the urban life of citizens and city users. Finally, according to Cutter et al. (2003), good quality of building maintenance reduces the chances of building being damaged during coastal flooding and, therefore, they are more resilient. In particular, the physical characteristics introduced in this research are: (1) urban permeable surface calculated as degree of permeability; (2) raised buildings, number of buildings in each category based on their degree of elevation above the ground floor; (3) number of buildings for level of maintenance.

As aforementioned, functional characteristics include those ones that refer to the localization of urban activities within and along coastal areas and 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 those public services that have to deliver in a continuous way, especially during coastal flooding. Furthermore, transport infrastructure has also to be designed and localized in order to guarantee accessibility to urban activities settled in the area during coastal flooding. Therefore, three functional characteristics were identified: (1) transport network, calculated as the presence of the main roads and railways near to the coastline; (2) ground floor activities, calculated as the number of buildings for classes according the use and occupancy of their ground floors; (3) public facilities, calculated as the presence of public facilities and assets close to the coastline.

The geomorphological aspects also influence the resilience of coastal cities. In particular, among these the following characteristics were considered: (1) slope of coastal area, measured as slope in percentage; (2) water body, expressed as the presence of water bodies near to the coastline; (3) distance from coastline, measured as the distance of each territorial points from the coastline.

With regard to the slope, as highlighted by Karymbalis et al. (2012) and Preston et al. (2008), it is one of the main aspects to estimate the impacts of coastal flooding. Indeed, it allows identifying coastal areas where water is most likely to runoff or accumulate. Although less discussed in the literature, also the distance from the shoreline plays a key role in the definition of the resilience level for a coastal area, since areas nearest to the coastline will be more exposed to coastal flooding. Finally, the proximity to the coastline of water bodies can greatly contribute to the extension of flooded areas and, consequently, the reduction of urban coastal resilience.

4.2.3 Normalization techniques for the data

After the definition of urban characteristics and their relative variables, the definition of the normalization methods is required since it allows the aggregation of datasets with different measurement units (JRC, 2008). Since the selected variables are spatial data and they are available in two main typologies, aggregated data referred 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. Generally, categorical scales are the most widespread method used for normalizing spatial data.

Category	**Characteristic**	**Class**			
		1	**2**	**3**	**4**
Socio-economic	SE1. Education level	*Elementary school or less*	*High School*	*College*	*University or higher*
	SE2. Age of population	*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	*0-25%*	*25-50%*	*50-75%*	*75-100%*
Physical	P1. Urban permeable surface	*0-20%*	*20-50%*	*50-75%*	*75-100%*
	P2. Raised buildings	*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	*Bad*	*Medium*	*Good*	*Excellent*
Functional	F1. Transport network	*Present*			*Absent*
	F2. Ground floor activities	*Residential*	*Tertiary, commercial and industrial*	*Storages*	*None*
	F3. Public facilities	*Present*			*Absent*
Geomorphological	G1. Slope of coastal area	*0-20%*	*20-40%*	*40-60%*	*>60%*
	G2. Water body	*Absent*			*Present*
	G3. Distance from coastline	*<50 m*	*50-300 m*	*300-1000 m*	*> 1000 m*

Table 11. Categorical classes for the varaibles of the urban characteristics

However, it has different limitations. As highlighted by the JRC (2008), *"Categorical scales exclude large amounts of information about the variance of the transformed indicators. Besides, when there is little variation within the original scores, the percentile bands force the categorisation on the data, irrespective of the underlying distribution"*.
In order to address these issues, starting from a categorical normalization of the selected variables (Table 11), 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 a poor contribution to the urban coastal resilience, while the "4" is assigned when a characteristic contributes substantially to it. The majority of variables are vector data and they were rescaled by calculating of a weighted arithmetic mean of the classes' values recorded by each spatial units. In particular, the formula is the following one:

$$\overline{x_i} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} x_i} \qquad (n = 4)$$

where $\overline{x_i}$ 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 and P3 variables. In the case of SE3, according to the brackets of the four categorical classes, it was used the *Min-Max* method by using the following formula:

$$\overline{x_i} = 4\,\frac{x_i - x_{min}}{x_{max} - x_{min}}$$

where $\overline{x_i}$ is the normalized value of the indicator in *i*th census block, x_i is the indicator's value, and x_{max} and x_{min} are respectively the maximum (100%) and minimum (0%) values of reference for the indicator.
For what concerns the P1, G1, and G3 variables, it was necessary to use a different method from those ones 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, it was used the Rescale by function tool to transform categorical classes for each variable in a continuous function. In particular, categorical class brackets were used as inputs 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 & Cooper (2010) and Palmer et al. (2011). For the "Urban permeable surface" brackets the data points introduced by Akan & Houghtalen (2003) and used by several studies (e.g. Giugni & De Paola, 2011; Saraswat et al., 2016) were used. Instead, in literature, the "Slope of coastal area" brackets are not univocally defined. Several definitions are due to both the territorial scale of interest (mainly, the regional one) and the analysed phenomenon.

In this perspective, Zanetti et al. (2016) was chosen as a literature reference for the definition of classes' brackets since their index was developed and applied on the local level. Therefore, according to the CoRI's purpose, it can also 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, as shown in Figure 7, Figure 8 and Figure 9. Finally, the F1, F3 and G2's categorical classes were univocally normalized since "0" corresponds to the absence of a transport infrastructure or water body in the analysed area, while "4" is assigned when these elements are present.

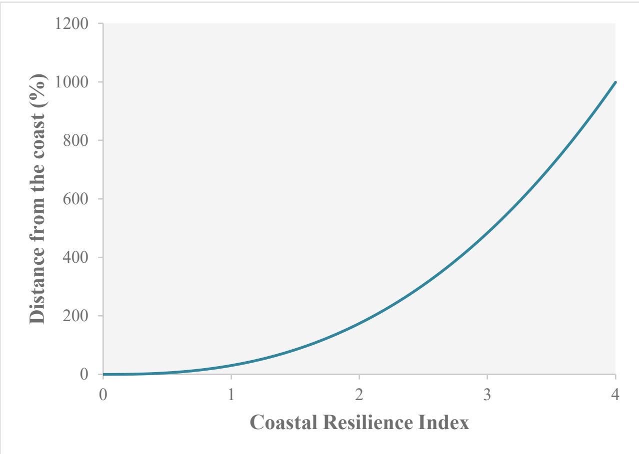

Figure 7. Relationship between distance from coastline and CoRI

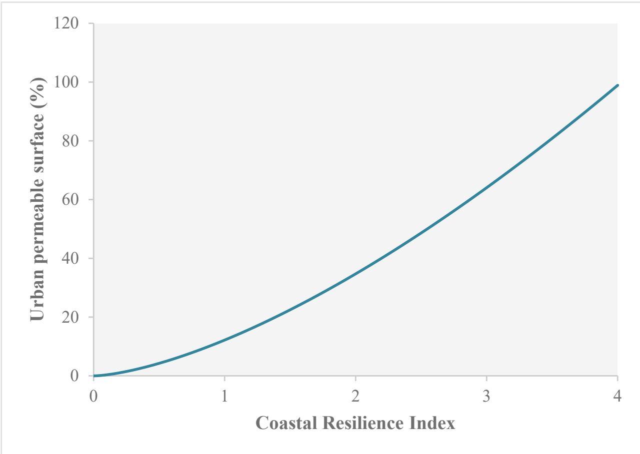

Figure 8. Relationship between urban permeable surface and CoRI

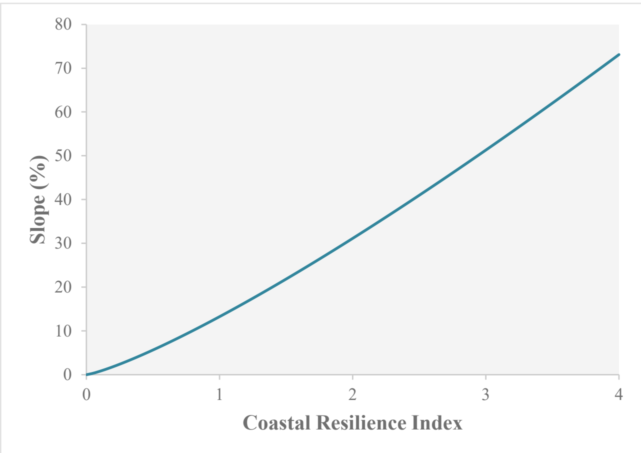

Figure 9. Relationship between slope and CoRI

4.2.4 Aggregation and Weighting method of the CoRI

As defined by the normalization method, the last step was the weighting and aggregation of the multiple variables for measuring urban coastal resilience. The methods choice should be done along the lines of the base concept expressed by the composite index (JRC, 2008).

Considering the most widespread aggregation methods used for developing vulnerability index, described in the Section 2 (see Paragraph 2.3), and taking into account that the CoRI is a novel composite index, the linear aggregation technique was used and the indicators' weights have been calculated by means of the use of the Analytic Hierarchy Process (AHP), developed by Thomas Saaty (1980). As defined by Saaty & Vargas (2012), the AHP is *"a nonlinear framework for carrying out both deductive and inductive thinking without use of the syllogism. This is made possible by taking several factors into consideration simultaneously, allowing for dependence and for feedback, and making numerical tradeoffs to arrive at a synthesis or conclusion"*. In research, AHP gained wide applications in site selection, suitability analysis, regional planning, and landslide susceptibility analysis (Yalcin, 2008). Furthermore, the GIS technology provides an effective support to the spatial decision problems. As highlighted by Chandio et al. (2012), *"the GIS is a powerful tool in spatial modeling which involves a large number of spatial decision problems providing alternative scenarios in the context of maps"*. Indeed, in recent years the integration of GIS and multicriteria decision analysis, especially the AHP, has increased. According to the purpose of this research, the AHP allows the weights, which each indicator assumes, to be defined. In particular, the indicators' weights quantify the relative importance of each of them in relation to the level of urban coastal resilience.

The AHP was developed into 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 & Pereyra-Rojas, 2017). In this case, the holistic-system approach was useful to set such hierarchy where the "goal" is to evaluate the urban coastal resilience of urban areas, "criteria" correspond to the four subsystems that compose the urban coastal system, while "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. As shown by Figure 10, the pairwise matrix is a square matrix where its diagonal elements are equal to 1 while the other ones verify two conditions:

- The $i-j$th element is equal to the comparison between element i and element j regarding the considered criterion;
- For i different from j, the $i-j$th element is equal to the inverse of the $j-i$th element.

$$\begin{bmatrix} 1 & a_{12} & \dots & a_{1i} & \dots & a_{1j} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2i} & \dots & a_{2j} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1/a_{1i} & 1/a_{2i} & \dots & 1 & \dots & a_{ij} & \dots & a_{in} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1/a_{1j} & 1/a_{2j} & \dots & 1/a_{ij} & \dots & 1 & \dots & a_{jn} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1/a_{in} & \dots & 1/a_{jn} & \dots & 1 \end{bmatrix}$$

Figure 10. AHP pairwise positive reciprocal comparison matrix (Source: Vidal et al., 2011)

Judgment's value	Definition	Explanation
1	Equal importance	The *i* and *j* activities contribute equally to the objective
2	*Weak*	
3	Moderate importance	Experience and judgment slightly favour *i* activity than *j* activity
4	*Moderate plus*	
5	Strong importance	Experience and judgment strongly favour *i* activity than *j* activity
6	*Strong plus*	
7	Very strong or demonstrated importance	*i* activity is favoured very strongly over *j* activity
8	*Very, very strong*	
9	Extreme importance	The evidence favouring *i* activity over *j* activity is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Table 12. Scale for pairwise comparisons (Source: Saaty & Vargas, 2012)

In the pairwise comparison matrix, indeed, each cell expresses the relative importance of two indicators through a numerical scale of comparison developed by Saaty (1980), as shown in Table 12.

In order to understand the importance of each pair of indicators, considering the lack of information about the indicators' relationships in literature, it was necessary to adopt a Delphi study. Indeed, a Delphi study is used when "there is incomplete knowledge about a problem or phenomenon" (Skulmoski et al., 2007). 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 (Table 13).

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.

Role	Invited	Attended	Attended Percentage
Academics and researches	78	36	46.1%
Technical experts in public administration	21	13	61.9%
Professionals	36	32	88.9%
Total	**135**	**68**	**50.4%**

Table 13. Composition of the experts' panel

For what concerns academic and researchers, starting from the literature review the selection of the main experts in the scientific debate on the topic was conducted. After that, all the experts were invited to fill in an electronic questionnaire that was sent to the panel by electronic mail. In the end, 68 experts (about 50% of the whole panel) filled in the survey and their opinions were collected in order to define each cell value of the pairwise comparison matrix. In particular, the mode of the expressed opinions for each relationships was used for constructing the pairwise comparison matrix.

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

$$\mathbf{Pw} = \boldsymbol{\lambda}_{max}\mathbf{w} \tag{1}$$

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

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

where m is the order of the matrix.

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

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

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

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

The last step of the AHP consisted of 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 & 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 or equal to 0.10. In this case, since the Consistency Ratio is equal to 0.08, the AHP weights are acceptable and they can be used for formulating the CoRI as follows:

$$CoRI = \sum_{i=1}^{n} w_{se_i}\, se_i + \sum_{i=1}^{n} w_{p_i}\, p_i + \sum_{i=1}^{n} w_{f_i}\, f_i + \sum_{i=1}^{n} w_{g_i}\, g_i \tag{3}$$

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 respectively the social-economic, physical, functional and geo-morphological weights; and

se_i , p_i , f_i and g_i represent the corresponding indicator.

In Table 14, the indicators' weights are reported.

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	*0.081*
	F2. Ground floor activities	*0.074*
	F3. Public facilities	*0.085*
Geomorphological	G1. Slope of coastal area	*0.128*
	G2. Water body	*0.088*
	G3. Distance from coastline	*0.121*

Table 14 CoRI indicators' weights

In particular, the geomorphological indicators affect mainly the urban coastal resilience's levels. However, also 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.

4.3 Definition of Urban Coastal Units

Generally speaking, 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 take into account the presence of urban areas along the coastline and introduce land-use characteristics in their classification (e.g. Wu et al., 2002).

The basic and most common classification refers to the regional level and divides coastal areas into urban and rural areas (e.g. McGrahnan et al., 2005; Wolff et al., 2018). Other studies are more specific in the land-use classification. In particular, Wu at al. (2002) consider eight land-use types (e.g. agriculture, forested wetland, beaches, etc.), among which there are also urban areas. At the local level, in order to assess coastal vulnerability, McLaughlin & Cooper (2010) consider five classes based on the land use and also the geomorphological features of the coastal area that are (1) Rocky cliffs, (2) Scrub, (3) Beach/Sand dunes/Forest/Rough, (4) Agricultural land/Tee boxes/Fairways/Amenity grass and (5) Urban Residential/Car parks/Greens. Instead, Zanetti et al. (2016) introduce 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.

From the analysis of these classifications, it is noted that the land-use (or functional) classifications of coastal areas are widespread. However, as highlighted by 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 the urban planning and in urban adaptation it is important to consider both physical and functional characteristics (Young, 2016). Furthermore, identifying homogeneous urban areas represents a key aspect for a better choice of the urban measures that should be implemented in an area (Gargiulo, 2014). 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. Mono-functional 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, station and other 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 touristic accommodations can be included in this class;
- *Class 5. Potential Redevelopment Areas*: urban areas abandoned that can potentially 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.

Starting from these definitions, 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. Considering the land use, the Urban Atlas classification was used. The Urban Atlas provides a detailed and cost-effective mapping of urban areas, besides the higher resolution on land-use data than other datasets. Indeed, from the comparison between the most used Corine Land Cover and the Urban Atlas it arises that the scale of Corine Land Cover is 1:100,000 with a minimum mapping unit of 25 ha. Instead, the scale of Urban Atlas is 1:10,000 and the minimum mapping unit is 0.25 ha for the artificial surfaces and 1 ha for the other ones (Prastacos et al., 2011). This difference is particularly relevant if the land-use data have to be used at local level (Figure 11).

In particular, according to the six UCUs definitions, the 20 classes proposed by Urban Atlas (Table 15) were reduced into four classes, associated to the built environment, the presence of infrastructure and public facilities or specialized functions (e.g. industrial, commercial, etc.), and, finally, the green and natural areas.

For what concerns the land-use intensity, the indicators are:

- *Population Density:* it defines the intensity of residential land use in an urban area, expressed as the number of inhabitants per square kilometre. This indicator is used mainly 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). For

McGranahan et al. (2005), population density in coastal areas is higher than in land areas (more than 25%). In 2005, the average population density in coastal EU regions was 100 inhabitants per sq. km and the highest population density was over 200 inhabitants/sq. km (Eurostat, 2009). According to Torresan et al. (2008), for the Veneto Region in Italy, it is possible to distinguish four population density classes. Of which, the highest one corresponds to a population of over 1,000 inhabitants for square kilometre. Instead, according to Eurostat (European Commission, 2012) and OECD (2012, 2013), in European cities, the urban areas are categorized as high population density urban areas when they have a value higher than 1,500 inhabitants per square kilometre (ISTAT, 2017);

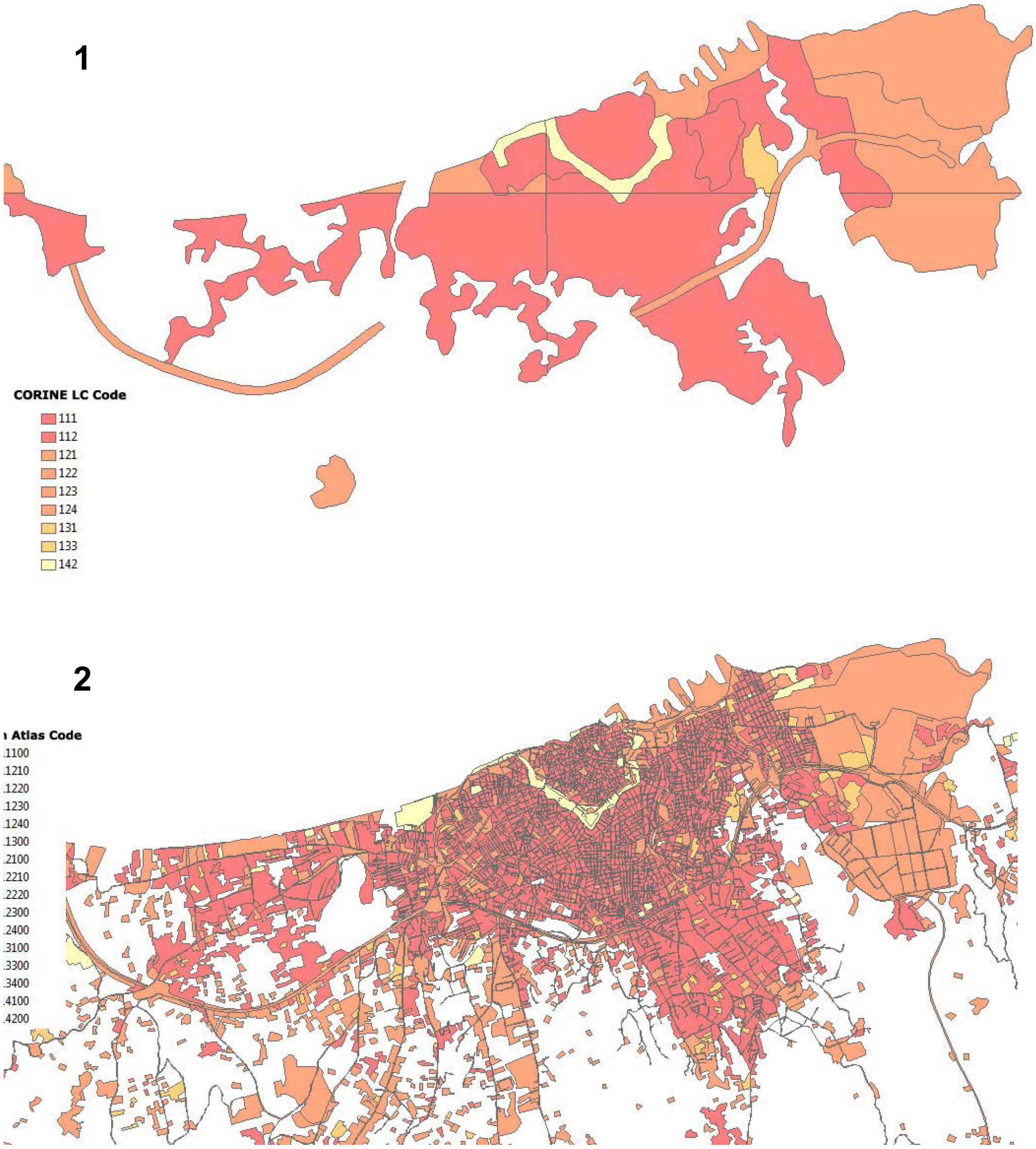

Figure 11. Difference between the resolution of the Corine Land Cover (1) and the Urban Atlas (2) (Source: Prastacos et al., 2011)

Urban Atlas class
11100 Continuous Urban Fabric (Sealing Degree > 80%)
11210 Discontinuous Dense Urban Fabric (Sealing Degree 50% - 80%)
11220 Discontinuous Medium Density Urban Fabric (Sealing Degree 30% - 50%)
11230 Discontinuous Low Density Urban Fabric (Sealing Degree 10% - 30%)
11240 Discontinuous Very Low Density Urban Fabric (Sealing Degree < 10%)
11300 Isolated Structures
12100 Industrial, commercial, public, military and private units
12210 Fast transit roads and associated land
12220 Other roads and associated land
12230 Railways and associated land
12300 Port areas
12400 Airports
13100 Mineral extraction and dump sites
13300 Construction sites
13400 Land without current use
14100 Green urban areas
14200 Sports and leisure facilities
20000 Agricultural + Semi-natural areas + Wetlands
30000 Forests
50000 Water bodies

Table 15. The 20 classes provided by the Urban Atlas

- *Job-Housing Ratio* (or *Employment to Housing Ratio*): it is an indicator used by city planners to examine the proportions between residents and jobs and services in an area. It is calculated as the ratio between the number of employees and the number of inhabitants in the area. It is often used for developing efficient city plans and transit networks (EPA, 2014) in order to define the land-use mix at the local level (Merlin, 2014) and, consequently, also to measure if an area is residential or specialized in economic activities that include manufacturing, commercial, public and touristic activities, based on the "economic base theory" (Andrews, 1953; Haig, 1928). In particular, a Job-Housing Ratio of more than 1 (that represents the Job-Housing Balance) indicates that in the area there are more workers than residents;
- *Tourism Employment*: this indicator expresses the prevalence of the tourism industry in relation to the totality of economic activities. It is calculated as the 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*: it expresses the tourist accommodation capacity of the area. It is calculated as the ratio of the total number of accommodation beds and the total of inhabitants in the area. In particular, even if it is useful to measure the tourist accommodation supply, this indicator shows which area can have a varied population density due to tourism-related activities, since this variability could increase the exposure to flooding events of these areas.

In relation to their definitions, for each indicator a benchmark value was set in order to define a first-level binary articulation of the urban area. In particular, for each indicator the benchmark value is shown in the Table 16.

Land-Use Intensity indicator	Description	Benchmark value
Population density	Number of inhabitants per square kilometre	1,500 people/sq. km
Job-Housing Ratio	Ratio between the number of employees and the number of inhabitants	1,00
Tourism Employment	Percentage of workers in the tourism industry	100%
Tourist Capacity	Ratio of the total number of accommodation beds and the total of inhabitants	1,00

Table 16. Benchmark values of the Land-Use Intensity indicators

Thanks to this articulation, the indicators were combined with the new land-use classification in order to define the six UCU classes (Figure 12).

4.4 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 (Wong et al., 2014). Furthermore, the 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 coastal flooding impacts on the coastal communities and, at the same time, it can be an opportunity for increasing the quality of life in those areas. As introduced by IPCC (Nicholls et al., 2007), the possible adaptation approaches available for coastal communities are threefold:

- *Accommodation*: it considers modifications to the urban layout and organization in relation to the flooding exposure. This approach includes mainly measures about the land use change, retrofitting buildings, development of more accessible routes for pedestrians and for the transit of safety means;

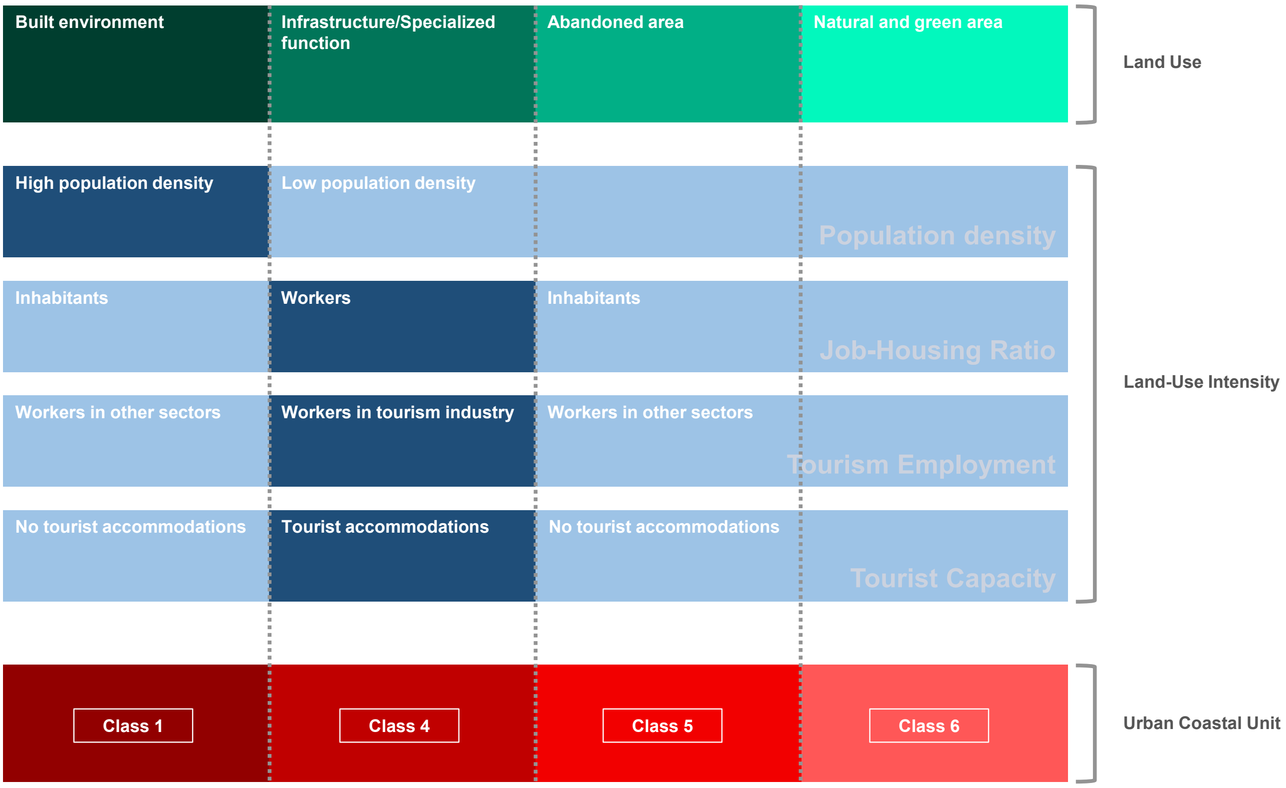

Figure 12. Scheme of the aggregation method for UCU definition

- *Protection*: it includes the placement of physical barriers in an exposed area in order to reduce the impacts of floods. 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);
- *Retreat*: it concerns the delocalization of activities and communities from high-risk areas to low-risk areas. This approach is adopted when nothing else option is possible and requires a careful decision-making and governance process (Wong et al., 2014).

In different ways, those approaches can refer to the urban transformations according to the General System Theory applied for the analysis of urban phenomena (Gargiulo, 2009). Indeed, if the coastal city is an urban system (see Section 2), 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, the urban adaptation actions have to be defined considering which relationships are expressed by (i) the land use, (ii) the land-use intensity, and (iii) the urban form.

The land use is defined as *"the functional dimension of land for different human purposes or economic activities"* (United Nations et al., 2005) and expresses the relationships between the urban activities localized in an area and the adapted urban space (Gargiulo, 2009). The land-use intensity is related to 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 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 the 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 (Figure 13).

According to these definitions, Accommodation, Protection and Retreat can be associated with these relationships among urban subsystems as shown in Table 17. In particular, it arises that Accommodation refers to all the relationships since accommodation measures can 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.

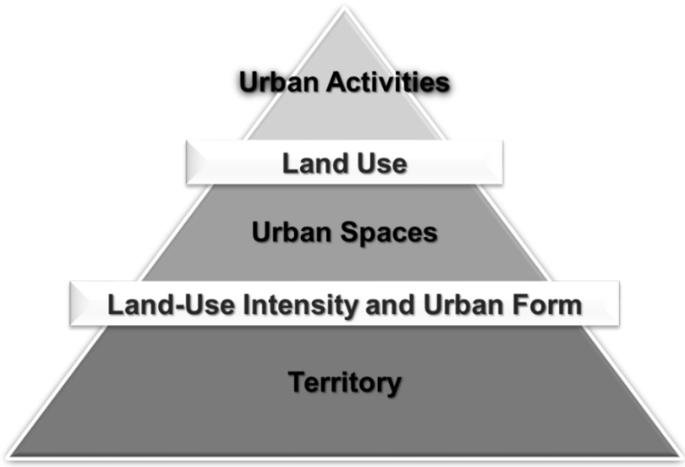

Figure 13. Relationships between urban subsystems' elements and Land Use, Land-Use Intensity and Urban Form (Source: by authors)

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

Table 17. Connections between adaptation approaches and relationships among urban subsystems

Considering these connections, it was possible to define four possible Urban Adaptation Action's classes, as follows:

- Maintain the Land Use (1);
- Reduce the Land-Use Intensity and maintain the Urban Form (2);
- Reduce the Land-Use Intensity and change the Urban Form (3);
- Change the Land Use (4).

While the (1) and (2) classes are related to the Accommodation approach (A), the (3) and (4) classes refer respectively to the Protection (P) and the Retreat (R) approaches. This articulation highlights the importance of the land use in the urban planning.

With regards to the first class, it includes mainly actions at building scale and on infrastructure. In particular, those actions are referred to: (i) retrofit existing buildings and build new ones that are or wet-floodproofed or dry-floodproofed; (ii) integrate infrastructure and public facilities with coastal defence solutions, and; (iii) maintain the existing permeable areas in order to guarantee a good drainage and storage of water during the flooding events.

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

The third class 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 are referred to: (i) adopt a compartmentalization of the area in order to reduce the flooded area and design new developable spaces; (ii) reinforce the existing "hard" infrastructure (dike, levees and seawalls) and/or realize new ones in order to protect strategic urban activities; (iii) adopt "soft" solutions such as a periodic beach nourishment, dune restoration, wetland creation, littoral drift replenishment and afforestation.

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

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

In order to define the most effective actions to implement in each kind of urban coastal area, the Urban Adaptation Action's classes were associated to each category of the Urban Coastal Units, in relation to their physical and functional characteristics (Figure 14).

From the diagram, it arises that all the UCUs can implement Urban Adaptation Actions referring to the four identified classes. There are only two exceptions, the Class 1 and Class 2 for low resilience level of the CoRI.

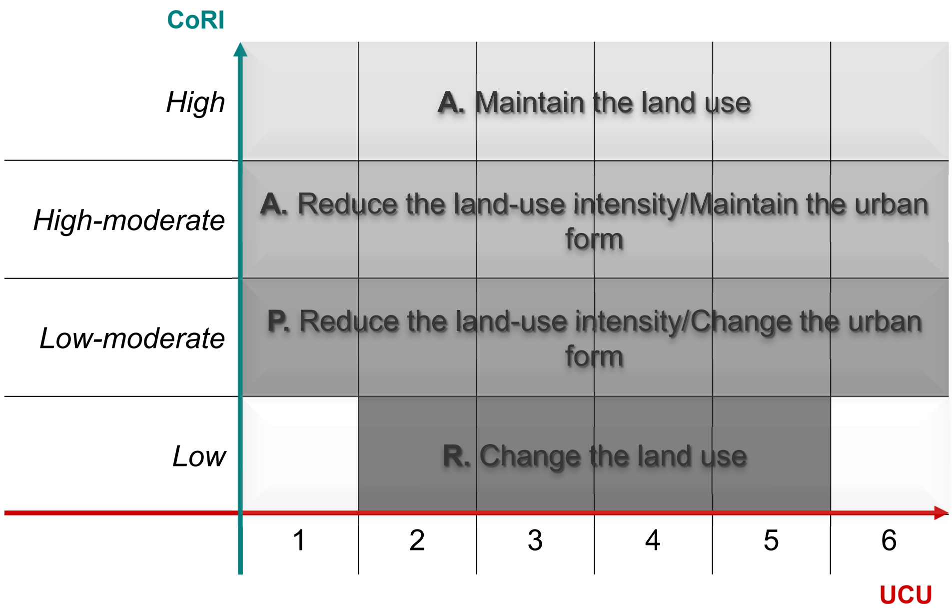

Figure 14. Relationships among CoRI levels, UCU and Urban Adaptation Actions (Source: by authors)

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 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 coherent land uses for protecting coastal areas from the impacts of coastal flooding.

4.5 Definition of the GIS-based tool framework

GIS is defined as *"a decision support system involving the integration of spatially referenced data in a problem-solving environment"* (Cowen, 1998). According to Goodchild (2000), GIS offers an important opportunity for the spatial analysis and its popularization, thanks to the balance between the capacity to develop complex operations and the efficiency of the visual communication.

Therefore, in this research, an extensive use has been made of GIS. The GIS, indeed, allows: (i) the integration of multiple data sources; (ii) the instant representation of complex data in a more intuitive form; (iii) the application of spatial analytic techniques for modelling urban phenomena.

Considering the potentialities of GIS, in this part of the methodology, a design workflow for developing the GIS-based tool was defined. The tool synthesizes the spatial-analysis process composed of all the methodological phases that were illustrated in the previous paragraphs. Since the tool has to support mainly public administrations and technicians for planning more resilient urban coastal areas, it was developed according to two criteria. The first one is the transferability. Indeed, in order to use this tool in different urban contexts, input data have to be easily available. In this perspective, this tool was constructed in line with the principle of open data because their use could guarantee the tool's feasibility in other urban areas. Furthermore, the tool was developed using ArcGIS[10], one of the most common GIS environments used by public administrations and technicians. The second criterion was to use a GIS methodology able to perform complex computational calculations.

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. Moreover, raster data are able to represent urban phenomena because each surface element is a measure of its intensity level or its relationship from a fixed point in space. (ESRI, 2002). This is also the most suitable (and common) form for representing the continuous spatial distribution of indices and modelling spatial phenomena. Furthermore, the raster-based spatial analysis is also used for other reasons. Generally, it is accepted that raster calculations are faster, while the vector methods give higher accuracy (Kennedy & Meyers, 1977). At the same time, a right spatial resolution can also guarantee a good accuracy for the raster-based approach (Mulrooney et al., 2017). However, a speed raster-based spatial analysis is strictly linked to the choice of spatial resolution. 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[11] 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 (Figure 15).

As for mapping the Coastal Resilience Index, this process of the tool is very complex because of the extensive input data and their aggregation in order to calculate the index. In particular, this process is articulated into six parts: (i) collection of input data; (ii) pre-processing of the input data; (iii) calculation of the urban variables' layers; (iv) normalization of the variables' layers; (v) overlapping and aggregation of the variables' layers by assigning the relative weights; (vi) reclassification of the final map in the four levels (from *Low* to *High*) of Coastal Resilience Index.

In order to map the Urban Coastal Units, the process of the first part of the tool is composed of six actions: (i) collection of input data; (ii) pre-processing of the input data; (iii) calculation of the indicators' layers; (iv) creation of suitability layers; (v) overlapping of the suitability layers; (vi) classification of the six Urban Coastal Units.

The third process is aimed at associating the Urban Adaptation Action class to the each Urban Coastal Units in relation to their levels of urban coastal resilience. For this reason, it was necessary to develop a database of the Urban Adaptation Actions. In particular, the urban adaptation measures are classified for the typology of Urban Coastal Units and level of Coastal Resilience Index. In this way, after having

[10] http://desktop.arcgis.com/en/arcmap/

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

intersected the raster layers of the UCUs with those of the CoRI, it is possible to join the new layer with the Urban Adaptation Actions' database. The result is the map of the Urban Adaptation Actions where each urban area is articulated in relation to the urban adaptation measures that it is possible to implement on the local level.

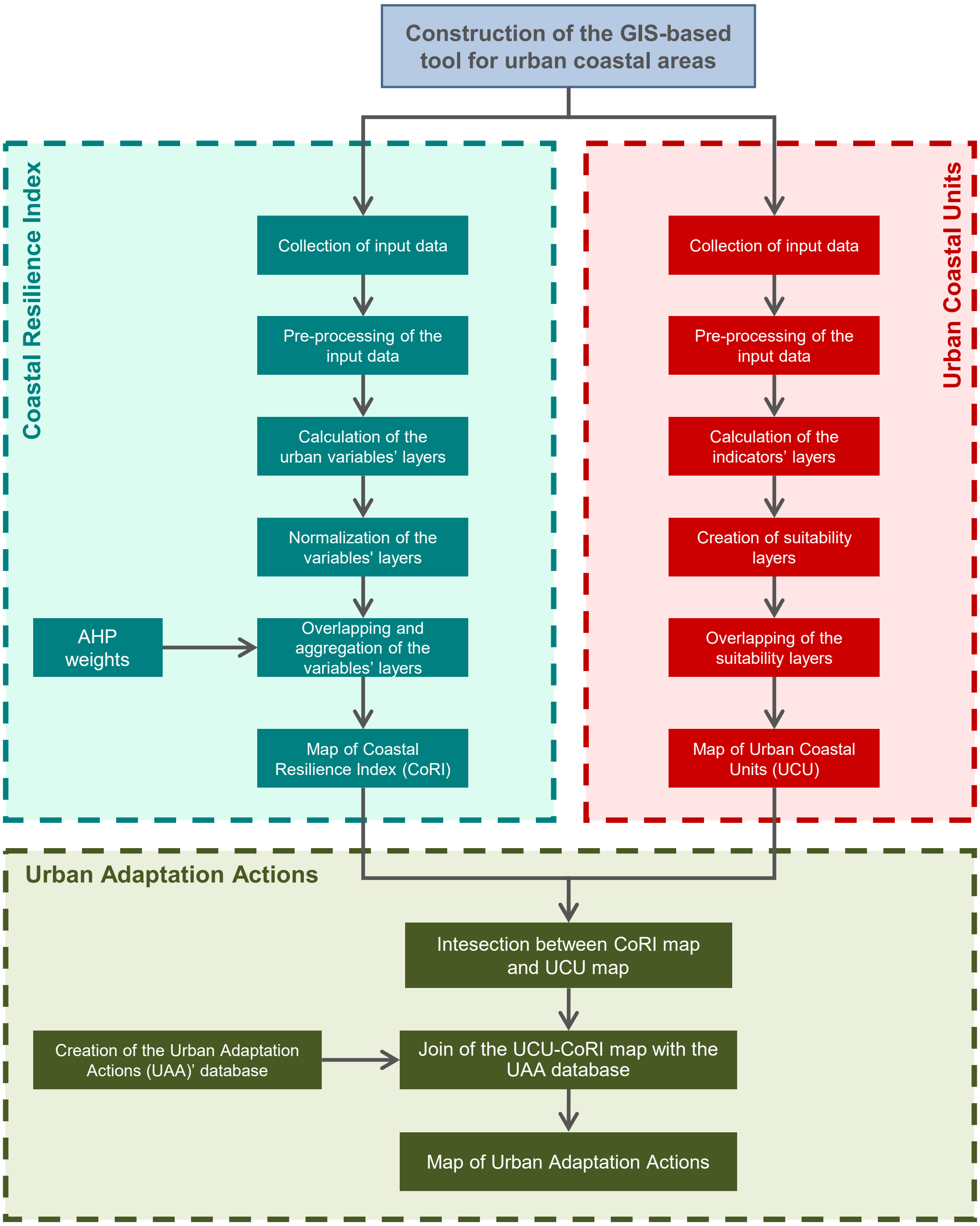

Figure 15. Design workflow of the GIS-based tool (Source: by author)

4.6 Conclusions

The purpose of this section was to illustrate the methodology for developing a new GIS-based tool for supporting the decision-making process of urban adaptation in cities to the impacts of coastal flooding.

By adopting a holistic-system 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 measures, defined as 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-system 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 relates the types of urban coastal areas with the adaptation actions, which should be implemented on the local level. Furthermore, the same CoRI could be also used to evaluate the effectiveness of implemented adaptation measures.

In light of this, in the next section, the proposed methodology for the development of a GIS based-tool and the design workflow will be applied to the coastal area of an Italian city: Naples. In particular, thanks to such application, it will be possible to not only implement the tool in GIS environment, but also verify the methodology and, eventually, improve and/or correct it.

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Section 5. Results and Discussion

5.1 Introduction

In this section, the procedure for the GIS-based tool's implementation and application is described.
In order to verify the methodology described in Section 4 and develop the GIS-based tool, the first step was the selection of a study area for implementing the tool. In particular, the study area was chosen along the coastline of the city of Naples (Italy). Naples is an important Italian coastal city and is well known for its rich cultural, artistic and environmental heritage and, at the same time, its several urban issues. From this viewpoint, this city can be an interesting test for the implementation of the tool. Moreover, since this research was conducted in the city of Naples, its direct knowledge enables the findings obtained by the application of the GIS-based tool to be verified.
After the selection of the study area, the data input for the tool's implementation were collected. Hence, the GIS-based tool's procedure was applied to the chosen coastal area. In particular, according to the methodology, the GIS-based tool was developed into three phases. In the first phase, the Coastal Resilience Index Tools were implemented for mapping the CoRI of the study area. After that, the Urban Coastal Units Tools were constructed for the identification of the UCUs. Finally, the CoRI and UCUs' maps were used for identifying the four classes of Urban Adaptation Actions by using the Urban Adaptation Actions Tool. For each phase, the obtained results were described and discussed in specific sub-paragraphs.
Section 5 is structured as follows. Paragraph 5.2 describes the city of Naples with its future coastal flooding scenarios and presents the criteria adopted for the selection of the study area and a description of its main urban features. Paragraph 5.3 illustrates the main findings obtained by the development and application of the GIS-based tool to the selected area, whereas Paragraph 5.4 includes the discussion of the most interesting results. Finally, the section ends with concluding remarks about the obtained findings.

5.2 Selection of the study area and collection of the relative data

5.2.1 Naples and the forecasted rising sea level

Naples is a city located in southern Italy. The Tyrennian Sea borders it. Naples has a population of around 1 million[12]. Even before its foundation, the sea had always played a key role for the city, its urban layout and its functional organization. The Neapolitan coastline is around 63 km in length, which corresponds

[12] According to the last census by ISTAT (2017), in Naples 966,144 inhabitants live.

to about half of the municipality limit length (119 km). Due to its morphology and the presence of hills in the north-western area and of marshy areas in the eastern part, in the beginning, the city's development had been concentrated in the coastal area. During the following centuries, Naples started to expand itself in these areas, but also towards the sea. Indeed, as shown from both the archaeological finds in the area of the Molo Beverello (the Seaport) (Figure 16) and considering the story for the realization of the Villa Comunale (the main seaside park in the city), in order to allow its development, urbanization transformed the natural configuration of the coastline.

Currently, along the coastline of Naples there are several public facilities and urban assets. Among them, there is the City Harbour and main roads such as via Marina, but also important elements of its historic and cultural heritage. Moreover, along the coastline high-density neighbourhoods are settled such as Chiaia, some parts of the Historic Centre and Bagnoli. Despite its important heritage, the high concentration of urban assets and inhabitants along the coastline, currently, in literature, there are no studies that investigate which future impacts of climate change, especially coastal flooding, could happen in the city of Naples and which areas of the city could be affected by them.

From this viewpoint, in order to identify the most suitable area where to implement and apply the GIS-based tool, described in the previous section, it was necessary to start from the definition of "Urban Coastal Area". In literature, there are several definitions of "coastal area" or "coastal zone". Usually those definitions refer to geomorphological features, in particular the distance from the coastline, and the elevation of the coastal area.

Concerning the distance from the coastline, a "coastal area" ("coastal zone") is defined as the area within a specific distance from the coastline. However, studies often do not use a common value of distance as reference. For example, Christian & Mazzilli (2007) and Nicholls & Small (2002) define coastal area as the land margin within 100 km from the shoreline, while Stewart et al. (2003) define 10 km as distance of reference. Instead, in relation to the presence of a riverine in the area, Scura et al. (1992) define 2 km of distance from the coastline otherwise the reference distance is 1 km. However, this definition does not enable the identification of low-lying coastal areas that are mainly exposed to seaward hazards. Hence, the definition of Low Elevation Coastal Zones (LECZ), which are contiguous areas to the coastline at less than 10 m above sea level, was introduced. In particular, the LECZs include areas that could be at risk from sea-level rise, stronger storms and other seaward hazards induced by climate change (McGranahan et al., 2007). Therefore, considering the LECZs' definition and the aim of this research, the identification of Naples' LECZs could be a suitable method for the identification of the study area where to apply the GIS-based tool. However, this definition does not allow the identification of an Urban Coastal Area since it would not take into account the presence within these areas of spaces and infrastructure that accommodate functions not only on the urban level, but also on the territorial one (e.g. hospitals, universities, ports, etc.).

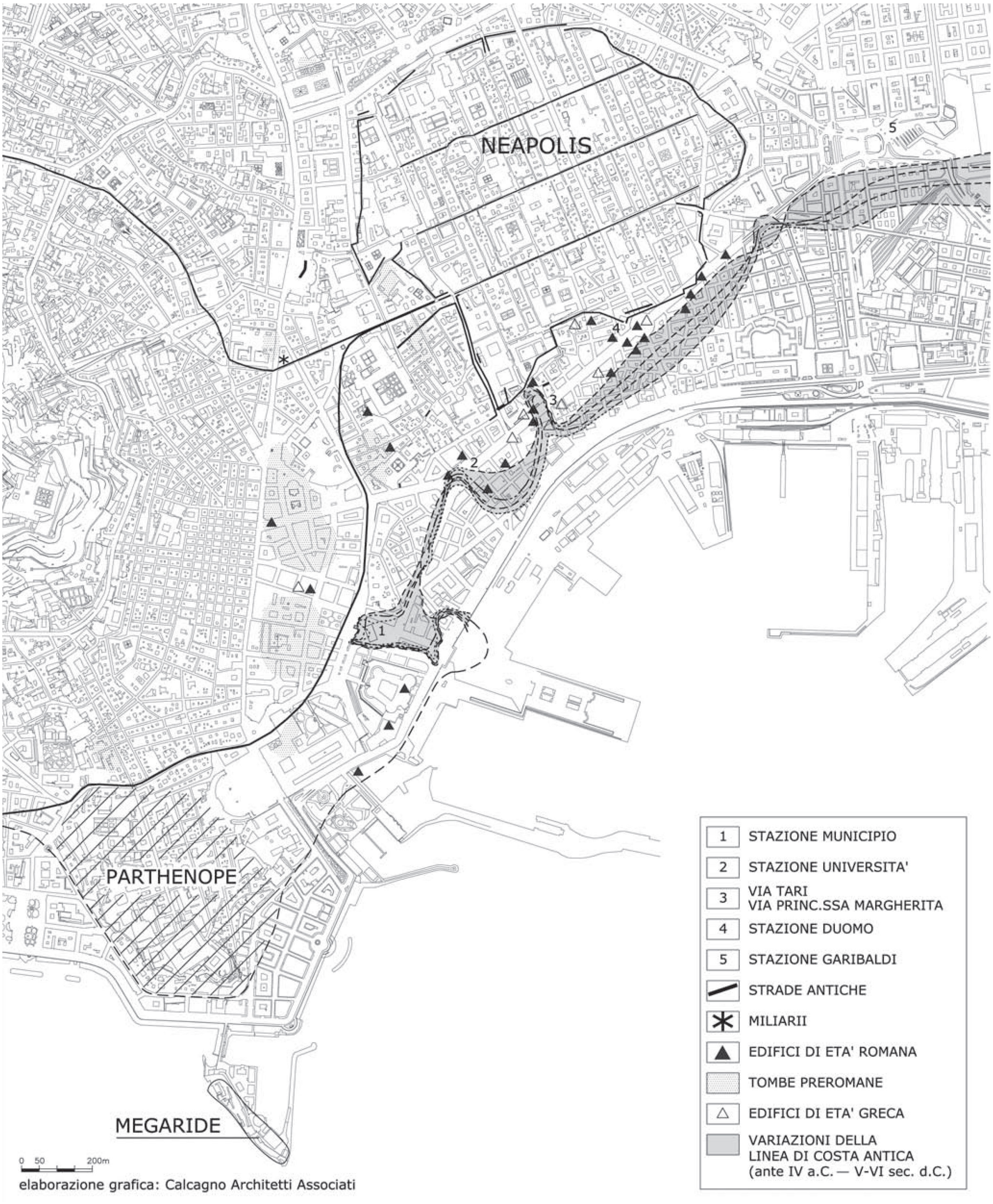


Figure 16. Hypothesis of the coastline variations (dashed line) for the area between Parthenope and Neapolis in the period before the IV century BC at the late ancient age (V-VI century AD) (Source: Carsana et al., 2009).

Therefore, from an urban planning perspective, the Urban Coastal Area can be defined as that area identified by an administrative limit (municipal or district one) that includes one or more Low Elevation Coastal Zones. Starting from this definition, Naples' LECZs were identified. In particular, using Spatial

Analyst tools by ArcGIS 10.3, a procedure was developed, based on that by Guandalini & Salerno (2015), which has allowed the identification of these areas. In particular, such analysis was carried out by using the Digital Terrain Model of Naples with a resolution of 1x1 meter, which allowed a more precise identification of these areas along the coastline.

As shown in Figure 17, the LECZs are 14% of the whole municipality area and it is possible to identify three main low-lying areas, the largest one in the eastern zone (that corresponds to 20.99% of the neighbourhoods' total area), and two smaller ones in the central (5.12%) and western zones (4.49%) (Table 18). However, the LECZs' analysis does not allow the consideration of possible future scenarios in relation to the change of sea level. Sea-level rise projections have a particular relevance for the future coastal management and planning of the city. Therefore, starting from the study of literature about the rise in sea levels, the potential coastal floodplains of Naples were identified.

As described in Section 1, according to Stocker et al. (2013), the Global Mean Sea Level Rise (GMSL) will vary in a range of 0.26–0.55 m for low-emission scenario or 0.45–0.82 m for high-emission one for 2100. However, some studies have highlighted that IPCC projections are underestimated, since its process-based models do not include the contribution of ice sheet mass (Füssel, 2017). Starting from the studies analysed in the recent report by IPCC (Hoegh-Guldberg et al., 2018), in Table 19 the sea level rise projections for the RCP8.5 scenario (the highest emission scenario) are shown.

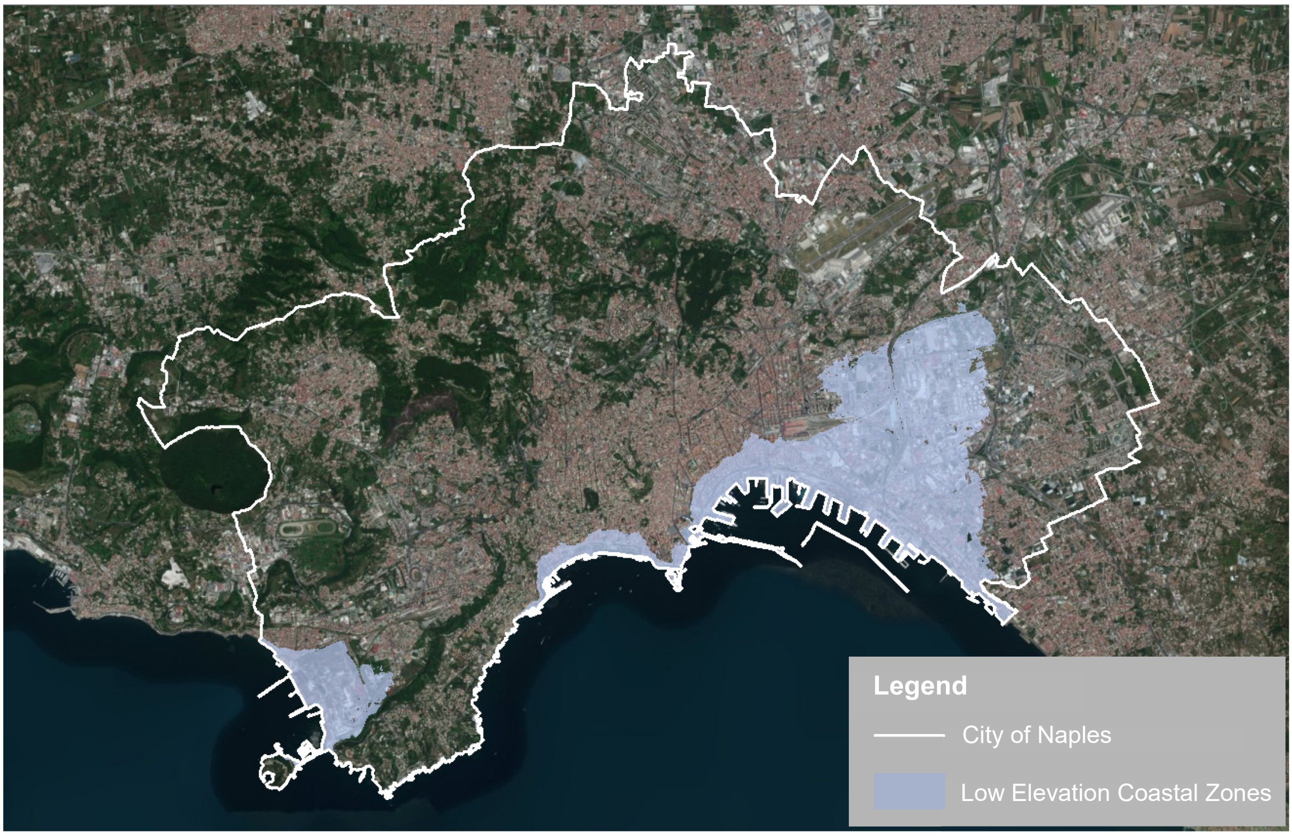


Figure 17. Low Elevation Coastal Zones in Naples

Naples' zone	Neighbourhood	Land Area [sq.km]	LECZ Area [%]
Eastern zone	Barra	7.69	47.39%
	Ponticelli	9.43	10.72%
	Poggioreale	4.58	41.05%
	San Giovanni a Teduccio	2.59	95.30%
	Industrial Zone	2.94	82.97%
Central zone	Chiaia	2.79	28.54%
	Mercato	0.57	93.80%
	Pendino	0.77	73.52%
	Porto	0.44	77.99%
	San Ferdinando	1.18	46.30%
	San Giuseppe	0.42	0.53%
	San Lorenzo	1.49	0.17%
Western zone	Bagnoli	8.13	27.04%
	Fuorigrotta	6.51	1.39%
	Posillipo	4.96	3.21%

Table 18. Land area and LECZs' percentage distribution for neighbourhoods with LECZs

It is possible to note that the lower limit is similar among the different studies (standard deviation is 0.03), while the upper limits vary in a range of 0.91 until 1.78 (standard deviation is 0.34).

Study	Sea level rise for the RCP8.5 scenario	
	5%	95%
Stocker et al., 2013	0.45	0.82
Goodwin et al, 2018	0.50	1.20
Jevrejeva et al., 2016	0.53	1.78
Kopp et al., 2014	0.52	1.21
Kopp et al., 2016	0.52	1.31
Nicholls et al., 2018	0.54	0.91

Table 19. Compilation of recent projections for sea level at 2100 (in m) for the RCP8.5[13]

As highlighted by Abadie et al. (2016), the GMSL is different from the Relative Sea Level (RSL) since it changes at the regional level. It is possible to describe the RSL as the interactions of four main factors: (i) eustatic determinants (e.g. thermal expansion, ice melting, etc.); (ii) static equilibrium effects; (iii) glacial isostatic adjustment; (iv) vertical land uplift. Some researches refer to coastal areas of the Mediterrenean Sea and in some cases they provide projections for the city of Naples. For example, Galassi & Spada (2014) state that by 2050 the sea-level rise in Naples will be in a range between 0.09 m (minimum value)

[13] Upper and lower limits are the 5-95% confidence intervals quoted in the original papers.

and 0.30 m. Kopp et al. (2014) provide the forecasts of the change in sea level for the major coastal cities, among which there is Naples, considering the RCP8.5 scenario's IPCC for 2030, 2050 and 2100. In particular, according to these forecasts, in 2050, the rise in sea level could be between 0.21 m (median value) and 0.49 m (95% probability), while by 2100 the sea level will increase by between 0.62 m (median value) and 1.04 m (95% probability). For the same year, Lambeck et al. (2011) predict the future sea level change for two areas near Naples (i.e. Volturno and Sele) in a range of 0.22 m and 1.44 m, based on the low scenario by IPCC (Solomon et al., 2007) as well as that provided by Rahmstorf (2007).

Since the uncertainty of future sea-level rise projections does not enable the definition of a specific coastal floodplain, the worst scenarios produced by Kopp et al. (2014), Lambeck et al. (2011) and Jevrejeva et al. (2016) were used to identify three possible urban areas that could be flooded in the coming years. In order to identify these areas, the same GIS procedure used for the identification of LECZs was implemented.

As shown in Figure 18, the potential floodable areas would affect the industrial and commercial area of the city port, as well as the two tourist ports of Mergellina and Nisida. Further floodable areas could be the urban area of Borgo Marinari on Megaride Island, the waterfront of the Bagnoli neighbourhood, and the beaches along the Posillipo neighbourhood. Finally, some pedestrian and vehicular parts of the main city's waterfront, named Francesco Caracciolo Street, may also be affected.

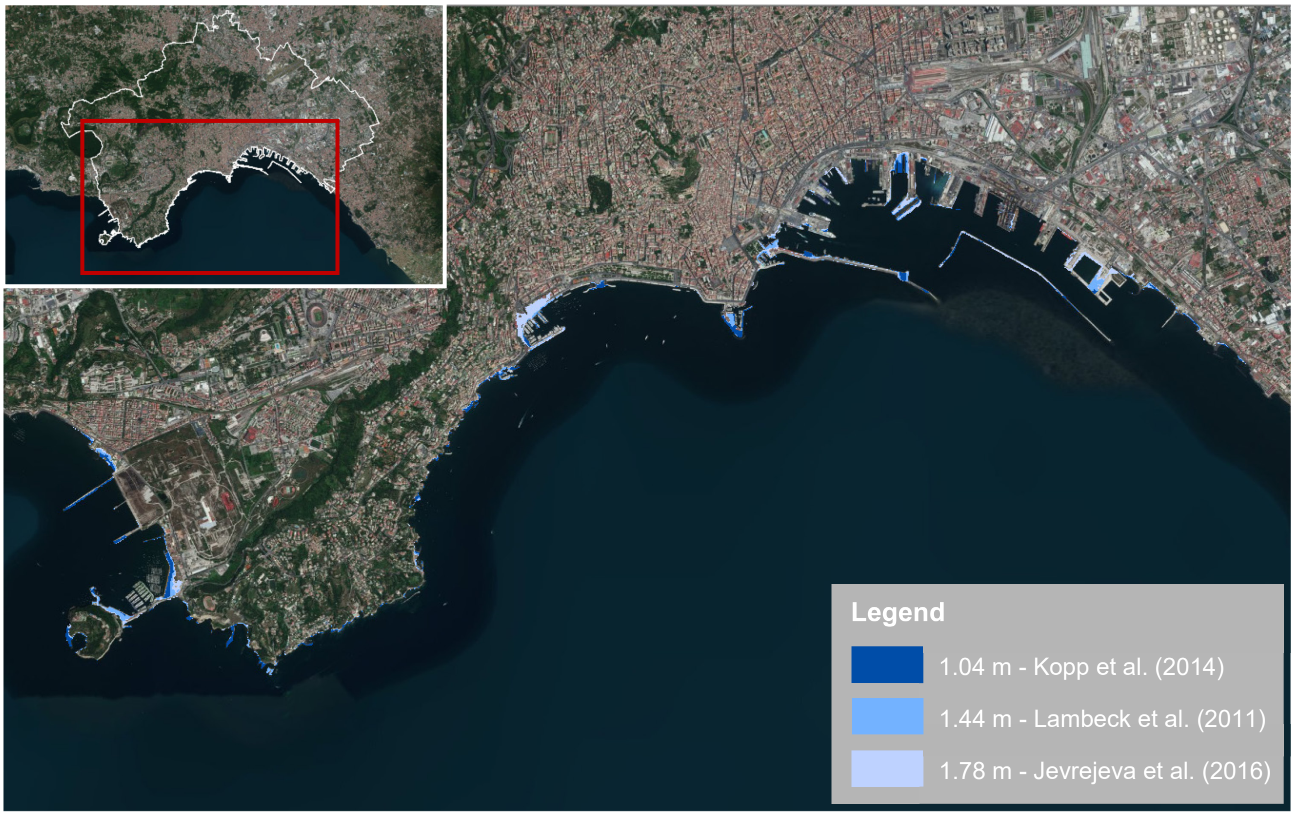


Figure 18. Floodplains based on the studies by Kopp et al. (2014), Lambeck et al. (2011) and Jevrejeva et al. (2016)

However, future sea-level rise will increase the intensity of storm surges and the area affected by coastal flooding (Wu et al., 2002). Therefore, the coastal floodplain could be wider than those developed by the three studies aforementioned. Thus, a further scenario that takes into account the combined effect of storm surges and a 1m sea-level rise for the coastline of Naples was developed.

In order to simulate this scenario and to calculate the coastal floodplain of the city, the open source model Delft3D (Deltares, 2014) was used. In particular, the model simulated the coastal inundation using the data recorded for the February 2016 storm event that hit the coastline of the city. The storm event was identified by analysing the observational data, provided by the ISPRA's National Tidegauge Network14. Instead, the topographic dataset that were used for implementing the model were the aforementioned Digital Elevation Model (DTM) of the city, while concerning the bathymetric data, they were provided by the EMODnet project[15].

The result of this simulation is the area flooded by a 100-years flood due to a storm surge event (storm tide of about 0.50 meters) that could occur at the end of the century when the sea level could increase to 1 meter, according to the sea-level rise forecasts of the aforementioned studies (Figure 19). Moreover, the identified coastal floodplain is very similar to those of the before analysed scenarios. The extent of these areas is not particularly wide and does not affect the most populated areas.

Figure 19. Map of the 100-years floodplain considering a 1-m sea level rise

[14] https://www.mareografico.it/?session=0S3691592812FM717779RP67&syslng=ita&sysmen=-1&sysind=-1&syssub=-1&sysfnt=0
[15] http://www.emodnet.eu/general-survey

However, it is noted that coastal flooding could hit areas and functions closer to the shoreline, including the urban waterfront (Francesco Caracciolo Street) and the city port with important consequences to the economy, not only on a local scale, but on a national one as well.
Given the results obtained from the identification of the floodplains and the LECZs, the eastern part of the city, where there is the largest LECZ of Naples, was chosen as the study area for the implementation and application of the GIS-based tool. Besides the availability of spatial data for the tool's implementation and application for this zone, thanks to its morphological and urban characteristics, this area represents a meaningful test for the development of the tool. Indeed, in this area there is a widespread presence of important urban assets (e.g. the port) but also public facilities, such as hospitals, a university, and civic buildings, as well as public functions at the local level (e.g. schools). Therefore, this area can be easily assimilated to a mid-sized coastal city.

5.2.2 Description of the selected study area

The study area includes the neighbourhoods of Mercato, Pendino, San Giovanni a Teduccio, Barra, and the Industrial Zone (Figure 20). It extends to about 30.47 sq. km (about 26 % of the whole municipality area) and hosts a population of 92,922 inhabitants in comparison to the total population of 962,003 inhabitants (ISTAT, 2011). This area is characterized by a strong heterogeneity of land uses, even if it is mainly known to be an industrial urban suburb. Indeed, in the area there is a part of the Historic Centre, most of the port area, the former industrial area, converted into an area of services and trade, and some residential areas, among which San Giovanni a Teduccio and Barra. From this viewpoint, this area is characterized by a high physical and functional complexity.
Therefore, the redevelopment and processes of regeneration in this area are particularly problematic. For what concerns the Historic Centre, in the area, there are several elements of particular historical, cultural and architectural value that are points of interest for the tourism in the city. Among the main monuments there are the Sansevero Chapel Museum, Basilica church of Santa Chiara, Piazza Mercato (or Market square), the Church of Sant'Eligio Maggiore and the Church of Santa Maria del Carmine. However, the main characteristic of the area is the high concentration of small and medium-sized manufacturing companies and, at the same time, the presence of large industrial zones nearby the Historic Centre. Indeed, the study area is characterized by the presence of an important industrial area (about 340 ha) that host petrochemical and mechanical companies. Even if most of this area is currently in disuse, its presence separates the Historic Centre and the neighbourhoods of Barra and San Giovanni. This is considered the main reason for the current degradation of the Eastern area of Naples. Indeed, Barra and San Giovanni a Teduccio did not originally belong to the City of Naples. Hence, the industrial development created conditions for separating the consolidated part of the Historic Centre from the historic nucleus of San Giovanni a Teduccio and Barra. These two neighbourhoods have a residential

function. In particular, in Barra, a new residential development was realized around the historic nucleus of the neighbourhood according to the post-earthquake social housing programme (Programma Straordinario di Edilizia Residenziale) of the 80s. This condition of urban suburbs was further increased by the presence of transport infrastructures in the area. Indeed, besides the port area, large primary roads (i.e. the A3 Motorway and Tangenziale) that connect the city with the metropolitan area cross the study area. The main street is Via Marina along the East-West direction. In particular, this street connects the Southern part of the city with the nearby municipality of San Giorgio a Cremano (Corso San Giovanni a Teduccio) towards East, while links the Eastern area of Naples with the urban centre and the Western area towards the West. In the area, there are also railway infrastructures. The railway stations include the Italian State Railway station of Napoli Centrale, the main transport hub and the most important railway station of the city, and the SEPSA station of Napoli Porta Nolana, which connects the city to the surrounding towns of the Vesuvius and Agro Nocerino-Sarnese zones. However, there is little transport infrastructure for internal links, especially for linking the neighbourhoods. In the area, there are also various public facilities and services, such as university offices, including the Polytechnic University of Naples Federico II, but also health facilities such as Loreto Mare Hospital. Moreover, the presence of large vacant lands is an opportunity to redevelop this urban area. However, it is also necessary to evaluate which urban transformations are the most suitable ones in relation to the proximity of the sea.

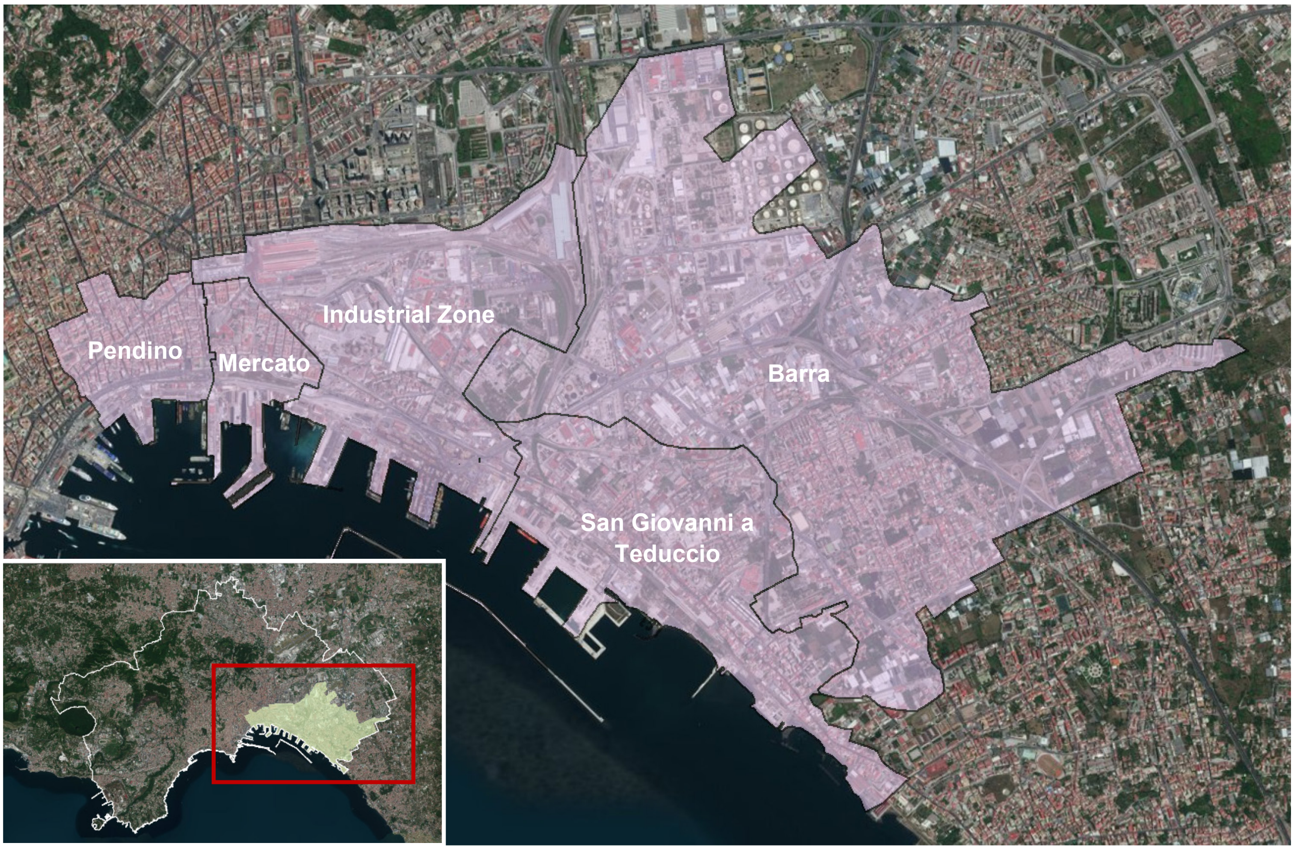


Figure 20. Neighbourhoods of the study area

5.3 Application of the GIS-based tool

The GIS-based tool was implemented by using ArcGIS 10.3. In particular, the Model Builder visual language was used, which allows the construction of geoprocessing workflows and, thus, performance of all the operations of the methodology to be developed and described in a sequential manner. In this way, it is possible to develop an application that it is easy to use. Furthermore, the implementation of the methodological process through Model Builder allows further implementation and/or modification of the tool and, if necessary, it can also be exported as a Python language script to develop more specific applications.

According to the design workflow, as shown in Section 4, the GIS-based tool was organized into three ArcGIS toolboxes by using the Model Builder language.

The first toolbox contains tool models for mapping the six Urban Coastal Units' classes. In particular, after processing the spatial input data identified and collected for mapping the UCUs, using Spatial Analyst tools, the tool model produces a raster data containing the articulation of the study area in Urban Coastal Units.

The second toolbox was organized in a similar way to the first one. However, given the several indicators for calculating the Coastal Resilience Index, this tool requires a more complex and long pre-processing phase. After that, using Spatial Analyst tools, each indicator is normalized in a range of values between 0 and 4 as raster data.

Finally, the indicators' raster maps are aggregated according to the weights calculated by AHP in order to obtain the map of Coastal Resilience Index.

Once the raster maps of UCUs and CoRI are obtained, they are intersected and joined to the Urban Adaptation Actions database through the implementation of the third toolbox. In particular, this tool allows each urban area (UCUs) to be assigned the type of urban adaptation measures that can be implemented in relation to its own level of CoRI.

The main data sources used for the tool's implementation were:

- the 15th Population and Housing Census and the 9th Industry and Services Census dated 2011, available on the web portal of the Italian Institute of Statistics16 (ISTAT);
- WFS and WCS download services provided by the Ministry for the Environment and Protection of the Sea and the Territory on the National Geoportal;
- the open data by the Municipality of Naples;
- the open data provided by the European program Copernicus;
- the data provided by the Provincial Tourism Authority (EPT) of Naples.

[16] https://www.istat.it/en/

Not all the data from these sources were shapefile or raster data to use in a GIS. In particular, for what concerns the EPT data, data was contained in web pages and transformed into spatial data by using the web scraping technique. Web scraping (or web harvesting) is a form of data mining that allows the extraction of data from HTML pages. Such data can be converted in KML or KMZ files that are a format used to represent geographic features in GIS applications such as ArcGIS. In this way, it was possible to collect all the data referred to the tourist accommodations in the city of Naples.
Moreover, data referring to the raised buildings and their ground floor activities was not available as open data. In this case, it was necessary to collect these data through the direct consultation of satellite images in order to define new feature classes.
Finally, the collected data was uploaded into the GIS environment in order to be processed, corrected in terms of topological errors, and verified with the homogeneity of their reference systems in order to build the database to support the development of the GIS-based tool.

5.3.1 Coastal Resilience Index

The toolbox for mapping the Coastal Resilience Index (CoRI) – named Coastal Resilience Index Tools - is articulated into two parts and is composed of thirteen model tools, where:

- twelve model tools aim at geoprocessing the input data (or model parameters[17]) for mapping the twelve indicators that constitute the CoRI in the study area (Table 20);
- one model tool combines indicators as model parameters with their relative weights (see Section 4) that are still set in the model (Figure 21).

In particular, this configuration of the toolbox allows the users - and those who are not experts in ArcGIS - to have a useful support both for the processing of data and for the CoRI calculation. Indeed, each model tool is provided by a description and a code sample that give even the least experienced user support for filling in the model parameters of the tool correctly and appropriately (Figure 22).
Taking into account the scale of interest for mapping the CoRI, a 1x1-meter cell dimension was chosen. Thanks to the implementation of the first part of the tool, the analysis of each indicator has been carried out and maps represented in Figure 23 have been developed. In detail, by means of the arising maps about each single indicator of each category, it is possible to make some considerations.
Starting from the socio-economic category, with regard to the Education Level indicator (SE1), about 50% of the area has a medium-high level of resilience. However, the most densely populated areas of the Historic Centre and the neighbourhoods of San Giovanni and Barra record medium-low resilience levels.

[17] Model parameter is a configuration variable of a model tool.

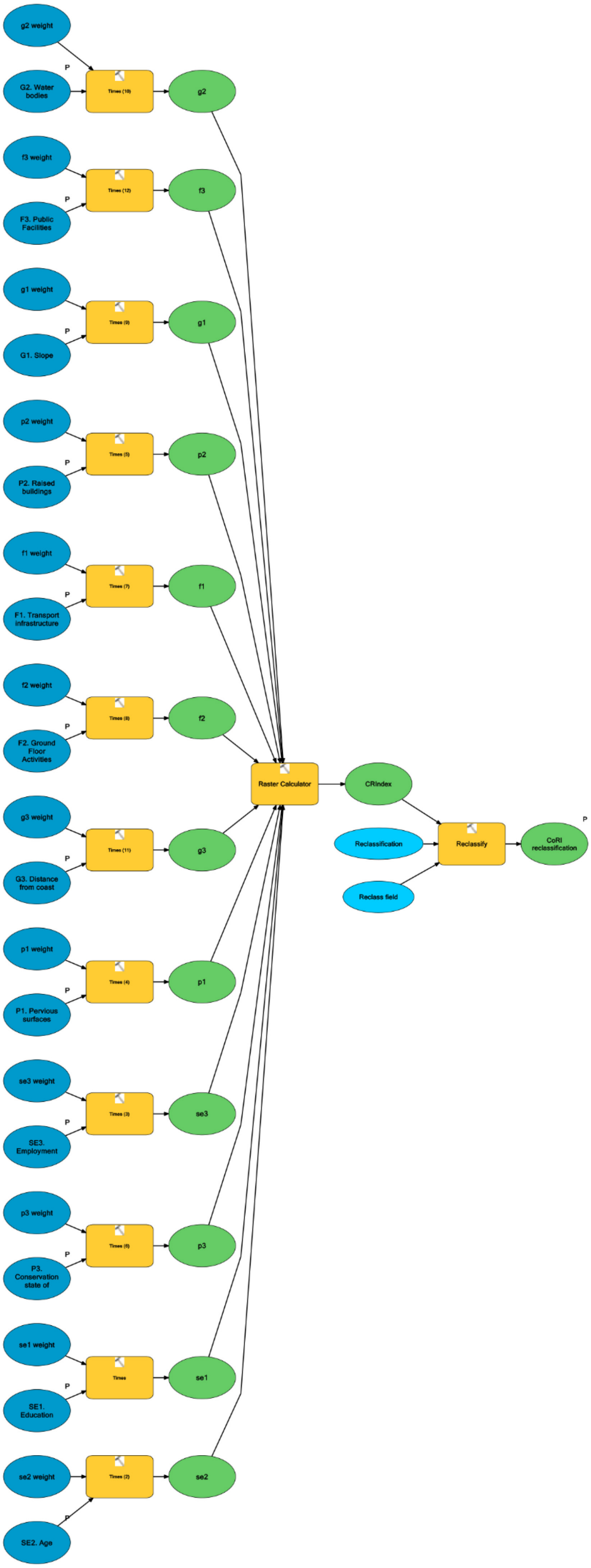


Figure 21. CoRI model in Model Builder

Model Parameter	**Data format**	**Source**
Population	Shape file	Italian Institute of Statistics (ISTAT)
Education level	Shape file	Italian Institute of Statistics (ISTAT)
Employees	Shape file	Italian Institute of Statistics (ISTAT)
Working Age Population	Shape file	Italian Institute of Statistics (ISTAT)
Imperviousness Degree	Raster Dataset	Copernicus
Buildings	Shape file	National Geoportal
Conservation State of Buildings	Shape file	Italian Institute of Statistics (ISTAT)
Total Number of Buildings	Shape file	Italian Institute of Statistics (ISTAT)
Main Roads	Shape file	National Geoportal
Railways Network	Shape file	National Geoportal
Digital Terrain Model (DTM)	Raster Dataset	National Geoportal
Water Bodies	Raster Dataset	National Geoportal
Coastline	Shape file	National Geoportal

Table 20. Model parameters for mapping Coastal Resilience Index

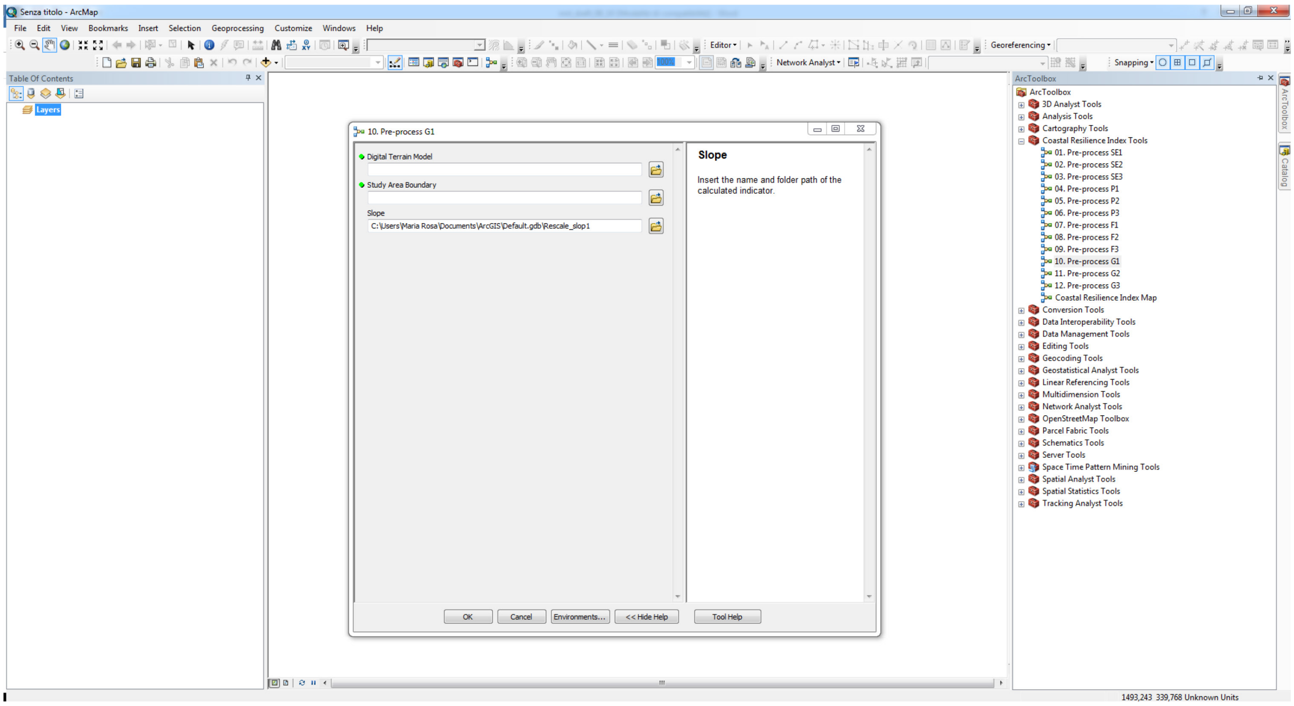
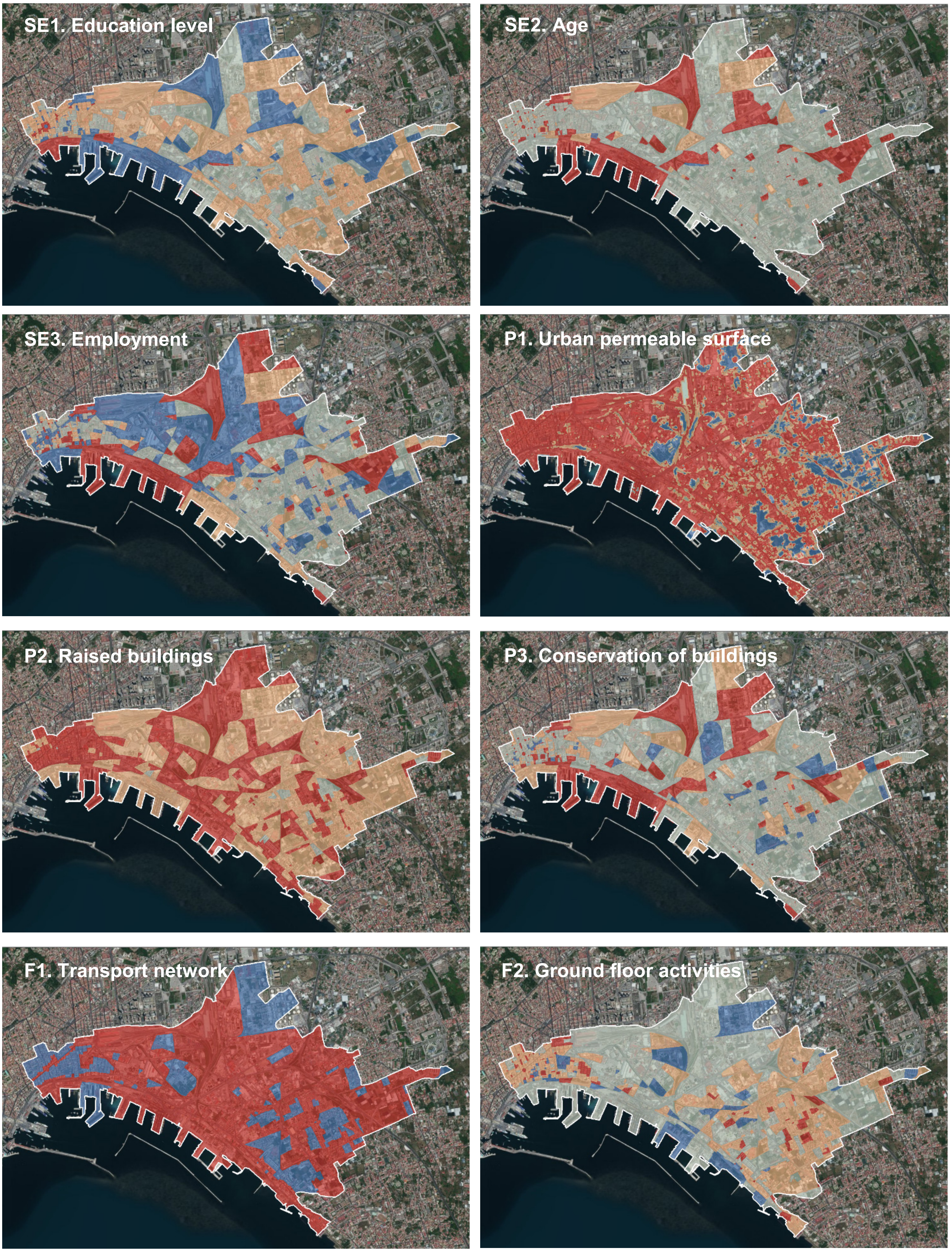


Figure 22. Interface of the model tool for calculating the G1 indicator

Instead, the areas where resilience level is lowest correspond to those where transport infrastructure (such as the railway network and port) are located or where population density is very low (commercial areas, former industrial zones, etc.). Similarly, regarding the SE2 indicator (Age), low levels of resilience (19% of the study area) are recorded in correspondence to the infrastructure zones and rural areas within the neighbourhood of Barra. However, the study area is generally characterized by a medium-high resilience level (70%). Urban areas with a high resilience level are few and not so meaningful. Oppositely, the resilience levels in relation to the Employment indicator (SE3) are particularly high in the Historic Centre, especially along one of the main commercial streets in the area, named Corso Umberto I, in the port area where offices are located, in the railway station area, industrial areas, and the main mixed-land use areas. Instead, the rest of the port area, vacant and abandoned lands, rural zones in Barra and in correspondence to the main squares of the study area (including Piazza Garibaldi, Piazza Mercato, and Piazza Nicola Amore) are characterized by low resilience levels. However, on average the study area records a medium-high resilience level for this indicator.

Concerning the physical category, the P1 indicator (Urban permeable surface) records high resilience levels for abandoned lands and green areas, including rural areas (9%). However, the study area is characterized by a high urbanization degree. Therefore, the imperviousness degree is very high (more than 65% of the whole study area). Considering the Raised Building indicator (P2), there are no areas predominantly characterized by buildings "on pilotis".

Rather, many zones have semi-elevated buildings from the ground level (less than 1.5 meters), which refer to 55% of the study area, while 43%, such as in the Historic Centre, are on the ground level. The Conservation of buildings indicator (P3), which takes into account only residential buildings, records low values, not only for areas where there is no such type of buildings (e.g. in the port), but also for the study area's squares. However, it is noted that the building stock of the area is mainly characterized by a good state of maintenance (54% of study area's census sections). Only in some cases, the residential buildings are in an excellent state (6% of study area's census sections). These cases refer to residential buildings located in some areas of the Historic Centre and in the neighbourhood of Barra and the industrial zone. With regards to the transport infrastructure, the study area is characterized by the presence of both railway infrastructure and main roads (75% of study area's census sections). In detail, the railway infrastructure starts from the Napoli Centrale station and is characterized by two main routes along the north-south direction, one towards the Vesuvian area and the other one towards the Sorrento coastal area and the province of Salerno. Concerning the road infrastructure, a motorway divides the area into two parts, and some main roads characterize the study area. Finally, considering the Historic Centre, two main roads characterize it. One of these streets is Corso Umberto I, which divides the historic nucleus from the waterfront of the city and connects the eastern part with the historic nucleus. The second main road is via Marina, which links the east and west of the city. With regards to the F2 indicator (Ground floor activities), it is noted that residential functions at the ground floor are localized especially in the Historic Centre and in the historic nuclei of San Giovanni and Barra (4% of the study area). There are also some spaces on the ground floors that are used for storage or are unused. From this viewpoint, this functional configuration corresponds to high resilience levels (10%), even if the study area is mainly characterized by medium-high resilience level (54%). Instead, considering the public facilities (the F3 indicator), they are several and quite widespread within the area.


SE1. Education level
SE2. Age
SE3. Employment
P1. Urban permeable surface
P2. Raised buildings
P3. Conservation of buildings
F1. Transport network
F2. Ground floor activities

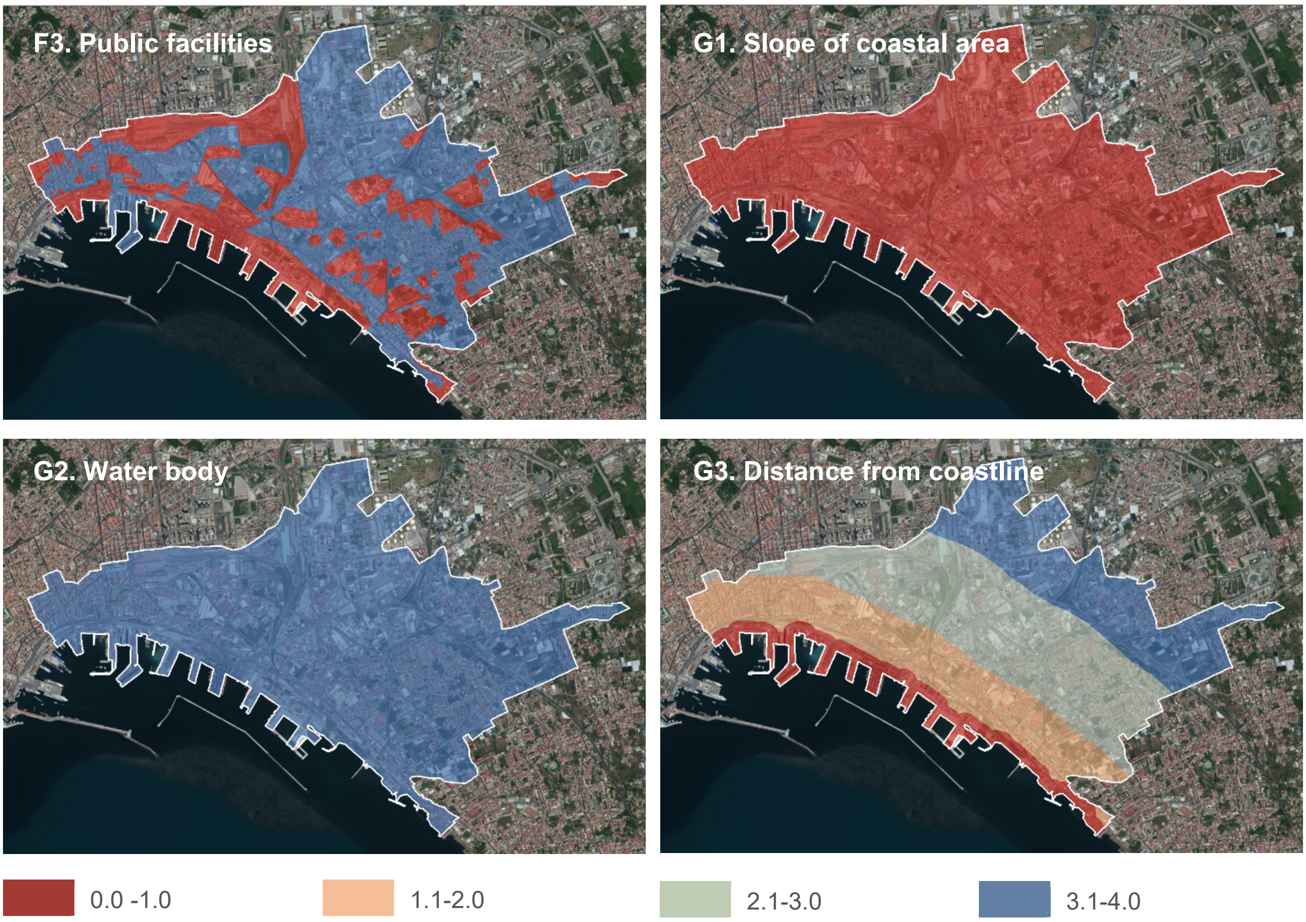


Figure 23. Maps of the CoRI's indicators

Public facilities, indeed, were built in the past to increase liveability and quality of life in the suburban zones that were not well integrated in the urban context of Naples. Moreover, the majority of them are mainly localized in proximity to the coastline.

Finally, some considerations about the geomorphological category. In general, the slope of the study area is low and, thus, such an area is likely to be exposed to coastal flooding. However, the absence of water bodies that could intensify externalities due to coastal flooding increases the resilience level of the whole area. In the end, in relation to the distance from coastline indicator (G3), the most exposed area along the coastline include mainly public facilities and assets in relation to the port activities. The other areas in proximity to the coast, instead, is characterized by a high urbanization degree and a high mixed land use.

By applying the model tool to map the CoRI, developed according to the aforementioned methodology (see Section 3), the obtained map shows that there are no areas with a high resilience level (Figure 24). According to the construction of the CoRI, the main variables that affect the values of urban coastal resilience are related to the geomorphological features of the urban area, but also to its imperviousness degree, the typology of building stock, to the presence of public facilities, and to the presence/distribution of transport infrastructures.

Figure 24. Map of the Coastal Resilience Index

Since the values recorded for each variable are in a range between 0 and 2, the study area is characterized by medium-low resilience values, which are recorded for 61% of the whole area. In particular, these areas are located in proximity to the port area and coastline. Furthermore, there are urban areas characterized by medium-high resilience (33%). Their presence is particularly relevant in the neighbourhood of Barra and it is possible to note a limited presence of these in the Historic Centre, especially in proximity to Corso Umberto. Low resilience levels make up only 6% of the study area. The most important of these areas is the port, in particular, the area where commercial activities of the maritime port are concentrated. Indeed, in addition to being likely exposed to coastal flooding due to its proximity to the coastline, this area has functional and physical characteristics - such as the presence of public facilities, the urban layout of the area, as well as the high imperviousness degree - that negatively affect its urban coastal resilience. Low resilience levels are also recorded for urban areas characterized by the presence of critical urban functions for the city (for example, the Loreto Mare Hospital, the Napoli Borgo Loreto Carabinieri barracks, the BRIN car park, etc.), or by touristic points of interest such as the National Railway Museum of Pietrarsa. Beyond the proximity to the coastline, the building stock characteristics (e.g. buildings not-raised from the ground floor), the imperviousness degree and the presence in these areas of strategic urban functions (for example, hospitals, civic buildings, etc.) are variables that negatively affect the capacity of the urban system to cope to coastal flooding and increase its exposure to its impacts. Finally, another category of urban areas characterized by a low urban coastal resilience level is composed of open spaces and some squares within the Historic Centre (e.g. Piazza Garibaldi, Piazza Nicola Amore, etc.) and the neighbourhoods of Barra and San Giovanni a Teduccio. In relation to the CoRI's variables, the open spaces and squares are assessed as not-built areas and, therefore, have no inhabitants and are characterized by a high imperviousness degree. The largest squares are often important hubs of the urban road networks (e.g. Piazza Nicola Amore and Piazza Garibaldi). All these urban features correspond to low resilience values that negatively affect the final CoRI measured for these areas.

5.3.2 Urban Coastal Units

The toolbox for mapping Urban Coastal Units contains three model tools.
Through the processing of model parameters (Table 21), the first two model tools produce the model parameters as raster data, which are necessary for the articulation of the study area in UCUs.

Model Parameter	Data format	Source
Urban Atlas	Shape file	Copernicus
Total Population	Shape file	Italian Institute of Statistics (ISTAT)
Total Employees	Shape file	Italian Institute of Statistics (ISTAT)
Workers in the tourism industry	Shape file	Italian Institute of Statistics (ISTAT)
Number of accommodation beds	Table	Provincial Tourism Agency Office of Naples (EPT)

Table 21. Model parameters for mapping Urban Coastal Units

In particular, the first model tool processes the land use layer starting from the Urban Atlas classes, while the second one works on the land-use intensity indicators and produces four maps, the Population Density, the Job Housing Ratio, the Tourism Employment, and the Tourist Capacity (Figure 25).
Finally, by inserting these five raster datasets in the third model tool, it maps the Urban Coastal Units (Figure 26). Since the output of processes in the Model Builder are in raster format, the three model tools are made up of a sequence of Spatial Analyst tools. Each model tool is also accompanied by help documentation, including descriptions and code samples, useful for allowing others to understand and use the tool efficiently. Furthermore, for the raster output format, considering the territorial scale of interest (the local level), a reference cell with a dimension equal to 1x1 meter was defined.
For what concerns the new land use classification (LU in Figure 27), the majority of the study area (71%) hosts transport infrastructure (railway stations, main roads, and port), public facilities (e.g. university, civic structures, etc.) and specialized urban functions (e.g. industrial areas, commercial areas, etc.). The built environment with mixed-land uses and residential uses is around 23% and is concentrated in the Historic Centre and in the neighbourhoods of San Giovanni and Barra. Furthermore, a small amount of area (6%) is characterized by the presence of abandoned lands.

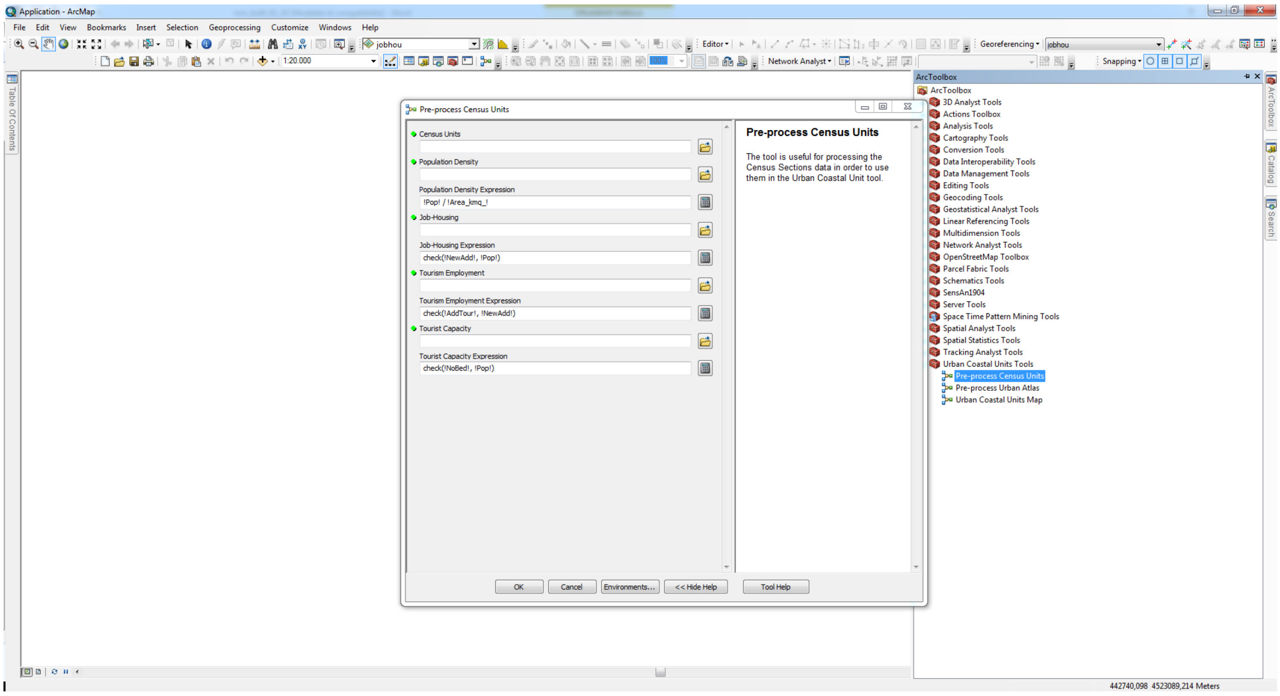


Figure 25. Interface of the model tool for pre-processing Census Units

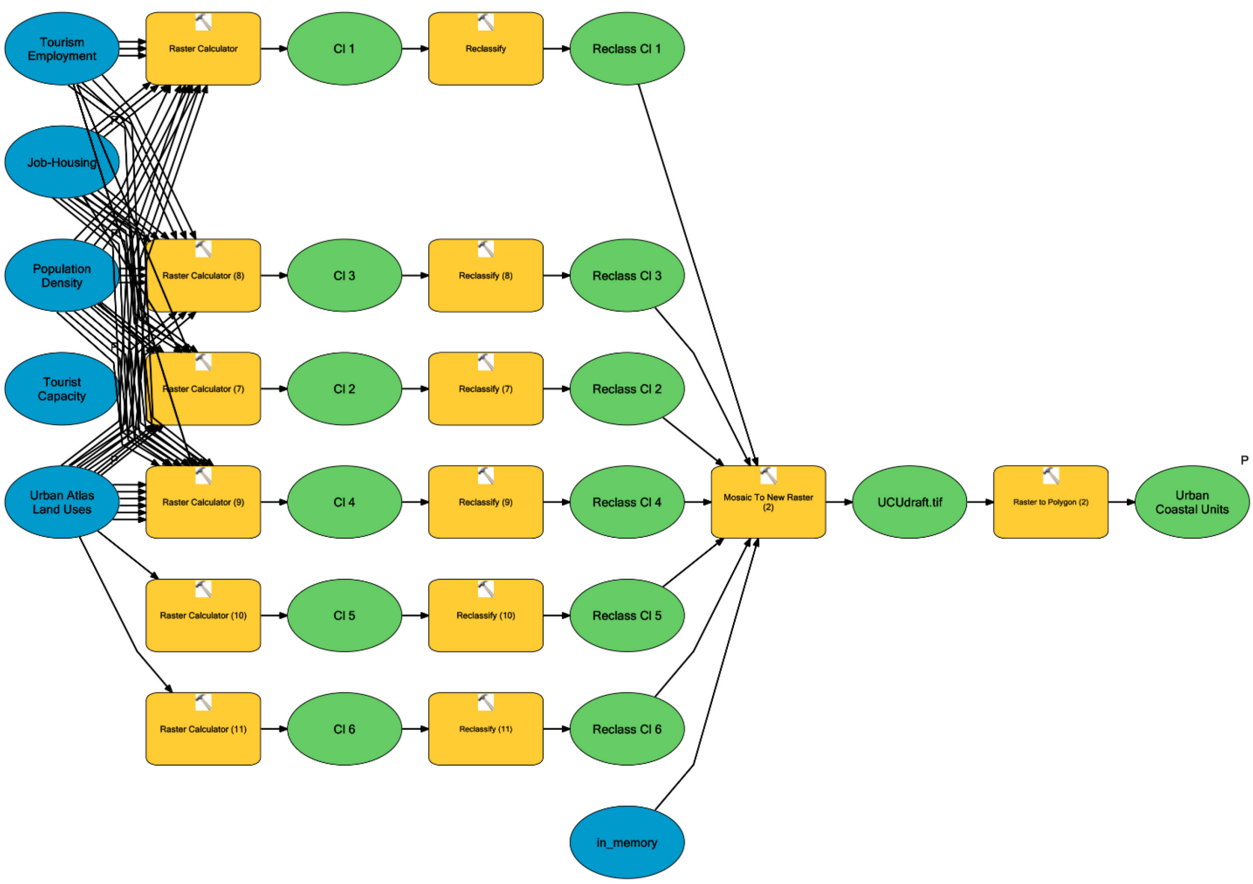


Figure 26. UCU model in Model Builder

These areas are mainly located in the former industrial area and along the coastline, especially in the port area and in the coastal area of San Giovanni.

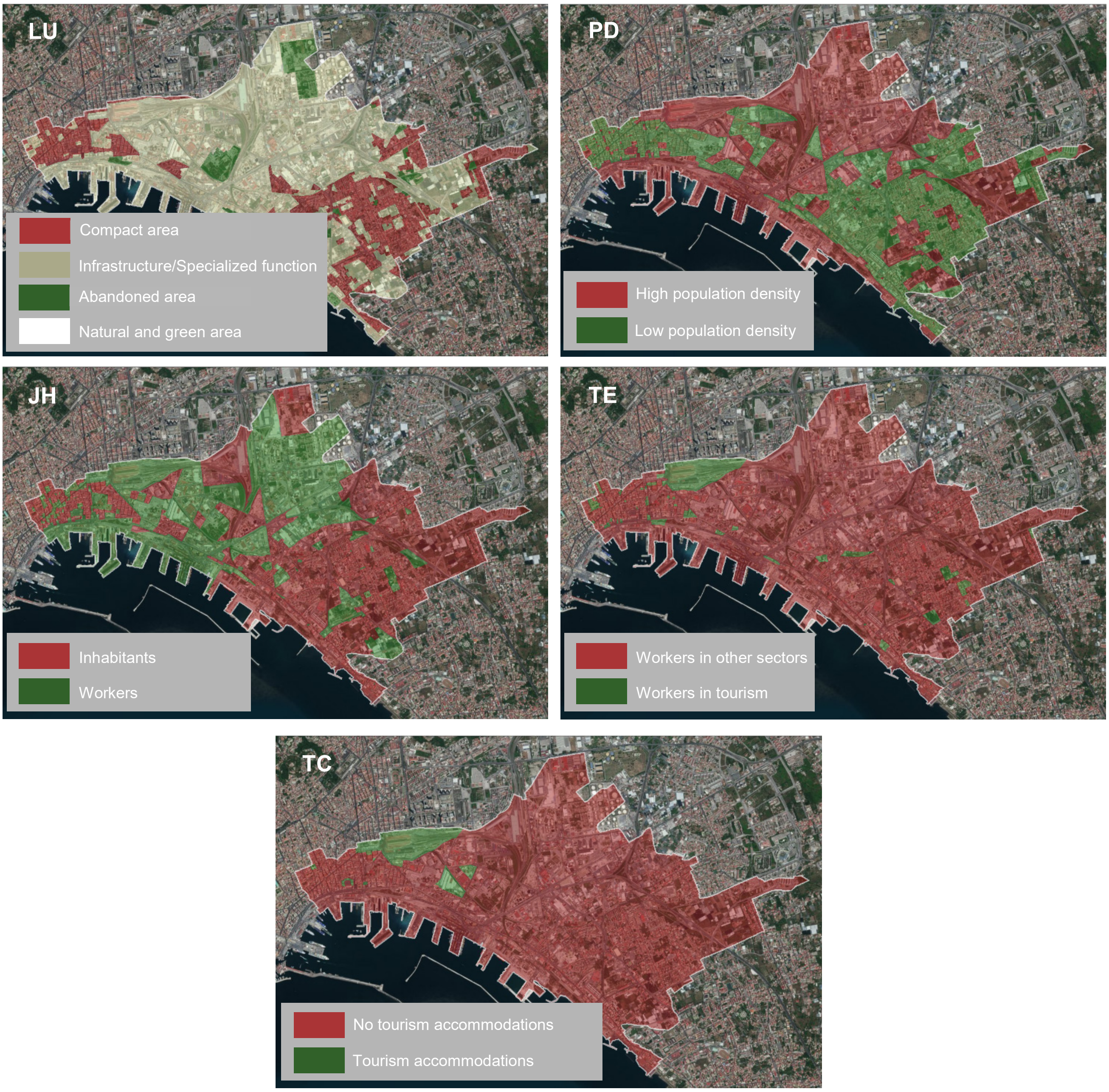


Figure 27. Parameters for the indentification of the Urban Coastal Units

With regards to the Population Density (PD in Figure 27), 40% of the area records a population density over 1,500 inhabitants/sq. km. In particular, those areas correspond to the Historic Centre and the residential areas of San Giovanni a Teduccio and Barra. However, it is possible to note that there are also zones in the central part of the study area with high population density even if they are located in areas characterized by a widespread presence of industrial and commercial activities.

Analysing the Job-Housing ratio (JH in Figure 27), the area of study is mainly residential (57%). However, the comparison of this information with the land use classification highlights that the indicator records high values especially in the Historic Centre, characterized by a stratified urban functional organization. Other high values correspond to the main transport infrastructure localized in the area (the port and

Napoli Centrale station) and its central part, characterized by a high functional specialization due to the presence of manufacturing and commercial activities.

With regard to Tourism Employment (TE in Figure 27), the tourism industry and activities related to it are not very widespread (5% of the study area). They are mainly located within the Historical Centre and near the railway stations of the study area, especially Napoli Centrale station and its surroundings. Besides the considerable number of activities related to the tourism industry, the Napoli Centrale station and the adjacent Piazza Garibaldi are also characterized by a good tourist supply in terms of accommodation beds (Tourist Capacity, TC in Figure 27). Other areas characterized by accommodation beds' availability are located in the Historic Centre. However, there are also two areas, external to the Historic Centre and near the industrial zone where there is a good tourist supply.

In accordance with the analysis of the new land-use classification and the land-use intensity indicators, the articulation of the study area in Urban Coastal Units (Figure 28) highlights the heterogeneity of the urban functions settled in the area, as aforementioned. However, it is appropriate to describe how UCU Classes are distributed and where they are localized in the study area.

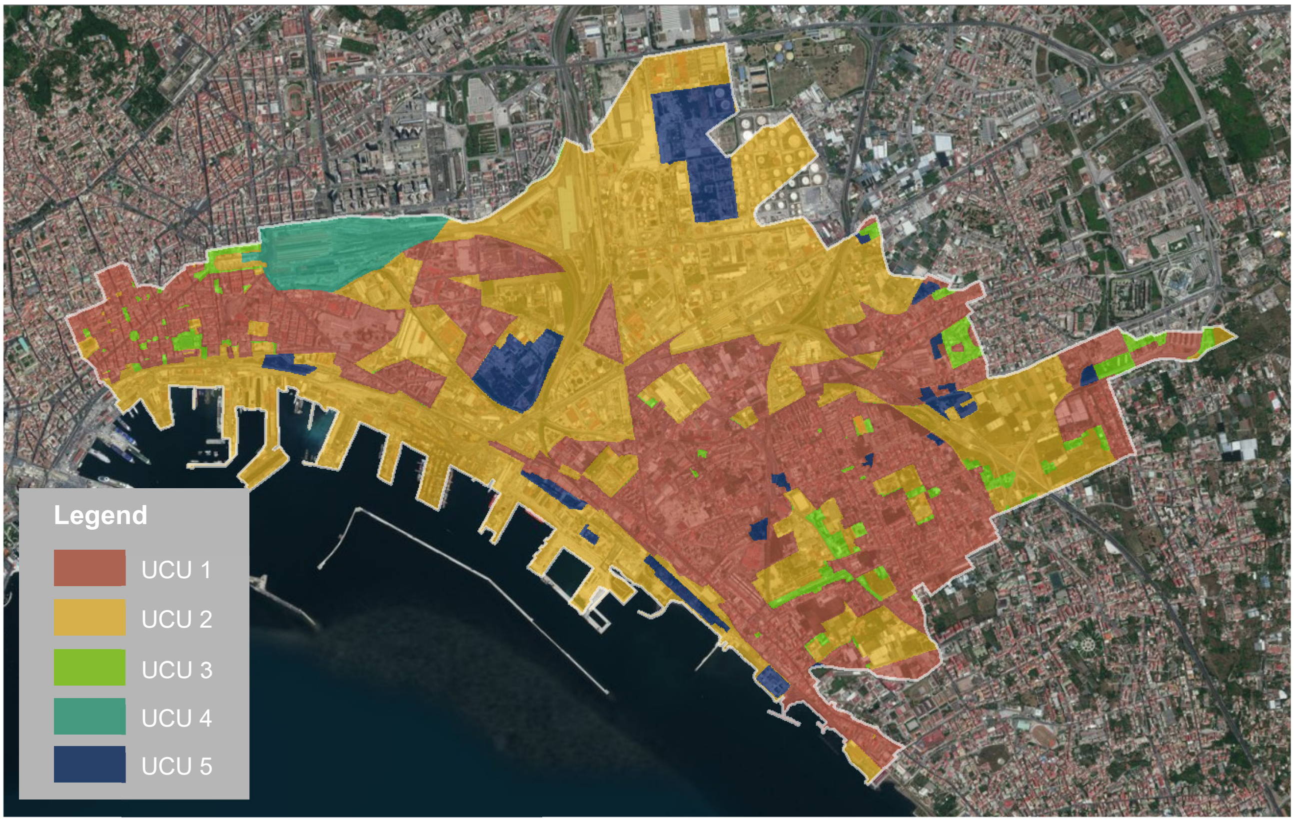


Figure 28. Articulation of the study area in Urban Coastal Units

In detail, there is a high share of UCU Class 2 zones (49%), given the presence of the industrial settlements and important transport infrastructures in the area. Instead, the UCU Class 1 areas correspond to 40% of the study area and are located on its two extremities. This urban layout highlights the presence of two separate urban nuclei, one that belongs to the Historic Centre and the other one that is a part of the suburban area of Naples. Besides Piazza Mercato, Piazza Garibaldi and some open spaces localized in the Historic Centre, the UCU Class 3 areas (3%) includes rural areas that are partially built. With regards to the UCU Class 4, starting from the overlapping of the collected data, it results that there is one area - it represents the 3% of the study area - where Napoli Centrale station is located. Such an area is characterized by a high concentration of tourist accommodations and activities related to the tourism industry. However, it is important to highlight that the identified area includes also the railway infrastructure that should be classified as UCU Class 2. Hence, the use of aggregated data by census sections can affect deeply the final articulation of the UCUs' mapping. In addition, there is a widespread presence of UCU Class 5. The majority of these areas are former industrial zones or vacant lands of the port area. Therefore, these areas can be redeveloped according to a future vision for the area and the future needs of the local community. In the end, there are no UCU 6 areas since the study area is highly urbanized.

5.3.3 Urban Adaptation Actions

After that the CoRI and the UCUs were mapped, a toolbox was developed in order to associate the possible urban adaptation action classes, defined in Section 4, to each UCU of the study area. In this case, the developed toolbox contains one only model tool (Figure 29), whose model parameters, i.e. the raster datasets of the CoRI and UCUs, were obtained by using the two toolboxes described in the previous paragraphs (Table 22). Furthermore, a database was developed for assigning the urban adaptation action classes to each area.

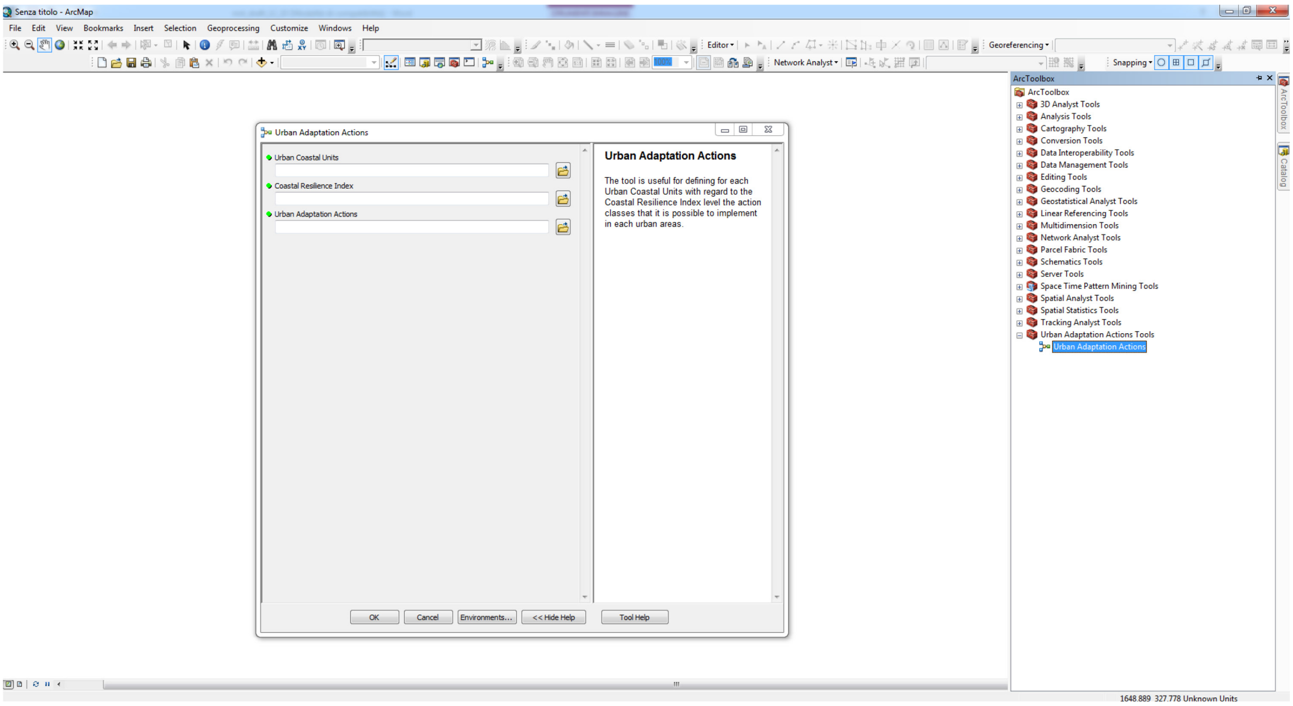


Figure 29. Interface of Urban Adaptation Actions model tool

Model Parameter	Data format	Source
Coastal Resilience Index map	Raster Dataset	Coastal Resilience Index Tools
Urban Coastal Units map	Raster Dataset	Urban Coastal Units Tools
Adaptation Actions	Table	By author

Table 22. Model parameters for mapping Urban Adaptation Actions

Indeed, according to Figure 13 shown in the previous section, in this database the urban adaptation action classes are codifying for UCU type and CoRI level with respect to the three adaptation approaches, which are Accommodation (A), Protection (P) and Retreat (C), i.e. A.1, A.2, P.3 and R.4.

As shown in Figure 30 in the study area there are no zones that belong to the A.1 class (i.e. Accommodation approach with maintenance of the land use). Instead, the majority of the study area require structural actions. Indeed, 61% and 6% of the study area are identified respectively as belong to the P.3 class (i.e. Protection approach with reduction of land use and change of urban form) and R.4 class (i.e. Retreat approach with change of land use). Moreover, there are zones (33%) where structural actions are not required, such as areas that belong to the A.2 class (i.e. Accommodation approach with reduction of the land-use intensity and maintenance of the urban form).

However, as highlighted in Section 4, the urban adaptation actions have to be contextualised with respect to the physical and functional characteristics of the area where these actions have to be implemented.

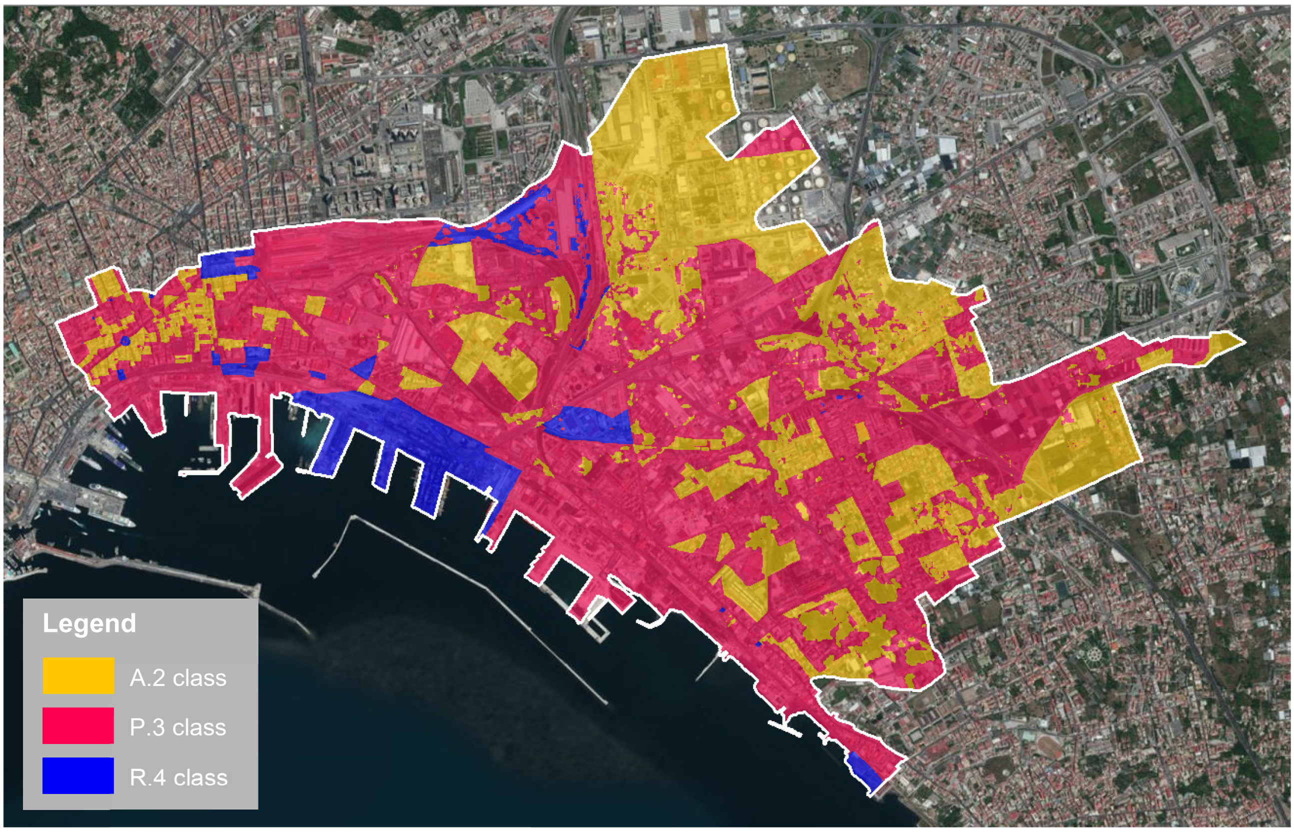


Figure 30. Articulation of the study area in Urban Adaptation Actions classes

Urban Adaptation Actions class/Urban Coastal Units	UCU 1	UCU 2	UCU 3	UCU 4	UCU 5	UCU 6	Total
A.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A.2	14.09	14.41	0.73	0.00	3.31	0.00	32.53
P.3	25.61	28.03	2.01	3.07	2.32	0.00	61.05
R.4	0.00	6.17	0.25	0.00	0.00	0.00	6.42
Total	**39.70**	**48.61**	**2.99**	**3.07**	**5.63**	**0.00**	**100.00**

Table 23. Percentage distribution of the Urban Adaptation Actions classes for Urban Coastal Units

Therefore, the Urban Adaptation Actions classes need to be associated with the UCU's classification. In particular, according to Table 23, it arises that the UCU 2, i.e. industrial/commercial areas, public facilities and infrastructure, need for more hardware interventions than software ones.

Indeed, this UCU category also includes the most extensive area that requires interventions of R.4 class (Figure 31). In particular, this area is the industrial and commercial zone of the city port. For what concerns the UCU 1 areas, most of these need P.3 class interventions (25.61%). However, some areas, such as those located along Corso Umberto I, have a medium-high level of resilience. For this reason, these areas require non-structural interventions (14.09% of the area belongs to the A.2 class).

Instead, the UCU 3, mainly require R.4 class interventions due to their low levels of CoRI.

For the UCU 4, which corresponds to the Napoli Centrale station area, instead, P.3 class interventions result. Therefore, the urban adaptation actions have to be oriented to protect people, infrastructure and services localized in the area and, at the same time, reduce the land-use intensity of the area, through delocalization of further functions that can increase the tourism supply in the area. Finally, the type 5 of UCUs need the implementation of both hardware (2.32%) and software (3.31%) interventions.

In order to provide useful support in the choice of which interventions to implement, an abacus of urban adaptation actions was developed. This abacus contains a set of actions that can be implemented in relation to the UCU category and Urban Adaptation Actions class. In particular, in Table 24, the set of actions that are possible to implement in the study area is highlighted.

It is important to highlight that the actions introduced by the abacus define all the interventions that can range from the A.1 class until to the R.4 class, in relation to the UCU category and according to the CoRI level.

With reference to this abacus, the UCUs belonging to the R.4 class of the Urban Adaptation Actions are particularly relevant. In these areas, especially, important functions are located. Among these, there is the commercial and industrial area of the city port. Besides the delocalization of some relevant functions of the area, other possible interventions can be the creation of raised platforms where it is possible to stock goods in order to reduce any damage to them during a flooding event.

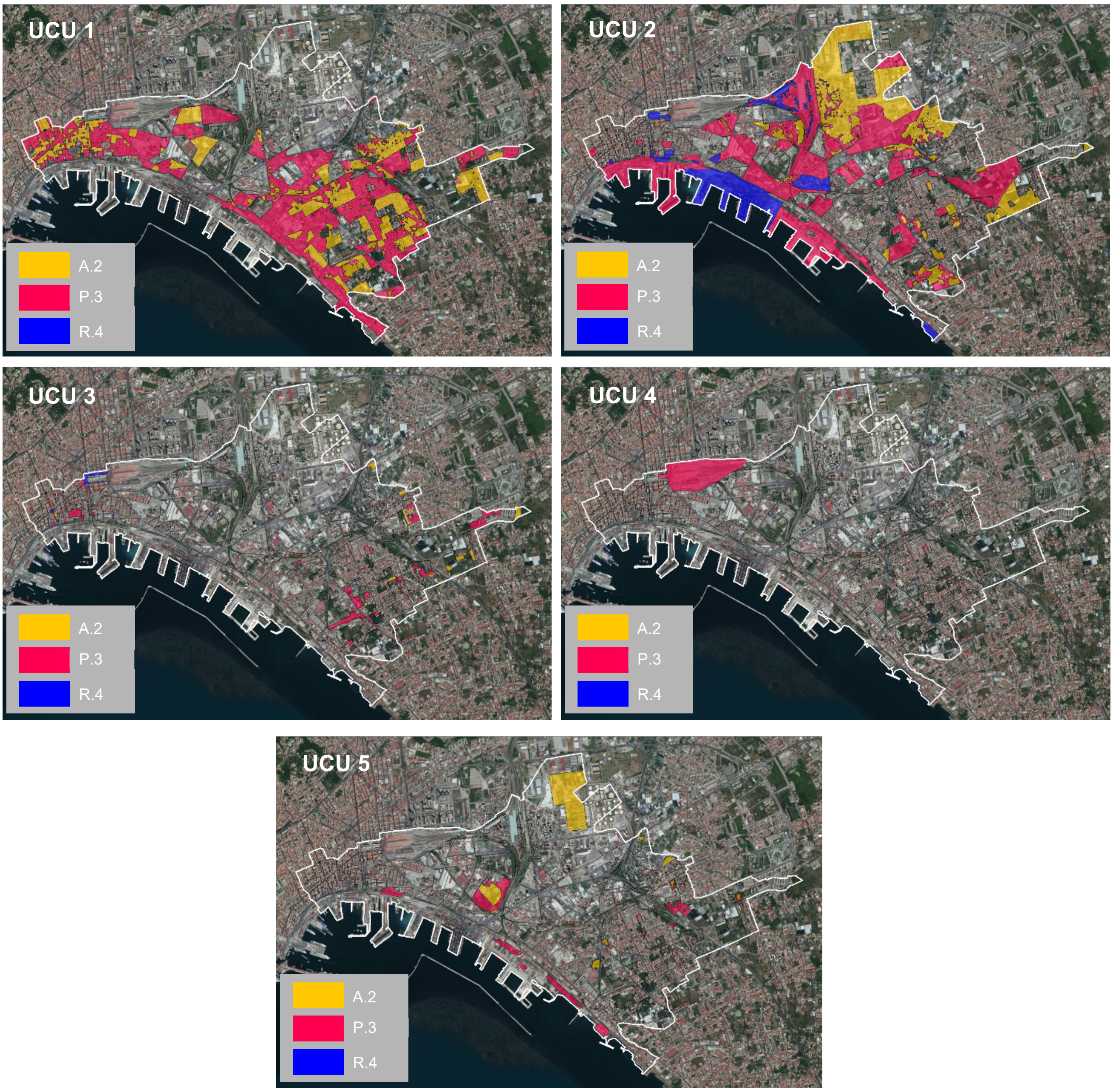


Figure 31. Urban Adaptation Actions classes articulated for UCU types

Moreover, the abandoned or vacant lands can be redeveloped as recreational areas, increasing the permeability of the whole area and consequently its levels of resilience. Two other R.4 class areas correspond to the Loreto Mare Hospital, located behind the city port and National Railway Museum of Pietrarsa, in close proximity to the shoreline. Although they are two relevant functions at the urban level, the urban interventions to implement may be different. In particular, for the Hospital a protective system could be introduced along its perimeter. Furthermore, adopting an integrated approach to the urban development, the redevelopment of the nearby abandoned area, called Parco della Marinella, could assume a key role for the protection of the hospital from any coastal flooding. For what concerns the Railway Museum, as well as increasing its permeable area, infrastructural solutions (e.g. flood walls, artificial reefs, etc.) could be introduced to protect the area. Finally, the main squares of the area, among which Piazza Garibaldi and Piazza Nicola Amore, also belong to the R.4 class. Beyond the increase of the permeable surface, these areas could be converted into water storage zones (or water squares) and designed to accommodate recreational uses that can represent an opportunity to requalify suburban areas such as those within the study area.

Adaptation	Adaptation class	Adaptation Actions	UCU 1	UCU 2	UCU 3	UCU 4	UCU 5	UCU 6
A	1	Realize new resilient buildings	•	•	•	•	•	
		Retrofit existing buildings according to resilient design standards	•	•	•	•		
		Protect vulnerable public facilities and infrastructure	•	•	•	•		
		Maintain of the existing permeable areas in proximity of coastline	•	•	•	•	•	
A	**2**	**Support alternative uses of the ground floor spaces (storage, parking and access to buildings)**	•	•	•	•	•	
		Avoid the localization of high-crowding urban activities	•	•	•	•		
		Insert recreational areas and maritime uses along the waterfront	•	•	•	•	•	
		Introduce strict land-use regulations in hazard zones	•	•	•	•	•	•
P	**3**	**Adopt the compartmentalization of the floodable areas**	•	•	•	•		
		Reinforce and improve the coastal protection system	•	•	•	•	•	
		Create urban wetland	•	•	•	•	•	•
R	**4**	**Move coastal settlements**			•	•		
		Relocate infrastructure, productive activities and public facilities from the coastline		•	•	•		
		Avoid new developments incorporating land-use changes in urban plans and land-use regulations		•	•	•	•	

Table 24. Abacus of the Urban Adaptation Actions (in red the urban actions provided for the study area)

5.4 Discussion

To date, there are not studies capable to analyse and, at the same time, support the decision-making process of urban adaptation to climate change impacts, in particular, coastal flooding. Hence, in this dissertation, a GIS-based tool was introduced in order to provide an operative tool that allows the assessment of "urban coastal resilience" in relation to coastal flooding and provides a set of possible urban interventions for improving urban resilience. As well as implementing the methodological process described in Section 4, the GIS-tool developed was realized by using a visual programming language based on Python scripts that permits the user to further implement and/or modify the tool in order to improve performances depending on the specific applications, if some other datasets are used.

In particular, as introduced in paragraph 4.5, the tool consists of three components. The first component aims at assessing the urban coastal resilience degree through the mapping of the CoRI for the study area. Such application highlights the absence of urban areas with high resilience levels. In general, the study area is characterized by medium-low resilience levels (61% of the whole area) and medium-high resilience levels (33%). Low resilience levels were recorded for squares, and transport infrastructure areas such as the port. It highlights that the low CoRI levels are strictly dependent from the absence of population and the building typology, despite the indicators' weights. However, according to the weights calculated by AHP, the presence of public facilities nearby the coastline also negatively influence the CoRI level: nearest strategic functions to the coastline, major exposure to the impacts of flooding and lower CoRI. Indeed, considering the weights of the "F3. Public facilities" and "G3. Distance from coastline", together they influence the final CoRI value for an amount of about 20%.

For what concerns the UCU mapping, the second component of the tool allows the classification of urban coastal areas according to the current physical and functional characteristics of these areas. In detail, the area study is characterized by a strong heterogeneity and a high urbanization degree (and, consequently, there are no natural areas that belong to UCU Class 6). The mayority of the area, instead, belong to UCU Class 1 (Compact Urban Areas) and Class 2 (Mono-functional and Facility Urban Areas). However, there is also a wide spread of former industrial zones or vacant lands of the port area (Class 5).

Through the overlapping of the data collected by the first and the second components of the tool, the third component articulates the UCUs into the four classes of Urban Adaptation Actions. As shown in Figure 30, there are no UCUs classified in the A.1 class[18] and the Urban Adaptation Actions are different in relation to the type of UCU. Firstly, it means that the study area mainly needs the implementation of "hardware" urban interventions in order to increase its urban coastal resilience and better adapt it to coastal flooding impacts. However, considering the hierarchical structure of the urban adaptation actions classes, the A.1 class's Urban Adaptation Actions can be implemented in areas classified as upper classes (i.e. A.2, P.3 and R.4).

From the analysis of these results, it is noted that the final articulation of the Urban Adaptation Actions classes is affected by the spatial resolution of input raster datasets. Indeed, the greater the resolution of the raster datasets, the greater the precision of the final raster dataset. However, this precision can lead to different issues for the application of the tool, in relation to both the computational calculations and the interpretation of the results. For example, the application of the tool to the study area shows that some UCUs are characterized by the presence of small parcelled areas that belong to a different class of

[18] Interventions based on the Accommodation approach with maintenance of the land use.

Urban Adaptation Actions but have similar characteristics to the surrounding areas. Therefore, the raster's accuracy can be an important factor for describing an urban phenomenon in a detailed way on the territorial or urban level. However, from an urban planning perspective, this precision could not be particularly meaningful on the local scale, when urban actions need to be planned.

Nevertheless, the map of the Urban Adaptation Actions represents an effective tool for supporting the decision-making process in the adaptation process of urban coastal areas to climate change impacts. In particular, thanks to the definition of a range of possible transformations to implement, it allows decision-makers to evaluate different options for the future development of the territory in relation to its physical and functional characteristics and, thus, choose which is more compatible with needs, requests and ambitions of the local community.

5.5 Conclusions

When it comes to define urban adaptation actions to implement in a coastal area, it is necessary to take into consideration not only the resilience levels of this area but also the other urban characteristics in order to avoid a "silo-approach". Based on these considerations, a GIS-based tool capable to take into account the relationships between urban characteristics of coastal cities and the resilience levels was defined and developed in order to provide urban decision-makers with suitable ranges of urban adaptation actions and make the coastal areas more resilient by adopting a holistic-system approach.

The GIS-based tool developed in this study was applied to a study area of the eastern part in the city of Naples. This area was then identified in relation to the potential exposure to future coastal flooding, according to the future scenarios and simulations developed by GIS, the coastal floodplain is limited to the areas nearby coastline. The tool is composed of three parts and is equipped with a help tool in order to allow even the least experienced users to use it. Its application highlighted that the studyarea is characterized by a low coastal resilience and, thus, needs of the implementation of urban interventions not only in relation its urban layout but also its functional organization. In particular, for the analysed study area, the absence of areas with high coastal resilience requires the adoption of a mix of urban "hardware" and "software" actions, where hardware solutions include intervention related to the realization or the improvement of coastal protection systems (e.g. integration of floodwalls in the urban environment, realization of storm surge barriers, etc.), whereas software actions refer to land use and land-use intensity regulation and limit interventions on the built environment. In particular, such actions refer to the building retrofit and the change of ground floors' uses, but also the reduction of the land-use intensity, the integration of flood protection systems into the built environment or the land-use change of urban areas. Notably, the need to implement such actions for more resilient coastal urban areas could be an opportunity to create synergies with different urban interventions and also to create opportunities for boosting the city's economy, improving the quality of urban environment and involving community in the decision-making process in order to support a real change.

Furthermore, the map of the Urban Adaptation Actions can also be used in the decision-making process to program and monetize future urban transformations and evaluate the synergistic potential among the different interventions, and to carry out on the territory in order to minimize the amount of resources needed for their implementation.

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Section 6. Conclusions

6.1 Conclusions

From a social, economic and environmental perspective, coastal areas represent important regions at the global level. In these areas, indeed, there is a high concentration of people and economic assets, besides relevant coastal ecosystems. In particular, coastal zones host towns and cities that represent important hubs on different territorial levels for the mobility and commerce thanks to the presence of ports, harbours and coastal transport routes. They are also repositories of cultural heritage, tourism and recreational uses. Moreover, in these areas, productive functions such as energy production through renewable sources or industrial areas are localized. In Europe, for example, almost half of the EU's population lives less than 50 km from the sea and the majority of the population is concentrated in urban areas along the coast. Furthermore, economic assets within 500 meters from the coastline have a value between €500 and €1,000 billion (EEA, 2016). Due to their several resources and high degree of accessibility, these areas are very attractive for people and, therefore, their population growth is expected to increase in the future (Neumann et al., 2015).

Globally, coastal cities are facing climate change effects. Coastal flooding is becoming be more frequent in some coastal areas due to the increase in storm surge intensity. In order to face this problem, some major cities have built robust system of coastal protection infrastructures. From this viewpoint, the European Union estimates a public expenditure for coastline protection from risks related to erosion and flooding of around euro 5.4 billion per year for the 1990-2020 period. Those costs are convenient in comparison to the evaluations provided by the Commission Staff Working Document on climate change adaptation of coastal areas, attached to the EU Adaptation Strategy (European Commission, 2013). Indeed, according to this document, without further upgrades to coastal protection, damages to coastal areas could be estimated at around €25 billion annually, five times the costs provided for the coastal protection.

However, a well-infrastructured and protected city towards coastal flooding is not enough to cope and recover after these events because the impacts of climate change are characterized by uncertainty. In this sense, in recent years, cities have also started to investigate strategies for addressing urban transformations towards a waterproof urban development. Specifically, in relation to the urban challenge of climate change, urban planning plays a key role. Indeed, not only strategies to address urban transformations are needed but also specific operative methodologies and tools for planning resilient cities to the climate impacts are required. However, to date, urban studies have not seemed to provide any effective operative support for planning the urban adaptation.

Therefore, the main aim of this research was to develop a tool that allows the most suitable actions to be identified, for increasing the capacity of cities to deal with coastal flooding events, due to future rising sea level and storm surges. Besides the use of the most innovative GIS-based technologies, the tool was developed by adopting a holistic-system approach. Indeed, one of the main features of this work is that the urban resilience concept is tailored according to the McLoughlin's system approach. In this way, the sectorial approach, adopted for the vulnerability indices' definition, is overcome and all the urban features that can affect the urban capacity to cope during a coastal flooding event are taken into account, going beyond the traditional approach that considers only geomorphological and socio-economic features. Hence, such a holistic-approach enables to deal more effectively with urban complexity and to obtain a "unique" instrument that is able to address the decision-making process with regards to the definition of the most suitable urban measures for enhancing urban resilience.

Thanks to this approach, this research introduces three main research innovations from a methodological viewpoint. Firstly, a quantitative methodology is introduced to better define urban adaptation actions to be implemented at the local level in relation to the urban characteristics of a coastal area. The developed tool, indeed, is based on the relationships between urban coastal characteristics and the possible urban adaptation actions to coastal flooding. Furthermore, the tool does not identify just one urban adaptation measures but provides a "palette" of possible urban solutions. Secondly, a new composite index was developed to improve support in the decision-making process of urban adaptation to coastal flooding events due to sea level rise and storm surges. To date, the developed indices mainly refer to geomorphological and socio-economic characteristics of coastal areas. Instead, thanks to the holistic-system approach, the Coastal Resilience Index (CoRI) allows the urban resilience of coastal cities to be evaluated in relation to their urban layout and functional organization. It could also be used to monitor future urban transformations provided for an urban area, to verify whether or not they have improved urban coastal resilience of a territory. Finally, another important innovation is related by the use of the GIS for the tool's development. In particular, using GIS allows the implementation of a tool that can provide detailed information on the local level. From a technical perspective, the use of Model Builder for the tool's implementation is an important advantage. Indeed, thanks to it, the tool can be exported in the Python programming language. Since Python is an open-source language, the tool script can be used for eventually developing a new application of spatial analysis, including all the methodological procedures described here, even outside the field of GIS. Furthermore, also thanks to the availability of wide institutional-and-not open data sources (Open Street Maps and Google Dataset Search[19]) at the European level, the tool could be easily applied in other urban contexts different from the Italian one.

[19] https://toolbox.google.com/datasetsearch

Anyway, the lack of data sources can be overcome by using data harvesting techniques, as done in this research.

From an urban planning perspective, application of the GIS-based tool to the study area in Naples highlights how the urban layout and spatial organization can affect the urban capacity to deal with coastal flooding. Indicators that compose the CoRI enable the in-depth study of urban contexts, and identify areas where there are major shortcomings in terms of urban resilience. Whereas the Urban Coastal Units (UCUs) classification enables the categorization of coastal areas in relation to their land use and land-use intensity in order to better identify the most appropriate "palette" of urban adaptation actions to implement. The identification of a set of urban actions for different urban typologies can be useful for not only defining and programming new urban transformations but also for allowing decision-makers to monetize possible interventions to carry out.

From this viewpoint, the application to Naples' case study and the definition of the forecasted coastal flooding scenarios are useful in addressing future urban transformations of the city and, especially, of its eastern suburban zone that represents a complex and problematic urban context. In this zone there is, indeed, a high concentration of infrastructure, public facilities and assets, and many social issues due to its peripheral localization in the city. The redevelopment and regeneration of this zone could play a strategic role in the future development of the whole city. Therefore, the results of this work can support not only future urban planning choices but also the urban measures that are currently in progress for the study area. As well as for some of the analysed case studies (i.e. Rotterdam, New York, Boston), urban adaptation measures can be integrated into urban planning in order to create "an attractive, lively and healthy city" (Rotterdam Climate Initiative, 2013). Therefore, implementing urban adaptation in this area means to not only create a waterproof city, but also to create opportunities in terms of urban transformations for sustainable development of the city by strengthening its economy, improving its living environment and increasing its urban biodiversity.

Finally, in order to be effective, this tool has to be used in combination with other decision-making tools. The programming and planning of urban interventions, indeed, is not enough. It is important to involve stakeholders and inhabitants in order to have the necessary resources in terms of funds and knowledge for the implementation of urban adaptation measures provided by the tool.

6.2 Limitations and further developments

The proposed work introduced varying research innovations. However, it is important to highlight that some improvements can be carried out for the final version of the tool for municipalities. The first one can be identified in the definition of the indicators' weights of the CoRI. Indeed, the CoRI is the result of different opinions expressed by experts. Therefore, in relation to the tool's structure aforementioned, the value of CoRI and, consequently, the map of Urban Adaptation Actions for a coastal city may change

in relation to each expert's opinion. Another aspect is related to the selected variables. The CoRI takes into account the urban layout and the spatial organization of the area. However, in order to increase urban coastal resilience, it is also necessary to take into account community engagement and, in general, governance for the implementation of urban adaptation actions (Tanner et al., 2009). The choice of specific variables for the development of the CoRI is also due to data availability and, especially, the lack of specific datasets on the local level (e.g. population income). Indeed, since the tool was developed to be applied to the neighbourhood level, the availability of open datasets on this level can be an issue. However, data referred to building typologies and their ground activities that may be extracted, e.g. by Open Street Maps, are not always freely available, as highlighted in Section 5 (paragraph 5.2) for this research. Therefore, the transferability of this tool in other contexts can be influenced by this factor. Besides this, there are also issues in relation to time periods of datasets. Indeed, although there is an availability of open data, they often concern different time periods, not providing real knowledge of the current state of an urban area. Even the resolution of raster's spatial resolution can influence the spatial analysis' result provided by the tool. Indeed, the accuracy of the result could not be particularly meaningful on the local scale. Finally, the last aspect to take into account for the improvement and the spread of this innovative tool is related to the use ArcGIS as software for the GIS-based tool implementation. Since ArcGIS is a proprietary software, the tool is not easily used by local administrations and urban planners, considering that public administrations and technicians often do not have GIS skills and/or have limited funds for buying high specialized software such as ArcGIS.
Considering these limitations, future developments of this research could be:

- implementation of an uncertainty analysis for evaluating how the experts' opinions affect the final map of Urban Adaptation Actions;
- improvement of the proposed methodology through the inclusion of other urban characteristics and factors referred to the implementation phase of the adaptation actions. In light of this, it could be necessary to review the urban indicators chosen for the definition of the Coastal Resilience Index and its aggregation and weighting techniques, according to the JRC (2008). Furthermore, in order to include new meaningful variables, it could be necessary to use data mining techniques for creating new spatial datasets for GIS analysis;
- development of the GIS-based tool by using an open-source GIS software (e.g. QGis). Moreover, it could be more effective to evaluate the opportunity to develop a free software application based on the programming language Python;
- application of the developed tool to other urban coastal contexts in order to carry out a sensitivity analysis for understanding which factors can effectively affect the result of the Urban Adaptation Actions mapping.

Finally, the methodology illustrated in Section 4 could be used for developing new tools in relation to other climate impacts and, eventually, for integrating those in order to develop a comprehensive tool for urban adaptation to different (possible) impacts of climate change (Wardekker et al., 2010).

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