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Spatial biophysical-economic impact assessment of Nature-Based Solutions (NBS) for Urban Climate Change Adaptation

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Declaration

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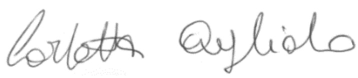

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I would like to dedicate this thesis to Alba, my loving grandmother.

Acknowledgment

During these three years of my PhD, I had an incredible learning experience, both in my professional and personal life. This path was challenging and not easy, but various people supported me with their encouragement and positive critiques.

Firstly, I would like to express my deepest gratitude to Prof. Alessandro Pezzoli, who has been a constant support, and who has always shown complete faith in me. I am thankful to him for believing in my capabilities by giving me the freedom to explore different ideas. He helped me strengthen my personality.

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I am grateful to all my friends, who always believe in my potential.

“All nature is doing her best each moment to make us well – she exists for no other end. Do not resist her. With the least inclination to be well we should not be sick.”

(**Henry David Thoreau** - Journal, 23 August 1853)

“Your preparation for the real world is not in the answer you’ve learned, but in the questions you’ve learned how to ask yourself”

(Bill Watterson)

Foreword

The rise of my scientific interest in this research field is strongly affected by my educational background and previous personal experiences, both as an academic researcher and as a person who is completely aware of the crucial value of the Natural Capital. Moreover, I think that 'who we are' and 'our choices' are inevitably influenced by the context we live in. I am surely glad for all the people I met during my path. I thank my family for giving me the possibility to pursue my studies, and each person that believed in me for helping me become who I am.

My choice to start a bachelor's degree in economics and trade – environment & territory allowed me to learn about environmental and territorial issues from a quantitative approach. This first decision on my path has been influenced by the experiences that I lived with my father, who, as a geologist and mountain lover, incentivized me to always approach the environment with a great observational attitude towards the complex dynamics of natural systems.

I decided to deepen the studies on environmental issues with a master's degree in environmental economics and policies. This experience allowed me to discover the ecological economy with a multidisciplinary approach. During these two year-long paths, I developed sensitivity for the issue of climate change and, particularly, the climate-related impacts of this phenomenon in the urban context. Indeed, my final dissertation is focused on the urban micro-climate variability analysis for temperatures within the city of Guayaquil (Ecuador), which was strongly affected by climate change.

My interests in the field of research guided me to the first experience in writing a scientific article and, subsequently, my background has been considered for a position as Junior research fellow at DIST Department (Politecnico di Torino (IT)), where I collaborated in various activities with the Responsible Risk Resilience Centre - R3C. My research has been focused on spatial analysis to define environmental and socio-economic vulnerabilities for selected territories and forwarding measures for urban resilience. This opened my eyes to the strict relationship among human, climate and natural systems. Therefore, I focused on the problems of urbanisation and climate change, improving my technical skills in the urban spatial environmental analysis (GIS analysis).

Moreover, I coordinated and developed two project proposals for the two-stage H2020-European programme on the topic SC5-14-2019: Visionary and integrated solutions to improve well-being and health in cities, and SC5-27-2020: Strengthening international collaboration: enhanced natural treatment solutions for water security and ecological quality in cities. Both these projects would foresee a range of integrated Nature-Based Solutions to improve human health, social cohesion and water security while reducing hydrometeorological impacts and enhancing resilience in European cities. During this experience, I discovered the role and potential of nature and ecosystem services provided by NBS in urban climate adaptation.

What I mentioned is part of my way of living and my research activity. I developed my passion for work in research during this PhD path, when I first realized that we never stop learning. Most of all, I grew up with the desire to have a better and deeper comprehension of the environment I live in. Moreover, as an environmental economist with an interdisciplinary background, I strongly believe in two key points that characterise my future research activity: quantification, and accuracy of used terminology. I believe that a quantitative approach helps deepen the understanding of issues, since it simplifies the real world, and promotes practical solutions. Such an approach is relevant for improving territorial and environmental analysis in support of spatial policies, especially to integrate ecosystem services into climate change adaptation planning. Generally, the academic literature underlines the gap and separation existing between theoretical research and practical application. There is no division between the way we analyse and comprehend a phenomenon, and the way we behave towards it. Indeed, the greater our awareness of the problem, the more we change our actions accordingly. This, in turn, is strictly linked to the quality of scientific communication, as the ability to disseminate complex studies and analyses in a simple and clear manner in order to change our actions and generate concrete application of this knowledge.

Recently, a wide range of multidisciplinary research areas is trying to define new fields (i.e. climate change or environmental sciences) by requiring linguistics innovation. Especially the new perspective of climate change adaptation through ecosystem-based approaches requires lexical coherence in a context characterized by evolving language in order to have a 'correct' comprehension of climate change phenomena. The 'correct' way to interpret these topics can only be achieved through a careful and rigorous use of the relevant terminology, and this is all the more relevant in multidisciplinary fields, as is the case of urban planning.. This is what I experienced during my contribution to the development of a project related to the communication of Climate Change issues with the University of Turin: "Lessico e Nuvole: Le parole del Cambiamento Climatico" (2019). The practical implementation presents several problems linked to the terminology used and the knowledge base that supports decision making processes. The act of knowing has a proactive meaning as the precondition of each methodological application. Understanding and knowledge determine all decisions and actions. To change our efforts, we have to change our ideas, which is once again down to expertise. The correct understanding is that which is easy to understand for the public at large. Thus, my approach to research is entirely based on a reflexive, in-depth comprehension of issues, with the goal of promoting an easier operationalization of the generated knowledge, leading to practical change.

Summary

Climate Change is considered the major present and future threat to the stability of cities, especially through the increase of related impacts. Out of all natural disasters, those related to hydrometeorological phenomena (e.g., coastal and pluvial-floods, storm surges, hurricanes/typhoons) have shown the fastest rate of increase in their frequency and intensity. Additionally, on a global level, flood events are the costliest natural hazards.

Changes in precipitation patterns and high levels of surface imperviousness result in increased runoff production in urban areas, increasing their sensitivity to flooding events. Particularly, coastal cities are facing significant compound floodings due to simultaneous rainfall runoff, storm surge and sea-level rise, all of which cause vast socio-economic and ecological impacts.

Various national and international climate change frameworks exist; however, these are vague, and have no practical effects on spatial planning tools. An urban climate adaptation strategy should address and include socioeconomic aspects in addition to the environmental ones to be effective and achieve benefits for all stakeholders. The concept of Nature-based Solutions (NBS) comes as the alternative that can act at several levels, being more than just an aesthetical improvement. NBS are considered the new planning tools for overcoming the boundaries of traditional 'predict and prevent' approaches, while playing a crucial role in addressing societal challenges and providing benefits through the supply of Ecosystem Services (ES). In this view, NBS impact simulation is considered a good practice to increase awareness about the solutions' multiple co-benefits. Raising the willingness to accept NBS can be done by creating evidence on their effectiveness at an urban level. However, combining the benefits and costs of such solutions in thorough studies is challenging.

The objective of this research is to develop and utilize a spatial assessment framework to estimate the NBS impacts under climate scenarios. The intent of this to comprehensively evaluate the biophysical and economic effects of NBS, by estimating costs and benefits, in mitigating pluvial flood risk. This research is developed in two parts: first a flood risk assessment is conducted to assess the biophysical flood-mitigation performance of NBS in urban areas, then, a value transfer method is used to assess NBS implementation costs and flood mitigation benefits, resulting in a partial cost-benefit analysis (CBA) aimed at evaluating the economic impacts

of such solutions. To achieve this, modelling tools (InVEST Urban Flood Risk Mitigation model) and economic valuation methods (value transfer methods) are employed; corresponding results are then combined and analysed using Geographic Information Systems (GIS). This theoretical framework is applied to the study of two Euro-pean coastal cities, namely the city of Aveiro (Portugal) and the city of Rapallo (Italy). NBS scenarios of green roofs and bioswales under current and future (mid-term) climate conditions are assessed and compared.

The main findings of this research show that green roofs scenarios generate economic benefits that offset between 32% (for Aveiro) and 65% (for Rapallo) of total flood damage expenses every year. On the other hand, when simulating bioswales scenarios, the difference between the two case study applications is smaller, with a 0.1% for Aveiro and 0.3% for Rapallo. Out of the two scenarios considered, results show that green roofs have the best performance. Furthermore, for both NBS scenarios, the economic performance improves under lower return period events, while the biophysical-economic performance is more promising under more extreme climate scenarios when compared to current climate. These results hold true when considering lower/higher NBS implementation and maintenance costs, as well as when applying positive discount rates (sensitivity analysis).

These findings are highly valuable as input for the development of nature-based flood risk adaptation strategies in a context of changing climate. The perception of NBS benefits can be improved if other co-benefits of these solutions are considered. Indeed, the results of this study can be used to inform decision makers in the design of new policies to improve resilience to flooding events from both a biophysical and economic perspective. Thus, by estimating impacts, costs and benefits of NBS, this research shows the important role of quantitative assessments of ES to support climate change adaptation planning.

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PART I - Scientific background

Chapter 1

Introduction

This chapter is partly based on (Quagliolo *et al.*, 2021).

1.1 Research topic

Today, about 55% of the world's population lives in urban areas, and this proportion is expected to increase to 68% by 2050 (UN DESA, 2018). In Europe, one-third of the population resides within 50 km of the coast, and experiences growing risks related to climate change, especially due to the combination of sea-level rise and extreme events (such as pluvial floods) (Ciscar *et al.*, 2018). Additionally, urban environments highly affect the magnitude and spatial distribution of hazardous events due to the concentration of buildings and socio-economic activities (I.M. Voskamp and Van de Ven, 2015). With fast urbanisation, as well as aging infrastructures, cities are struggling to cope with the stresses of sewage, water and basic infrastructures. The increase in impervious surfaces leads to a decline in the capacity of the environment to naturally infiltrate and store water, which results in runoff and higher flood risk frequencies (Chan *et al.*, 2018). Climate change is projected to cause even more unpredictable adverse effects in cities due to an increase in the magnitude and frequency of extreme weather events. A wide range of impacts will transform cities in hubs of increased inequities in terms of resource distribution and cause greater urban system instability. Furthermore, natural disasters did costed the European Union almost 100 billion Euros until 2005 (Faivre *et al.*, 2018). Despite this increasing evidence, climate policies still tend to focus on national scale initiatives rather than being integrated into local urban planning.

Urban-level initiatives to support understanding of the potential impacts of climate change are gaining importance. Some examples include ICLEI – Local Governments for Sustainability network and C40 Cities Climate Leadership Group globally to the Covenant of Mayors for Climate & Energy at European level. It becomes evident that urban areas, independently of their size, are ideal settings for the implementation of adaptation measures, and for achieving urban climate resilience[1].

Figure 1 shows a selection of tools and initiatives that are particularly relevant at European level in the urban climate adaptation context. This list is not exhaustive;

[1] **Resilience**, here, is intended as “the ability of social, economic, and environmental systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation” (IPCC, 2014a).

for a better overview of actions to adapt cities, as well as, the scientific progress on the topic generated since 2012, the authors recommend analysing the Climate-ADAPT[2] platform.

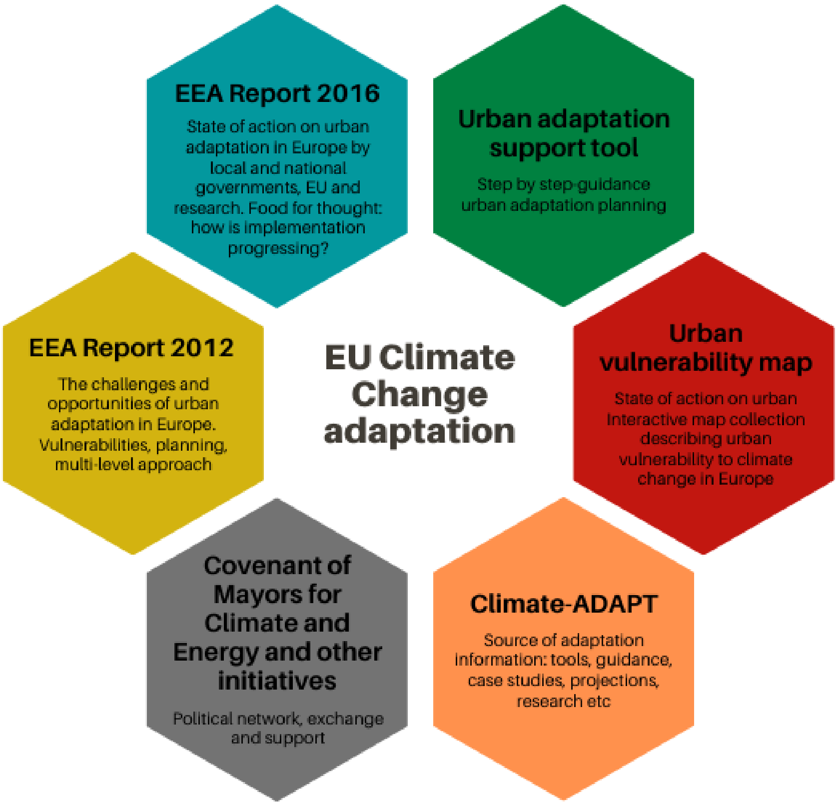

Figure 1. *List of relevant tools and initiatives on urban adaptation in Europe (adapted from European Environment Agency (EEA) (2016). More information at Climate-ADAPT (http://climate-adapt.eea.europa.eu/cities).*

Over the last decade, the use of Nature-Based Solutions (NBS[3]), rather than traditional "grey" measures, has been proposed with the goal of supporting climate adaptation. NBS have a proven positive impact on humans well-being, and provide a wide range of Ecosystem Services (ES) (European Environmental Agency (EEA), 2012). Thus, increasing awareness about NBS co-benefits by proving their effectiveness improves the willingness to accept and adopt these solutions. Determining NBS costs and benefits distributed over time (current and future climate scenarios) and space helps integrate these solutions more effectively into traditional planning (Quagliolo *et al.*, 2022). However, designing and evaluating long-term adaptation strategies is still a complex challenge (Aerts, 2018).

[2] http://climate-adapt.eea.europa.eu/cities

[3] Under a society centric perspective, nature-based solutions are defined as "*actions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource efficient, and systemic interventions*." (European Environmental Agency (EEA), 2021b)

In climate change adaptation, the utility of spatial models and scenario assessment refers not to an exact future prediction, but rather to narrow possible ranges of a subset of plausible place-based outcomes (even if uncertain), identifying vulnerabilities and suggesting appropriate adaptation options (IPCC, 2014a). Indeed, scenario-based spatial analysis has become a standard tool in climate change assessment (de Sherbinin, 2013; Magalhães Filho *et al.*, 2022).

Keywords
Climate Change adaptation, Climate Change scenario, Pluvial flood, Nature-Based Solutions, Integrated biophysical-economic assessment, Geographic Information System, InVEST software, Cost-Benefit analysis, Coastal cities.

1.2 Background and motivations

Climate change and increased variability of climate stimuli continue to critically impact socio-economic and ecological systems of urban societies in the 21st Century (Cardona *et al.*, 2012). The vulnerability of cities is strictly linked to their geography, which determines the proximity to specific eco-zones. For instance, historically, a large number of cities have been developed along coastlines, where flooding issues are becoming more frequent. Coastal zones have traditionally been crucial and attractive for humans due to their abundant supply of resources, for logistical reasons, to establish trade and transport activities, as well as recreational and cultural reasons (Sekovski, Newton and Dennison, 2012). Critical infrastructures, such as ports, are key elements for the economic growth of both coastal and inland areas, enhancing land-sea connection. Moreover, oceans, and particularly coastal zones, contribute by more than 60% of the total economic value of the biosphere, while providing ecosystem services with considerable environmental and economic value (Costanza, d'Arge, *et al.*, 1997). In this context, there are increasing concerns about climate change as a result of the combined effects of sea-level rise and extreme climate events with localised human effects; all of which pressure coastal zones (IPCC, 2019; Oppenheimer *et al.*, 2019).

Although coastal areas cover only 4% of the Earth's total land area, coastal population densities are about three times larger than the global average of inland areas (Sanchez-Reaza and Carletto, 2013). Moreover, the future population is projected to increase rapidly in the Low-Elevation Coastal Zone - LECZ (coastal areas below 10 m of elevation), specifically by 50% to 71% until 2050, compared to the year 2000; this is equivalent to an increase of 630 million people (McGranahan, Balk and Anderson, 2007; Lichter *et al.*, 2011; Merkens *et al.*, 2016). Traditionally, migration towards coastal urban areas has been strong, as a result, 15 out the 20 present-day world's megacities are located in low-lying coastal regions (Neumann *et al.*, 2015; Mehvar *et al.*, 2018). This trend with high population densities is driving coastal cities to expansion while causing heavy stresses from an environmental perspective.

According to the Fifth Assessment Report (AR5) of the IPCC, urban climate change-related risks are increasing. Even though direct consequences of climate change are limited to temperature extremes and sea-level rise, changes in flooding features and other hydrometeorological hazards are associated with climate change processes, leading to higher probability and severity of these events (IPCC, 2019). The trend of flood frequency will rise by 42% of the land area, more likely due to the increased frequency of extremes weather events (Hirabayashi *et al.*, 2013).

Indeed, among all natural disasters, climate change-related floods are considered the most damaging to urban areas (Middelmann-Fernandes, 2010; European Environmental Agency (EEA), 2012; Rosenzweig *et al.*, 2019; Alves *et al.*, 2020). Especially, extreme rainfall events and local storms lead to pluvial flooding in many cities when runoff production exceeds the drainage capacity (Houston *et al.*, 2011; Costa *et al.*, 2021). In general, and historically, urban drainage systems have had a limited hydraulic capacity designed to cope with low magnitude precipitation events, such as a 10-year return period rainfall (Sörensen and Mobini, 2017). This means that even when design standards are followed, urgent climate-flood risk action is needed to minimize future monetary losses. Extreme rainfall events have become more common and frequent during the last decade (Zhou *et al.*, 2013; Pagano *et al.*, 2019), although, it is still challenging for modelers to accurately estimate the impacts of these extreme events on urban hydraulic systems. As a result, the estimated impacts of these extreme events come with high uncertainty, thus, flood adaptation measures should be flexible and multifunctional, especially considering local spatial variability within the urban environment (Voskamp *et al.*, 2021).

The need to plan with natural systems, such as NBS, is the key for building resilience in cities. The concept of NBS is seen as the operationalization of the ecosystem services approach within spatial planning policies by fully integrating the ecological dimension in cities (Dushkova and Haase, 2020). Therefore, the assessment of the greatest potential of natural habitats to reduce climate-related risks needs to be deepened. NBS offer a new perspective by providing a range of benefits (i.e. provisioning, regulating and cultural services) while addressing complex urban challenges (Kabisch *et al.*, 2017; Frantzeskaki, McPhearson, M. J. Collier, *et al.*, 2019). Such solutions have the capability to mitigate disturbances caused by climate extremes and urbanization (Liu *et al.*, 2016). Increasing evidence shows that NBS have positive effects on climate adaptation (Zölch, Wamsler and Pauleit, 2018). This knowledge is crucial for decision makers, as assessing the benefits provided by NBS can better inform evidence-based decisions (Alves *et al.*, 2020).

However, national intentions to incorporate NBS in climate change adaptation can vary in relation to the level of economic development and region, and have to be translated into quantifiable evidence-based targets (Chausson *et al.*, 2020). One of the major reasons for this is the gap of synthesis of the evidence on the effectiveness of NBS for climate change adaptation in comparison with other, more traditional approaches (Seddon *et al.*, 2020). During the last decade, scientists and government bodies have begun to conduct assessments on first and second order impacts of climate change at an urban level through the development of complex models for urban stressor analysis (i.e. urban heat islands, flooding or air pollution)

(Rosenzweig *et al.*, 2011). Lately, more attention is still given to the hazard assessment, while the economic impact assessment of damages receives less attention within the climate change adaptation planning framework (Merz *et al.*, 2010). Despite this, the scientific community recognizes how economic analysis of NBS benefits, co-benefits and costs can have a relevant influence in decision-making, allowing a more intuitive visualization of its financial effects (European Environment Agency (EEA), 2016). To date, only few studies partly assess the biophysical-economic impacts of NBS for flood risk mitigation, and the employed methods are diverse. In this context, the policy interest concerns even more of an urgency to effectively carry out climate change adaptation assessments (such as NBS studies) within local urban planning, thus integrating the know-how into policy (Preston, Yuen and Westaway, 2011).

1.3 Key gaps for managing climate adaptation planning

Spatial analysis and urban planning play a crucial role in managing climate change adaptation. However, a number of key methodological challenges to effectively integrate adaptation solutions, such as NBS, at an urban level can be highlighted.

Climate and environmental-ecological issues have become the new pattern of contemporary urban planning. Therefore, many researchers are debating the most effective way to improve climate change adaptation and resilience by including the possibility to cope with rapid changes in the future (Zölch, Wamsler and Pauleit, 2018; Chausson *et al.*, 2020). Indeed, climate change and related risks for the environment and society require an ecological approach to manage human settlements, as well as the economy and social aspects connected to the degradation and inequalities of our cities. Thus, evaluating the role of NBS in mitigating societal challenges, as well as their economic assessment, are essential for decision-making.

Over the last decade, the valuation of NBS benefits and ecosystem services has been recognised to be a crucial element in quantifying the contribution of ecosystems and biodiversity to human well-being (OECD, 2006). Prioritising intervention areas within the urban environment requires knowledge of where habitats are most likely to reduce exposure to flash flooding due to extreme weather events. Spatial assessment is the only approach for providing precision in identifying spatial dynamics of vulnerabilities while targeting adaptation measures (Preston, Yuen and Westaway, 2011).

Nevertheless, widespread implementation of NBS remains limited due to the lack of knowledge about how to embed urban ecological science within urban planning practices and policies (Hansen *et al.*, 2019). Still, a considerable debate concerns how to conduct decision analyses in contexts where valuation and understanding of the natural world is likely to remain relatively uncertain (OECD, 2006). One of the main problems is related to the non-market values of natural resources, and for this reason it is difficult to value the benefits NBS provide (Collins, Schaafsma and Hudson, 2017). The absence of market prices for ecosystem services does not mean they lack value; instead it is related to the fact that many environmental goods are in the form of public goods and services (positive) or externalities (Perman *et al.*, 2003). Indeed, many ecosystem services are freely available, such as fresh water in aquifers, and atmosphere used as a storage for pollutants; for this reason, their "*depletion and degradation*", which "*represents a loss of capital asset, is not reflected in conventional indicators of economic growth or growth in human well-being*" (Millennium Ecosystem Assessment, 2005). Therefore, the importance of price and its variation is due to the need to inform consumers and producers about scarcity of a particular resource. This is why the 'price' is considered a scarcity indicator (Perman *et al.*, 2003). Nonetheless, giving an economic value to environmental resources does not mean to determine, in absolute terms, their intrinsic value. Rather, the aim is to measure people's preferences. This can be explained by generally taking as an example other common market goods: the economic value of a good is given by the willingness to pay (WTP) for it. In other words, people are implicitly valuing pros and cons of a product when they have to choose a product and whether to buy it, and thus revealing if, in their opinion, such a product is worth that amount of money (Perman *et al.*, 2003). This is what happens in Environmental Economics, where the WTP measures "*the value people attach to natural resources and the services these resources provide*" (Brouwer, 2000). Hence, improving ES valuation is a useful tool for policymakers to perform cost-benefit analysis for NBS upscaling in urban areas. In-depth analysis aimed at demonstrating the evidence of costs and (co-)benefits of NBS should be performed to better integrate NBS into traditional planning (Hobbie and Grimm, 2020; Quagliolo *et al.*, 2022).

Regarding the value of NBS in future conditions, a small portion of studies considers climate change data when conducting integrated scenario-based analysis with NBS adaptation scenarios (Moore *et al.*, 2016; Boelee *et al.*, 2017; Dong, Guo and Zeng, 2017; Locatelli *et al.*, 2020; Matos and Roebeling, 2022). Contemplating the complexity of urban adaptation, scenario-based assessment is a crucial tool for addressing trade-offs in climate change research. This approach also helps policymakers visualize and identify near- and long-term impacts in a context of future uncertainties (Riahi *et al.*, 2017; Magalhães Filho *et al.*, 2022). Historically, urban planning did not adopt strategic tools to cope with climate change and extreme weather hazards in a systematic way. Indeed, globally, only a few cities developed knowledge systems including uncertainties associated with future non-stationary climate while integrating 'Climate Adaptation Plans' into the everyday planning (i.e. the Cloudburst Management Plan adopted by the City of Copenhagen in 2012). Some climate adaptation planning efforts already use climate change data and services. However, this information is usually too broad or sectorial to directly inform decision-making at the local scale, where adaptation measures are taken (Howarth and Painter, 2016).

Chapter 2

Research design

2.1 Aims, research objectives and specific questions

The study of NBS impacts for climate adaptation is a developing field with limited empirical and conceptual work performed. Most studies partly assess the impacts, costs, or benefits of NBS implementation, focusing individually on either of them. Indeed, an integrated methodological framework explaining how to assess NBS impacts is still missing (Price, 2021). Hence, keeping in mind the previous shortcomings, this research aims to contribute to filling the gap between the theoretical debate on climate change adaptation through ecosystem-based approaches (such as NBS) and real application in urban design tools and spatial policies. This gap is the purpose behind the definition of the research objective. Thus, the research objective is to assess to what extent NBS provide flood risk mitigation benefits in coastal urban areas. To achieve this objective, a biophysical-economic impact assessment has been developed to estimate how NBS contribute to damage mitigation in different scenarios (current and future climate) of pluvial flood risk.

The application of a spatial modelling approach to assess the flooded areas, in combination with value transfer method to value and assess the NBS cost (investment and maintenance) and benefits, allow for the integrated economic evaluation through a partial Cost-Benefit Analysis (CBA) to rank the economic viability of different scenarios. Benefit categories include the values of flood mitigation as avoided flooding costs due to the installation of NBS. This evaluation is scenario-based, meaning that different climate and NBS scenarios have been included. This challenge focuses on green roof and bioswale scenarios at the neighbourhood level.

Through the employment of environmental-economic analysis techniques, this research evaluates the NBS scenarios' performance by assessing the flood damages, as well as NBS benefits and costs, across coastal cities. The application of this research has been developed for the cities of Aveiro (Portugal) and Rapallo (Italy) in order to make a comparison between two contexts. This assessment aims at informing and building a decision support system to improve urban planning practices. This is achieved by providing measurable findings, which allow for a better understanding of how cities could adapt to climate change.

The main objectives described above can be explained by structuring them into research questions. **Table 1** shows the identified research questions for each specific objective.

Table 1. *Specific objectives and research questions of the thesis.*

	Specific objectives	*Research questions*
1	**To prioritize intervention areas by operationalising model maps to apply eco-system-based measures (e.g. NBS).**	• Why use mapping tools for the investigation of climate change-related risks that affect urban areas? • Which spatial models are better at evaluating the bio-physical performance of NBS in flood risk assessment? • Which site-specific NBS could be used to reduce plu-vial flood hazard?
2	**To integrate Climate Change issues into spatial planning analysis.**	• What is the level of integration of climate projections into spatial assessment, including different perspectives (e.g. short-, medium-, long-term) for adaptation? • Contemplating the urban adaptation complexity, how to address trade-offs in climate change planning? • How to visualize near- and long-term NBS impacts in a context of future uncertainties?
3	**To create evidence of NBS performance in monetary terms (benefits and costs).**	• Why use value transfer methods to assess NBS costs and benefits? • What are the flood mitigation benefits of implementing green roof and bioswale scenarios? • What are the costs of implementation and maintenance of green roof and bioswale scenarios?
4	**To define the economic vi-ability of NBS scenario implementation.**	• How to develop and integrate the environmental cost-benefits analysis? • Why should urban planning integrate nature-based ad-aptation solutions into ordinary planning? • What is the economic viability of implementing NBS?

2.2 Characteristics of the research and thesis outline

This research intends to contribute understanding regarding how to integrate climate change issues and ecological aspects for an effective urban planning. To do that, this PhD thesis passes from a critical-reflexive approach on theoretical knowledge around climate change adaptation to a methodological framework that integrates spatially explicit modelling (InVEST), economic impact evaluation (value transfer; partial cost-benefit analysis), and mapping tools (GIS) to synthesise pluvial hazards, climate scenarios, demographics, economic losses, and ecological data.

More in detail, the theoretical and reflexive part is represented by a literature review on how NBS biophysical performance and economic impact evaluations are developed and integrated into urban planning adaptation. By systematically reviewing the biophysical and economic assessments of such measures to address flood extremes in coastal cities, this first part discusses the role of NBS in climate change adaptation planning. This first analysis is fundamental to have an in-depth analysis of the emerging literature on climate change and coastal cities to inform the development of the research design. A deep investigation of the scientific background is necessary for positioning this work and scientific contribution, as well as for the application of a methodology to improve the effective implementation of NBS into climate change adaptation frameworks. For these reasons, the theoretical insights will cover different types of literature references, to provide a literature overview, as comprehensive as possible, with regard to the key drivers of several European urban climate adaptation planning and policies, among which are the IPCC Assessment Reports, the EU Adaptation Strategy, the EU 2020 Biodiversity Strategy, the EU Mapping and Assessment of Ecosystems and their Services (MAES) reports.

The second part of the research is comprising two sections: first, a flood risk assessment was conducted to assess the biophysical performance of NBS: next value transfer methods were used to assess NBS costs and flood mitigation benefits to, finally, conduct a cost-benefit analysis (CBA).

The operational part of this research is represented by the application of the methodology to two case studies. The knowledge of biophysical and economic performance values in terms of flood risk mitigation services related to NBS implementation is useful to operationalise ecosystem-based planning. By spatially quantifying the potential flood mitigation impacts and benefits of NBS, one could encourage a greater integration of NBS into traditional urban planning. Indeed, this section is crucial to understand how to define the viability of NBS scenarios. The utilisation of mapping tools through modelling approaches, and GIS operations and visualisation methods, contribute to the design of performance-based solutions. This practical application in two cities, from two different countries, will prove how, by re-adjusting the proposed framework to fit other cases, this method can be replicated.

The remainder of this PhD dissertation consists of 6 sections (Part I-II-III-IV-V-VI) subdivided into 15 chapters.

Part I deals with the scientific background of the thesis. Particularly, *Chapter 1* presents an introduction to the research topic, the background and motivations, as well as key gaps found in literature. *Chapter 2* introduces the main objectives and related research questions, including characteristics and thesis outline.

Part II focuses on the state of the art. *Chapter 3* introduces the rapid systematic literature review, firstly, by explaining the search methodology, and secondly, by providing a descriptive analysis of results. Then, the discussion around the focus thematic areas is presented, and conclusive remarks are offered. The information collected from the literature review, together with other references, is organized to develop *Chapter 4,* which gives an overview of the Climate Change Adaptation issue in European cities focusing on pluvial-related flood impacts. It also highlights the role of ecosystems and NBS in the attempt to achieve climate resilience.

Part III shows the applied methodology behind this research. *Chapter 5* introduces the theoretical framework to integrate both the biophysical-economic and the impact assessment of NBS. Then, the expected results, the contribution, and target subjects of this research have been presented. *Chapter 6* concerns the urban flood impact assessment method, essentially composed of two steps: a biophysical assessment through spatial modelling evaluation, followed by an economic assessment. This second part of the methodology includes the theoretics of Cost-Benefit analysis (CBA), the Benefit Transfer method, and the flood damage estimation.

Part IV constitutes the application of the proposed approach to the real case studies, thus representing the operative part of the thesis. *Chapter 7* introduces the study areas considered in this research: the city of Aveiro (Portugal), and the city of Rapallo (Italy). *Chapter 8* illustrates the InVEST model selected for this research by explaining the model's characteristics and data employed. *Chapter 9* contains the description of the NBS scenarios design. *Chapter 10* provides the description of the practical steps for the NBS costs and benefits calculation, plus the useful data for the analysis.

Part V is dedicated to the organization and presentation of results using a GIS environment. *Chapter 11* presents the outputs derived from the simulations without adaptation measures, which are needed to define the prioritization areas of intervention. *Chapter 12* and *Chapter 13* provide the results of the simulated green roofs and bioswales scenarios for the two study cases, respectively, both in biophysical and economic terms (discounting equal to zero). Both *Chapter 12* and *Chapter 13* provide a sensitivity analysis by considering discount rates set at 2% and 4 %.

Part VI deals with the discussion and conclusions. *Chapter 14* is a synthesis, which summarises the main findings of the chapters by firstly discussing this research in comparison with previous studies, and also by concluding with a comparison between the two study cases. This section presents a reflection on the strengths and weaknesses of this simulated approach in the urban adaptation framework by briefly discussing its policy implications. Finally, *Chapter 15* presents conclusive remarks and future perspectives beyond this work.

PART II – State of the Art

Chapter 3

Systematic literature review

This chapter is adapted from (Quagliolo *et al.*, 2022).

3.1 Introduction

Climate and flood risk adaptation should be flexible and multifunctional because of the uncertainty of climate impacts, especially considering local spatial variability within the urban environment instead of differing only in geographical locations (Voskamp *et al.*, 2021). Consequently, urban design principles should be driven by ecological ideas of non-linearity and heterogeneity (Wu and Wu, 2013). The European Commission (EC) is addressing these challenges by emphasizing the potential of Nature-Based Solutions (NBS) as an urban climate change adaptation strategy, being multifunctional, as well as providing connectivity and multiple co-benefits (Dushkova and Haase, 2020; Hobbie and Grimm, 2020). To be effective, NBS require trans-sectoral and integrated planning into urban climate change adaptation for their mainstreaming at the local level. Despite the potential of NBS being increasingly recognized, comprehensive knowledge, especially to what concerns the availability of consistent data about their benefits, is still missing (Alves *et al.*, 2020). In this perspective, specific assessments of NBS biophysical and economic performance could give a significant contribution to overcoming certain barriers that are limiting a wider implementation of NBS in cities. Such analyses can aid the urban planning practice by adopting site-specific, performance-based solutions that are suitable for future urban strategies even in the face of climate change. Such approaches help selecting, simulating and evaluating NBS applications, thus assessing related costs and benefits of flood adaptation (Alves *et al.*, 2020; Quagliolo, Comino and Pezzoli, 2021b).

One of the major challenges faced by NBS research is closing the gap between the solutions' performance, impact evaluation, and integration into urban planning. Different types of NBS for flood risk mitigation ranging from the building scale, such as green roofs and facades, to the street and park scale, such as rain gardens and permeable paving, exist in literature. Given their ability in retrofitting existing structures, the NBS effectiveness to reduce flood risk in terms of peak flow, runoff, flood volume and flooded areas has been addressed by a range of prior studies (Lee, Hyun and Choi, 2013; Mei *et al.*, 2018; Bae and Lee, 2020; Costa *et al.*, 2021; Salata *et al.*, 2021). To the author's knowledge, however, more quantitative results by integrating biophysical and economic co-benefits regarding the impacts of NBS implementation are needed (Davis, Krüger and Hinzmann, 2015; Pagano *et al.*, 2019; Alves *et al.*, 2020).

3.2 Literature gap

Through the literature review, it has been possible to infer that, so far, a large number of studies assess either the biophysical or economic (cost and co-benefits) impacts of NBS-scenario implementation. Moreover, most studies do not mention specific practices and methodologies, rather, they often cite general ecosystem-based adaptation. Research on compound flood vulnerabilities in coastal cities through spatially-explicit analysis integrated with climate change and ecosystem-based adaptation scenarios requires even more effort. More recently, methodological frameworks and modelling tools have been developed to quantify ES for integration in decision-making processes (Francesconi *et al.*, 2016). However, Ecosystem Services and Climate Change variables integrated into the real process of urban planning adaptation is still lacking. Additionally, a large part of research on nature-based adaptation to flood vulnerability concerns engineering aspects focused on hydraulic modelling and on the adaptation solutions' specificity. Therefore, the aim of this Chapter is to analyze how NBS biophysical performance and economic impact evaluations are developed and integrated into urban planning adaptation in coastal urban areas. Particularly, this Chapter aims to compile the existing knowledge on this issue, and further identify the ways in which these analyses could be used to provide science-based evidence for policy making in the framework of Urban Climate Change Adaptation.

By systematically reviewing the biophysical and economic assessment methods used to measure NBS potential for flood mitigation, this review discusses the role and integration of such measures in climate change adaptation planning. A rapid literature review was carried out systematically, consistently examining recent literature in a thorough, unbiased manner (Grant and Booth, 2009; Baumeister, Bertone and Burton, 2021). Conducting rapid reviews, as opposed to full systematic ones, allows one to perform a literature review in a shorter time and under financial limitations while maintaining a robust methodology (Ganann, Ciliska and Thomas, 2010; Leite and Pita, 2016).

3.3 Research Methodology

Through the literature review, it has been possible to infer that, so far, a large number of studies assess either the biophysical or economic (cost and co-benefits) impacts of NBS-scenario implementation. Moreover, most studies do not mention specific practices and methodologies, rather, they often cite general ecosystem-based adaptation. Research on compound flood vulnerabilities in coastal cities through spatially-explicit analysis integrated with climate change and ecosystem-

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3.3.1 Search strategy

The flowchart of the systematic literature review is shown in **Figure 2**. A sensitive systematic search phase was carried out using the online scholarly database Scopus (www.scopus.com), which is commonly used for this purpose by researchers (Thompson, Garfin and Silver, 2017; Sadiq, Tyler and Noonan, 2019). Since the need is to conduct a careful search analysis, meaning that inclusion criteria were initially defined, Google Scholar database has been excluded because it does not adapt to our research.

The inclusion criteria for the search strategy were: 1) studies must be written in the English language; 2) studies must have been published up to, or during, December 2020. The literature search was finalized in July 2021. This literature review does not represent an exhaustive inventory. In this case, the rapid systematic review has been limited to two electronic search databases. Firstly, the search was carried out using the online database Scopus (www.scopus.com; accessed on 16 March 2020) through the combination of different search parameters. The search strategy includes a complex string of terms and their synonyms, which the search engine uses to identify articles containing the relevant key terms in the title, abstract or keywords:

(flood) AND (urban* OR city OR cities) AND ("nature-based solution*" OR "nature based solution*" OR "NBS") AND (planning OR adaptation)*

It should be noted that the asterisk symbol ‘*’ is used to refer to a number of different variations of the term in question. As an example, a search using the term “flood*” would return matches including the terms “flood”, “flooding”, “flooded”, among others.

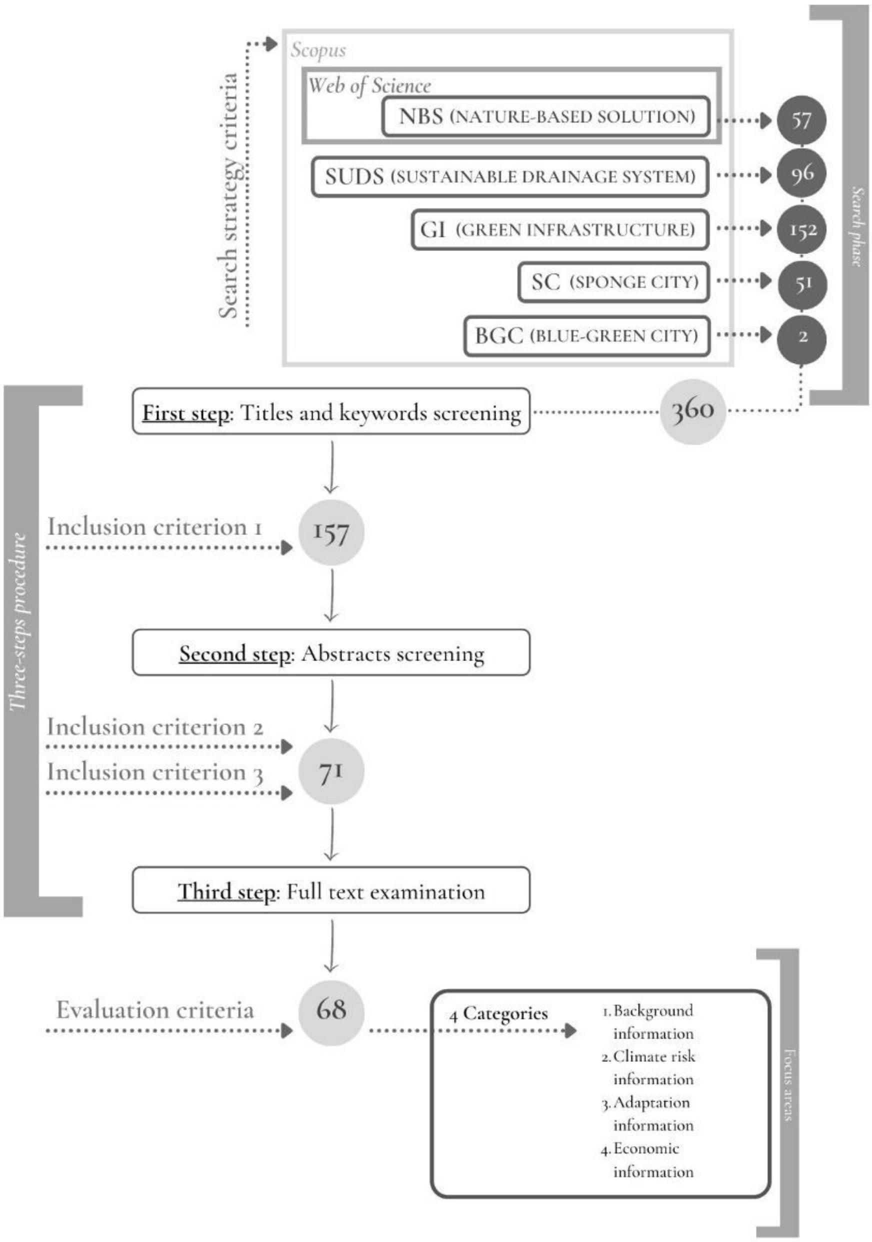

Figure 2. *Systematic literature review flowchart.*

The review question was intentionally left broad, aiming at identifying all studies assessing nature-based adaptation to reduce flood-related risk while describing the policy implications into urban planning.

Given the main focus on exploring NBS, which is a relatively recent term, an additional search was conducted using the scientific database Web of Science

(WoS; www.webofknowledge.com;accessed on 16 March 2020) (Eggermont *et al.*, 2015; Mendes *et al.*, 2020). The Scopus search returned 45 articles, while the WoS search yielded a total of 57 articles. Indeed, using two literature databases allowed for the inclusion of a wide range of literature, with the total number of resulting articles being after excluding the repeated papers.

To conduct a comprehensive review of nature-based adaptation to mitigate urban flood issues, additional terminologies meeting the conceptual definition of NBS have been considered. Indeed, urban stormwater management has become even more complex and, consequently, the terminology describing the practices of urban drainage is increasingly diverse (Fletcher *et al.*, 2015). Different terminologies originate and evolve locally in their own institutional context, including: Low Impact Development (LID), Best Management Practices (BMPs), Sustainable Drainage Systems (SuDs), Water Sensitive Urban Design (WSUD), Blue-Green Cities (BGC), Sponge City (SC), Green Infrastructure (GI) (Fletcher *et al.*, 2015; Huang *et al.*, 2020). A significant overlap among various terms exists resumed in two broad principles: 1) mitigation of urban flood risk by adopting natural features to restore and maintain the natural hydrological processes of a city; 2) improvement of water quality. **Figure 3** depicts the relationship between NBS, LID, BMPs, SuDs, WSUD, BGC, SP, and GI by considering the focus and the specificity of each type of measures. Therefore, four additional terms overlapping with the broad principles of NBS were selected for this search step: Sustainable urban drainage system (SuDS), Green infrastructure (GI), Sponge city (SC) and Blue-Green city (BGC). The additional searches on Scopus have been conducted using the following key terms:

SUDS: *(flood*) AND (urban* OR city OR cities) AND ("Sustainable Urban Drainage Systems" OR "Sustainable drainage system*" OR "SuDS") AND (planning OR adaptation)*

GI: *(flood*) AND (urban* OR city OR cities) AND ("Green infrastructure*") AND (planning OR adaptation)*

SC: *(flood*) AND (urban* OR city OR cities) AND ("Sponge cit*") AND (planning OR adaptation)*

BGC: *(flood*) AND (urban* OR city OR cities) AND ("Blue green cit*" OR "Blue-green cit*") AND (planning OR adaptation)*

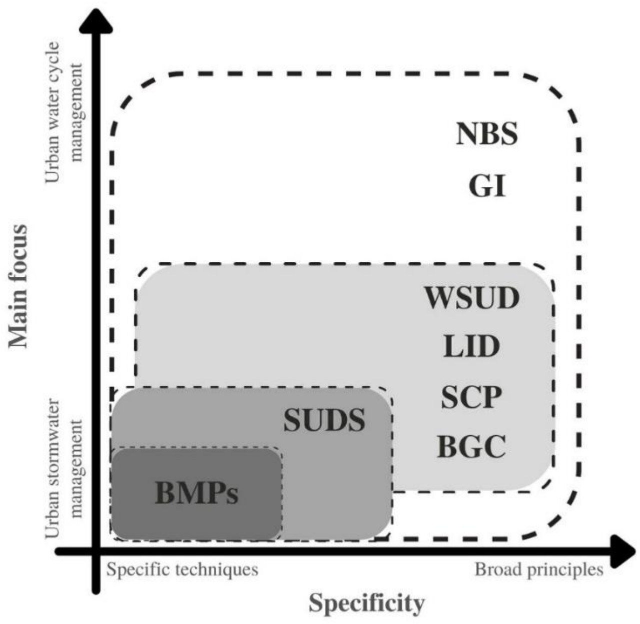

Figure 3. *Ecosystem-based adaptation classification terminology according to their specificity and main focus of application (elaborated from Fletcher et al. (2015) and Qi et al. (2020).*

After the exclusion of repeated papers, the total number of publications is 57 for NBS, 96 for SUDS, 152 for GI, 51 for SC, and 2 for BGC.

3.3.2 Inclusion criteria

To identify potentially relevant studies for this review, a three-step procedure, illustrated in **Figure 2**, has been adopted. After the exclusion of duplicates, 360 publications remained.

The first step consisted of title and keywords screening. Specifically, studies focused on the following aspects (criterion 1 - **Figure 2**) were excluded from further analysis because they were out of scope:

- Governance and institutional aspects;
- Hydrological and engineering aspects;
- Hazards other than urban and coastal flooding;
- Inland cities or rural areas.

This screening resulted in 157 studies for inclusion in the second step of the review process. Abstracts were scanned using indicator analysis. Four indicator groups with a set of related keywords were selected in order to have an overview of this review topic (**Table 2**). The second screening limited the publications to peer-reviewed articles and book chapters (criterion 2 - **Figure 2**) and studies that contained at least one economic-related keyword in the abstract (criterion 3 - **Figure 2**).

Table 2. Group of indicators and related keywords.

Indicator	Keywords
Generic nature-based adaptation	BGC
	GI
	NBS
	SC
	SUDS
Nature-based categories	Bioswale
	Green Park
	Green roof
	Infiltration basin
	Permeable paving
	Pond
	Wetland
Climate-related hazard	Pluvial – precipitation – rain
	Runoff
	Sea-level – Surge
	Storm
Economic aspects	Benefit
	Cost
	Damage
	Economic

The nature-based category group is based on the most frequent ecosystem-based adaptation measures to address urban flood issues in accordance with a review of 125 NBS application in Europe, summarized in **Table 3** (McVittie *et al.*, 2018).

Table 3. *Water sensitive urban design measures (adapted from McVittie et al. (2018); UNaLab (2019); European Environmental Agency (EEA) (2021)).*

Category	Broad measure	Specific measure
Urban	Green Infrastructure	Bioswale
		Green roof
		Rain garden
		Urban green park
	Blue infrastructure	Basin
		Detention pond
		Infiltration basin
		Permeable paving system
		Retention pond
		SUDS
		Constructed Wetland

Finally, after this step, 71 studies fulfilling all the inclusion criteria remained, and full-text documents were downloaded to conduct the in-depth evaluation. The final number of publications included for the third step of the procedure is 68, because of the exclusion of studies that could not be accessed. Refer to **Appendix A** (**Table 59**) for the full list of selected studies.

A set of defined evaluation criteria was systematically applied to each study in the final stage. These criteria addressed geographical information, methodological and other research-related issues, adaptation planning processes, climate change perspectives, and economic evaluation methods.

3.3.3 Review focus areas

To ensure consistency across all selected studies, the publications were analysed using a standardized data extraction sheet (Excel) inspired by previous review articles (Hanson, Wickenberg and Alkan, 2020; Voskamp *et al.*, 2021). The use of predefined evaluation criteria has been refined in an iterative process by considering four sections (**Table 4**): 1) background information, 2) climate risk information, 3) economic information, and 4) adaptation information. For each publication, the whole content was considered in the review.

The first part of the database is aimed at framing the studies in temporal and spatial terms. Information considered relevant to grasp the background of this analysis of the study type, as well as the data used and provided by the peer-reviewed publications, have been included. The information on the applied methodology is useful to identify if and how the researchers performed NBS impacts assessment. The collected information on the data used serves to provide knowledge of the ways in which the analysis has been conducted. Therefore, based on the information provided, the studies were classified as qualitative, quantitative, mixed (both qualitative and quantitative), or spatial analysis.

The second part of the database includes three focus areas to be addressed by this review. The first focus area concerns the climate risk category, and aims to understand the level of integration in the literature in relation to the topic of compound flood hazards in coastal cities. Within this area, data on the climate change perspective have been extracted to identify how this issue has been addressed by the researchers. This information was classified as 'background', when the topic of climate change was mentioned only as context, 'analytical', when climate change data were used in the analysis, and 'scenarios', when climate change projections were included in the assessment. The second focus area concerns the economic category, which explores how economic evaluation related to NBS implementation has been addressed in the literature. This aspect includes the type of economic assessments, the currency and unit used by the authors. Finally, the third focus is related to the climate adaptation challenge, namely, by comprehending how NBS implementation is integrated into urban planning in practice. This category aims to identify the kind of biophysical assessment employed in the studies through the collection of information related to the specific natural solutions implemented. This process is used to classify different NBS according to how frequently they are assessed, as well as to their biophysical flood-mitigation performance.

Table 4. *Evaluation criteria used for the in-depth analysis.*

Category	Description	Indicator
Background information		
Temporal scale	Time of analysis	Reference year(s), NA
Spatial scale	Scale of analysis	Global, national, regional, local/city, district, neighborhood
Geographical area	Setting of conducted analysis	Country – Region – City, NA
Study type	Type of methodology used	Conceptual/empirical framework, spatial assessment, modelling
Data used	Type of information and data employed for the analysis	(Short explanation)
Data provided	Type of data provided by the study	Qualitative, quantitative, spatial, and mixed data (quantitative and qualitative)
Climate risk information		
Climate hazard	Climate and natural hazards addressed by the studies	Single, compound, and multiple hazards
Climate Change perspective	How climate change issue has been addressed by the studies	Background, analytical, scenarios, NA
Economic information		
Economic assessment	Type of approach employed in the analysis	Cost-benefit analysis, Life-cycle cost analysis (LCCA), flood depth damage analysis, unit cost value analysis, cost effectiveness analysis, NA
Currency	Currency used for the analysis	
Unit	Unit used for the analysis	
Adaptation information		
Adaptation planning perspective	How adaptation through NBS implementation is integrated into urban planning	(Short explanation)
NBS type	Specific NBS to reduce flood-related effects	(Most common measures to flood reduction)
NBS approach	Kind of information provided on NBS	Qualitative, quantitative, NA
Biophysical assessment	Numeric value of biophysical flood reduction	Flood depth values

3.4 Descriptive analysis of results

Data extraction from the three-step procedure covered both quantitative and some qualitative aspects. Sections 3.3.1 and 3.3.2 discuss the results of the first and second review steps as a comparative, quantitative analysis. This descriptive analysis was carried out with the help of graphs and figures.

3.4.1 Statistical Overview of the first review-step

Given the relatively large number of publications when combining the searches with different terms, a first general overview as a statistical descriptive analysis has been conducted. This summary starts by showing the evolution over time of publications on ecosystem-based adaptation concepts related to flood issues that resulted from the first review step (N=360). The bars show the number of publications per year and the dotted line represents the cumulative values of the studies until 2020. The number of studies published on that topic have been rapidly increasing over the last couple of decades (**Figure 4**) – especially as of 2016. About 90% of publications are from the period 2013 to 2020. From 2016 onwards, the number of studies started to increase exponentially.

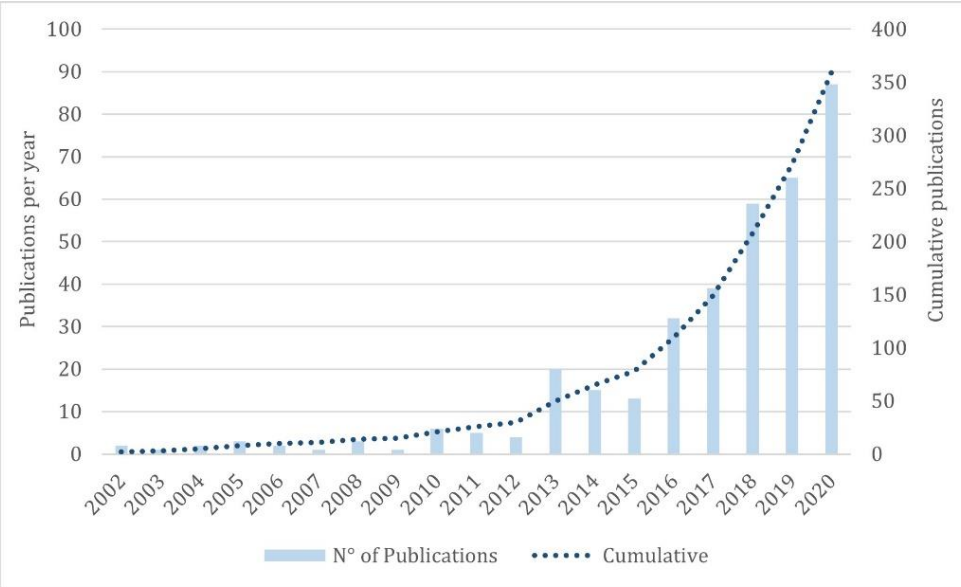

Figure 4. *Publications per year with cumulative studies over time (N = 360).*

Looking at the distribution of publications over time by nature-based adaptation terminologies (see **Figure 5**), SuDS is the first term used in literature, appearing as early as 2002. The first two publications in this year concern more qualitative descriptions of SuDS and, particularly, the application of permeable pavements. NBS and SC are more recent concepts, appearing for the first time in 2015 and 2016, respectively. Publications on GI resulted in the largest number of studies, with a significant rise from 2012 to 2020. The publications are from 138 journals and 71 conference proceedings. Most of the studies (65%) are from three journals: ‘Water’ (24%) which started to publish on this topic in 2014; ‘Sustainability’ (21%), and ‘Science of the Total Environment’ (20%), both of which show their first publications in 2016.

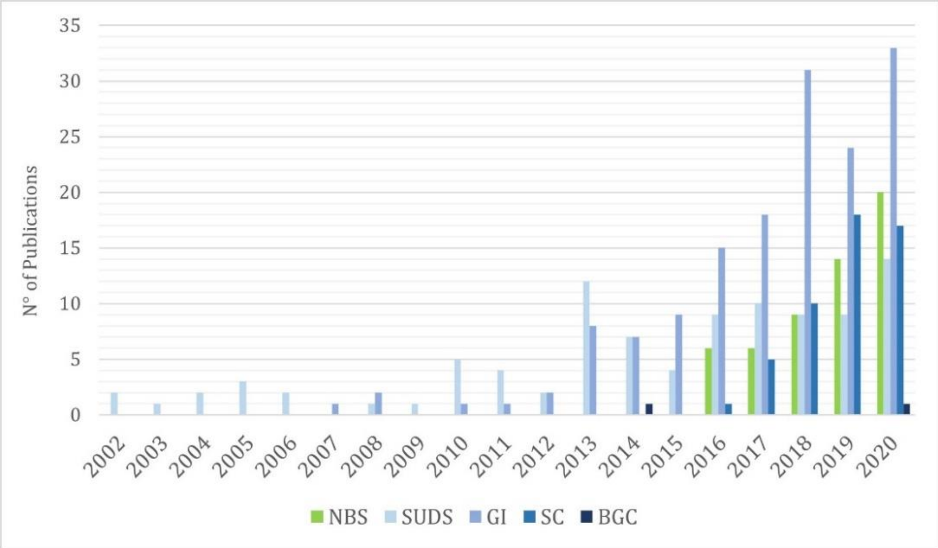

Figure 5. *Number of studies over time per generic nature-based adaptation (N=360).*

Figure 6 shows the distribution of the studies by year for each kind of nature-based measure adopted. Green roofs, ponds and wetlands are the most studied solutions, having had a particularly significant with a rise in number of publications in 2015.

The biggest part of the research conducted on this topic has been published in the form of research articles (68%) while review articles represent only 7% of the total (**Figure 7**). Moreover, environmental science and social science are the most common subject areas, with 44% and 17%, respectively, of the listed total of 360 publications (**Figure 8**).

The last two years of the temporal range of this review (2019 and 2020) were the most prolific in what concerns peer-reviewed articles. The most frequently occurring journals during this period were Sustainability, Water and Science of the Total Environment, each having published between 6 and 7 articles per year (**Figure 9**).

Figure 10 shows the geographical distribution of the 360 publications by considering the first affiliation country. Most of the studies (20%) were conducted in the United Kingdom, in the United States (18%) and in China (16.6%).

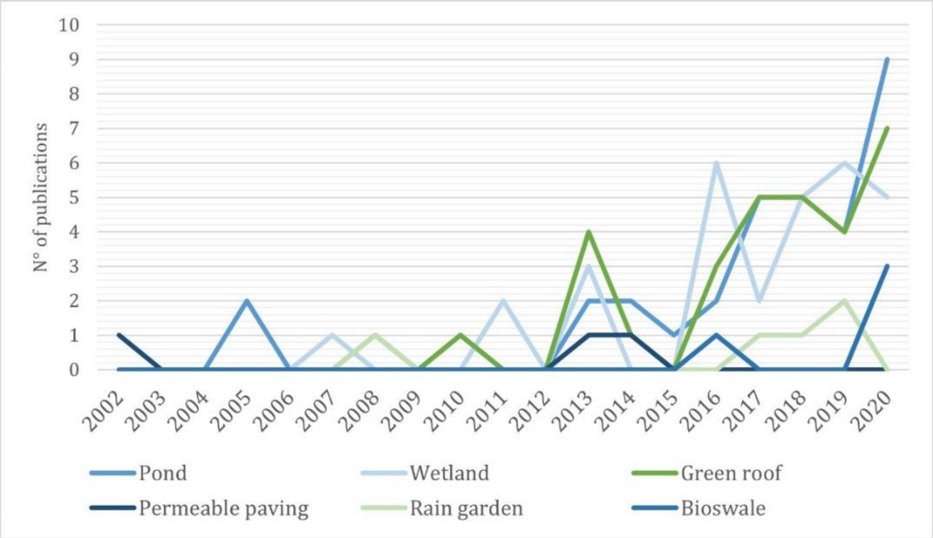

Figure 6. *Number of studies per each kind of nature-based measure by year (N = 360)*

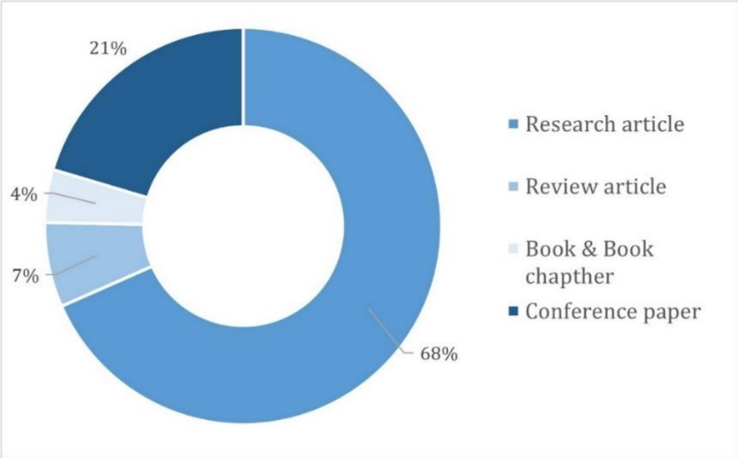

Figure 7. *Number of studies by type (N = 360).*

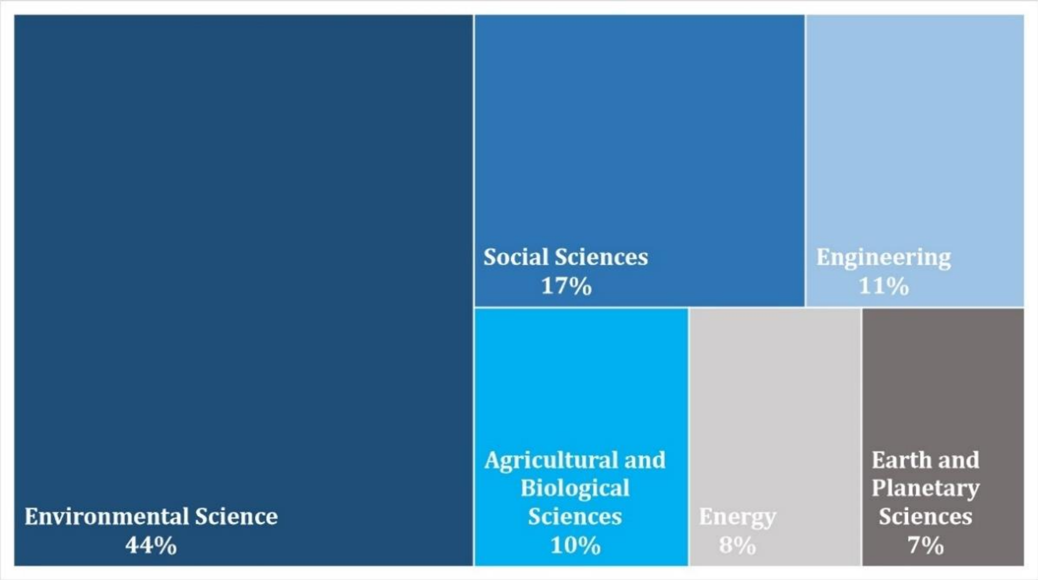

Figure 8. *Number of studies by subject area (N = 360).*

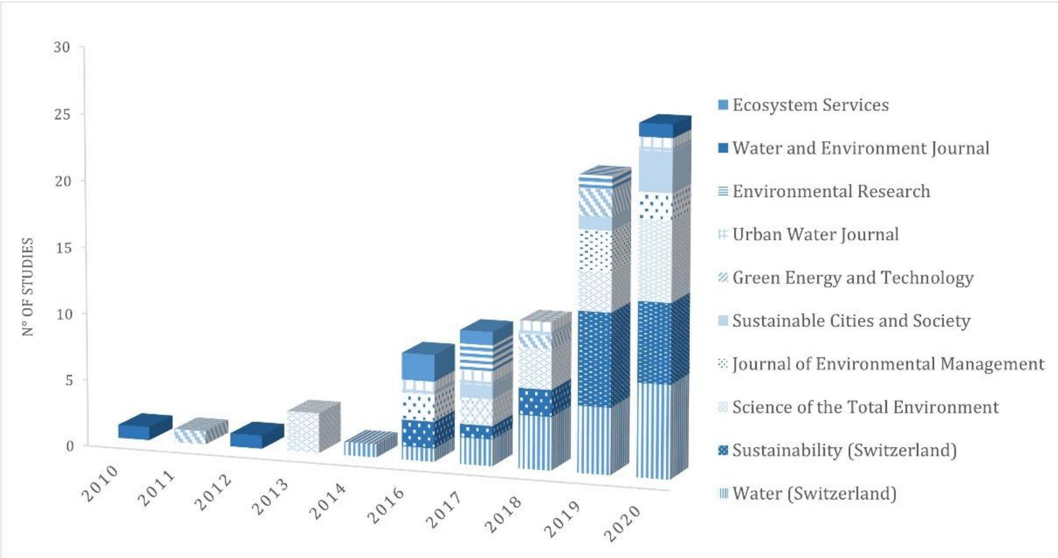

Figure 9. *Most frequent source by year (N = 360).*

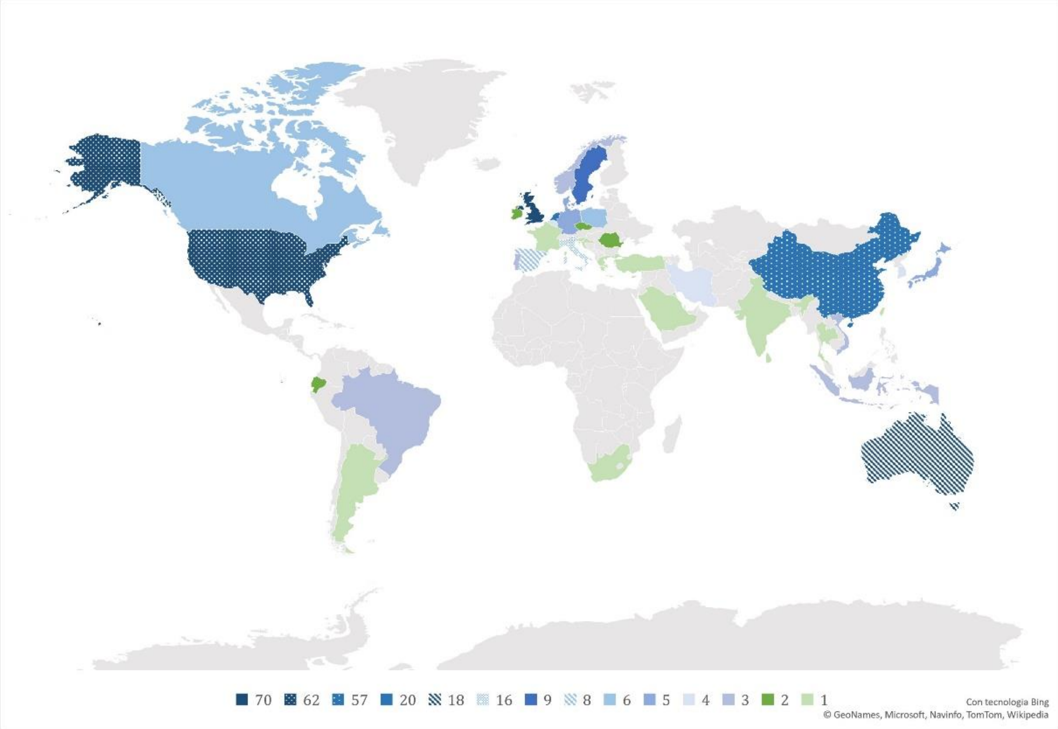

Figure 10. *Studies by first affiliation country (N = 360).*

3.4.2 Statistical overview of the second review-step

This section represents a quantitative analysis of data from the second review step. The second round, based on the abstracts screening, analyses the frequency of appearance of keyword categories in each document. For this quantitative analysis, radar charts and bar plots serve to visualise single-category or pair-category variables. Radar charts compare the aggregate values of data, represented by the covered area in the graphic. Bar charts illustrate comparisons among different individual items (vertically or horizontally oriented).

The second review step highlighted that the GI concept has been extensively applied to urban flood adaptation in peer-reviewed studies, especially when compared to the other generic nature-based adaptation approaches (see **Figure 11**). The NBS concept rapidly gains interest over time. Most of the studies that address this topic are research articles (64%), followed by the review articles (29%), which are more frequent in this category than they are among studies of all the other generic nature-based concepts. However, the use of specific kinds of measures is not yet widely studied. By looking at **Figure 12**, where the main typologies for urban drainage measures has been considered (see **Table 3**), "Pond" is the most popular solution (16 studies) followed by "Wetland" (15 studies) and "Green roof" (13 studies), even if relatively few studies examine the application of such measures.

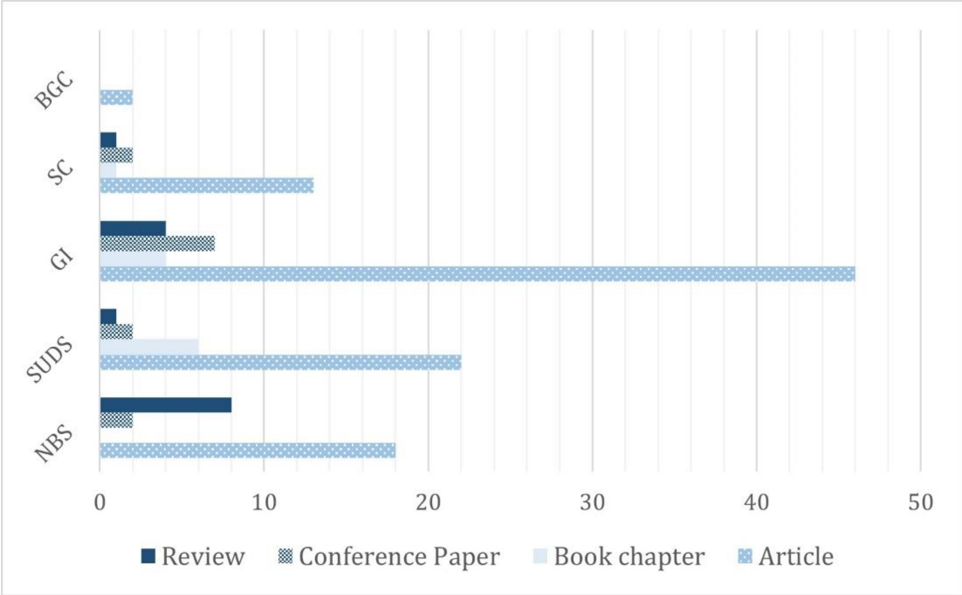

Figure 11. *Frequency of nature-based adaptation category by type of study (N = 157).*

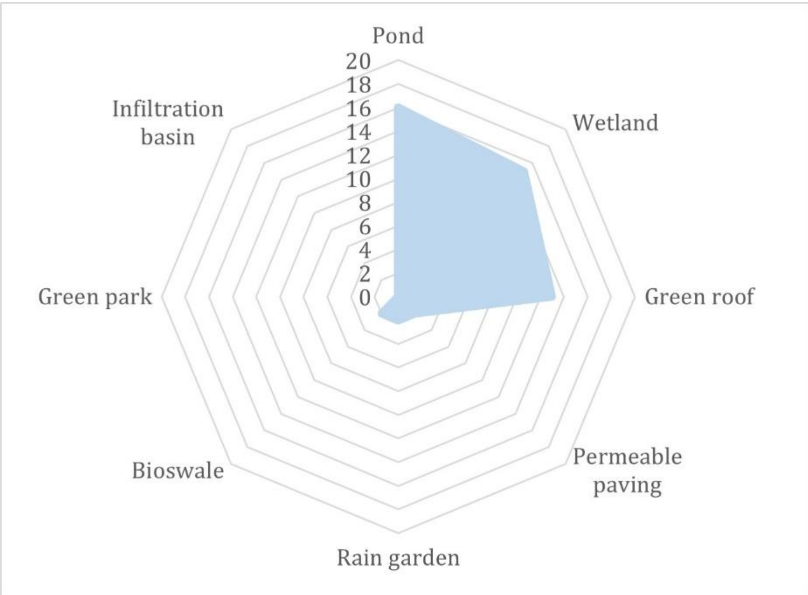

Figure 12. *NBS types by frequency of study (N = 157).*

Despite many of the case cities being located on the coast, hazards specific to such locations were scarcely studied. Most studies address pluvial flood risk as a hazard, while only 3% analyse "sea-level rise" or "storm-surge" hazards (only 7 studies) (**Figure 13**).

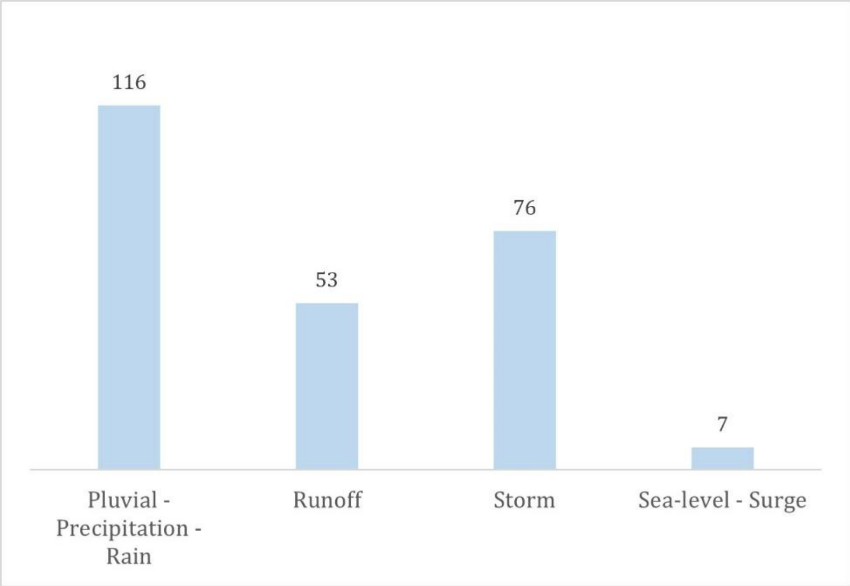

Figure 13. *Climate-related hazards by frequency of study (N = 157).*

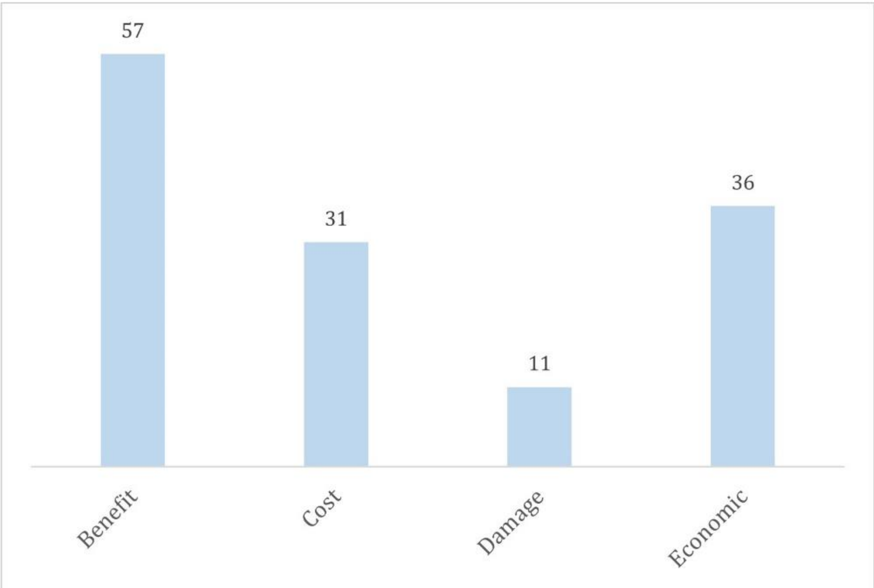

Figure 14. *Economic aspects by frequency of study (N = 157).*

With respect to economic evaluation of nature-based approaches, a large portion of studies mentioned the term "benefit" (almost 40%) while the term "damage" received the least attention (only 11 studies) (**Figure 14**). Most studies which mentioned at least one of the economic aspects' terms frame their research in the context of GI adaptation with 43% of frequency (**Figure 15**). This picture suggests deepening attention on costs/benefits assessment related to NBS implementation.

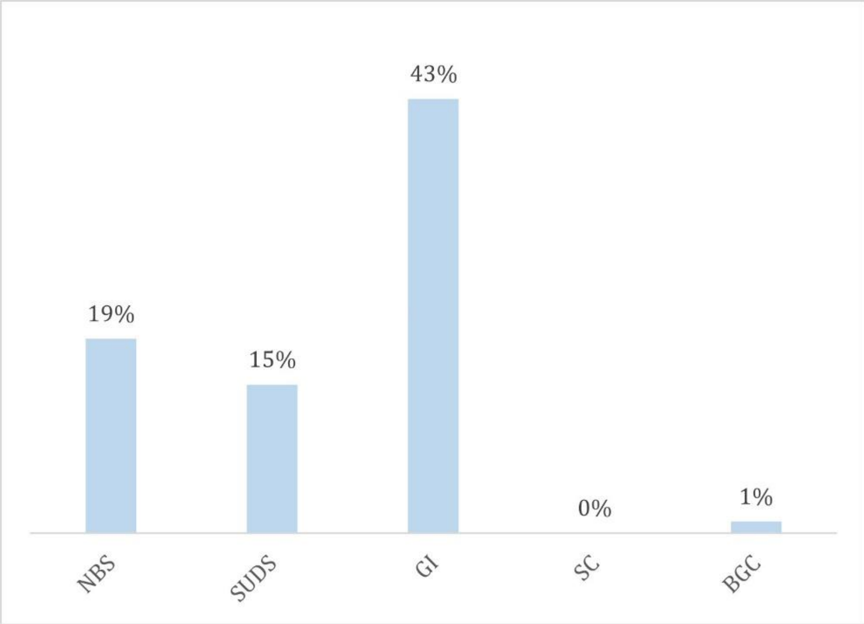

Figure 15. *Generic nature-based adaptation category by frequency of study that cited economic aspects (N = 157).*

3.5 Third review-step: focus areas analysis

This section shows an in-depth analysis of the results in relation to the focus areas by presenting, firstly, a background that frames the NBS studies. The following sections represent an in-depth evaluation about three emergent themes this review analysis deals with: climate risk, economic, and planning perspectives.

3.5.1 Background: Framing the application of NBS

From a geographical perspective, about 8% of publications perform assessments with a global scope. Only one publication concerning a conceptual framework is independent of geographical context. The remaining studies, that are all reviews, employ data from different geographic areas. Most publications have applied case studies, as shown in **Figure 16**. The map illustrates the distribution of the NBS applications by showing the number of cases in relation to the spatial scale for each Continent. The local level includes different scales of analysis, such as city level, neighbourhood level, district level and catchment level. Around 40% of case studies cover European contexts, of which only 3 applications are at the national level, while 22 are at the local level. Among the applications at local level in Europe, only 7 cases are at the city level. In what concerns NBS applications in Asian and American countries, the percentage of coverage is almost the same (26% and 25%, respectively); additionally, coverages of only 6% and 3%, respectively, are observed for Oceanian and African countries. In relation to applications at the local scale in American countries, only five cases focus strictly on flooding-related issues, while the majority address multiple hazards. There are even less for Asian countries, specifically China, where only three case studies work on a single hazard (flood).

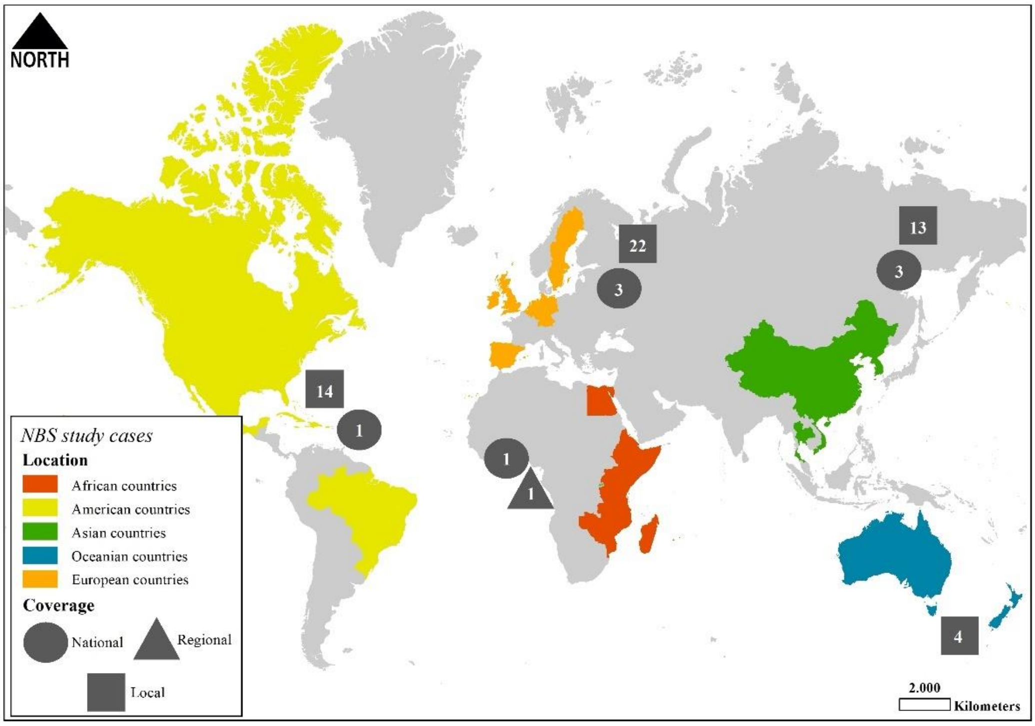

Figure 16. *Geographical distribution and scale of the NBS case studies identified in the rapid systematic review.*

For the study types, most of the publications (44%) cover two different kinds of methodologies: review (15) and spatial assessment (15) **Figure 17**. Among the review studies, 53% provide qualitative data and can be divided in two sub-groups. The first group gives information based on surveys (O'Donnell, Lamond and Thorne, 2017; Xie *et al.*, 2019), while the second group builds on current evidence of NBS applications for flooding challenges (Faivre *et al.*, 2018; Morris *et al.*, 2018; Rubinato *et al.*, 2019; Hobbie and Grimm, 2020). Around 27% of reviews provide both qualitative and quantitative data (mixed data) (O'Sullivan *et al.*, 2012; Saleh and Weinstein, 2016; Butt *et al.*, 2018) and only 7% of reviews present quantitative information about the unit cost estimates for flood adaptation (Aerts, 2018), while 14% don't give details (NA). The spatial assessment studies are either quantitative (27%), quantitative & spatial (47%), mixed (13%) or mixed & spatial (13%).

A large portion of publications (40%) covers two other study types, namely conceptual/discussion (14) and modelling (13) studies (**Figure 17**). Most of the data and information provided by conceptual/discussion typology are qualitative (64%). One paper presents a comparative analysis between SUDS and SCP in the UK and China, respectively, to identify the barriers and enablers for the adoption of GI through 12 in-depth semi structured interviews with stakeholders (L. Li *et al.*, 2020).

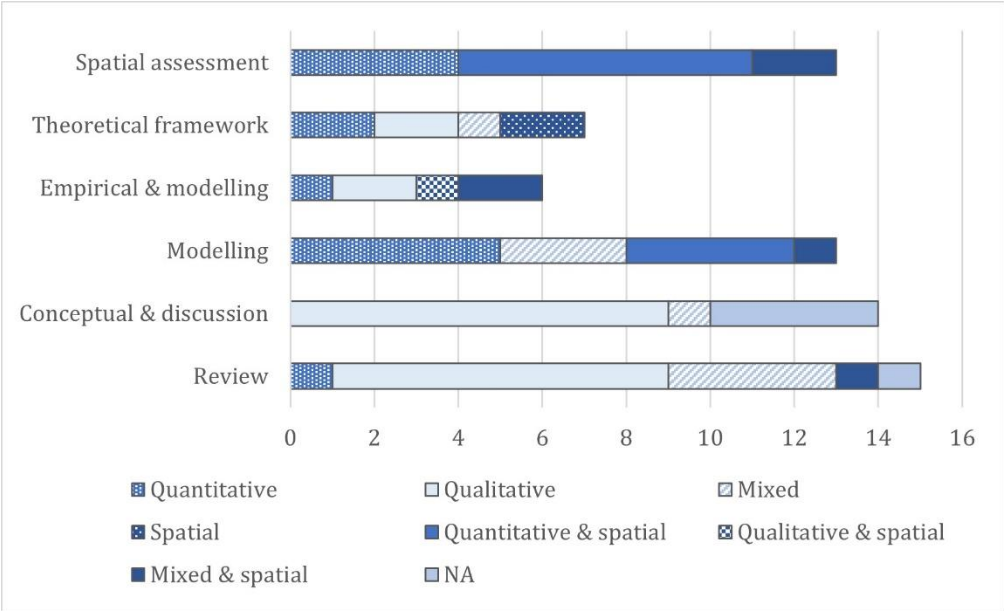

Figure 17. *Kind of data provided by each study across different study type*.

Figure 18. *Kind of data provided by each study across different study type*.

Four publications describe case studies to test conceptual frameworks or demonstrate how project research collaborations addressed many biophysical and socio-political barriers on the NBS applications (Everard and McInnes, 2013; Lawson *et al.*, 2014; Connop *et al.*, 2016; O'Donnell *et al.*, 2020). Data from modelling studies are mostly quantitative (38%), quantitative & spatial (30%) and, a few mixed (23%) and mixed & spatial (8%). Most modelling studies apply hydraulic models by estimating the NBS impacts without developing any economic assessment (Rozos, Makropoulos and Maksimović, 2013; Ramírez, Qi and Xiaobo, 2016; Boelee *et al.*, 2017; Fenner *et al.*, 2019). Porse (2014) uses risk-based modelling to assess cost-effective (costs/benefits analysis) urban floodplain development decisions by providing quali/quantitative data (Porse, 2014). Schubert et al. (2017) apply stormwater flow and quality modelling to assess the GI impacts by assuming fixed construction costs which ignore the potential savings resulting from the benefits by the measures' implementation (Schubert *et al.*, 2017). Alves et al. (2019) develop a monetary analysis of different co-benefits related to the implementation of green-blue-grey infrastructure. This study provides spatial data from the 2D hydrodynamic models to assess the expected annual damage (EAD) for buildings to finally have quantitative data derived from the cost-benefits analysis of flood risk mitigation measures by comparing the expected annual benefits and costs converted to the net present value (Alves *et al.*, 2019).

Few papers (9%) develop empirical studies. Of the remaining five theoretical framework papers (7%), different subjects have been covered. One study tests a conceptual model to assess the groundwater table variation by providing both qualitative and quantitative data on groundwater infiltration and storage capacity

(Lancia *et al.*, 2020). Two studies provide qualitative data through the application of the analytical framework that conceptualizes Ecosystem-based adaptation in urban environments and, the employment of a HAMIED framework (Hydrological Assessment and Management of green Infrastructure to Enhance Decision-making) to systematically identify and manage the aspects that stakeholders would like to be assessed using specific models within the SuDS system (Brink *et al.*, 2016; El Hattab *et al.*, 2020). The other two studies provide quantitative data. One focuses on a new formula of resilience based on three parts of system severity: social severity affected by urban flooding, environmental severity caused by sewer overflow, and technological severity considering the safe operation of downstream facilities (Dong, Guo and Zeng, 2017). The other article presents an evaluation framework that aims to quantify the co-benefits of implemented NBS (Watkin *et al.*, 2019).

3.5.2 Emergent theme: Climate Change perspective into NBS analysis

The first challenge identified concerns how climate change and which climatic risks were addressed by NBS analysis. The level of integration of the climate change issue varies across publications (**Figure 19**). Most of the studies (51%) show a low level of integration related to the climate change concept into NBS analysis ('background' indicator). Of those publications that only mentioned climate change as a background condition, 21 are focused on a single hazard (flooding) (e.g., (Diaz-Nieto, Lerner and Saul, 2016; Webber, Fu and Butler, 2018; Sörensen and Emilsson, 2019; Venkataramanan *et al.*, 2020)), while the rest (14 studies) are focused on multiple hazards (flooding, drought, coastal erosion, heat island effect, air quality, etc.) (e.g., (Brink *et al.*, 2016; Faivre *et al.*, 2018; Im, 2019; Hobbie and Grimm, 2020)). Those studies use the term climate change in at least one section of the publication (e.g., the title, abstract, keywords, introduction, methods, results or discussion/conclusion).

Among the publications that do not mention climate change (34%), most (17 studies) analyse the flooding hazard (e.g., (Cook, 2007; Alves *et al.*, 2018; Bertilsson *et al.*, 2019)), while the other six publications broadly mention and focus on multiple hazards, by considering, especially, sea-level rise, air temperature, and drought (e.g., (Everard and McInnes, 2013; Connop *et al.*, 2016)).

Only three studies show a medium level of integration of climate change issues ('analytical' indicator; 4%). A review paper focuses on flooding as a single hazard, by discussing internal and external aspects that are influencing flash flood events. Climate change is included as an external factor that induces heavy precipitation (Wu *et al.*, 2020). One paper focuses on multiple hazards (flood and drought), while another study focuses on a compound hazard, by considering river–fluvial flooding, high tides, and sea-level rise (Duy *et al.*, 2018; Pimentel-Rodrigues and Silva-Afonso, 2018).

The seven studies that integrate climate change issues to a large extent consider climate data to build different scenarios ('scenario' indicator; 10%). The major part of these studies (five) tackle a single hazard (flooding), while one article analyses flooding and sea-level rise as a compound hazard and one concerns multiple hazards (flood, drought, temperature, and sea-level rise) (Moore *et al.*, 2016; Boelee *et al.*, 2017; Dong, Guo and Zeng, 2017; Jenkins *et al.*, 2017; Kunapo *et al.*, 2018; Kirshen *et al.*, 2020; Locatelli *et al.*, 2020).

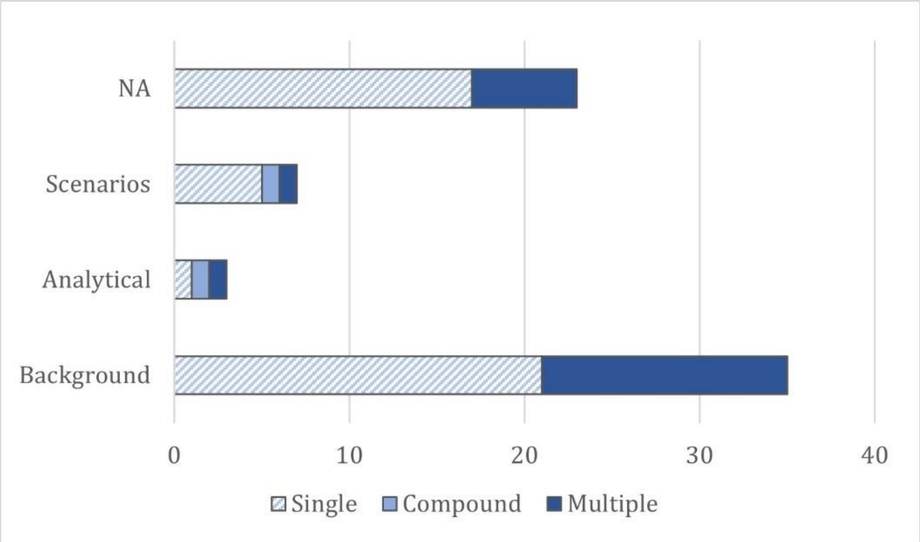

Figure 19. *Level of integration of climate change issue into NBS studies.*

3.5.3 Emergent theme: Economic perspective into NBS analysis

For the second challenge, only 19 publications (28%) report on economic research approaches. **Figure 20** shows the number of studies per each specific economic approach, by showing the currency employed. About 10% of the studies develop a flood-damage analysis. These studies use a flood-depth damage function to estimate the economic damages – two studies use buildings and the other one works with income classes for flood-costs calculation (Jenkins *et al.*, 2017; Webber, Fu and Butler, 2018; Bertilsson *et al.*, 2019). The currency is mentioned in just one of these studies, which is GBP. Most of the publications (37%) develop cost analysis on NBS implementation to reduce flood risk. Three studies include construction and maintenance costs of NBS in the analysis by using USD (Zidar *et al.*, 2017; Karamouz and Heydari, 2020) and GBP as currencies (McClymont *et al.*, 2020). The other part of the studies include only the construction costs of the measures by using the currencies USD (Moore *et al.*, 2016; Dong, Guo and Zeng, 2017), RMB (Bu *et al.*, 2020), or AUD (Schubert *et al.*, 2017), respectively. About 26% employ cost-benefit analysis (CBA) to conduct the economic calculation of NBS. One study is a review on the unit-cost information of adaptation measures, by including the currency GBP and USD (Aerts, 2018). Two publications use EUR as the currency (Alves *et al.*, 2019; Locatelli *et al.*, 2020), while one economic assessment conducted in China is expressed in RMB (Liu *et al.*, 2016). Only one of those studies does not explicitly state the currency (Kirshen *et al.*, 2020). Among the remaining 20% of studies, one focuses on life-cycle cost analysis (LCCA), by including USD (Xie *et al.*, 2017) m and one conducts a value-transfer methodology to monetize the natural capital (NC) benefits by using GBP (Gunasekara *et al.*, 2018). The other two studies, which do not explicitly state the currency, show a historical comparison and a least-cost path analysis (Diaz-Nieto, Lerner and Saul, 2016; Wu *et al.*, 2020).

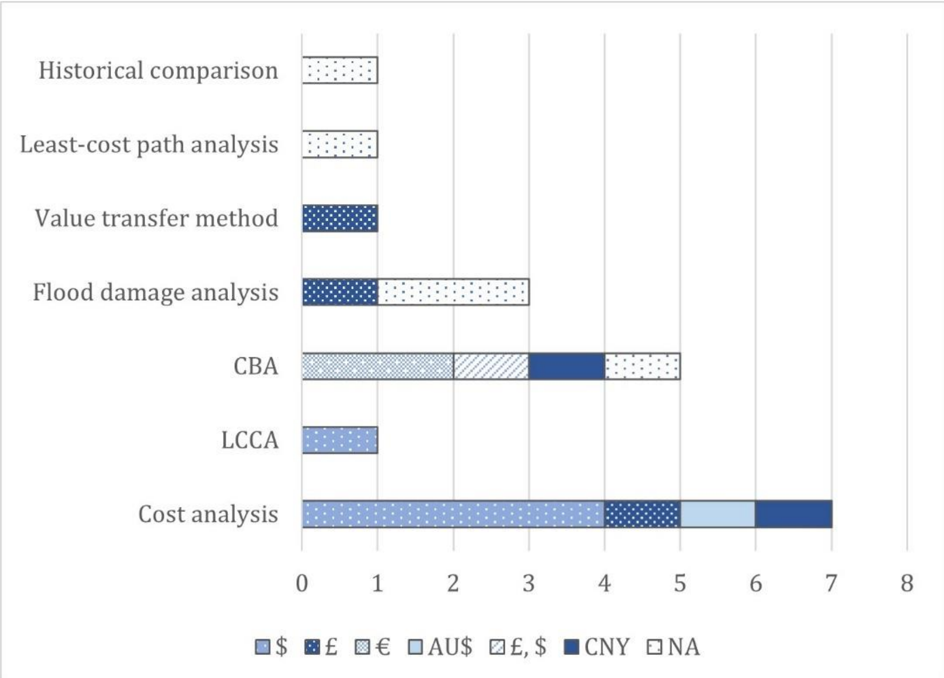

Figure 20. *Economic approaches and currency employed for each NBS studies.*

3.5.4 Emergent theme: Planning perspective into NBS analysis

Finally, the third theme addressed in this research is related to the adaptation challenge, essentially by highlighting the biophysical assessment employed by the studies through the collection of the information related to the specific natural solutions implemented. Only 31 publications address this theme, which helps to classify the most used NBS types linked to their biophysical flood-mitigation values. **Table 5** shows the number of times that each of the most common NBS are employed in the literature, addressing the different types of information (quantitative and/or qualitative) provided. Green roof and permeable paving are the mostly studied solutions, for which quantitative evidence is available. For example, most of the studies provide the numeric runoff-reduction values of flooding, as water infiltration or retention capacity in terms of percentage, mm, or m^3 (Yu, 2013; Liu *et al.*, 2016; Zellner *et al.*, 2016; Webber, Fu and Butler, 2018). One study expresses the numeric flood-risk values related to the climate change mitigation in terms of kg of CO2 reduction (Senosiain, 2020). Green roof and permeable paving studies are also the ones for which most qualitative evidence is available, followed by rain garden. The kind of evidence presented refers to qualitative ranking expressed in terms of reduction capacity (i.e., low–medium–good or including fixed values as 0-1), as developed by the authors (Alves *et al.*, 2018; Chan *et al.*, 2018; McClymont *et al.*, 2020). Green facade, green park, and green street are the less-studied solutions. In general, only a few studies provide both qualitative and quantitative information (Cook, 2007; I. M. Voskamp and Van de Ven, 2015).

Table 5. *Number of times that specific NBS address different types of information. Colours vary from red (none or a few times) to green (several to most of the time).*

	No. of times NBS is studied	**Type of information on NBS**			
		Quantitative	Qualitative	Quantitative & Qualitative	NA
Green façade	**2**	1	0	1	0
Green park	**3**	0	2	1	0
Green street	**3**	0	1	2	0
Green roof	**20**	10	7	2	1
Infiltration basin	**10**	6	2	2	0
Permeable paving	**19**	10	7	2	0
Pond	**10**	3	5	1	1
Rain garden	**11**	4	6	1	0
Swale	**11**	4	5	1	1
Wetland	**9**	3	4	2	0

Note: Dark red is associated to a low level of times in which NBS address different type pf information. Moving to even lighter red, orange, yellow and finally light green and dark green where NBS address several or most of the time this different kind of information.

3.6 Discussion

What emerges from this literature review are research gaps for each of the deepened focus areas and an overall lack of studies integrating the three themes together. The first theme about climate hazard and the level of integration of climate change issues into NBS analysis, essentially highlights the gaps in the two fields. One is related to gaps on vulnerability and risk assessment, due to the compound effects of urban flooding and storm surges. Generally, compound climate events are an integral part of almost all climate- related risks and pose significant challenges to many risk-reduction measures (Zscheischler *et al.*, 2020). Better comprehension of compound events is crucial for improving risk assessment and defining site-specific NBS to reduce the associated impacts (Wahl *et al.*, 2015; Zscheischler *et al.*, 2020). Moreover, a small portion of the literature works with climate change scenarios. The level of integration of climate change data into analyses is weak, even though defining scenarios is a useful tool to visualize potential futures and to address the related trade-offs (European Environmental Agency (EEA), 2009). For the second theme, the first issue that can be pointed out is related to the kind of economic assessment employed. Some studies are unclear as to which currency has been employed to address the economic evaluation. In addition, the reference year associated to the analysis is specified only a few times. This shows the important role in economic analysis of clarifying this information, thus helping to build useful and consistent data for further implementation. Another issue is linked to the cost components or cost-benefit analysis, which should be addressed. Uncertainties are associated with the NBS cost of operation and maintenance, while NBS benefits are often not clarified and partial. Future research should address these issues and expand the research by estimating both the cost and benefits of flood adaptation measures. Finally, some gaps should be addressed on the third focus area concerning the adaptation theme. Urban planning is the process of developing and designing urban areas to meet the needs of a community. Among the different disciplines – architecture, engineering, economics, sociology, public health, finance, etc. – involved in planning, few of them have been prioritized in the process of NBS promotion. Some studies highlighted the social dimension by fostering stakeholder involvement and participatory planning to identify co-benefits and barriers in the process of NBS integration into urban adaptation, e.g., (O'Sullivan *et al.*, 2012; O'Donnell, Lamond and Thorne, 2017; El Hattab *et al.*, 2020). However, most of them underlined the need to cover the economic and finance area of planning. These focused on broadly proving multiple co-benefits versus different barriers in NBS implementation, as compared to traditional solutions such as (Connop *et al.*, 2016; Dong, Guo and Zeng, 2017; Kunapo *et al.*, 2018). Few studies highlighted the relevant role of evaluative tools (such as cost–benefit analysis) to support the decision-making process in planning (as in Locatelli *et al.* (2020) and Senosiain (2020). The lack of studies in this field is probably related to the scarcity of biophysical studies that assess the multiple impacts of NBS, which underpin such analyses. What emerges as one of the most important barriers to increased implementation of NBS is related to finance, both in upfront and maintenance costs, as in (Huang *et al.*, 2020; L. Li *et al.*, 2020). Thus, filling these gaps through long-term monitoring and demonstration of impacts and benefits of NBS helps to overcome such barriers and promote implementation of NBS. Additionally, specific vegetation information has not been mentioned, even though it plays a crucial role when considering climate change. The choice of specific NBS should be strictly related to the vegetation type to be effective. A repository concerning the technical aspects (as dimensions) of each specific NBS is also still missing.

Through this review, it is possible to infer that a large number of studies only partly assess the biophysical and economic impacts of NBS scenarios' implementation. Moreover, most of the studies do not mention specific practices or procedures to systematically conduct biophysical-economic assessment on NBS scenarios' implementation. Many attempts at ecosystem services (ES) quantification and NBS biophysical benefit evaluation, for their inclusion into the decision-making process, have been carried out (Francesconi *et al.*, 2016). Moreover, a great number of NBS studies on flood vulnerability concerns engineering aspects (hydraulic modelling assessment). However, it is argued that developing this kind of analysis as standalone is not enough for mainstreaming wider implementation of NBS. Especially, under changing climate conditions, it is urgent to focus on spatially integrated environmental-economic assessments of NBS, by simulating climate change and adaptation scenarios. Given the relevance of NBS in the execution of the United Nations (UN) Sustainable Development Goals (SDGs; https://sdgs.un.org/goals (accessed on 14 July 2022)), in particular SDG 11 (sustainable cities and communities) and SDG 13 (climate action), it becomes even more important to contribute to overcome barriers that hamper a wider NBS implementation. An essential aspect derived by this review is related to how climate adaptation through nature-based implementation is integrated into traditional urban planning. This is related to the disciplines involved in the planning and implementation of such adaptation measures. Some studies focus on presenting and evaluating perceived barriers to NBS implementation, which are compared a few times to the potential benefits, mainly related to increasing urban ES, as in (Ganann, Ciliska and Thomas, 2010; Diaz-Nieto, Lerner and Saul, 2016; Zellner *et al.*, 2016; O'Donnell *et al.*, 2020; Venkataramanan *et al.*, 2020). Another part of the publications shows methodological frameworks and evaluative tools, by working with adaptation scenarios to help local governments, as in (I.M. Voskamp and Van de Ven, 2015; Ramírez, Qi and Xiaobo, 2016; Zidar *et al.*, 2017; Webber, Fu and Butler, 2018). One study highlighted the crucial role of CBA as a relevant tool for decision-making for urban planning, by comparing different scenarios of adaptation and future climate (Locatelli *et al.*, 2020). These aspects are essential strategies towards more structural incorporation of NBS in urban planning. However, a widespread implementation of NBS still remains limited by the lack of knowledge about how to embed urban ecological science within urban-planning practices and policies (Hansen *et al.*, 2019). For instance, the uncertainty and lack of information on NBS' long-term behaviour and effects, together with the difficulty of quantitatively assessing their multidimensional impacts. This rapid systematic review is not lacking shortcomings. Firstly, the number of publications included come from two electronic databases (Scopus and Web of Science) and may exclude some other important publications that are not stored in those databases. Secondly, the data extracted are also limited by the areas that this study focuses on. Rather, a reflection of the emergent themes has been carried out, even though the lack of climate, biophysical, and economic data for some cases undermined the comparison between the different studies.

3.7 Conclusive remark

Research interest and efforts to evaluate NBS impacts has been growing rapidly over the last decade. So far, current approaches for NBS impact assessment are diverse and often vague, especially in relation to the idea of integrating NBS into the adaptation planning process. This review, therefore, aims to systematically analyse how NBS biophysical performance and economic impact evaluations are developed and integrated into urban planning adaptation.

The four focus themes identified by the review process provide a basis for the discussion around the role of NBS in climate change adaptation for flooding issues in coastal cities. This study contributes to the existing body of knowledge, especially by highlighting the emergent importance of NBS in flooding-related urban planning, as well as the lack of spatially explicit simulation and economic assessment. Indeed, the NBS approach helps with urban-flood management and, especially, dealing with the more extreme flooding events due to climate change. For this reason, the information extracted by this review can be useful for future studies that focus on comparative discussion of NBS application and economic assessment for urban-flood management. Looking at the results from an integrated perspective, which combines climate and economic analysis by overcoming the boundaries of adaptation planning, it seems to become even more important to conduct studies on integrated assessment methods for policy support. This would help delineate future research aimed at assessing the significant role of NBS to reduce the biophysical and economic impacts of flood events. Such research reflects the growing interest in further research to develop spatially integrated environmental-economic assessments on NBS implementation, by underlining the need for trans-disciplinary approaches to provide science-based evaluations supporting policy- making in the framework of urban climate change adaptation. By further performing in-depth analyses to demonstrate the multiple costs and (co-)benefits of NBS, as compared to traditional approaches, these studies will help to better integrate such solutions into traditional urban planning. Once sufficient studies are available, meta-analyses can be performed to derive conclusions about the factors and conditions that determine the effectiveness of NBS. Based on this consideration, further research on the role of specific vegetation and on the interaction between plants and substrate, should be developed to optimize the NBS' efficacy.

Chapter 4

Urban Climate Change Adaptation

This chapter is partly based on Quagliolo *et al.* (2021).

4.1 Climate change: basics and modelling

Recently, climate change has been recognised as major issue in modern society (European Environment Agency (EEA), 2016).

The International Panel for Climate Change (IPCC) defined climate change as a “variation of the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer", which refers to alterations in the chemical composition of atmosphere and changes in land use (IPCC, 2014a). Climate change may be due to natural internal processes or external forcings (such as solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use). In this view, climate change represents each climate-related event, as well as various aspects at scales ranging from global to local, and which result from these changes, thus involving different disciplines and actors.

The collected data of global average annual land surface temperature over the past century (1906-2005) shows an increase of 0.74 ± 0.18 °C (IPCC, 2014b). Temperature projections for the end of the 21st century estimate increases ranging from 1.1 to 6.4 °C, compared to end-20th century, based on the Special Report on Emission Scenarios (SRES) scenarios for greenhouse gas emissions (IPCC, 2000, 2007). These changes in the global average temperature have a wide variety of effects on global, regional and local levels, such as: changes (average and extremes) in temperature, sea levels, precipitation and river runoff, drought, wind patterns, food production, ecosystem health, species distributions and phenology, and human health (IPCC, 2007). Based on observations of global air and ocean temperatures, as well as changes in snow extent and sea level, the IPCC reported that the climate system has warmed ‘unequivocally’ (IPCC, 2007). The human influence has been the dominant cause of the observed rapid changes in climate variables (IPCC, 2014c). As a result, various impacts on physical and ecological systems have been observed, which can differ strongly at the regional level (IPCC, 2007).

Climate models (called General Circulation Models - GCMs) are advanced tools for modelling the climate system and simulating its response to changes in atmospheric concentrations of greenhouse gases. GCMs simulate the climate system at the global scale (at a resolution that ranges between 50 and 250 km) based on the physical, chemical and biological properties of its components, their interactions and feedback processes (IPCC, 2014d). On the other hand, regional climate models (RCMs) are useful for more detailed regional climate impact assessment. RCMs typically have a resolution ranging between 2 and 50 km, which enables a better representation of topographic features and regional-scale climate processes.

In order to determine future climate change impacts, the IPCC has developed a set of emissions scenarios (greenhouse gas emissions) to get a range of possible future climate projections. These projections are based on differing sets of assumptions about population changes, economic development, and technological advances (Rafael, 2017). Up to 2010, most climate projections employed emissions scenarios published by the IPCC in 2000, in the Special Report on Emissions Scenarios (SRES) (IPCC, 2000). These SRES scenarios provided socio-economic storylines and greenhouse gas emissions scenarios for four world regions. The SRES scenarios are organised into families, meaning that the scenarios are based on similar assumptions regarding demographic, economic and technological development. Based on their cumulative emissions throughout the 21st century, they have been grouped into low (B1), medium-low (B2, A1T), medium-high (A1B) and high (A2, A1FI) scenarios. These emission scenarios are characterized by baseline scenarios, which means they do not consider specific agreements or policy measures to limit the emission of greenhouse gases (e.g. the Kyoto Protocol) (IPCC, 2000).

The follow-up generation of scenarios to support climate change research employs the term 'representative concentration pathways' (RCPs). These projections are representative of greenhouse gas concentration (not emission) trajectory for future atmospheric composition and land-use change up to 2100. Four RCPs pathway were used for climate modelling (IPCC, 2014c): RCP2.6 (very stringent), RCP4.5 (moderate pathway), RCP6.0 and RCP8.5 (rising pathway) according to their radiative forcing level in the year 2100 (see **Table 6**).

Table 6. *AR5 global warming increase (°C) projections (elaborated from IPCC (2014b)).*

Scenarios	**Mid-21st century (2046-2065)** Mean (likely range)	**Late-21st century (2081-2100)** Mean (likely range)
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP6	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)

Climate projections under the RCPs pathways predict changes in the dynamics of the climate system in most parts of Europe (IPCC, 2014d):

- An increase of the European annual average land temperature by the end of this century in the range of 1-4.5°C under RCP4.5, and in the range of 2.5-5.5°C under RCP8.5;

- An increase in the magnitude of extreme heat waves, which are projected to occur as often as every two years in the second half of the 21st century (increase in frequency); the impacts will be particularly strong in southern Europe;
- An increase in annual precipitation is generally projected in northern Europe, while a decrease is projected in southern Europe (especially in the summer). However, heavy precipitation events are projected to become more frequent in most parts of Europe, particularly in the winter.

4.2 Climate change impacts in European cities: hydrological hazards

Generally, urban areas experience the same exposure to climate hazards as their surrounding region. However, the urban design can strongly alter exposure as well as the impacts of these hazards at the local scale. For instance, the impacts of flooding are typically more intense in cities because the land use dominated by built-up area, which inhibits the infiltration of rainwater and causes excessive runoff (Shanableh *et al.*, 2018).

The morphology of the urban surface is different from that of the natural landscape. The walls and roofs of buildings affect the waterflow across the surface. Urbanisation has widely modified local, regional and national water cycles through the traditional drainage systems' evident inability to cope with new urban sprawl phenomenon (Hernández-Hernández, Olcina and Morote, 2020). Modification from permeable to impervious land, especially in urban contexts (i.e., streets, roofs, buildings), leads to a higher peak flow rate of runoff while limiting the groundwater recharge. Indeed, urban catchments cause runoff to be two to six times over what would occur on natural terrain, leading to peak flow rate increases ranging from 1.8-8 times the normal values (U.S. Geological Survey (USGS), 1998). Soils that reduce infiltration result in an increasing amount of runoff water, which contributes to accelerating erosion. Surface runoff is the volume of excess water that runs off a drainage area, with rainfall being the primary source of this process (Berndtsson *et al.*, 2019). Indeed, not all the rain that hits the ground reaches the watershed outlet or infiltrates the soil.

The main factors affecting the rainfall volume that runs off are soil, land cover or land use, and vegetation. It is well known that vegetation cover in essential to improve soil permeability. The materials that make up cities (concrete, brick, and asphalt) have different hydrological properties than natural materials (soil, trees, grass), and that affects how the surface absorbs and stores water. Vegetation cover affects soil infiltration by changing the hydrological process of rainfall-infiltration on slopes and modifying the soil pore spaces (Huang, Wu and Zhao, 2013).

Due to their low permeability and the above-mentioned aspects, cities are highly vulnerable to extreme rainfall events, so-called cloudburst, which result from relatively short periods of high intensity rainfall, and which cause flash floods over the extent of entire cities. The term ‘cloudburst’ is not considered new; it was formally defined in meteorology by Woolley et al. (1946), and became frequently used in urban resilience literature (Woolley, Marsell and Grover, 1946). Therefore, research on the spatial and temporal variability of the hydrological cycle in urban areas has become one of the most important resilience planning issues (Brunetta *et al.*, 2019).

Usually, hydrometeorological hazards are categorised based on their driving mechanisms and their statistical behaviour (i.e. duration and magnitude of extreme events, the potential of occurrence). Among hydrometeorological hazards, floods, storm surges, landslides, drought and heatwaves are recognised as the critical natural events. Anomalies trigger these events in the atmosphere and the hydrological cycle as weather-, climate- and hydrological-related events, which are projected to increase in their frequency and magnitude due to climate change impacts (Debele *et al.*, 2019).

Worldwide, losses from flooding have been estimated 723 billion of $ in the period between 1990 and 2016 (Nguyen *et al.*, 2021). In this context, future damages are expected to increase, as temperature changes are positively correlated with flooding events. Indeed, the Clausius-Claypeyron relationship explains that with an increase of one degree in temperature, the air can hold 6-7% more water. In other words, precipitation events will be more intense in the future. and flood risk is expected to increase within mid- and long-term across Europe (Tabari, 2020). Meanwhile, other studies showed how projected growing patterns for storm surge risk are one of the primary causes of coastal flooding, along with the sea-level rise (Alfieri, Burek, *et al.*, 2015; Alfieri, Feyen, *et al.*, 2015; Vormoor *et al.*, 2016). Coastal cities are particularly exposed to several climatic hazards as a results of compound impacts due to pluvial floods (local high-intensity precipitation), fluvial floods (high flows in river-prone systems), coastal floods (high sea levels, high tides and stormy conditions) and coastal erosion (IPCC, 2014b).

In Europe, flood events are estimated to be the most damaging natural hazard during 1980-2018 (Debele *et al.*, 2019), and especially, the coastal flood is considered the most catastrophic type of flood (Simmonds, Gómez and Ledezma, 2019). Particularly, the results from a regional analysis on sea-level rise projections conducted in the Languedoc-Roussillon coastline (France) by Hériveaux et al. (2018) showed that, overall, around 39.000 ha of coastal area might be exposed to coastal flooding in 2100 compared to 15.000 ha in a scenario without sea-level rise. This area is likely to be affected mainly by extreme flooding, with estimates predicting flooded areas to increase by 55% by 2100 (Hérivaux *et al.*, 2018).

The study by Alfieri et al. (2015) shows the potential flood impact influenced by climate change at the European level. The flood events are represented by all kinds of flooding (coastal, pluvial, river, etc.). **Figure 21** represents the multi-model ensemble mean of 30-years expected annual damage per country for the baseline scenario (1976-2005) (a), together with the projected mean relative changes due to climate change only, for 2020 (b), 2050 (c) and 2080 (d) (Alfieri, Feyen, *et al.*, 2015). **Figure 21** (a) shows the expected annual damages due to floods (million €). **Figure 21** (b, c, d) show the variation from (a) in %. From this representation, which refers to a simulation, emerge increasing variations of the potential impacts of flood hazards in many European countries (such as Portugal and Italy). Moreover, most European cities are projected to go from housing nearly 73% of the population now to more than 80% by 2050 (European Environment Agency (EEA), 2016).

In recent years, dramatic river and pluvial flooding has occurred in several regions of Europe, causing numerous casualties and damages by reaching unprecedented proportions. Indeed, the agenda of the European Union is directly addressed by the European Regional Development Fund aimed at protecting human beings and capital assets from such hazards (Paliaga, Luino, Turconi, Marincioni, *et al.*, 2020).

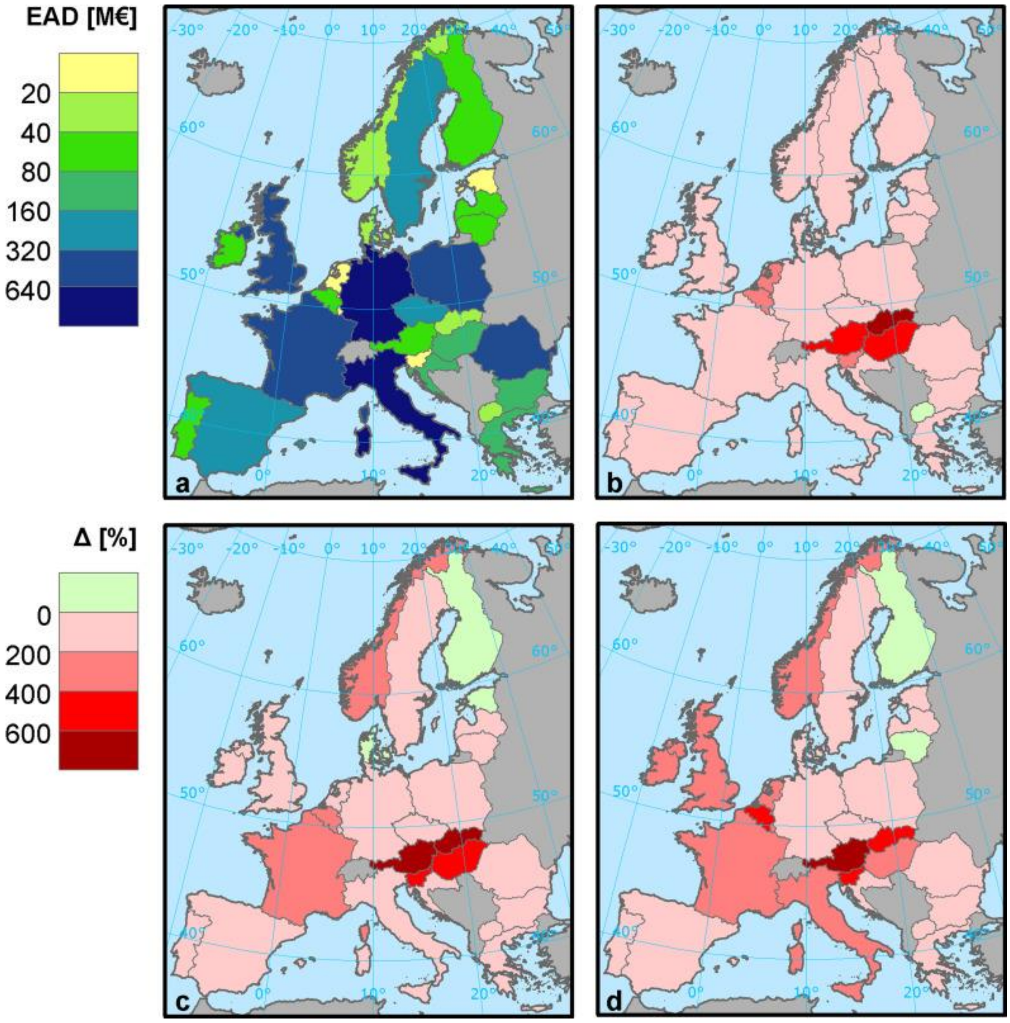

Figure 21. *Flood impact due to climate change, presented as aggregated expected annual damage per country (ensemble mean) (from Alfieri et al. (2015).*

Italy is the European country with the widest areal distribution and highest recurrence of large landslides and floods, causing severe losses of lives and goods (Salvati *et al.*, 2010; Paliaga, Luino, Turconi, Marincioni, *et al.*, 2020). Data gathered from recent reports of the Research Institute of Geo-Hydrological Protection of the Italian National Research Council show that, over the period 1964-2013, landslides and floods have caused 2007 casualties and 87 missing people. Such phenomena occurred in 2034 municipalities across Italy, causing 25% of the total casualties from all natural hazards (Salvati *et al.*, 2016). All Italian regions have suffered at least one landslide or flood event with casualties (Guzzetti, Stark and Salvati, 2005). Further, the 2014 flash flood in Genoa (Italy) caused damages to buildings and their contents of approximately € 100 million according estimates and data by the CIMA Foundation[4].

Between 1865 and 2010, flooding events in Portugal produced 1,012 deaths, 478 injuries and the displacement of 13,372 people. More than 50% of these losses are estimated to be caused by flash floods (Santos, Santos and Fragoso, 2017). Given the trend of hydro-geomorphological events from 1900 to 2008, 75.6% of total flood cases happened between November and February, mostly the period of increasingly intense and frequent extreme short-term events, like storms and heavy precipitation, in climate change context (Schleussner *et al.*, 2020).

Apart from river-related flooding, coastal storms and climate-induced sea-level rise are damaging low-lying coastal areas, such as river deltas and estuaries, where natural ecosystems are degraded by increasing urbanization and other marine hazards. Roudier *et al.* (2016) reported that Portugal, among a few European countries, will be most affected by coastal-related extremes under the 2°C global warming scenario. Especially the north-western region of Portugal is becoming even more vulnerable to these extremes.

4.3 Pluvial flood and compound flooding in coastal area

Instead of fluvial or coastal flooding, pluvial flood (or flash flood) is considered as the 'invisible hazard' because it often occurs in areas not obviously prone to flooding, as the drainage system struggles to quickly discharge the runoff. Particularly, rainfall generated flash floods are classified as short-duration floods which occur within six hours of a rainfall event. Most flash flooding is caused by thunderstorms or heavy rains (e.g. from hurricanes and tropical storms) and are characterized by a sudden increase in level and velocity of the surface water (Borga *et al.*, 2008). Pluvial flooding represents the conversion of rainfall into runoff when the rain rate exceeds the maximum infiltration capacity of stormwater by the land (Houston *et al.*, 2011). This kind of floods have been identified as the type most likely to be influenced by climate change, which increases the severity of occurrences. These floods are also the most difficult to predict, and it is challenging to provide adequate warning times to populations (Houston *et al.*, 2011).

Globally, urbanisation influences precipitation patterns, resulting in increased runoff and more frequent pluvial flooding events. This results in exacerbated effects of future heavy rainfalls, which are further changing due to anthropic impacts on climate (Scholz, 2013; Zhou *et al.*, 2019; Zhu *et al.*, 2019).

Events related to severe storms, such as hurricanes, are the leading cause of coastal floods. A coastal flood can be induced by a stormwater surge along the coast due to high tides combined with low atmospheric pressures and strong winds. Storm

[4] https://www.cimafoundation.org/

surges can have an impact several kilometres upstream, causing further flooding (Debele *et al.*, 2019). Storm surges are predicted to exceed the relative sea-level rise along the European coast by 30% under the Business as Usual (BAU) IPCC scenario (Vousdoukas *et al.*, 2016).

Even though fluvial flood hazards decrease in some regions due, for instance, to reductions in seasonal rainfall totals, globally, the aggregated pluvial, fluvial and coastal flood hazards are likely to increase. Indeed, changes in short-term precipitation do not necessarily relate directly to changes in fluvial flood hazards. In the cities, for instance, variations in flood hazard become more dependent on changes in rainfall accumulation and runoff risk over days or, at maximum, weeks. During the 21st century, the major threats of coastal flooding and erosion are significantly influenced by episodic storm surge and wave setup[5], or their time of occurrence with the astronomic tide, instead of the increase in mean sea level (Kirezci *et al.*, 2020). This situation is likely to become even more relevant and dramatic in the future along most of the European coastlines if no additional investments in adaptation measures will be considered (Marcos *et al.*, 2019). Indeed, compound flooding due to simultaneous storm surges and high river and runoff flows exacerbates the risk of coastal hazards, and is expected to be increasingly frequent in several European coastal cities (Berndtsson *et al.*, 2019; IPCC, 2019).

The IPCC Special Report on climate Extremes (SREX) defined compounding events as the ‘combinations of events that are not themselves extreme, but lead to an extreme event or impact when combined’ (IPCC, 2012). Indeed, compound events indicate the co-occurrence of multivariate climate drivers or hazards in the same geographical region. The term multivariate refers to a ‘compound hazard’, in hazard and risk literature, by including the concurrent climate extremes and climate anomalies that are not necessarily extremes themselves, but whose joint occurrences cause larger impacts.

In low-lying coastal areas, floods often result from a combination of multiple drivers, such as the co-occurrence of storm surges, waves, higher discharges, and direct surface runoff from high sea level and heavy precipitation (Zscheischler *et al.*, 2020). Several studies have examined potential climate change effects on the occurrence and intensity of some compound events. Indeed, interactions between rising sea levels, storm surges and extreme precipitation are likely to cause more frequent and more intense compound coastal flooding events (Bevacqua *et al.*, 2019). These coastal hazards can result in substantial damages. Some cases of compound flooding (CF) in Europe the flash floods in Lisbon (Portugal, 1967), or the Ravenna flood in Italy (2015) (Bevacqua *et al.*, 2017). Other examples listed by the HANZE (Historical Analysis of Natural Hazards in Europe) database showed various co-occurrences of storm surges and floods along UK, Irish and Belgian coasts, the French Atlantic, Mediterranean and Italian Adriatic coastlines (Paprotny, Morales-Nápoles and Jonkman, 2018). CF risk varies along coastlines, and can be estimated indirectly by quantifying the dependence of extreme storm surge with

[5] The wave setup refers to the temporary increase in mean water level due to the presence of breaking waves.

each precipitation. For example, Bevacqua *et al.* (2019) showed how the Mediterranean coasts are experiencing the highest CF probability in the present scenario. On the other hand, compound precipitation-storm surge flood risk for future scenarios is projected to more than double along a large part of the northern European coasts, mostly due to the increase in heavy precipitation, and aggravated by mean sea level rise.

The co-occurrence of storm surge and heavy precipitation is strictly related to the deep low-pressure system. Although the precipitation alone could be driven by convection process without intense cyclone activity, the latter is a precondition for storm surge through strong winds pushing water towards the coastline (Wahl *et al.*, 2015; Bevacqua *et al.*, 2019). Different mechanisms can cause CF starting from the storm surge that blocks or slows down the precipitation runoff drainage into the sea, and generates flooding along the coastline (Bevacqua *et al.*, 2017). Even, runoff from precipitation or river floods may require time to drain into the sea, such that rainfall may have to occur before a storm surge event (Van Den Hurk *et al.*, 2015). Moreover, any significant amount of rain may increase the flood level of a storm surge. The activation of these mechanisms in a specific context is strictly linked both to the local climate and the topography, but it is essential to consider dependence between storm surges and extreme rainfall runoff to properly evaluate CF risk (Wahl *et al.*, 2015).

Despite the CF relevance, a comprehensive hazard assessment beyond individual locations is missing, and no studies have examined CF in future climate (Bevacqua *et al.*, 2019; Zscheischler *et al.*, 2020).

4.4 Adaptation in cities: the role of Ecosystem Services

Two main responses have emerged to deal with climate change: mitigation and adaptation. The IPCC defined mitigation action as “anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases” and, adaptation action, as an “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (IPCC, 2014a). Adaptation and mitigation differ in both temporal and spatial scale. For instance, benefits derived from mitigation actions are typically visible on a global scale and with a long-term perspective. On the other hand, adaptation actions contribute with disaster risk reduction and increased resilience, and are, thus, viewed at local scale and on a shorter-term perspective (Moller, 2016).

Ambitious initiatives have been taken at global level, such as the 2015 Paris Agreement on Climate Change and the 2015 Sendai Framework for Disaster Risk Reduction, as well as several European policy actions like the EU Strategy on Adaptation to Climate Change (Ciscar *et al.*, 2018). Even if climate change has mostly been presented as a global problem requiring global solutions, urban areas are increasingly recognised as strategic arenas for actions. Cities are recognised at the frontline of global responses to Climate Change through increasingly mitigative and adaptative actions. Local processes addressing climate change are responsible for the reconfiguration of international environmental politics (Castán Broto, 2017).

There is high confidence that extreme and non-extreme weather events affect vulnerability to future climate by modifying the resilience, coping, and adaptive capacity of communities or ecological systems affected by such events (Cardona *et al.*, 2012). In this context, resilience has been recognised as a priority worldwide. Urban resilience is defined as "*the ability of the system (the city) to adapt and adjust to changing internal and external processes*", and plays a crucial role in the adaptation to climate change impacts (IPCC, 2014a). Resilience to climate change can be enhanced by implementing blue and/or green measures (ecosystem-based approach) rather than traditional 'grey' ones. 'Hard strategies' (such as dam) can temporarily withstand climatic variability and extremes. On the other hand, Nature-Based Solutions (NBS) have recently shown their potential for mitigating climate-driven extremes while contributing to adaptation and resilience in the urban context (Frantzeskaki, McPhearson, M. Collier, *et al.*, 2019). Consequently, NBS are needed to reduce risk and increase climate resilience. In this sense, the urban design principles, especially in the face to climate variability, should be driven by ecological ideas of heterogeneity and non-linearity (Wu and Wu, 2013).

By applying NBS, multiple co-benefits can be achieved. The enhancement of those co-benefits is intrinsically related to the human well-being (Alves *et al.*, 2018). Indeed, human well-being is strictly connected to the provision of vast array of ecosystem services (ES), which are the benefits that humans obtain from ecosystems (Millennium Ecosystem Assessment (MEA), 2005). The supply of ES is the result of the linkages between biodiversity and ecosystems (**Figure 22**). Historically, ES are considered the ecological characteristics, functions and processes which, directly or indirectly, contribute to human well-being (Costanza, D'Arge, *et al.*, 1997; Millennium Ecosystem Assessment (MEA), 2005; Braat, 2013). This definition was subjected to some clarification during these more than twenty years of ES debate. Ecosystem processes and functions describe the biophysical relationships which contribute to the functionality of ES, independently to the human co-benefits. This viewpoint underlines our vital interdependence with nature and ecosystems (Costanza *et al.*, 2017).

The first framework for the evaluation of ES was proposed by De Groot *et al.* (2002) and later used by the Millennium Ecosystem Assessment as the basis of ES classification. As reported in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment (MEA), 2005), ES include four categories: provisioning, regulating, cultural and supporting. Provisioning services include water, food, medicinal resources, timber and fibre; regulating services include regulation of climate, air and water quality, carbon sequestration and storage; cultural services include recreation, aesthetic enjoyment and spiritual fulfilment; and finally, supporting services include soil formation, photosynthesis and nutrient cycling.

The concept of ecosystem services dates to the 1980s, and they were defined as those services that can keep and ensure the continuity of essential gene pools as well as nutrient and hydrological cycles (Pearsall, 1984). In the following years, other definitions of ES have been formulated. Costanza *et al.* (1997) defined ES as flows of materials, energy, and also of information, from the natural capital to the human capital; this interaction results in the creation of human well-being. Other two recent definitions stated that ESs are direct and indirect benefits that people can get from biodiversity, thus contributing to human well-being (Bateman *et al.*, 2014; Wu, 2014). These are some examples and authors use either an ecological or an economic perspective when defining ecosystem services (Wangai, Burkhard and Müller, 2016).

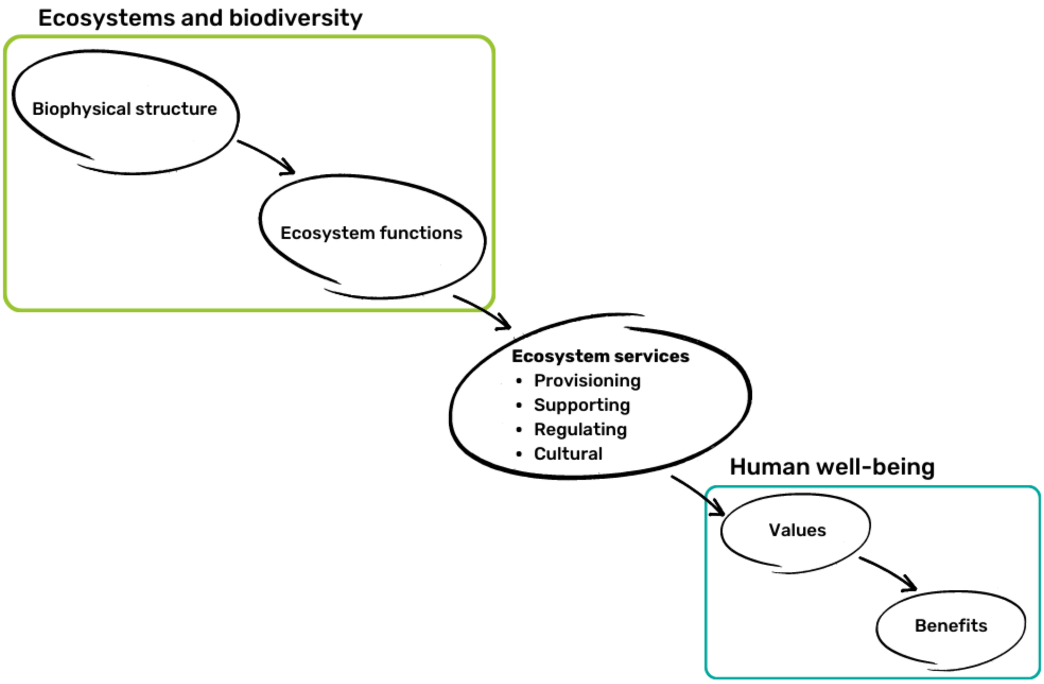

Figure 22. *Relation among ecosystems and biodiversity with human well-being (adapted from Alves et al. (2018)).*

As above-mentioned, ES are essential for human well-being because, through biodiversity, they provide a range of direct and indirect benefits. At the same time, as humans are considered an integral part of ecosystems, they mostly modify and exploit ecosystems by causing degradation and biodiversity loss. Thus, green areas and vegetations are crucial in the city context (D'Antonio, 2019).

Figure 23 shows a new framework around the concept of risk, by focusing on the strong interactions among the climate system, ecosystems (including their biodiversity), and human society. As defined by the last IPCC report (2022), these interactions are the basis of emerging risks from climate change, ecosystem degradation, as well as biodiversity loss, and, at the same time, they offer opportunities for the future (IPCC, 2022). In **Figure 23**, (a) human society causes climate change. Climate change, through hazards, exposure, and vulnerability, generates impacts and risks that overcome limits to adaptation, and result in losses and damages. Human society can adapt to, maladapt, or mitigate climate change, while ecosystems can adapt and mitigate within limits. Human society impacts ecosystems and can restore and conserve them. (b) Meeting the objectives of climate resilient development, thereby supporting human, ecosystem and planetary health, as well as human well-being, requires society and ecosystems to transition to a more resilient state. The identification of climate risks can strengthen adaptation and mitigation actions by supporting the transitions that reduce risks. Acting is enabled by governance, finance, knowledge, capacity building, technology, and catalysing conditions. In **Figure 23** (a) arrow colours represent the main human society interactions (blue), ecosystem (including biodiversity) interactions (green), and the impacts of climate change and human activities, including losses and damages, under continued climate change (red). In (b) arrow colours represent human system interactions (blue), ecosystem (including biodiversity) interactions (green), and reduced impacts from climate change and human activities (grey).

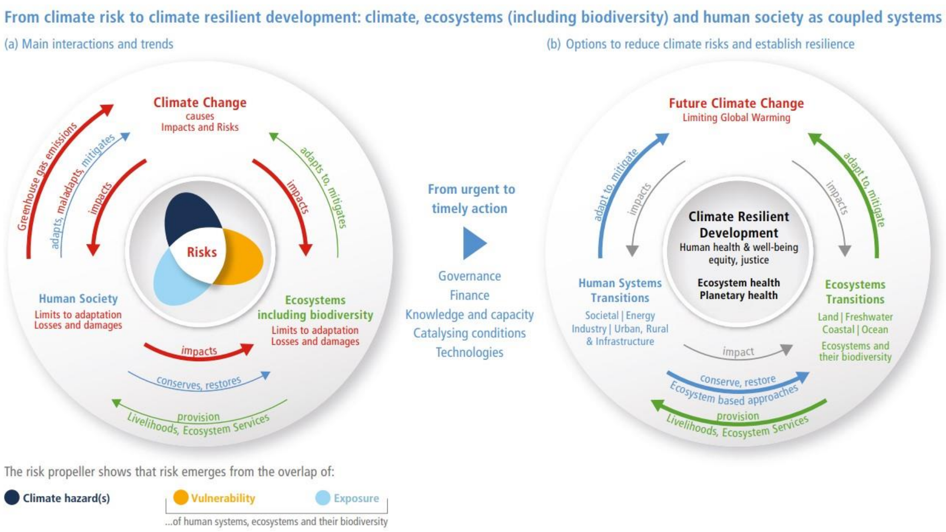

Figure 23. *Interaction among climate system, ecosystems (including biodiversity) and human society (from IPCC (2022)).*

The adoption of natural processes in response to climate change impacts – building with nature - is self-adaptive through the ES production contributing to the resilience of the cities (Fryd, Pauleit and Bühler, 2011; Wu and Wu, 2013). Though, some cities are considering how ecosystems in urban environments can help mitigate climate change impacts or create spaces that increase adaptive capacity for post-effect recovery. McPhearson, Hamstead and Kremer (2014) argued that cities will need to plan and manage urban ecosystems for enduring supply of services in dynamic urban systems affected by global environmental change. For this reason, they stated that ES and resilience are related in two ways: resilience can be fostered by incorporating the concept of ES in urban planning–ecological systems; and cities need to safeguard resilient supply of ES in the long-term to ensure urban human well-being (McPhearson *et al.*, 2015).

Three links exist between climate change adaptation and ecosystem services (**Figure 24**): firstly, how ecosystem services are affected by climate change; secondly, how ecosystem services can be used for climate change adaptation; and third, how ecosystem services are affected by human adaptation actions. This research is focused on the second link, also known as ecosystem-based adaptation (EbA). In climate change adaptation literature, the EbA concept coincides with that of NBS in the transformative potential of adaptation (McPhearson *et al.*, 2015; Brink *et al.*, 2016). Indeed, preserving and restoring ecosystems by preventing biodiversity losses improves resilience to climate change. For this reason, it is necessary to achieve coherency between their respective policy agendas and actions (European Environmental Agency (EEA), 2021b).

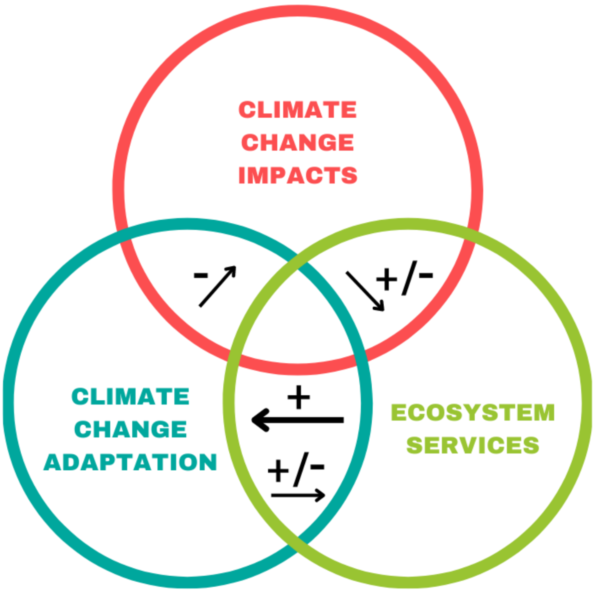

Figure 24. *Connections between climate change and ecosystem services. The arrows show the positive or negative effect among climate change impacts, climate change adaotation and ecosystem services (adaptated from Brink et al. (2016)).*

4.5 Nature-Based Solutions

As cities are rapidly growing and densifying, urban green spaces play an increasingly vital role in addressing the sustainability challenges associated with urbanization (Kabisch *et al.*, 2017). Therefore, green infrastructure (GI) represent primary local sources of ecosystem services (ES) in urban contexts (Langemeyer *et al.*, 2020). NBS appeared as an attempt to face this issue. NBS is a term introduced by the European Commission (EC) in 2015. EU defines NBS as "*Solutions that aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature, both using and enhancing existing solutions to challenges as well as exploring more novel solutions. Nature-based solutions use the features and complex system processes of nature, such as its ability to store carbon and regulate water flows, in order to achieve desired outcomes, such as reduced disaster risk* *and an environment that improves human well-being and socially inclusive green growth*" (European Environmental Agency (EEA), 2021b).

By connecting people with nature, Nature-Based Solutions have a proven positive impact on citizens' well-being, such as on public health, physical and social resilience, equity, inclusiveness, and social cohesion (European Environmental Agency (EEA), 2012). At the same time, they reduce the environmental footprint of cities, if wisely designed, constructed and managed (Grêt-Regamey *et al.*, 2017). Their effects - often referred to as ES - depending on the way the NBS align with the physical, social, economic and environmental determinants in an urban district.

The concept of NBS emerged in the late 2000s, after the publication of the Millennium Ecosystem Assessment (2005), and further the World Bank report, Biodiversity, Climate Change and Adaptation: Nature-Based Solutions from the World Bank Portfolio (World Bank, 2008). Then, NBS has been further developed by the International Union for Conservation of Nature (IUCN) and the European Commission (EC). **Figure 25** shows the timeline in the development of NBS concept (from Cohen-Shacham *et al.*, 2016).

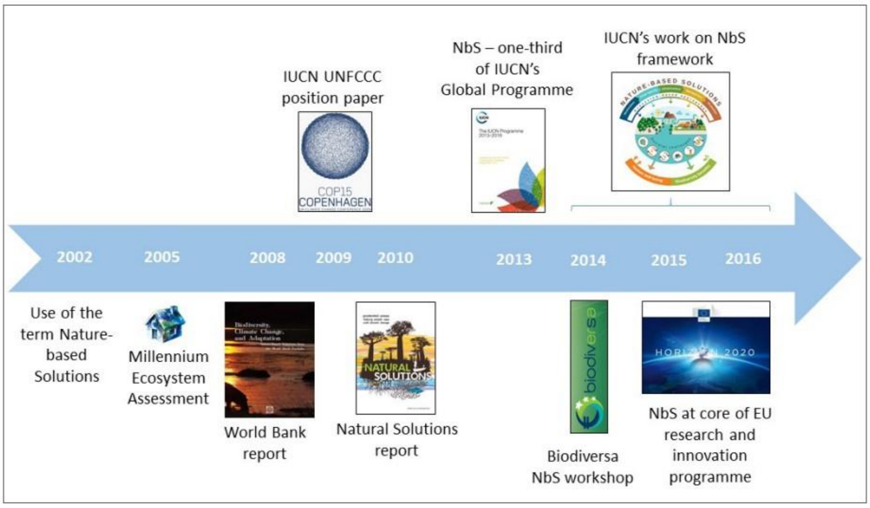

Figure 25. *Milestones in the development of the NBS concept (from Cohen-Shacham et al. (2016)).*

NBS include a variety of approaches, which have been classified by IUCN (2016). These include ecosystem restoration, issue-specific ecosystem-related approaches, infrastructure-related approaches, ecosystem-based approaches and ecosystems protection (see **Figure 26**). Specifically, such methods refer to ecological and forest landscape restoration, risk reduction through mitigation and adaptation based on ecosystems, green infrastructure, as well as management of water resources, coastal zones and protected areas. As shown in **Figure 26**, NBS are intended to address major societal challenges, like food security, climate change, human health, disaster risk mitigation, and water security (Cohen-Shacham et al., 2016). Indeed, when compared to traditional approaches, NBS are well known for their multifunctionality.

NBS can be implemented alone or integrated with other technological and engineering solutions (Cohen-Shacham *et al.*, 2016; Vojinovic, 2020). Working with nature and enhancing crucial ecosystem services is the basis for using NBS for climate change adaptation and disaster risk reduction. Such solutions reduce social and environmental vulnerabilities and can bring multiple co-benefits, such as mitigating climate change, improving human health and well-being, and providing jobs and business opportunities.

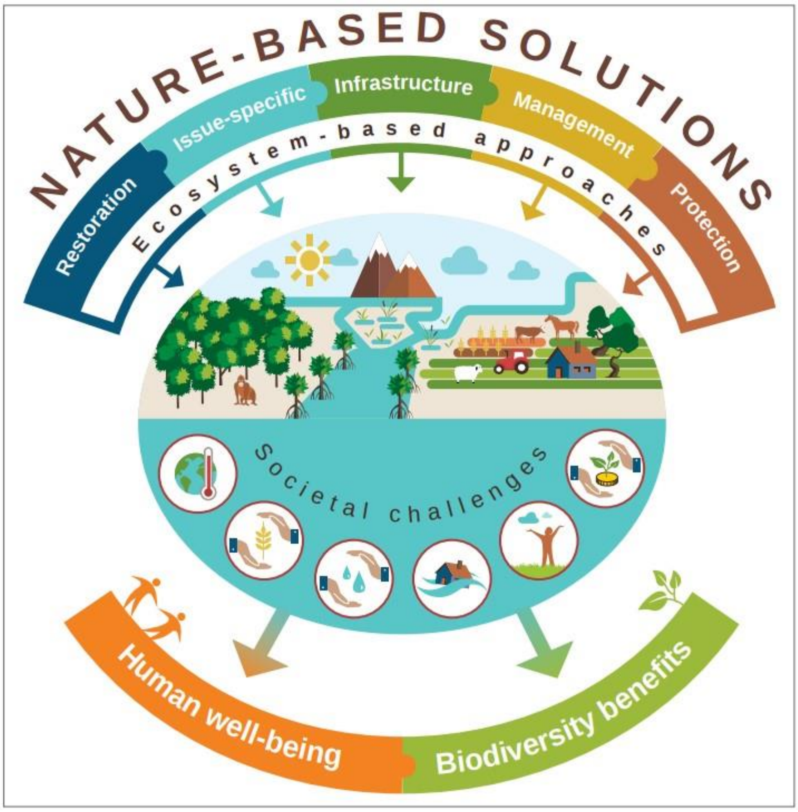

Figure 26. *NBS concept for ecosystem-related approaches (from Cohen-Shacham et al. (2016)).*

PART III - Methodology

Chapter 5

Methodological approach

5.1 Theoretical framework

As mentioned in the previous sections, this research proposes a methodology to assess and map the spatial dynamics of Nature-Based Solutions (NBS) to reduce pluvial flood risk at local level (neighbourhood scale).

The general assessment method consists of an interdisciplinary and spatially explicit approach developed with Geographic Information System (GIS) tools. Three stepwise-integrated phases are included, as shown in **Figure 27**. Firstly, the biophysical assessment has been developed by employing the Urban Flood Risk Mitigation model part of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software developed by the Natural Capital Project[6], as to identify the most flooded areas in terms of flood depth. Secondly, by intersecting these inundation maps with the asset layers, buildings and roads at risk have been identified. The economic assessment has been developed using value transfer methods (Brander, 2013), in order to estimate the costs (construction and maintenance) and benefits (avoided flooding costs) of NBS for flood risk mitigation. By employing flood-depth damage functions, the expected costs of the assets at risk, as well as the annual cost of flooding, were calculated. The NBS impact assessment was developed by integrating climate (current and future) and adaptation (green roofs and bioswales) scenarios (see section 9.3) under different flood return periods (10, 50 and 100 years), as to obtain the different benefits (i.e. the expected annual flood risk mitigation benefits) for current/future climate and NBS scenarios. Finally, a partial cost-benefit analysis (CBA) is performed by combining the flood risk mitigation benefits of green roofs and bioswales with the expected costs (i.e. the expected annual construction and maintenance costs) of these solutions. CBA is used to finally assess the ranking of the economic viability of the different NBS. The Evaluation criteria include the Net Present Value (NPV) and Benefit Cost Ratio (BCR) indicators, while applying a constant time discount rate (equal to zero, as to obtain upper-bound estimates). Finally, the robustness of the model is verified through a sensitivity analysis on costs and discount rates, for which largest variations are observed/argued.

This study is conducted through the application of the above-mentioned approach in two European study cases. To perform a comparative analysis in the context of European Adaptation, a Mediterranean area and an Atlantic area have been

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[6] Available at https://naturalcapitalproject.stanford.edu/software/invest

identified: the urban catchment areas are the coastal lagoon city of Aveiro (Portugal), and the sea city of Rapallo (Italy). The application to case studies aims at bridging the gap between theory and practice by presenting a performance-based approach, which is one of the key issues of this PhD research. Particularly, these European cases are characterised by different urban systems with morphological, ecological and climate aspects to consider.

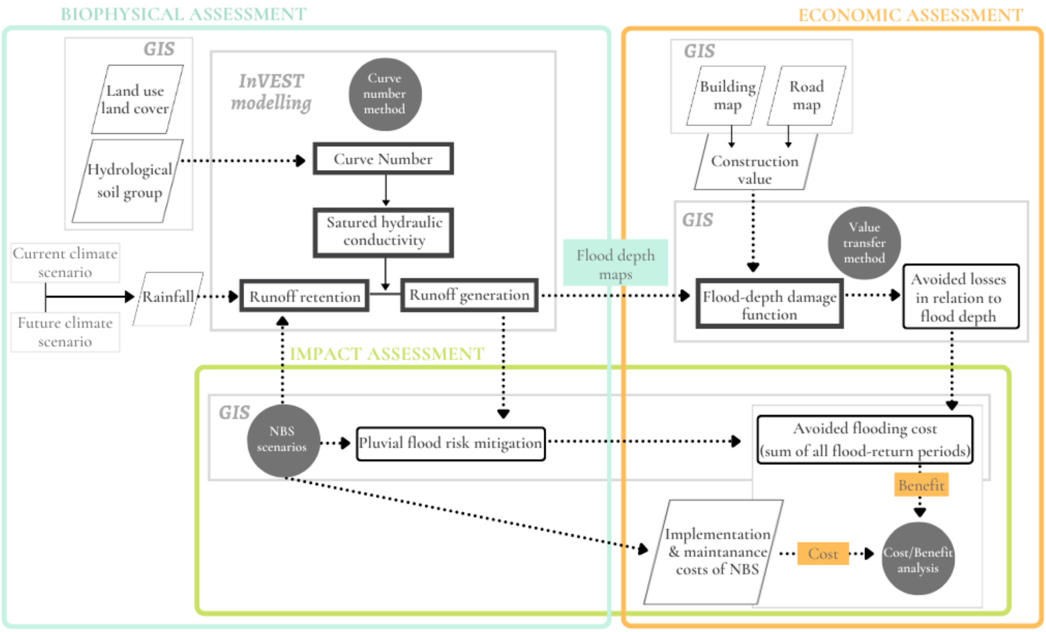

Figure 27. *Methodological framework.*

5.2 Expected result

The integrated spatial modelling approach demonstrates its utility for understanding and evaluating the dynamics of Ecosystem Services in the context-specific area (Costanza *et al.*, 2017). Indeed, quantification of ecosystem services provided by NBS implementation is a key challenge for planners and policymakers, such that these values can be accounted for when assessing alternative adaptation solutions (Zölch, Wamsler and Pauleit, 2018). Using these data, as well as assessing the benefits provided by NBS, can better inform evidence-based decisions (Alves *et al.*, 2020).

Economic analysis of NBS co-benefits can have a relevant influence on decision-making, allowing to visualize their financial effects (European Environment Agency (EEA), 2016). Benefits of flood adaptation strategies are often expressed as the avoided "expected annual damage" (EAD) achieved by the implementation of NBS (Aerts *et al.*, 2014; Haer *et al.*, 2017). This focus is crucial to understand the practical implications of incorporating NBS in urban adaptation planning, as it helps to understand the economic viability of adaptation scenarios. Therefore, through the application of scenario-based spatial modelling, this research is expected to provide insights in a replicable method of analysis that can be applied to multiple temporal and spatial contexts by allowing the evaluation of policy scenarios. The methodological framework may be used as guide on how to replicate spatial biophysical-economic assessment of NBS implementation to reduce urban pluvial flood damages in the context of climate change.

This research uses GIS tools to generate visual-friendly composite impacts and benefit maps based on the results and patterns obtained from the model simulations. Indeed, a synthetic representation is requested to simplify information using composite indicators as a proxy of values, while overcoming the complexity of multiple and interdisciplinary analysis with a wide range of variables (Salata and Gardi, 2015).

5.3 Contribution of the research and target subjects

Considering the main characteristics of this research, the contributions and target subjects can be relevant in several fields.

Firstly, this research contributes in an operative and theoretical way to one of the main challenges in urban planning by showing how rapid changing conditions, due to climate change effects, require a new, more ecologically-oriented, approach to urban analysis and spatial policies. To cope with climate change effects, one of the major issues for territorial governments has become managing risks (IPCC, 2012). As the urban context is defined as the greatest example of a complex system, managing risk means considering the wide range of relations among built and unbuilt areas located in trans-boundary regions, which are characterised by diffuse agglomerations. That system includes its environmental surrounding and natural landscape in the new view of the city, where urban biodiversity becomes an emerging paradigm to enhance urban quality (Salata, 2019).

Secondly, linked to the above mentioned, this research contributes to filling the gaps between scientific understanding of climate change variables, Ecosystem Services, and their effective enhancement through NBS in traditional urban planning. Nowadays, the interdependence of climate, ecosystems and biodiversity, and human societies is well recognised. Even if a list of solutions (such as NBS) to respond to climate-related risk exists, that alone is not enough to promote the inclusion of NBS in urban planning. The proliferation of theories often remains vague and without any practical effects on the planning tools. Still, the process of NBS institutionalization is not clear (Mendes *et al.*, 2020). Therefore, checking NBS feasibility and effectiveness represents a crucial effort towards normalizing climate adaptation (IPCC, 2022).

Thirdly, climate variables and Ecosystem services, if considered, are generally accounted in spatial planning tools via statistical application of indices (i.e. to a specific land use category) to simply obtain an evaluation of how predictable changes can affect the urban system. However, this 'statistical' approach has limits, essentially because it does not consider the complex spatial interactions among the urban components (i.e. climate variable, urban density and green system). As ecosystem functions could be altered by land-use, land-cover or climate change, urban planning needs to consider spatially-explicit approaches to inform practical implementation. Mapping tools are crucial to achieving a spatial knowledge of the city. As outlined by the Millennium Ecosystem Assessment (MEA) report (2005), there is the need to engage scientific approaches in measuring, mapping and modelling ecosystem service dynamics towards sustainable use of ecological resources (Haines-Young and Potschin, 2018). Mapping increases the integration of measurable standards in urban planning, and brings quantitative information (environmental and economic knowledge) into the practical design of planning strategies. For these reasons, this thesis tries to overcome one of the main weaknesses related to effective NBS implementation and integration into decision-making processes. This research will propose a methodological framework on how to practically assess benefits and costs (in biophysical and economic terms) of NBS to reduce climate change-related flood damages, in order to meet the emerging issues posed by contemporary living in urban areas.

Considering the intent to inform decision-making processes, the target subjects of this research are represented by different figures and maps in the context of urban climate adaptation. Measurable and verifiable integrated NBS impact assessment undoubtedly helps urban planners and administrators (such as water management practitioners). Mapping tools are useful for this purpose, dealing with an in-depth knowledge of spatial analysis, and providing insight on whether solutions are obtaining the expected results. In this sense, policymakers should also be directly interested by this approach, as it is a meaningful way to help achieve the main goal of normalizing urban climate resilience. In general, this research will take into account the need for addressing the gaps in the practical usability of the models' outputs and maps to inform politicians and urban planners.

Chapter 6

Urban flood impact assessment

6.1 Spatial modelling tool: biophysical assessment

'Models' are typically numerical simulations of real-world systems, calibrated and validated using observation data, with the intent to capture necessary and sufficient dynamics of reality, including the minimum required components. This represents both a strength and a limitation, as models seem realistic, but the requested assumptions sacrifice the details of reality (Littell *et al.*, 2011). Nevertheless, simplifications are necessary to have a comprehension of real-world processes – only through the simulation of integrated climate change effects, we can inform policies for climate adaptation (IPCC, 2014c). Moreover, models often require a huge amount of spatially-explicit and statistical input data that are not directly available for users (Salata, 2019). Modelling is a critical and crucial part of the analysis that determines the precision of it.

Spatial biophysical assessments, and particularly flood inundation maps, are developed using hydrological modelling tools, such as, HEC-RAS (Rangari, Umamahesh and Bhatt, 2019), MIKE Urban (Bisht *et al.*, 2016), ANUGA (Issermann and Chang, 2020), Infoworks ICM (Costa *et al.*, 2021), 2D and 3D hydrodynamic models (Rong *et al.*, 2020), Tuflow and SWMM (Quan *et al.*, 2019). These deterministic tools are computationally intensive and require precise input datasets, making their effective utilization challenging. For high-resolution urban flood modelling, a combination of different data, such as sewer network systems, refined topographic maps, elevation model maps, buildings, and narrow watercourses, are crucial (Bulti and Abebe, 2020). Indeed, the benefit of complex flood modelling is not satisfied when there is a lack of proper data (Afifi *et al.*, 2019). In addition, the scalability of flood depths over the entire urban area is questionable due to the interaction of numerous local factors that, in turn, poses challenges to the applicability of complex hydrodynamic models. On the other hand, simpler empirical models based on statistical correlations or machine learning algorithms (Darabi *et al.*, 2019), GIS (geographic information system) applications (Rong *et al.*, 2020), and hybrid approaches (Nkwunonwo, Whitworth and Baily, 2019), become crucial tools when there is a limited availability of hydrological data. Thus, the successful conversion of modelling results from high to low spatial resolution is important for wider applicability of the models without losing the hydrological essence (Hou *et al.*, 2019). These simple models are well agreed over large study areas (Olesen, Löwe and Arnbjerg-Nielsen, 2017).

Instead of expecting models to quantify the biophysical performance of a system accurately, their added value is the possibility to i) obtain a spatial assessment, thus understanding the location of vulnerable areas, and ii) use the model to estimate simulated adaptation alternatives (such as NBS), and understand the range of benefits that the system could reach (Salata *et al.*, 2022).

Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) is an open-source modelling platform developed by Natural Capital Foundation (www.naturalcapitalproject.org), a partnership between the Stanford University, University of Minnesota, The Nature Conservancy and the World Wildlife Fund, with the aim to integrate the value of ecosystem services (ES) into decision making and policy planning. InVEST is a modular tool for simplifying the process of mapping ecosystem services and functions. Through terrestrial, freshwater, coastal and marine ecosystem service maps, InVEST is specifically designed for urban planning evaluation, its usability ranging from general environmental assessment to local scale evaluations, with the goal of helping restore and protect natural capital.

Why the InVEST modelling tool? Firstly, InVEST is a freely downloadable software. Other free softwares exist which require medium technical skills but good knowledge of ES and their processes, such as ARIES (Artificial Intelligence for Ecosystem Services) and LUCI (Land Utilization and Capability Indicator). These tools are designed for non-experts, in order to encourage urban researchers in the field of spatial and computational ES modelling (Salata, 2019). Secondly, one of the main advantages of InVEST is related to the consistent format of data input and output of the models, which facilitates their integration with other spatially explicit tools for ecosystem assessment. Third, another benefit of the InVEST model is related to its low data requirements, keeping in mind the data scarce environment. Finally, the InVEST model for urban flood assessment (the Urban flood risk mitigation (UFRM) model is a relatively new module (from 2019) and very few studies have employed it (Kadaverugu, Nageshwar Rao and Viswanadh, 2021; Salata *et al.*, 2021). The InVEST UFRM module is designed to accommodate the hydrological aspects for easy implementation in policy research. Biophysical, morphological and climate aspects are used in combination to simulate pluvial flooding. As natural infrastructures play a crucial role in reducing flooding events, this model focuses on the action of these infrastructures mainly by reducing flood depth, slowing surface flows, or creating space for water (in floodplains or basins). Chapter 8 describes the theory behind the UFRM model together with the data input needed.

Nevertheless, various limitations and uncertainties affect spatial modelling tools. Firstly, the problem with urban flood management is linked to field measurements. Comprehensively quantifying the potential inundation area due to pluvial flooding during yearly or short-term rainfall events is challenging. Peak flows are measured on the stream network, but these volumes do not represent the flood size (Salata, 2023). Specific literature on this dynamic demonstrates how the biophysical quantification of the runoff in the built environment can be difficult to estimate because of various factors, such as the quantity, quality, and surface of buildings, the sewer system, the soil types, and the soil humidity/aridity, can affect discharge volume during an extreme rainfall event.

Second, hydrological aspects are synthetized by a simple approach (Soil Conservation Service "SCS" – Curve Number (SCS-CN) method), which introduces large uncertainties. The SCS-CN method is a parameter that assumes that the volume of water will be highest where there is a highly sealed surface and where the soil has low conductivity capacity. Therefore, the results of this study should be evaluated bearing in mind that the UFRM model uses an empirical simplification, which excludes the land slope as a parameter. Additionally, the model does not consider soil conditions. For example, it is well-known that soil conditions before an extreme rainfall event can play a significant role in changing the infiltration capacities of landscapes. After a long dry season, the first rainfall event can be dangerous because the soil can be "sealed" (Salata *et al.*, 2022).

In addition, the high level of variation of the impacts of ecosystems on hydrology systems (depending on ecosystem type, location, condition, climate, and management) determines the feasibility of achieving generalized assumptions about NBS. For example, green roofs, bioswales, infiltration trenches, or even single trees can increase or decrease water infiltration according to their location, size, age and vegetation type and density. The UFRM model does not come with built-in mechanisms to model specific NBS. At the same time, the model interface also lacks detail about the features and attributes of vegetation type for the considered NBS. However, the ranking between different land uses is generally well captured by the model, to the extent that the effect of natural infrastructure is qualitatively represented in the model outputs.

Albeit limited or partial, spatial modelling is beneficial when used to support knowledge around decision-making as it provides a holistic view of the characteristics and behaviour of the urban systems.

6.2 Environmental cost-benefit analysis

Ethics in environmental and resource economics

Modern normative environmental economics is predominantly founded on utilitarian ethics. 'Utility' is the term introduced by early utilitarian writers for the individual's pleasure, and is still used by modern economics in that way. In utilitarianism, the term 'welfare' is used to refer to the social good, hence welfare economics is the aggregation of individual utilities. In this perspective, utilitarian actions which increase welfare are right and actions that decrease it are wrong (Perman *et al.*, 2003).

Welfare economics is based on a particular form of utilitarianism, which is 'consequentialist' and 'subjectivist' in nature. Utilitarianism is a consequentialist theory of moral philosophy, as it claims that only the consequence of an action determines its moral worth, and thus, that the ends might justify the means. It is subjectivist in the sense that the measure of what is good for an individual is that individual's own assessment ('consumer sovereignty') (Perman *et al.*, 2003).

In the vision of anthropocentric utilitarianism, the founding fathers took as self-evident that only humans have 'moral standing', and they decide whether an action is right or wrong. The philosopher Peter Singer claimed that this restriction to human beings needs not to imply that interests of non-human entities should be ignored. Some species of plants and animals 'have values' to humans because they affect human utility. For this reason, environmental economics is about inducing market systems to properly consider what happens to these non-human entities that influence human utilities (Perman *et al.*, 2011). Given that humans decide what is right or wrong, there remains the question of how we should decide. The anthropocentric utilitarianism theory does not imply consumer sovereignty; however, it is true that it aligns well with the form of economic organisation that dominates human society – the market.

In the 1980s, economists and natural scientists concluded that progressing while addressing environmental problems, was needed to study phenomena in an interdisciplinary way. Economics and ecology were seen as the two disciplines most directly connected to and concerned with sustainability. Through their common roots 'eco' – 'oikos' means 'household' – ecological economists acknowledge that the scale of human housekeeping (economic study) is now such that it threatens the viability of nature's housekeeping (ecological study) in a way that it will adversely affect future generations. As stated by one of the founding fathers of ecological economics, Kenneth Boulding (1966), the view that dealing with price incentives to address environmental problems should not be considered wrong. The key point of ecological economics is that the economic system is part of a bigger system that is planet Earth (Perman *et al.*, 2011). The ecological economics view is based on the perception that the world's resource base is not unlimited and contains a set of ecosystems that are physically limited in their capacity to receive or supply material and energy flows.

In the sustainability literature, a distinction is made between weak and strong sustainability. This difference concerns the condition that should be met to realize sustainability, rather than two diverse conceptions (Perman *et al.*, 2011). Weak sustainability is the idea within environmental economics which states that 'human capital' can substitute 'natural capital' (Solow, 1991). This paradigm from the 1970s began as an extension of neoclassical economics, and refers to environmental assets as 'natural capital' and implying substitutability between capital types. The proponents of strong sustainability argue that the sum of 'human' and 'natural' capital' should be non-declining. From an ecological perspective, strong sustainability assumes that 'natural capital' is not substitutable, and should be non-declining over time. This vision implies that nature has the right to exist and, as collective good, should be preserved for future generations. Common and Perrings (1992) argue that ecological sustainability is a prerequisite for sustainability of the joint system of environment-economy, and that ecological sustainability requires resilience. The uncertainty that pervades the ecological system behaviour determines difficulties to know whether a system is resilient to a future shock *ex ante*. Additionally, the economic idea of monitoring the stock of capital as a sustainability indicator cannot be a reliable instrument to guarantee resilience.

Environmental goods and services are perceived in different ways according to the mainstream scientific lens. For this reason, it is critical and important to acknowledge that diversity of values of nature, and its contribution to the quality of life, are associated to different institutional contexts that, thus, result in more complex comparisons. The conceptual framework of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) identifies three elements in the interaction between human and non-human world: nature, nature's benefits to people, and a quality of life (Pascual *et al.*, 2017) (see **Figure 28**). "Nature's benefit" has later been replaced by "nature's contribution", because it is more comprehensive and neutral (Díaz *et al.*, 2015). The focus of IPBES is on "nature's contribution to people" (NCP), as it represents the channel between nature and quality of life. The NCP category is defined as the contributions, both positive (benefits) and negative (losses), that people receive from nature.

The wide and different perspectives of values through which people give meaning to NCP is challenging and barely recognized; thus, it is rarely considered in decision making. The consequence is that the outcomes produced are unsustainable. Therefore, IPBES developed a guide with a pluralistic approach to evaluate the diversity of values underpinning the nature-human relationships. The contrast between the use of unidimensional value framings (economic, socio-cultural, or ecological) with the application of a more integrated perspective that aims at bridging different value dimensions (associated with value pluralism) is illustrated by IPBES. It considers the utilitarian value ethics based on individual self-interested behaviour, which is often associated with a belief in material economic growth as the basis for a good quality of life that should result in protection and conservation of the environment as well as in equity. On the other hand, value pluralism ethic takes into account the diversity of worldviews looks at nature, NCP, and good quality of life as interdependent within a social-ecological perspective. This approach acknowledges the existence of different perceptions of what constitutes 'a good life' among cultural and social groups, while recognizing the intrinsic value of 'nature' for decision making (Pascual *et al.*, 2017). The IPBES perspective supports incorporating the diversity of NCP values into decision-making processes.

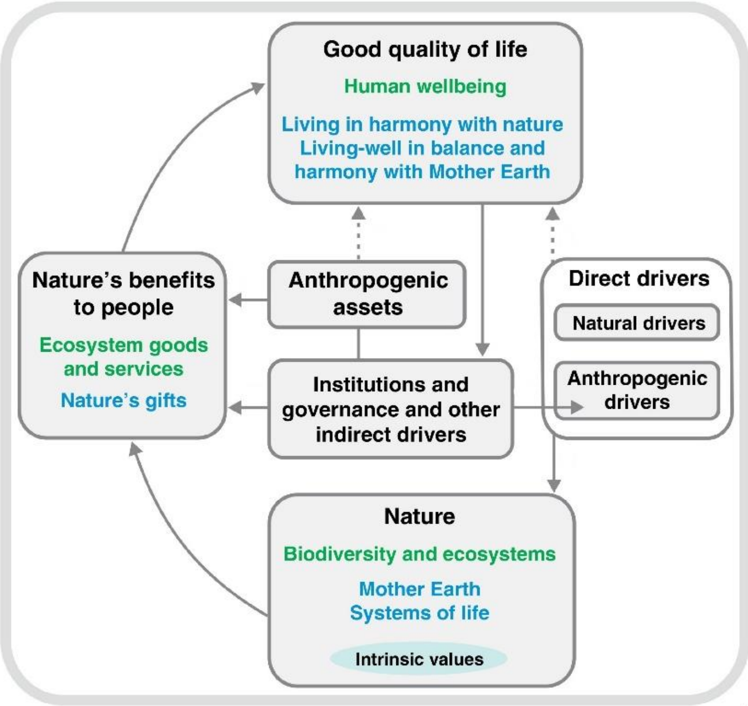

Figure 28. *The IPBES Conceptual Framework shows the boxes and arrows which denote the elements of nature and society. The black headlines in the boxes are inclusive categories that should be relevant to all stakeholders involved in IPBES. The blue and green categories are illustrative, not exhaustive, by including the categories of Western science (in green) and other knowledge systems (in blue). Solid arrows denote influence between elements while the dotted arrows represent links that are acknowledged as important. The anthropocentric values of nature are embedded in nature, nature's benefits to people and quality of life boxes, and in the arrows connecting them. The intrinsic values of nature are independent from human experience and thus do not participate in these arrows* (Díaz *et al*., 2015).

Not all NCP services have a market price; thus, they cannot be included in the decision-making process through project appraisal. The question is whether we should value nature in monetary terms or not (Kallis, Gómez-Baggethun and Zografos, 2013). Two schools of thought (from 1998) divide ecological economists about monetary valuation of ecosystem services. Costanza *et al.* (1997) accepted valuing nature in monetary terms as a pragmatic choice. Rees (1998) rejected it on ethical grounds by claiming that giving monetary values to ecosystems is a partial solution and may be counterproductive.

The original, and still principal, motivation for environmental valuation is to enable environmental impacts to be considered in cost-benefit analysis (CBA). Monetary valuations are not to be considered as isolated phenomena of methodological interest, but as part of a commodification process that includes institutional and technological changes needed to reshape the ways humans relate to nature. In this sense, monetary valuation of ecosystem services does not mean their commodification, but it paves the way for this process to take place. Commodification is here intended as the process through which goods and services that were not for sale enter in the sphere of market exchange. On the other hand, there are biophysical, political and ethical limitations to monetization that, in turn, limit commodification (Kallis, Gómez-Baggethun and Zografos, 2013).

Philosophical roots and ethical issues in environmental cost-benefit analysis

Nowadays, it is widely accepted that economic welfare is deeply dependent on environment and human well-being. Environmental CBA is applied welfare economics; for this reason, some implications for economic appraisal have to be considered (Perman *et al.*, 2011; O'Mahony, 2021).

Globally, economic analysis and environmental CBA have undergone a significant change in recent years, mainly driven by the urgency of global warming and ecological disasters (Allen *et al.*, 2018; IPBES, 2019). Indeed, there are several implications for the appraisal of public and private investments. The IPCC emphasised the limits of economics in guiding decision-making, as economists often aggregate welfare, while other ethical considerations may not be reflected in the economic evaluations (IPCC, 2014c; O'Mahony, 2021). The environment is a core constituent of welfare economics and human well-being. In the context of climate change, a few limitations are raised for economic methods; for instance, in case a change is non-marginal and it could affect macroeconomics. Additionally, the timescale is long, thus making the choice of discount rate controversial and highly crucial. Of equal importance and difficulty is the measuring and evaluation of non-market values including the variety of species, ecosystems and cultures (O'Mahony, 2021). These aspects are the major challenges to the use of standard economic approaches like CBA, leading to significant questions about when they are suitable, or what technical changes are needed to make them applicable.

There are practical and ideological objections to environmental CBA (OECD, 2006). Many people take the view that it is simply the wrong way, on ethical grounds, to inform social decision-making regarding the serious environmental impacts of a specific event or phenomenon. In practice, the claim that the benefits of a project exceed its costs is not persuasive when both values rely on arbitrary valuations, such as for environmental resources or human life. There are inherent limitations to the accuracy of non-market valuation and, thus, to produce reliable information for environmental CBA. From an ideological perspective, two classes of ethical objections are raised. The first claims that only humans have moral standing, however, rejects consumer sovereignty by arguing that individual preferences are weak to guide human interests. This view reflects the idea of individuals that make decisions based on what is good for society. The second class argues that animals and plants should have 'moral standing', as humans do, otherwise CBA cannot be legitimately applied. However, they argue that 'destruction of nature' should be considered only if this affects 'quality of life'. Both theories are restricted to human interests even if the uncertainties related to future costs of current environmental damage are recognised (Perman *et al.*, 2011).

The European Commission guidance on CBA states that "not taking into account environmental impacts will result in an over- or underestimation of the social benefits of the project, and will lead to bad economic decisions" (Sartori *et al.*, 2014). The use of CBA is encouraged by organizations such as the OECD (2006) and the European Commission (2016) to deliver the 'integration of the environment into economic policies' and improved wellbeing (OECD, 2006; European Commission, 2016). Indeed, a proper environmental CBA supports decision procedures for achieving desirable results (Adler and Posner, 1999).

As CBA is sensitive to ethical and philosophical issues, this analysis should be treated as a tool to aid decision-making by organizing thinking about decisions and not as the decision itself (Zerbe and Dively, 1994). As a decision procedure for evaluating welfare gains or losses derived from an investment, CBA is not a moral standard (O'Mahony, 2021). Indeed, CBA could be more or less accurate/costly than others (Adler and Posner, 1999).

Environmental cost-benefit analysis and alternatives

CBA is a policy assessment method that quantifies in monetary terms the value of the consequences of a policy. The basic strategy of CBA in relation to the environment is to attach monetary values to the environmental impacts so that they are considered along with, and in the same way as, inputs and outputs from a project (Perman *et al.*, 2011). The broad purpose of CBA is to help social decision-making and to improve allocative efficiency (Boardman *et al.*, 2018). CBA is an economic approach that assesses, considering a limited number of scenarios, the most economically viable alternatives – identifying the benefits (i.e. increase in human well-being) and the costs (i.e. reduction in human well-being) to finally calculate the trade-off between them (OECD, 2006).

CBA is often contrasted with other decisional procedures used in the environmental field, such as environmental impact assessment (EIA), risk assessment (RA), risk benefit analysis (RBA), cost-effectiveness analysis (CEA) or multi-criteria analysis (MCA),(OECD, 2006).

EIA is a systematic procedure for collecting information about environmental impacts of a project, which ignores non-environmental impacts and costs. Impacts may be weighted and become input for the CBA.

RA includes either health or environmental risk assessment of a project, product or policy. This technique may be expressed as the probability of some defined death or ecosystem effect occurring. In general, RA may not translate into decision rules easily.

RBA aims at valuing benefits, costs and risks, where risks are treated as costs and expressed in monetary terms. The function is not far from CBA rule (Eq. 1):

$$[Benefit - Costs - Risks] > 0 \tag{1}$$

CEA is a technique that assumes a single indicator of effectiveness (E) to be compared with costs (C). CEA is based on the idea of selecting the option which, at least cost, achieves specific objectives. It differs from the CBA in that it gives absolute priority to one aspect of performance (Perman *et al.*, 2003). The methodology applied in this type of analysis is to estimate the costs (investment and maintenance) for different alternatives to finally evaluate the physical pros and cons over a medium/long-term time horizon. The common function (Eq. 2), indeed, is the cost-effectiveness ratio (CER):

$$CER = \frac{E}{C} \quad (2)$$

where E is in some environmental unit and C is expressed in money units. These two different units create an important implication. This is the reason why CEA can be used solely as guidance for selecting several alternative projects, by ranking a set of policies.

MCA is similar for some aspects to CEA however it involves multiple indicators of effectiveness. This technique provides various effectiveness indicators measured in different units which must be normalised by converting them to scores that are aggregated through a weighting procedure. MCA differs from CBA because not all criteria employed are monetised. The outcome of the MCA is a weighted average of the scores, with the option providing the highest weighted score being the "best option". The final score for a project is expressed by the following function (Eq. 3):

$$S_i = \sum_j m_j * S_j \quad (3)$$

where i is the ith option, j is the jth criterion, m is the weight and S is the score. MCA offers a broader interpretation of CEA as it openly envisages the existence of multiple objects.

In conclusion, only MCA can be considered, among the above-mentioned techniques, as comprehensive as CBA. All the other procedures either deliberately narrow the focus on benefits or ignore the costs. However, these methods are not all interchangeable. Generally, each approach reveals insights into features of good decision-making, with CBA having the most comprehensive approach. One main reason to look at alternatives is to perform quicker procedures, given that political decisions cannot always wait for the results of a CBA, which normally is information and time demanding (OECD, 2006).

Cost-benefit analysis criteria

Cost-benefit analysis (CBA), as part of financial analysis, helps identify the attractive investment projects (Zerbe and Dively, 1994; Roebeling, 2003). Indeed, during the last decades, CBA emerged as one of the major streams of investment theories (Roebeling, 2003).

CBA was developed by Jules Dupuit in 1848, and then formalized with the founding concepts of CBA by the economist Alfred Marshall (Watkins, 2003). Since 1960, CBA is recognised as the major appraisal technique for public investments and policies (OECD, 2006). This includes a systematic cataloguing of impacts as benefits (pros) and costs (cons), valuing the impacts in monetary terms (assigning weights), to finally determine the net benefit of the proposal related to the current policy (with net benefit equalling incremental benefits minus incremental costs) (Boardman *et al.*, 2018).

The *net benefit* or *net present value* (*NPV*) is the most common criterion used to compare those benefits and costs. Formally, *NPV* is defined as the discounted sum of the differences between (discounted) benefits B_t and (discounted) costs C_t attributed to the installation of a project and that occur in each period t over the entire lifetime of a project T (Zerbe and Dively, 1994) (Eq. 4):

$$NPV = \sum_{t=0}^{L} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{L} \frac{C_t}{(1+r)^t} \quad (4)$$

Where r is the time discount rate. The correct rule is to adopt any project when *NPV* is positive (*NPV*>0), and to rank projects by their *NPV*. In other words, the analyst should recommend proceeding with the project if its incremental benefits exceed its incremental costs (Boardman *et al.*, 2018). The *NPV* approach has several advantages when compared to other approaches (shown later in this section). Firstly, the calculation is quite easy; secondly, it produces correct financial decisions; and third, it is applicable to financial and non-financial problems (Zerbe and Dively, 1994). For these reasons, *NPV* is considered a fundamental financial equation of cost-benefit analysis. However, its shortcoming is related to the fact that *NPV* can only be employed to compare projects with the same lifespan.

While the NPV criterion results in a more efficient allocation of resources, it does not necessarily recommend the most efficient allocation of resources because the most efficient alternative might not have been actually considered by the analyst, or might not have been feasible because of budget constraints, political concerns, or other reasons. **Figure 29** shows this situation. By considering a set of proposed projects that vary according to the amount of output (Q), which is related to the scale of the project, the benefits and costs associated with alternative scales are represented by the functions B(Q) and C(Q), respectively. B(Q) increases as the scale increases, but at a decreasing rate, while C(Q) increases at an increasing rate. A small-scale project (such as Q1) has a positive net benefit relative to the status quo policy, Q0. As the scale increases, the net benefit increases up to the optimal scale, Q*. As the scale increases beyond Q*, the net benefit decreases. Essentially, the net benefit is positive as long as the benefit curve is above the cost curve, it is zero where the cost curve and benefit curve intersect, and it is negative for yet larger-scale projects (Boardman *et al.*, 2018).

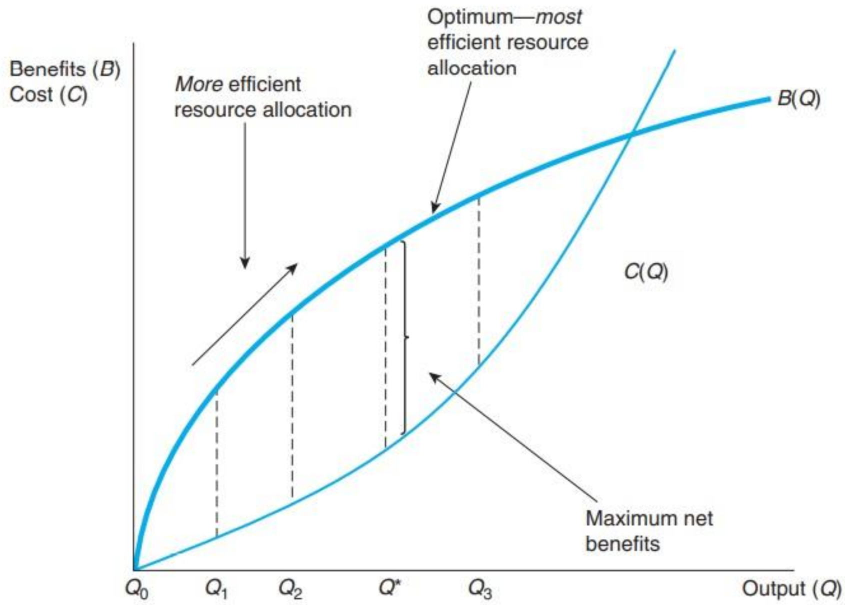

Figure 29. *Cost-benefit analysis and efficient resource allocation (from Boardman et al. (2018)).*

It is important to highlight the limitations of CBA. Two types of circumstances make the NPV criterion an inappropriate decision rule for public policy. First, technical limitations may make it impossible to quantify and monetize all relevant impacts as costs and benefits. Second, goals other than efficiency are relevant to the policy (such as equity). Nevertheless, even when the net benefits criterion is not appropriate as a decision rule, CBA usually provides a useful benchmark for comparing alternative policies in terms of efficiency along with other goals (Boardman *et al.*, 2018).

The discounted *benefit-cost ratio (BCR)* is another important approach that leads to project decisions that are identical to those reached using *NPV* . Formally, *BCR* is defined as the ratio of the present values of total discounted benefits and costs for the installation of a project that occur in each period t over the its entire lifetime T (Zerbe and Dively, 1994; Boardman *et al.*, 2018) (Eq. 5):

$$BCR = \frac{PV(B)}{PV(C)} = \frac{\sum_{t=0}^{L}\frac{B_t}{(1+r)^t}}{\sum_{t=0}^{L}\frac{C_t}{(1+r)^t}} \quad (5)$$

where r is the time discount rate. Essentially, a proper use of *BCR* requires a given time discount rate and the available capital. Similarly, to *NPV*, investment should take place in the case of *BCR*>1 (*NPV*>0). In respect to *NPV*, *BCR* holds some constraints: benefits and costs should be carefully defined because of the method’s sensitivity to these factors; *BCR* is subjected to scale issues; all projects compared should present an equal lifespan and outlay basis (Zerbe and Dively, 1994).

Other important procedures for making financial decisions include *payback period*, *internal rate of return (IRR)* and *wealth-maximizing rate (WMR)*. However, these approaches have not been included in the discussion as they are considered out of the scope of this research.

Discounting in cost-benefit analysis

In the context of economic activity and the natural environment, the question of how we should behave in respect to future generations is crucial. In CBA analysis, costs and benefits which impact the future over years need to be aggregated. For this reason, benefits and costs are discounted relative to present benefits and costs, in order to obtain their present values (PV). Discounting is a financial tool to conduct analysis comparing costs and benefits that are received at different moment in times, as a way to reflects the true value of these payments (Perman *et al.*, 2011). The discounting process is needed for two main reasons. First, there is an opportunity cost to the resources used in a project in the way they could earn a positive return (such as ecosystem conservation). Second, most people prefer to consume now rather than later. Discounting is not related to inflation, although inflation must be considered (Boardman *et al.*, 2018).

A cost or benefit that occurs in year t is converted to its present value by dividing it by the present value factor/discount factor (as $(1 + r)^t$, where r is the time discount rate). Lower time discount rates give more weight to the future values, while higher time discount rates put less weight on future values.

There is a controversial debate in the dichotomy of whether to consider a high or low time discount rate. Financial time discount rates are typically higher than economic time discount rates. This is because public entities (such as governments) have more patience than individuals and private entities. Generally, the discount rate should reflect the degree of risk of a project. Hence, ecosystem conservation (as opportunity cost) is difficult to handle because of its vulnerability and instability. Once uncertainty about the future (whether in terms of interest rates or economic prospects) is introduced, there are situations where the correct discount rate declines over time. A practical use of time-varying discount rates might overcome the "tyranny" of discounting, even if it leads to other problems like "time-inconsistency". Time inconsistency or incongruence refers to the situation where plans made in the present are contradicted by later behaviour. Some experts consider unacceptable any time declining discount rate to overcome the issue of "time inconsistency" (OECD, 2006). Some critics pointed out that exponential discounting, even at low rates of discount, discriminates against future generations (Perman *et al.*, 2011). In modern utilitarianism, a low discount rate should be considered to guarantee well-being to everyone in the future.

Should future humans be treated equally as current generations? Two schools of thought exist for discounting the future utility. The descriptive perspective argues that a positive discount rate is required because that is what is observed. This view is based on the theory of maximisation of social welfare (as consumption growth). The utility of the individual is bigger when the utility of the society (wellbeing) increases on average. The prescriptive perspective refers to the use of a positive time discount rate on the decreasing probability of human existence with greater futurity (Perman *et al.*, 2011). This second perspective considers positive constant time discount rate to be normally taken low (approaching zero).

The use of a high discount rate is appropriate for risky investments that provide a stream of gains and losses that accrue to the investor personally. Based on classical utilitarianism principles, opting for low time discount rates is justified if one is focused on welfare rather than on investment narrative. The major criticism to a low discount rate is due to the strong inconsistency with the preferences revealed in market decisions. Essentially, people do not care about the future as they morally should do. The Stern Review (2006) highlighted the role of ethics in the choice of discount rates within the economics of climate change, and argued that many previous economic analyses did not pay enough attention to ethics (Stern, 2007). Taking climate change action now, to secure benefits in the forms of avoided climate change effects, would continue to generate benefits far into the future. In essence, stabilizing the climate decreases the incidence of disasters in the future. A concerning thought is the idea that climate change will turn out much worse than we are anticipating, and that damages will be catastrophic. Thus, discounting is going to affect how much humans should do now to abate greenhouse gas emissions. Stern took a stronger prescriptive line on discounting, by arguing that an r of 0.001 is the most reasonable value to consider, and the only ethical basis to make it non-zero is the extinction argument. The Stern review concludes that early climate change action makes good economic sense (Stern, 2007; Perman *et al.*, 2011).

6.3 Benefit transfer method

The valuation of ecosystem services is an important tool for decision-making, but the collection of site-specific information and data is costly and for this reason benefit transfer methods became common in this field (D'Antonio, 2019). Benefits or value transfer (BT) can be used to estimate the non-market value of environmental resources and, especially, of ecosystem services (Bateman *et al.*, 2000; Brouwer, 2000). This method involves economic values of ecosystem services using value data and information from other, similar, ecosystems and populations of beneficiaries. Value transfer is a procedure of estimating values of an ecosystem service of current policy interest (at a "policy site") by assigning an existing value estimate for a similar ecosystem elsewhere (at a "study site") (Brander, 2013). It is well accepted that transfer studies are the core of practical policy analysis (OECD, 2006). This method has been rapidly growing in literature over the past 15 years because it reduces the need for costly and time-consuming original studies of non-market values. Early development has been found in the water resources research in 1992. An important milestone was the publication of Desvousges, Johnson and Banzhaf (1998) on the validity of BT, that distinguished two basic definitions.

The first one is a wider concept based on the use of existing information designed for one specific context to address policy issues in another context. These kinds of studies are not limited to CBA. The second definition is a narrower concept built on the use of values of a good estimated in one site as a proxy for vales of the same good in another site. Values are being transferred from data-rich countries to countries where there is a paucity of such information. This type is commonly used in CBA.

The transfer procedure needs to adjust values which reflect the differences at the original study site and the new policy site. At least three main types of adjustment exist: unadjusted (or naïve) willingness to pay (WTP) transfer, WTP transfer with adjustment, and WTP function transfer (OECD, 2006).

The first procedure "borrows" an estimate of unadjusted WTP in context S (the study site) and applies it to context P (the policy site), such that (Eq. 6):

$$WTP_S = WTP_P \tag{6}$$

With this method, a variety of unit values may be transferred, but the most common are mean or median measures. Mean values are compatible with CBA studies as they allow simple transformation of aggregate benefit estimates. The main advantage is the simplicity of this approach which can be applied once suitable original studies have been identified. However, it fails to identify important differences and divergences between the characteristics of an original study site and a new policy site.

The second approach uses income per capita (Y) to adjust the WTP (see Eq. 7):

$$WTP_P = WTP_S \left({}^{Y_P}\!/_{Y_S} \right)^e \tag{7}$$

where e is the income elasticity of WTP. The income elasticity is an estimate of how the WTP for the non-market good in question varies with changes in income. In this approach, the only feature that is changed between the two sites is income, probably because it is considered the most influential factor for changing WTP. This method requires detailed information on the income at the study and policy site.

Thirdly, a more sophisticated approach is to transfer the benefit from S to P by considering other physical features as well as the socio-economic and demographic characteristics of the population at the site. The function of WTP_S at the site might be expressed as follows (Eq. 8):

$$WTP_S = f(A, B, C, Y) \tag{8}$$

where A, B, C are additional and significant factors affecting WTP in addition to Y at site S. This method is even more complex as it requires extensive and detailed information on the study and policy site.

An even more ambitious approach is that of the meta-analysis (Bateman *et al.*, 2000). This method is a statistical analysis of summary results from a large group of primary valuation studies, which might take an average of existing estimates of WTP for ecosystem services values to be used in policy site studies.

A common aspect for all three typologies is the level of accuracy; this is linked, in part, to the measurement errors of the original studies, meaning it is unavoidable to also transfer part of those (Wilson and Hoehn, 2006). Another source of error is linked to the adjustments needed when accounting for differences in biophysical and socio-economic characteristics, in particular for income level (Wilson and Hoehn, 2006). For these reasons, Wilson and Hoehn (2006) state that a benefit transfer can be considered if the study shows consistency concerning the ecosystem commodity to be valued.

Generally, the choice of which value transfer method to use is largely dependent on the availability of primary valuation estimates, as well as the degree of similarity between the study and policy sites. When value information is available for a highly similar study site, unit value transfer may provide the most straightforward means of conducting value transfer. In cases where study sites and policy sites are different, value function or meta-analytic function transfer offers a means to systematically adjust transferred values in order to reflect those differences (Brander, 2013).

Ecosystem service values estimated using BT methods may be inaccurate for various reasons. Indeed, values estimated using BT come with a level of uncertainty, dictated by the following factors (European Environment Agency (EEA), 2010; Brander, 2013):

1. Possibility of inaccuracies in primary valuation estimates (e.g. weak methodologies, unreliable data, analyst errors, etc.).
2. The available information on ecosystem service values may be unrepresentative due to the processes through which primary valuation study sites are selected and results are disseminated, which can be biased towards certain regions, services, methods, and findings.
3. The number of reliable and high-quality primary valuation results may be limited, especially for some ecosystem services and regions. For this reason, some geographical areas and certain ecosystem services provide good quality value estimates whereas others are still relatively few.
4. The process of transferring study site values to policy sites can also potentially result in inaccurate value estimates named ‘generalisation error’. It occurs when values for study sites are transferred to policy sites that are different without fully accounting for those differences (in terms of beneficiary characteristics, such as income, culture, demographics, education etc.; or biophysical characteristics, such as quantity and/or quality of the ecosystem service, availability of substitutes, accessibility etc.).
5. Temporal source of generalisation error may be an issue as preferences and values for ecosystem services may not remain constant over time. A value function that predicts current values well may not perform as well in predicting future values.

6.4 Flood damage assessment

6.4.1 Basic concepts

Damage assessment of natural hazards, as is the case of flood events, plays a crucial role in giving information to decision support systems in the field of climate change adaptation planning. Particularly in Europe, the economic evaluation of flood damages has become a dominant approach in flood risk management (Merz *et al.*, 2010). New concepts in flood management are even more related to risk analysis in respect to traditional approaches, concentrated essentially on controlling and reducing flood hazards (in terms of decreasing the probability of occurrence and intensity of floods). As defined by Merz *et al.* (2010), the focus on risk is defined as damage that occurs, hence this aspect needs to be assessed in the evolving context of flood management that considers, among others:

- Flood vulnerability assessment;
- Flood risk mapping;
- Flood risk reduction measures evaluation.

Flood damages are differentiated into two categories: direct and indirect damages. Direct damages are the effects derived from the contact of flood water with humans, buildings, or other objects. The costs of direct damages are generally easier to quantify than those of the indirect kind. Indirect damages are induced by direct impacts, but they appear outside the flood event in terms of space and time. Both types of damages are classified into tangible and intangible, which is related to their possibility to be assessed in monetary terms (Parker, Green and Thompson, 1987; Merz *et al.*, 2010). Tangible damages are relatively easily quantified in monetary values while the intangible damages are not traded in a market, and are difficult to express in economic values. Some examples for the different types of damages are shown in **Table 7**:

Table 7. *Types of flood damage.*

	Direct	**Indirect**
Tangible	Damage to buildings (structures and content), infrastructures (i.e. roads), land erosion, etc.	Disruption of public services out of the flooded area, cost of traffic disruption, etc.
Intangible	Loss of life, injuries, damage to cultural heritage or ecosystems, etc.	Traumas, loss of trust in authorities, etc.

Direct monetary damage assessment

The most frequent procedure for monetary assessment of direct flood damages is based mainly on three steps:

1. Homogenous classification of element at risk;

2. Exposure analysis by defining the type of elements at risk and estimating their asset value;
3. Sensibility analysis by linking relative damage of the elements at risk to the flood effects.

Firstly, the common adopted classification of element at risk is based on economic sectors, such as private households, companies, infrastructure, and agriculture, with other differentiations into sub-classes. This is because different economic sectors show different characteristics concerning assets and susceptibility. For example, elements at risk in the residential sector are mainly buildings; this is only partly the case in other sectors like the commercial or agricultural sector. Moreover, flood impact varies between sectors. For instance, flood damage to residential buildings is strongly dependent on the water depth of a flood, whereas for damage to agricultural crops the timing and duration of the flood are more significant (Förster *et al.*, 2008; Merz *et al.*, 2010). Furthermore, a pragmatic reason for using economic sectors as classification criteria for the elements at risk is that economic values are usually aggregated according to economic sectors.

Secondly, the exposure analysis is developed by intersecting the flood maps with the asset values through Geographic Information Systems (GIS) (Merz *et al.*, 2010; Baptista Borges, 2013).

Third, the sensibility analysis introduces the vulnerability of the element to the flood hazard. Assessing the expected damages of a flood event is conventionally done employing the depth damage-functions (DDF) approach, considering the relation between floodwater depth and percent damage for a variety of sectors. The damage-function methodology represents the economic loss (as absolute or relative values) as a function of the maximum water depth. Nonetheless, other factors may influence the amount of damage caused by a flood event, such as flow velocity, duration of flood, effectiveness of the emergency response, etc. (Middelmann-Fernandes, 2010). A common approach is to define the damage percentage as "the ratio of the total cost to replace the damaged components of a flood-affected property to the pre-disaster market value of the property" and with the costs of the repair and the market value referring to the same period (Pistrika, Tsakiris and Nalbantis, 2014). DDF can be developed through two approaches (Merz *et al.*, 2010):

- Empirical approach employing data collected after a flood event (real data);
- Synthetic approach based on estimating the expected damages for a specific scenario (for instance, the expected damage on a building when the water depth is 2m (Baptista Borges, 2013)).

As stated by Huizinga, de Moel and Szewczyk (2017), in damage modelling, the expected maximum damage values can be presented as: building based; land-use based, and object based. The first type of damage value represents the maximum damage calculated with the building area in square meter if the footprint of individual buildings is used for damage calculation. The second concerns the maximum damage calculated in square meter for buildings if land-use maps are used containing a mixture of houses, roads and empty space between individual buildings. The third type presented is applied when only building locations are known. In this case a building having "general" characteristics will be applied.

Figure 30 shows an example of DDF curve for German economy. **Figure 30(a)** shows the inflation-adjusted average maximum damage. **Figure 30(b)** represents the generic relative depth-damage functions. Both maximum damage and relative depth-damage functions have been adapted from Huizinga, de Moel and Szewczyk (2017). With higher portion of population and services in the most flooded areas (in terms of flood depth), the damages and related costs on infrastructures might increase.

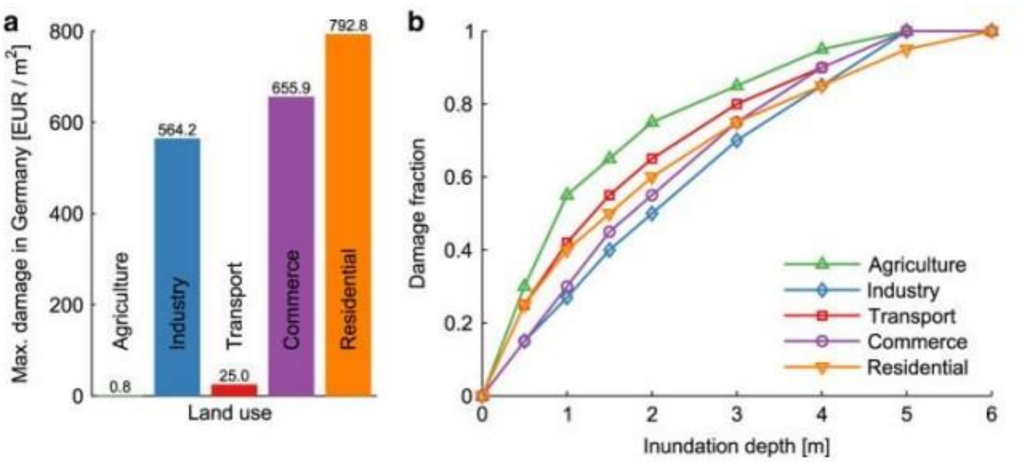

Figure 30. *Depth-Damage function for different economic sectors in Germany. (a) Average maximum damage per m^2 (inflation adjusted). (b) Relative depth-damage functions for each economic sector (from Prahl et al. (2018)).*

Direct flood damages are generally easier to assess than indirect damages. Indirect damages may have effects on time scales of months and years and, thus, complicate the quantification of those damages. Ensuring that everything is counted is crucial to conduct this kind of assessment (Merz *et al.*, 2010). Nevertheless, estimating direct-tangible damages without considering the “social” flood effects (e.g., those caused by the disruption of people and communities, and that do not or cannot carry a monetary evaluation) is limiting. As mentioned in **Table 7**, floods can cause health impacts that are enduring, including the stress and trauma created over months or years afterward. Hence, intangible damages should be measured to be accounted as costs when evaluating policy options, and thus avoiding the underestimation of flood damages.

6.4.2 Depth-damage function: mathematical derivation and application

This section contains the conceptual definition of the mathematical relation between precipitation, with a certain return period, and the total and annual expected damage costs. This mathematical derivation is explained by firstly describing the set of equations along with the derived damage cost function, and then by showing a numerical application.

Firstly, it is crucial to define the equation that relates the damage factor and the water depth of a flooded area. The equation is derived from DDF curves from the JRC report of the European Commission (Huizinga, de Moel and Szewczyk, 2017). Equation (9) presents the normalized damage equation, explaining the relation between the damage factor (DF) and the water depth (D):

$$DF(D) = (a * D) - (b * D^2) \tag{9}$$

where a and b are parameters.

The second step is to explain the relation between the total damage to an object and the water depth. Equation (10) is the total damage cost equation (TF), and explains this relation. To calculate the total damage cost of an object, Equation (9) is multiplied with the real estate value (v) of said object:

$$TF(D) = v * [(a * D) - (b * D^2)] \tag{10}$$

Then, to obtain the damage costs per return period, the relation between return period and water depth is necessary. Equation (11) describes this relation between return period (R) and water depth (D), which is derived from Gensen et al. (2020). Equation (12) has rearranged the water depth (D) to the left-hand-side. Hence:

$$R(D) = c * EXP(d * D) \tag{11}$$

$$D = \ln\left(\frac{R}{c}\right) * \left(\frac{1}{d}\right) \tag{12}$$

where c and d are parameters.

The next step is to explain the relation between the total damage cost and the return period. The total damage cost (TD) per return period (R) (Eq. 13) is obtained by substituting Equation (12) into Equation (9). Hence:

$$TD(R) = v * \left(\frac{a * \ln\left(\frac{R}{c}\right)}{d} - \frac{b^2 * \ln\left(\frac{R}{c}\right)^2}{d^2}\right) \tag{13}$$

To be able to calculate the annual damage costs from the total damage Equation, the relation between the frequency of an event (i.e. the probability of an event happening) and the return period is needed. Equation (14) explains this relation between frequency (F) and return period (R), such that:

$$F(R) = \frac{1}{R} \tag{14}$$

The final step is to calculate the annual damage costs by multiplying the total damage costs of an event with the probability of an event happening. Equation (15) explains the relation between annual damage costs (AD) and the return period (R), which is obtained by the multiplying Equation (13) and Equation (14), such that:

$$AD(R) = v * \left(\frac{a * \ln\left(\frac{R}{c}\right)}{d} - \frac{b^2 * \ln\left(\frac{R}{c}\right)^2}{d^2} \right) * \frac{1}{R} \tag{15}$$

The last part of this subchapter aims at showing a numerical application of the above-mentioned equations, to give a visual representation of the relation between the flood damage costs and the flood return period. The base parameters are shown in **Table 8** (Huizinga, de Moel and Szewczyk, 2017).

Table 8. *Parameters and corresponding values (from Huizinga, de Moel and Szewczyk (2017) and Bennink (2022)).*

Parameter	*a*	*b*	*c*	*d*	*v*
Value	0.3626	0.0338	0.0315	1.796	300,000

By formally substituting the values a and b in Equation (9), the damage factor can be calculated in relation to the water depth:

$$DF(D) = (0.3626 * D) - (0.0338 * D^2)$$

Figure 31 represents the curve calculated using Equation (9). It shows that with higher water depth, the damage factor increases at a low rate (decreasing rate).

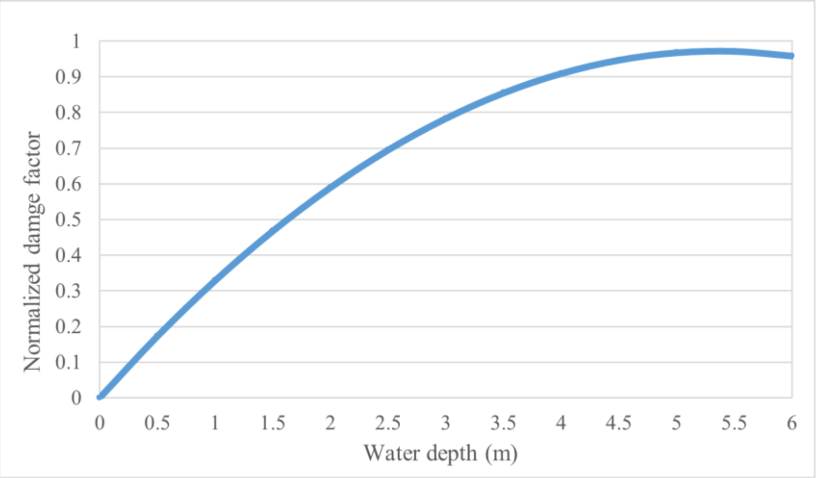

Figure 31. *Normalized damage factor per flood water depth (m).*

To obtain the function of total damage cost per water depth per object, the real estate value (v) is included by using the Equation (10):

$$TF(D) = 300000 * [(0.3626 * D) - (0.0338 * D^2)]$$

From **Figure 32**, the curve of total damages is shown. As for the normalized damage factor, the total damage costs increase with the first meters of water depth (until 5 m). This increasing is, again, shaped by a decreasing rate, meaning that a variation of water depth determines a smaller variation of total costs.

In order to describe the relation between the total damage costs with the return period, Equations (10 and 11), which relate the return period and the water depth, have been employed:

$$R(D) = 0.0315 * EXP(1.796 * D)$$

$$D = \ln\left(\frac{R}{0.0315}\right) * \left(\frac{1}{1.796}\right)$$

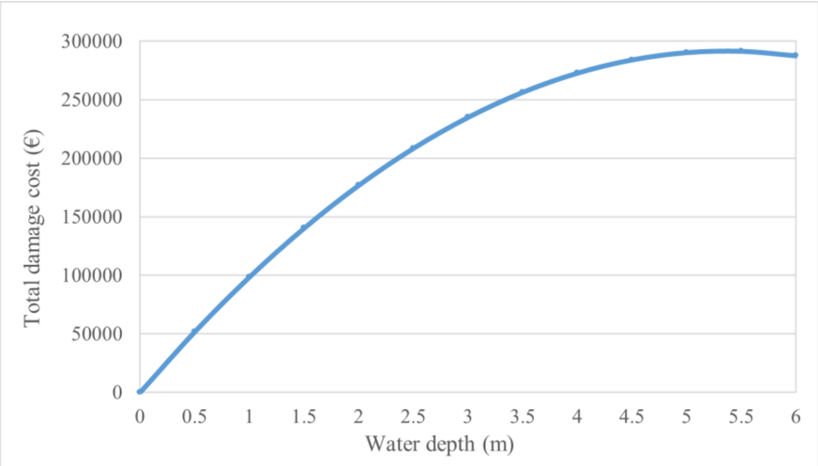

Figure 32. *Total damage costs (€) per water depth (m).*

The function of the water depth per return period is presented in **Figure 33**. The curve increases with an increasing rate. The depth of water substantially increases with differences in minor return periods, while at higher return periods the water depth levels stabilize.

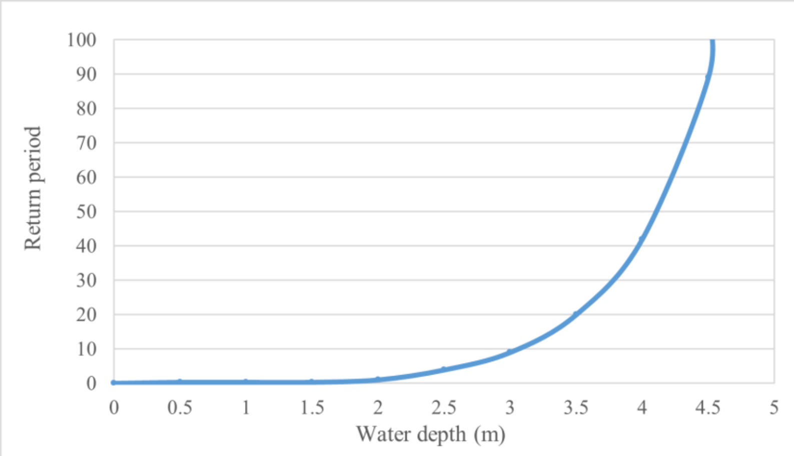

Figure 33. *Water depth (m) in relation to the flood return period.*

The following function (TD(R)) (from Eq. 12) and **Figure 34** describe the relation between total damage costs and return period. The curve increases with a decreasing rate, which means that for small differences in the return period, the total damage costs grow significantly. At higher return periods (such as 100-years), it is shown that the total damage cost does not increase, remaining almost stable. In general, the bigger increase in damages is related to small flood return periods.

$$TD(R) = 300000 * \left(\frac{0.3626 * \ln\left(\frac{R}{0.0315}\right)}{1.796} - \frac{0.0338^2 * \ln\left(\frac{R}{0.0315}\right)^2}{1.796^2} \right)$$

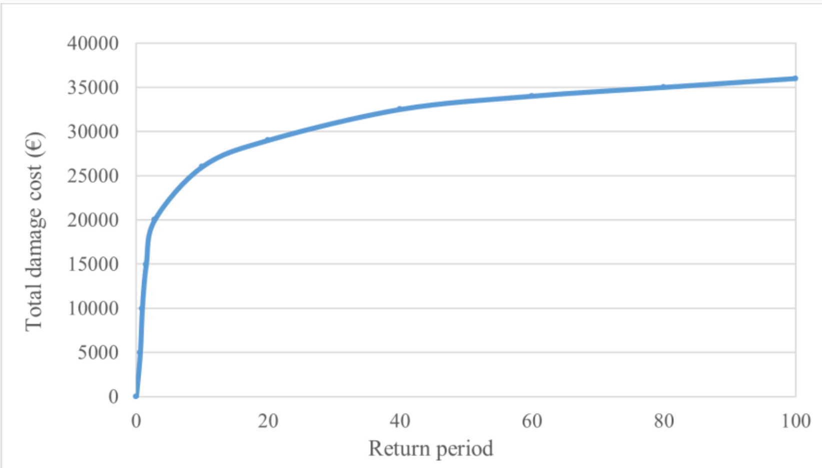

Figure 34. *Total damage costs (€) related to the flood return period.*

To finally calculate the annual damage costs (AD(R)) (see Eq. 15), the probability of occurrence of a flood event should be considered. As the return period is the expected period of time in which a flooding event occurs, the frequency is described as the probability of occurrence (i.e. 10-years return period with F(R)=1/10, as shown in Equation (14).

$$AD(R) = 300000 * \left(\frac{0.3626 * \ln\left(\frac{R}{0.0315}\right)}{1.796} - \frac{0.0338^2 * \ln\left(\frac{R}{0.0315}\right)^2}{1.796^2} \right) * \frac{1}{R}$$

Firstly, **Figure 35** points out this relation between flood return period and frequency of a flooding event. The curve behaviour decreases at a decreasing rate. Generally, a small flood return period occurs frequently, while a large return period happens rarely.

Then, **Figure 36** presents the annual damage cost curve which decreases at a decreasing rate. With smaller return periods the differences in annual damage costs are relatively high, and with larger return periods, the differences in annual damage costs are relatively little. Clearly, the smaller the return period, the higher the annual expected damages.

To conclude, this application has shown that although a high return-period (e.g., 100-years) determines larger total expected damages, by considering the frequency of occurrence of each event, the annual damages are bigger when considering a small return period (as 10-years). In other words, the total expected damage costs of a less intense flood event are significantly lower than those of a high flood return-period, however, their frequent nature means that their cumulative damage exceeds the annual expected damage costs of intense flood events.

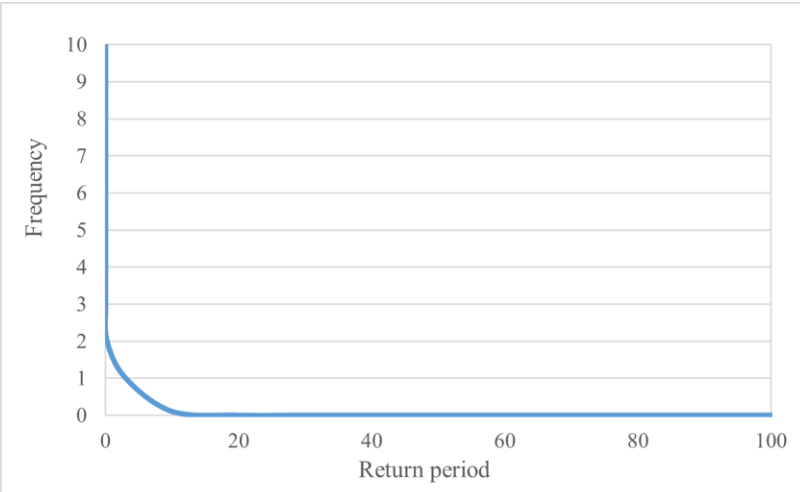

Figure 35. *Frequency of event occurrence related to the flood return period.*

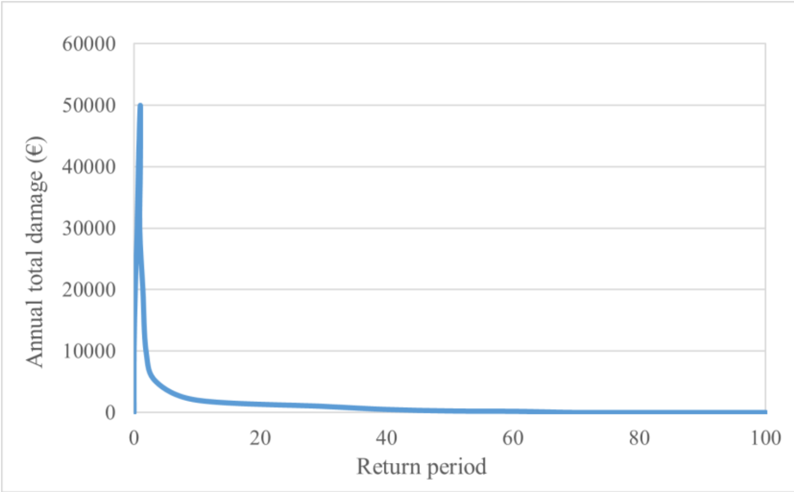

Figure 36. *Annual total damage (€) related to the flood return period.*

PART IV - Application

Chapter 7

Study Areas

This chapter is partly based on two publications: Quagliolo, Comino and Pezzoli (2021a, 2021b). The application of this research has been conducted on two European study areas: Aveiro (PT) and Rapallo (IT). Nowadays, socio-economic vulnerabilities to flood risk have been increasing in Italy and Portugal, as well as in other European countries (Paliaga, Faccini, *et al.*, 2020). Aveiro is a coastal lagoon city, while Rapallo is a coastal city. The intent is to compare the results of NBS implementation in different contexts which still present common aspects. Both study cases were chosen thanks to the support received throughout the development of this research. The areas present differences in terms of spatial scale, anthropogenic occupation, climate condition and waves energy, geomorphology, etc. However, both cities have similar dimensions (middle-size urban areas), and are facing climate change-related issues, such as compound flooding. In general, southern Europe is expected to experience an overall decrease in precipitation in a future climate scenario (Representative Concentration Pathway - RCP) with an increase in heavy rainfalls and length of dry spells. In addition, mean and extreme sea levels have increased along most coastlines in Europe, with the exception of the northern Baltic coast (Schleussner *et al.*, 2020). Indeed, the global mean sea level is about 19 cm higher than it was in 1900 (European Environmental Agency (EEA), 2021a).

The following sub-chapters introduce the general characteristics of the study areas by presenting land use, environmental, socio-demographic, and climatic contexts. The data used are open-source, and directly downloadable from either local/national geo-repositories (e.g. Geoportal Liguria for Italian case as well as EPIC WebGis Portugal), European (EUROSTAT, Copernicus, Global Human Settlement Layer) or Global sources.

7.1 Aveiro – coastal lagoon city (Portugal)

7.1.1 Biophysical characteristics

The first case study considered is the city of Aveiro (District of Aveiro) in the Northwest Atlantic coast of Portugal, located at 40°38’N, 8°45’W, 19m above sea level (**Figure 37**). The municipality of Aveiro has an area of approximately 197.58 square kilometers, representing one of the most populous cities in the Centre Region of Portugal. Also known as “the Portuguese Venice”, Aveiro is characterized by a system of canals and boats like the Italian city of Venice. Located next to a coastal lagoon environment, the city is part of a fragile ecosystem, strongly influenced by both natural and anthropogenic factors, as well as climate change.

The coastline is approximately 75 km long and located on the Portuguese northwest coast (**Figure 37**), approximately N 21° E oriented. The Aveiro coastline includes areas from the following seven municipalities (from north to south): Espinho, Ovar, Estarreja, Murtosa, Aveiro, Ílhavo and Vagos.

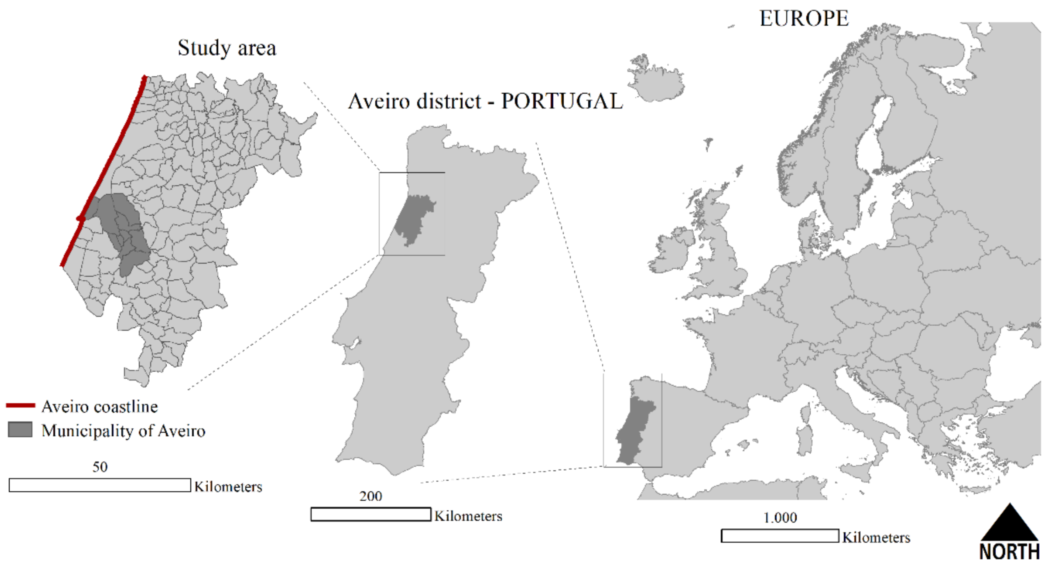

Figure 37. *Context of study for Aveiro.*

The mean significant wave height is usually around 2 m, however waves have registered heights of 8 m during storm events (Narra, Coelho and Fonseca, 2015).

Storm events usually last for less than 2 days, but storms that persist for up to 5 days were also recorded. The tide is semidiurnal and ranges between 2 m to 4 m (neap tide and spring tide) (Narra, 2018). This induces the sea level variation around 0.45m – 3.80 m at the mouth of the lagoon (Lopes, Lopes and Dias, 2019).

The 'Ria de Aveiro' is a coastal lagoon with a complex geometry and wetland system; it is 45 km long and 10 km wide, and is characterized by many channels and tributaries. Four main channels (Mira, S. Jacinto, Ílhavo and Espinheiro) and one artificial inlet built in 1808 connecting the lagoon to the Atlantic Ocean are present (Lopes, Lopes and Dias, 2019). Large areas of mud flats and salt marshes characterize the lagoon which normally is ebb dominant at the mouth and flood dominant at the upper parts, exporting sediments to the ocean (Oliveira, Fortunato and Dias, 2007). From previous studies, the Ria de Aveiro lagoon has been characterized in two main areas: (I) the central zone, strictly related to the tidal action with a strong current which may reach values higher than 2 m s^{-1} close to the lagoon mouth and with progressively low intensity values towards inner channels; and (II) the far end channels, mainly characterized by shallow intertidal areas with decreasing current intensities with values ~ 0.1 m s^{-1} (Fortunato *et al.*, 2013).

The Ria de Aveiro has been widely studied accross different scientific fields (biology, physics, environment, etc.). Through the application of hydrodynamic and morphodynamic models, it was found that the morphological aspects of this area are strongly influenced by tidal action, while the wind and wave stresses on the lagoon water levels are smaller in comparison (Dias, 2001; Lima, 2018). The deepening of the lagoon is caused by the increase of tidal wave amplitude and a faster propagation along the channels. Consequently, several areas on the margin of the lagoon are threatened by sea water and saltwater intrusion. In this context, the extension of urban flood area tends to increase under climate change scenarios when we consider the predicted mean sea-level rise for the region (Lopes *et al.*, 2013).

The Ria de Aveiro lagoon plays a crucial role from an ecological point of view. Since numerous species of flora and fauna have established in several habitats, the lagoon presents high biodiversity (Lopes, 2016). Saltmarshes, mudflats, and seagrass meadows were identified by LAGOONS as key equilibrium elements of the Ria de Aveiro ecosystem against tidal action and erosion (LAGOONS, 2011). The high ecological value of the lagoon integrates the European Network of Nature 2000 sites as a Special Protection Area (SPA) and a Site of Community Importance (SCI).

The lagoon has historically supported a wide range of natural services and goods for the establishment of human communities, and it has been always shaped by human activities.

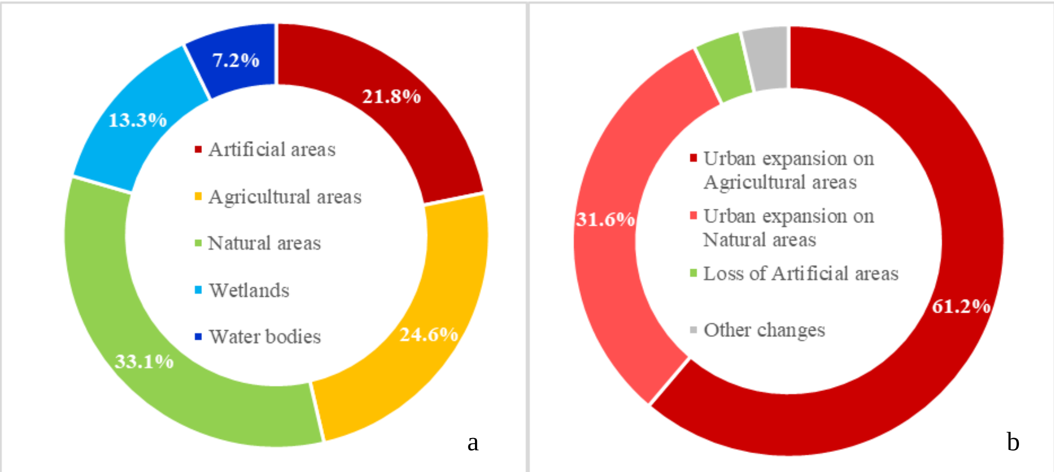

***Figure 38. (a)** Land Use and Land Cover (LULC) statistics for Aveiro; **(b)** Changes between Urban Atlas 2012 and Urban Atlas 2018 (km^2).*

The Municipality of Aveiro covers a land surface of approximately 208 km^2.

According to Urban Atlas 2018[7], the project of Copernicus Land Monitoring and Services which provides European comparable land use land cover (LULC) data for Functional Urban Areas (FUA)[8], the predominant land use categories in the Aveiro municipality (**Figure 38(a)**) comprise natural (33.1%) and agricultural (24.8%) areas. The artificial surfaces represent approximately 21.8% of the whole area, and are used for residential, industrial, and commercial purposes. Wetlands

[7] Accessed on June the 10th 2021: https://land.copernicus.eu/local/urban-atlas
[8] Urban areas with more than 50,000 inhabitants.

and water bodies represent an important share of land use for Aveiro, covering more than 20% of the total area.

Figure 38(b) shows the changes to land use occurred between the period of 2012 and 2018. The urbanization for the Municipality of Aveiro shows a positive trend between the period 2012-2018. The urbanization uptake is of about 61.2% on agricultural lands and of 31.6% on natural areas.

Figure 39 depicts the land cover map of Aveiro according to the Urban Atlas LULC 2018. The wetlands and water classes delineate the Ria de Aveiro lagoon in **Figure 39**. Industrial and commercial units are mainly located in the north-west part of the lagoon. Historically, Aveiro was an economic link in the production of salt and commercial-industrial shipping due to the location on the shore of the Atlantic Ocean. The region is also known for tourism and ceramics industries, reflecting the traditions of late Roman and early Medieval periods.

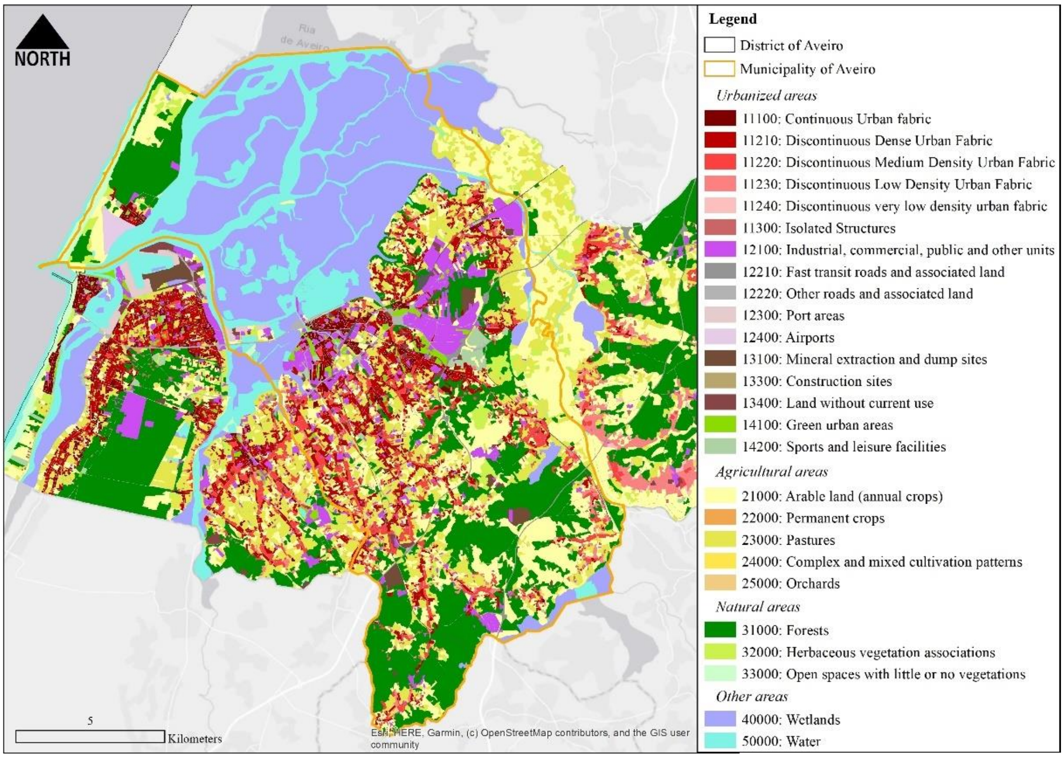

Figure 39. *Land Cover of Aveiro (adapted from Urban Atlas LULC).*

To what concerns the impervious/sealed areas**, Figure 40(a)** highlights the characteristics of urbanized areas within the District of Aveiro. The imperviousness captures the percentage of soil sealing, meaning areas characterized by the substitution of the original (semi-) natural land cover or water surface with an artificial, often impervious, cover. The imperviousness HRL (High resolution layer) represents the spatial distribution of artificially sealed areas, including the level of sealing of the soil per area unit. For the Aveiro case, the data set used was the HRL

2018 Imperviousness at 10m of spatial resolution from Copernicus website[9]. This map is based on a 0 (low impervious land) to 100 (high impervious land) set of values. The impervious surfaces are distributed quite equally across the territory of the Aveiro District, with hotspots in the northern part (municipalities of Esmoriz, Espinho, Ovar, Santa Maria da Feira, etc.) and the surrounding areas of Aveiro (municipalities of Ilhavo and Vagos).

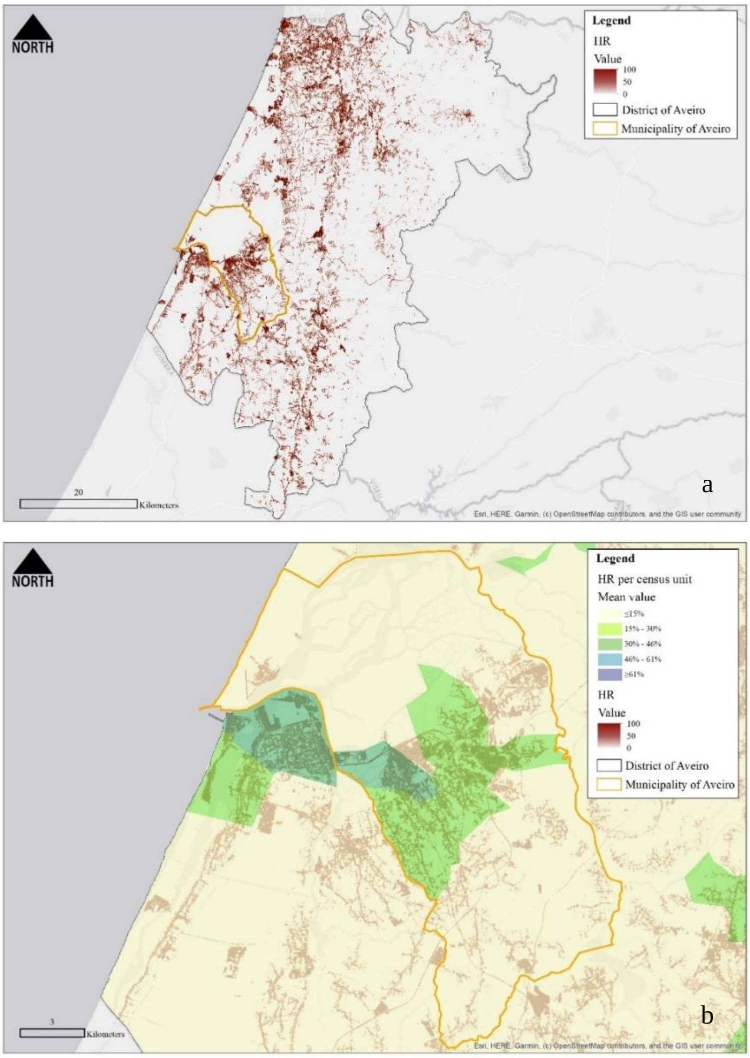

Figure 40. *(a) Imperviousness map and (b) Imperviousness per census unit.*

Figure 40(b) shows the mean value of HR per census units (EUROSTAT 2011[10]). The mean value of HR is dived in five classes ranging from the lowest values of soil sealing (under 15%) in yellow to the highest values of imperviousness (over 61%) in dark blue. The most impervious areas within the Municipality of Aveiro are located in front of the Lagoon with sealed soil values lower than 50%.

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[9] Accessed on February the 18th 2021: https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness.

[10] Accessed on February the 18th 2021: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units.

7.1.2 Socio-demographic characteristics

Recent demographic dynamics largely determine the priorities for climate adaptation in Portugal. The concentration of the biggest part of population along the coasts between the two largest metropolitan areas (Lisbon and Porto) is increasing exposure to urban heat islands, flash floods, landslides, and coastal risks.

The total population living the city of Aveiro is estimated to be of approximately 80,880 inhabitants (preliminary results from the INE Census 2021[11]). This area experienced a rapid population increase in the last decade, as the INE Census of 2012[12] state the region had 26078 inhabitants at the time.

Figure 41 aims to show the human presence on the study area by employing the Global Human Settlement Layer (GHSL) data 2015 (GHS-BUILT & GHS-POP) (Florczyk *et al.*, 2019). Even if the spatial resolution of the data source is 250 m, both representations (**Figure 41**) give an overview of the density per square kilometres (Km^2) in terms of population (**a**) and buildings (**b**). It is quite evident how the most central and historical parts of the Municipality of Aveiro, facing the Lagoon, are among those with the largest population density within the Aveiro district. This area is coincident with the most urbanized zones, showing the highest building density values (from 608 to 2,032 building/Km^2).

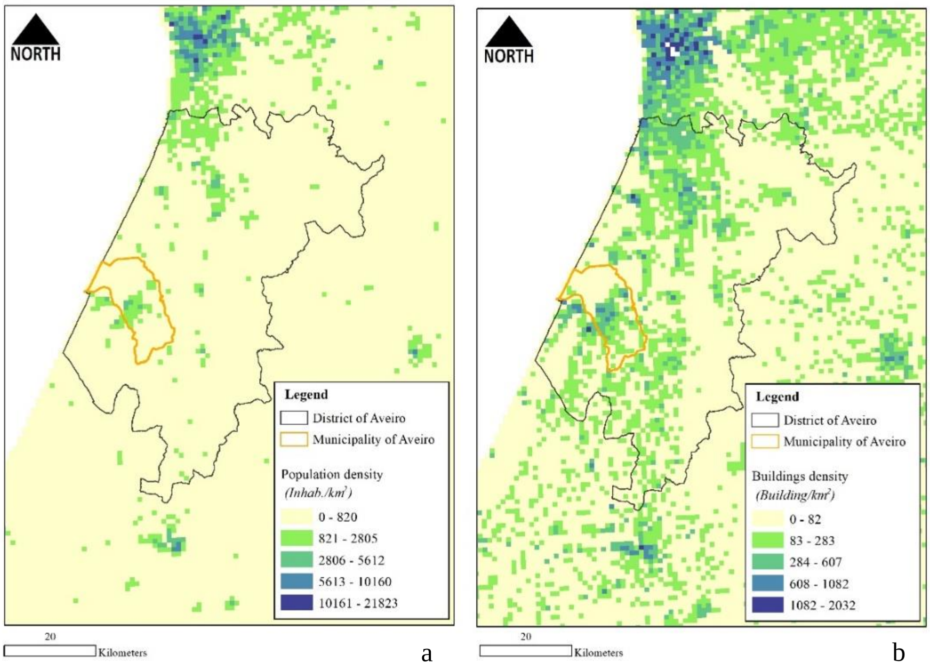

Figure 41. *(a) Population density map and (b) Building density map.*

[11] Access on November the 2nd 2021: www.ine.pt
[12] Access on November the 2nd 2021: www.ine.pt

7.1.3 Climatic characteristics and Climate Change context

Portugal is characterized by a large spatial climatic variation, especially for precipitation gradients in the north-western region, which is highly affected by Atlantic storms (Schleussner *et al.*, 2020). The Mediterranean climate influenced by Atlantic Ocean's proximity has typically warm and dry summers, and wet winters. Coastal and maritime features cause a narrow yearly temperature range resulting in 14.4°-19.5°C for average high and 6.3°-11.5°C for average low. The warm climate in the Aveiro region results in significant rainfall throughout the year (about 900 mm of annual precipitation), where the driest month is July with 5 mm, while the wettest one is December with an average of 151.2 mm[13].

To give good indications of typical climate patterns and expected conditions (temperature, precipitation and wind) of weather in Aveiro, **Figure 42 -Figure 43 - Figure 44 - Figure 45** represent simulated weather based on 30 years of hourly information[14]. Even if the simulated data may not reproduce all local weather effects, such as thunderstorms, local wind or tornadoes, they have a spatial resolution of approximately 30 km.

Figure 42 shows mean daily maximum (solid red line), which depicts the maximum temperature of an average day for every month in Aveiro. Likewise, mean daily minimum (solid blue line) shows the average minimum temperature. Hot days and cold nights (dotted red and blue lines) show the average of the hottest day and coldest night of each month of the last 30 years. Mean values of temperatures range from 6°C for minimum to 28°C of maximum throughout the year, with the hottest days, between June and July, sometimes reaching 37°C.

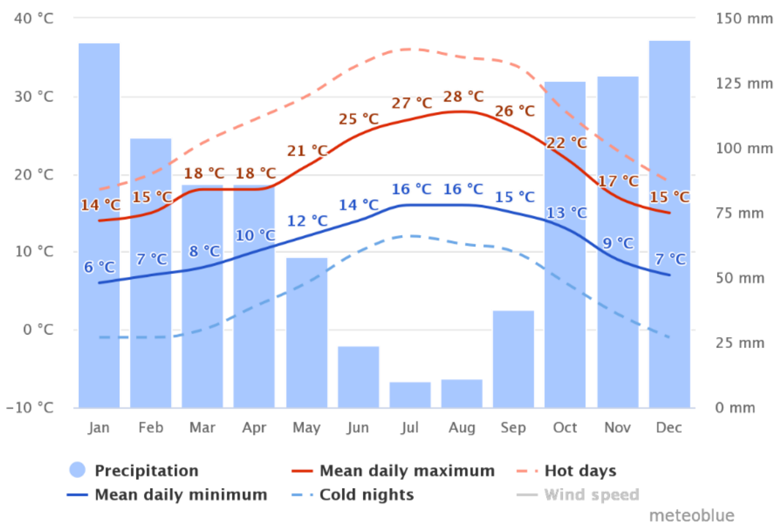

Figure 42. *Average temperatures and precipitation (from Meteoblue).*

[13] Instituto Português do Mar e da Atmosfera - 2020: https://www.ipma.pt/.
Portal do Clima - Climate Change in Portugal: http://portaldoclima.pt/.
[14] Accessed on February the 2nd 2021: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/aveiro_portugal_2742611

According to Fussel et al. (2017) the total annual precipitation has decreased by 90 mm per decade in Portugal. The precipitation chart is useful to identify which amount of rain determines seasonal effects, such as wet or dry seasons. In general, monthly precipitation values above 150 mm correspond mostly to wet seasons, while values below 30 mm correspond mostly to dry seasons. **Figure 43** is a precipitation diagram for Aveiro showing on how many days per month certain precipitation amounts are reached. It highlights that 9 months out of 12 have at least a few days of extreme rainfall ranging from 50 mm to 100 mm. Wind speed for Aveiro is represented by the wind diagram in **Figure 44**. It shows the days per month during which the wind reaches a certain speed. During spring and winter time, wind speed may exceed 38 km/h. Finally, **Figure 45** is the wind rose, showing how many hours per year the wind blows from the indicated direction. Mainly, winds in Aveiro blow from West to East (W) and from East-North-East to West-South-West (ENE).

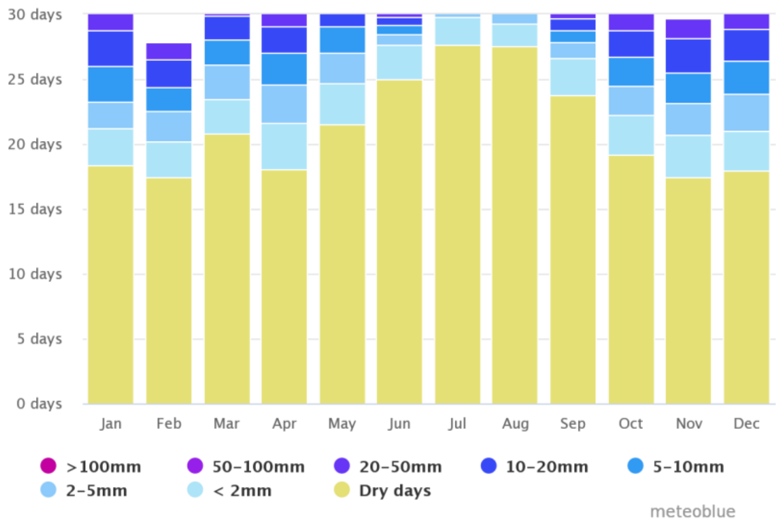

Figure 43. *Precipitation amount (from Meteoblue).*

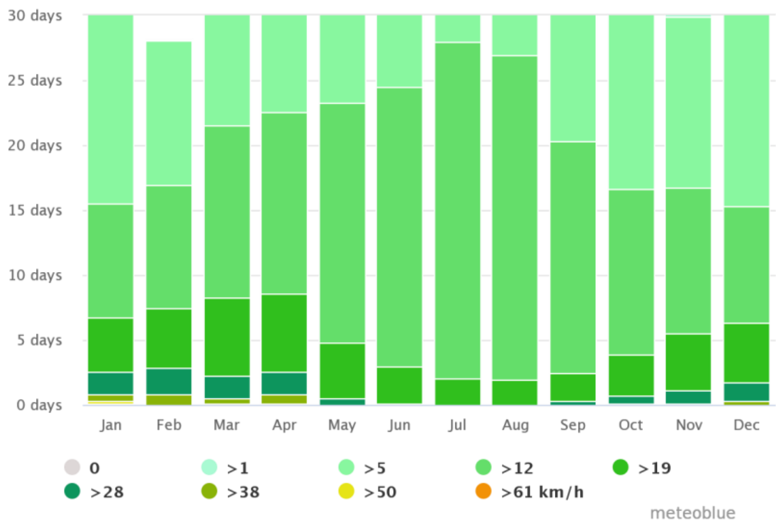

Figure 44. *Wind speed (from Meteoblue).*

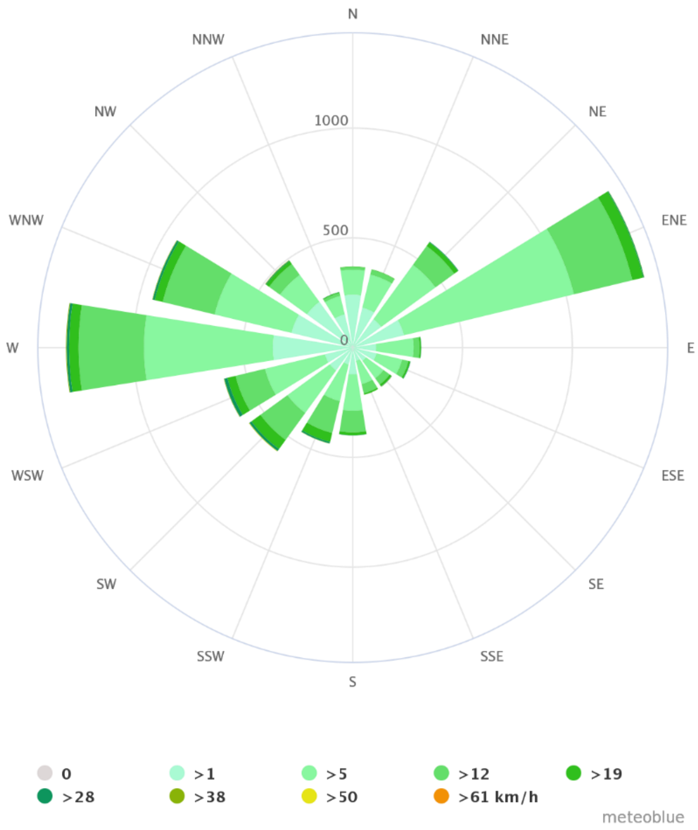

Figure 45. *Wind rose (from Meteoblue).*

In a context of Climate Change, a future global warming scenario of 2.8°C by 2100 (under Representative Concentration Pathways (RCPs 6.0) scenario developed for Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Intergovernmental Panel on Climate Change (IPCC)) would lead to a decrease of 15% in mean annual precipitation in the northern parts of Portugal. Instead, heavy precipitation events are likely to increase during winter over Portugal. These projections can lead to soil moisture decrease, which in turn will increase sensible heat flux by heating the atmosphere. The extreme precipitation susceptibility index (EPSI) calculated for Portugal (present and future situation) shows that more than 60% of the Portuguese municipalities have an high or very high probability to be affected by precipitation-driven disaster given the set of conditions (Santos *et al.*, 2019). This trend is expected on the north-western part of Portugal.

Mean sea level projections may highly affect estuaries and coastal lagoons in Portugal, such as the Ria de Aveiro where resulting socio-economic impacts will be greater (Schleussner *et al.*, 2020). As a result of climate change, coastal conditions will be exacerbated by even more frequent flooding and coastal erosion due to weakening of river-sediment supplies (Coelho *et al.*, 2009). Especially, when storm surge and high tide coincide, these events can be worsened by climate change due to the predicted sea-level rise in the coming years (Ribeiro *et al.*, 2021).

7.1.4 Past floods' context in Aveiro

Most of the flooding events in the Ria de Aveiro occur during adverse weather conditions associated with the presence of low pressure in the northwest of the Iberian Peninsula. In these conditions, heavy precipitation induces a combination of impacts: high river discharges, water flow in urbanized areas, and storm surges related to the low pressure (Lopes, 2016). In addition to the tidal level, an abnormal sea level rise can occur during specific atmospheric conditions. When strong southern winds are generated, storm surges may occur due to low pressures located at the N/NW Portuguese coast. There are records of the occurrence of storm surge events every year that persist over three days and cause extreme coastal flooding in this region (Ribeiro *et al.*, 2021).

On 27th February 2010 the tropical storm 'Xynthia' that reached the Portuguese coast caused an abnormal sea level rise of 70 cm. The parts of the city located on the margins of the Ria de Aveiro were strongly damaged.

Details related to past flood events and the most critical areas in Aveiro (until 2005) were also highlighted by the SECUR-Ria project[15] and the PhD research of Lopes (2016). According to this inventory, the riskiest areas of the Lagoon are the mouth of the tributaries. In the scope of this research, an exploration of the flood-prone regions around the city has been made by consulting newspapers and photos from past occurrences of extreme weather conditions.

Overflows from the city channels occurred several times during its history, even after the installation of a flood control system (sluices and flood gates at the city entrance) to prevent ocean water entry in 1985. Indeed, since this moment, the frequency of flooding events has decreased, and similarly, the resulting waterflow volume was lowered. However, the city of Aveiro continued suffering several inundations. The floods occurred in October 1999 (see **Figure 46**) and April 2008 represent examples of rainwater-induced inundation. Recently, extreme events are becoming more frequent in the Aveiro Region, alternating abnormal situations of dry or wet and warm or cold weather. This situation is leading to severe river runoffs and flash floods, as are the cases of June 2006, September 2008, February 2009, and May 2009. From January to February of 2016, the northern and central parts of Portugal suffered extreme flooding[16]. **Figure 47** represents one of the most flooded parts of Aveiro city during the extreme flooding event that occurred in February 2016. **Figure 48** shows a critical area in the city of Aveiro (between the University and the hospital) often inundated because of intense rainfall events.

The most adverse floods occur generally when high freshwater inflows and high sea levels are coincident. The combinations of both factors occurred many times in the past, especially in Aveiro town which is a low-lying region (Baptista Borges, 2013; Lima, 2018).

[15] http://securria.regiaodeaveiro.pt/
[16] https://floodlist.com/europe/portugal-1-dead-after-weekend-storm-brings-floods-and-landslides

Figure 46. *Flooded area in the lower part of the city of Aveiro in October 1999 (from Campeão das Provincias 28th Ocober 1999).*

Figure 47. *Flooded street in the city centre of Aveiro in February 2016 (from Agencia Portuguesa do Ambiente (APA) (2020)).*

Figure 48. *Street of the University which gives access to the hospital in Aveiro (from Lima (2018)).*

7.2 Rapallo – coastal city (Italy)

7.2.1 Biophysical characteristics

The second case of study, Rapallo, is a coastal city part of the Metropolitan area of Genoa within the Liguria Region in Italy (**Figure 49**). The municipality is located at 44.4°N 8.94°E, about 25 km^2 southeast of Genoa, in the Tigullo Gulf. Liguria is one of the smaller regions of Italy covering 2% of Italian territory, while the population density of the region is almost 287 inhabitants/km^2. Rapallo city is recognised mainly for its touristic activities.

Considering the orography of the territory, and that more than 50% of the territory is covered by forest, the coastline, and particularly the Metropolitan area of Genoa, show the highest population density values in the Region (population amount of 850.000 only in the metropolitan area). Indeed, this Region went through a rapid urbanization in coastal areas, combined with a population that has doubled in a rather short period (about 150 years until 2009) (Arvati, 2011). Despite the high administrative fragmentation, the territory of the Liguria Region is highly and continuously urbanized.

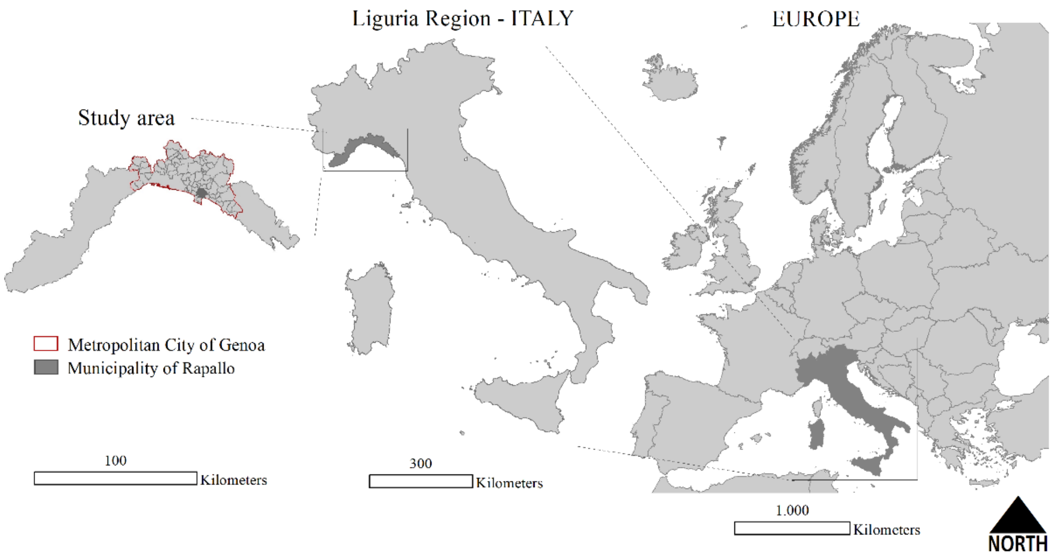

Figure 49. *Context of study for Rapallo.*

The town lies 3 m above sea level, mainly extending through a lowland between Boate and San Francesco streams. A few other, smaller, rivers cross the municipality (i.e. San Pietro, Santa Maria, Sellano, Cereghetta, Carcara). Rapallo covers one major natural watershed linked to the Boate stream and seven other, smaller, basins. The city is characterized by a narrow coastal zone with hills and steep mountains inland. Because of this steep topography behind the city, this catchment area has a particular drainage system. A range of water courses have been historically incorporated into the urban area through processes of expansion of the city. These processes did not consider the rising of runoff volume, especially during extreme events, therefore the city is plagued by frequent flooding.

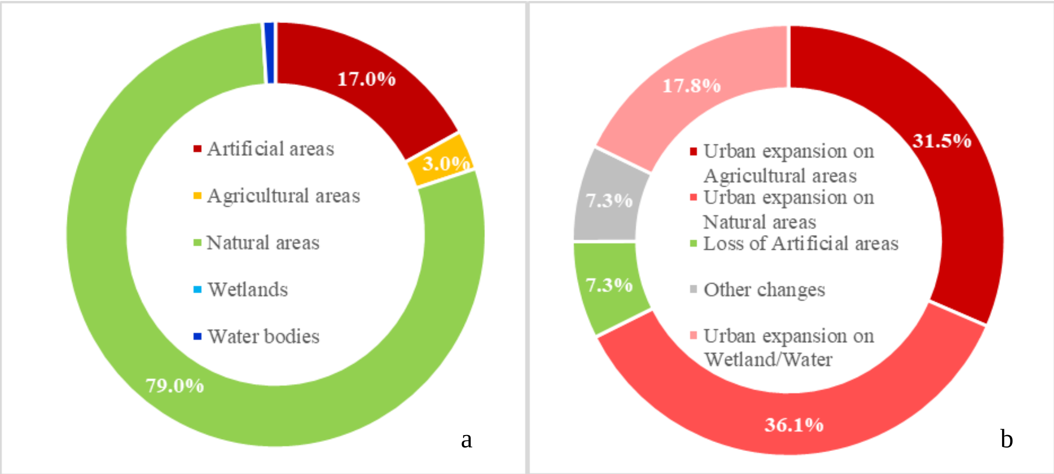

Figure 50. (a) *Land Use Land Cover (LULC) statistics for Rapallo;* ***(b)*** *Changes between Urban Atlas 2012 and Urban Atlas 2018 (km^2).*

The Municipality of Rapallo covers a land surface of approximately 33,62 km^2.

According to Urban Atlas 2018[17], the project of Copernicus Land Monitoring and Services – local component which provides European comparable land use land cover (LULC) data for Functional Urban Areas (FUA)[18], the predominant land use category in the Genoa municipality (**Figure 50(a)**) consists of natural areas (79%). The predominant land use, together with the agricultural areas, strongly characterize this territory by globally presenting 82% of agroecosystems and forestry lands. The artificial surfaces represent approximately 17% of the whole area, and they are used for residential, industrial, and commercial purposes. Particularly, as shown in the land use map for Rapallo (which was generated from the Land Cover Liguria (2019)[19] by following the classification of Urban Atlas LULC 2018 - **Figure 51**), the urbanized areas concentrated along the Boate stream show residential units mainly on the coast. By observing **Figure 51** it is evident how most of the urbanized zones are dense. A major part of Rapallo Municipality is covered by green areas and forests. Wetlands and water bodies represent a little share of land use in Rapallo, occupying less than 2% of the total area.

Figure 50(b) shows the changes to land use that occurred between the period of 2012 and 2018 in the metropolitan area of Genoa. The urbanization uptake saw a positive trend, with an urban expansion on agricultural areas of approximately31.5%, and on natural lands of about 36.1%, both in terms of square kilometers (km). Artificial areas saw a decrease of 7.3%. A worrying change corresponds to an urban expansion of 17.8% on wetlands and water land uses. The delineated

[17] https://land.copernicus.eu/local/urban-atlas
[18] Urban areas with more than 50,000 inhabitants.
[19] Accessed in September 2020: https://geoportal.regione.liguria.it/catalogo/mappe.html

situation represents a serious issue in this territory, which has been historically exposed to frequent flooding, resulting in significant destruction, primarily due to intense rainfall on highly urbanized flood-prone areas. Secondly, the continuous coastal erosion phenomenon related to sea-level rise and coastal floods is strongly compromising the entire Ligurian coast.

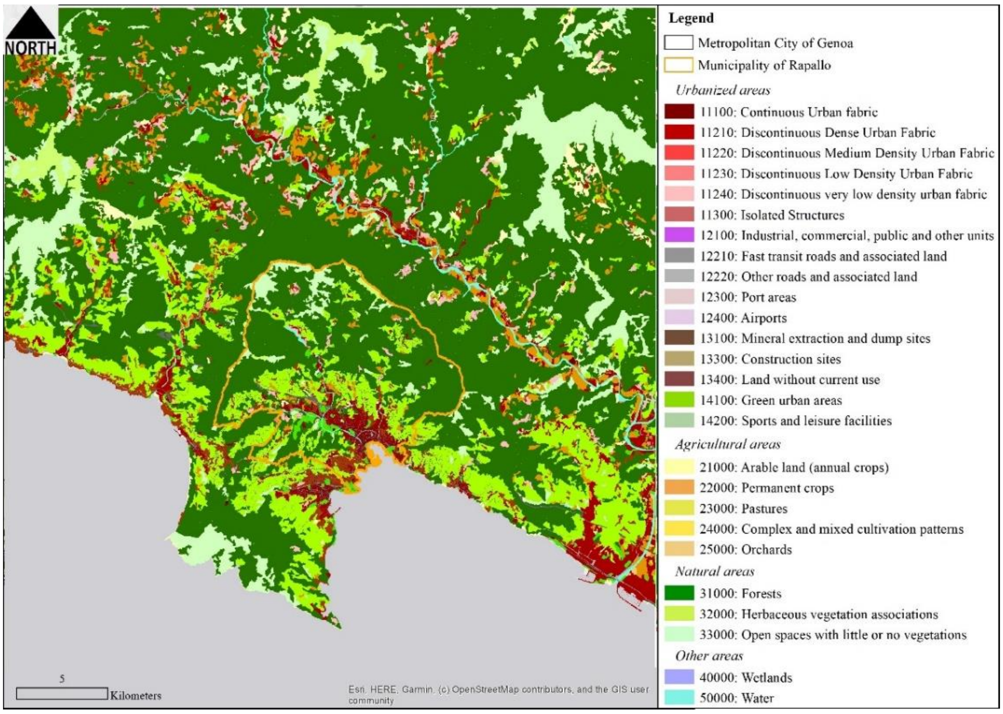

Figure 51. *Land Cover of Rapallo (adapted from Land Cover Liguria (2019)[20] based on the classification of Urban Atlas LULC).*

To what concerns the impervious/sealed areas, **Figure 52(a)** highlights the highly urbanized coastal areas typical of metropolitan cities of Genoa. The imperviousness captures the percentage of soil sealing, that means areas characterized by the substitution of the original (semi-) natural land cover or water surface with an artificial, often impervious cover. The imperviousness HRL (High resolution layer) represents the spatial distribution of artificially sealed areas, including the level of sealing of the soil per area unit. This map is based on a 0 (low impervious land) to 100 (high impervious land) set of values. Municipality of Rapallo presents an evident built-up distribution and higher values of imperviousness along the Boate stream and near to the coast (city center).

Figure 52(b) shows the mean value of HR per census units (ISTAT 2011). HR is dived in five classes ranging from the lowest values of soil sealing (under 20%) in yellow to the highest values of imperviousness (over 80%) in dark blue.

[20] Accessed in September 2020: https://geoportal.regione.liguria.it/catalogo/mappe.html

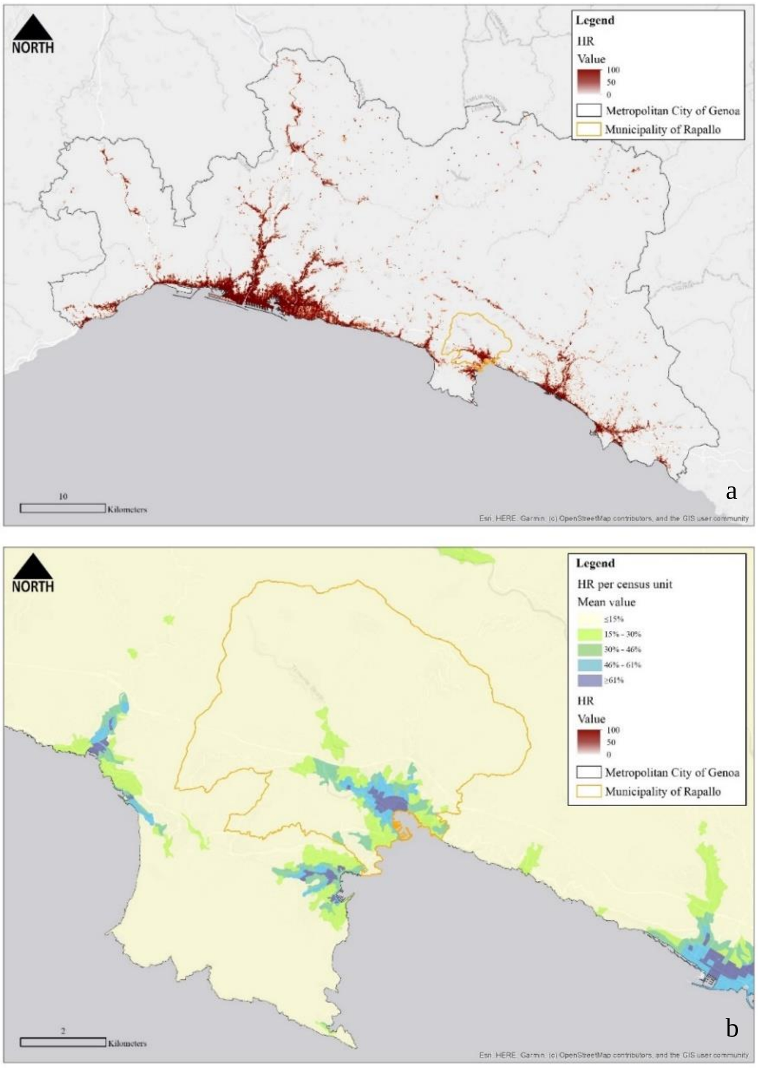

Figure 52. *(a) Imperviousness map and (b) Imperviousness per census unit.*

7.2.2 Socio-demographic characteristics

The surrounding area of Rapallo is very popular for tourism throughout the year. Every year, over a million tourists visit the town of Rapallo, while the nearby town of San Fruttuoso receives about 400,000 tourists by boats from the sea. There are also a considerable number of hikers that come to this area because of the wide hiking paths that extend over 80 km in length (Turconi *et al.*, 2020).

Rapallo has a population of 29,030 inhabitants (results from ISTAT 2020), earning it the sixth rank on the list of most populous municipalities in the Liguria region (out of 234 municipalities)[21]. Recent demographic dynamics show a slight decrease in population in this area. The annual average variation (2015-2020) is

[21] Accessed on November the 15th 2022: https://ugeo.urbistat.com/AdminStat/it/it/demografia/dati-sintesi/rapallo/10046/4

about -0.44 in percentage[22]. On the other hand, the migration balance showed a positive trend in 2020 (+288 inhabitants)[23].

Figure 53 aims to show the human presence in the study area by employing the Global Human Settlement Layer (GHSL) data 2015 (GHS-BUILT & GHS-POP) (Florczyk *et al.*, 2019). Even if the spatial resolution of the data source is 250 m, both representations (**Figure 53**) give an overview of the density per square kilometres (Km^2) in terms of population (a) and buildings (b). It is quite evident how the most central and historical parts of the Municipality of Rapallo, facing the coast, have among other the largest population density, as is the case in the other areas of the Metropolitan area of Genoa. This area is coincident with the most urbanized ones, which is shown in **Figure 53** (b) as the building density with the highest values (from 76 to 100 building/Km^2).

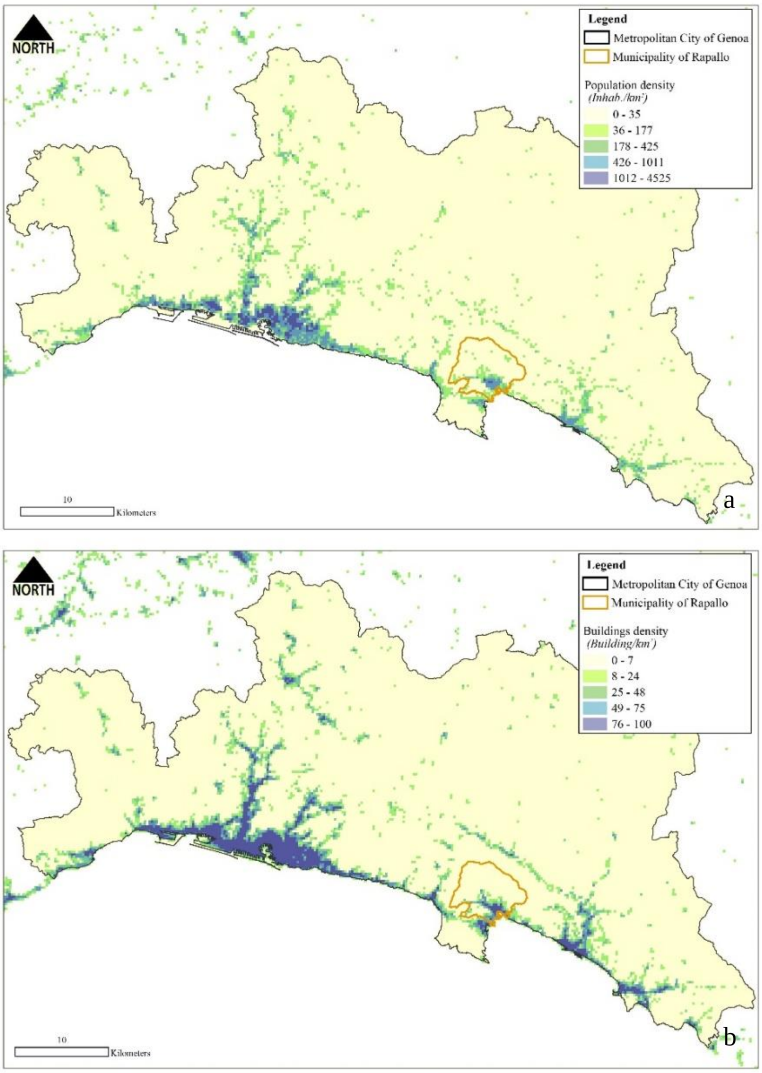

Figure 53. *(a) Population density map and (b) Building density map.*

[22] Accessed on November the 15th 2022: https://ugeo.urbistat.com/AdminStat/it/it/demografia/dati-sintesi/rapallo/10046/4
[23] Accessed on November the 15th 2022: https://ugeo.urbistat.com/AdminStat/it/it/demografia/dati-sintesi/rapallo/10046/4

7.2.3 Climatic characteristics and Climate Change context

The climate of this area is typical Mediterranean, warm, and temperate with rainier months during winter season. During summer, this area is under the influence of tropical pressure, while during winter, it is under polar pressure. Particularly, during the dry period (summer), the average temperature is higher than +22°C, and rainfall events generate less than 30 mm of precipitation (Colombari, 2020). Generally, the average annual temperature is 14.7 °C, and about 1086 mm of precipitation falls annually, with a difference of 125 mm between the driest and the wettest months[24]. Although rainfall is on average with Mediterranean climate, during the last few years, numerous extreme rainfalls and storms occurred, causing short and intense flooding events across the city. The orographic characteristics of Liguria facilitate the pluviometry, due to the Apennine and Alps ridges that surround the region. By analysing precipitation time series from 1961 to 2010 of Liguria, it has been outlined that the western part of the region – Ponente – is less rainy than the eastern part – Levante – in terms of average cumulative rainfall[25]. Rapallo is included in the rainiest part of Liguria region (Levante).

To give good indications of typical climate patterns and expected conditions (temperature, precipitation and wind) of weather in Rapallo, **Figure 54 - Figure 55 - Figure 56 - Figure 57** present simulated weather based on 30 years of hourly data information[26]. Even if the simulated data may not reproduce all local weather effects, such as thunderstorms, local wind or tornadoes, they have a spatial resolution of approximately 30 km.

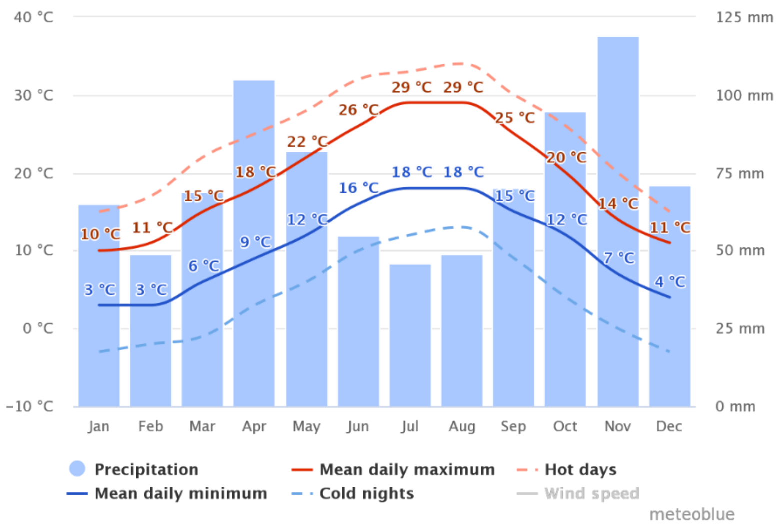

Figure 54. *Average temperatures and precipitation (from Meteoblue).*

[24] https://en.climate-data.org/

[25] Accessed on February the 2nd 2021: https://www.arpal.liguria.it/homepage/meteo/analisi-climatologiche/atlante-climatico-della-liguria.html

[26] Accessed on February the 2nd 2021: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/genoa_italy_3176219

Figure 54 shows mean daily maximum (solid red line), the maximum temperature of an average day for every month in Rapallo. Likewise, mean daily minimum (solid blue line) shows the average minimum temperature. Hot days and cold nights (dotted red and blue lines) show the average of the hottest day and coldest night of each month of the last 30 years. Mean values of temperatures range from 3°C for minimum to 29°C of maximum throughout the year, with the hottest days during the month of August reaching 34°C. Coldest days occur mainly between December and January, with minimum temperatures slightly below 0°C. The precipitation chart is useful to identify which amount of rain determines seasonal effects like wet or dry seasons. In general, monthly precipitation events above 150 mm are occur mostly during wet seasons, while those below 30 mm correspond mostly to dry seasons. **Figure 55** is a precipitation diagram for Rapallo, showing on how many days per month certain precipitation amounts are reached. It highlights that, during the Autumn season and the months of February and April, at least few days of extreme rainfall have been estimated, ranging from 50 mm to more than 100 mm.

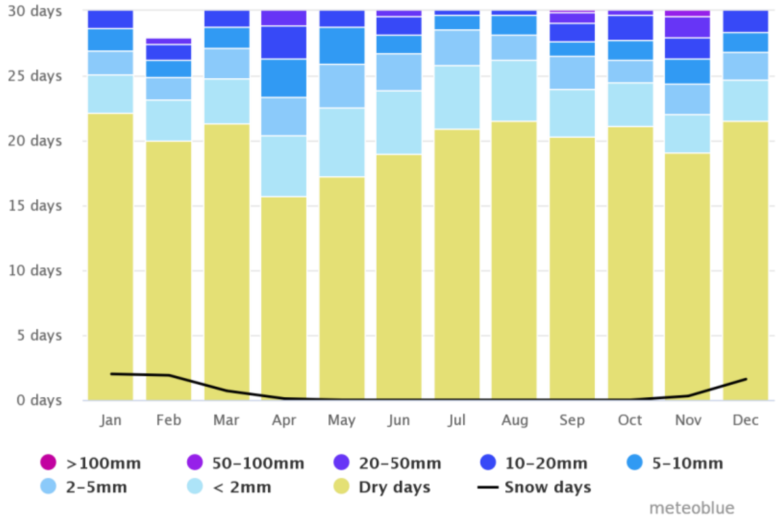

Figure 55. *Precipitation amount (from: Meteoblue).*

Figure 56 the wind diagram for Rapallo that means the days per month, during which the wind reaches a certain speed. On a few days, wind speed may exceed 28 km/h from December to April, while it has been estimated at least 1 or 2 days in February with wind speeds of more than 38 km/h. Finally, **Figure 57**, depicting the wind rose for Rapallo, shows how many hours per year the wind blows from the indicated direction. Most of the hours, the wind direction is either from North-North-East (NNE) to South-South-West (SSW) or from South (S) to North (N).

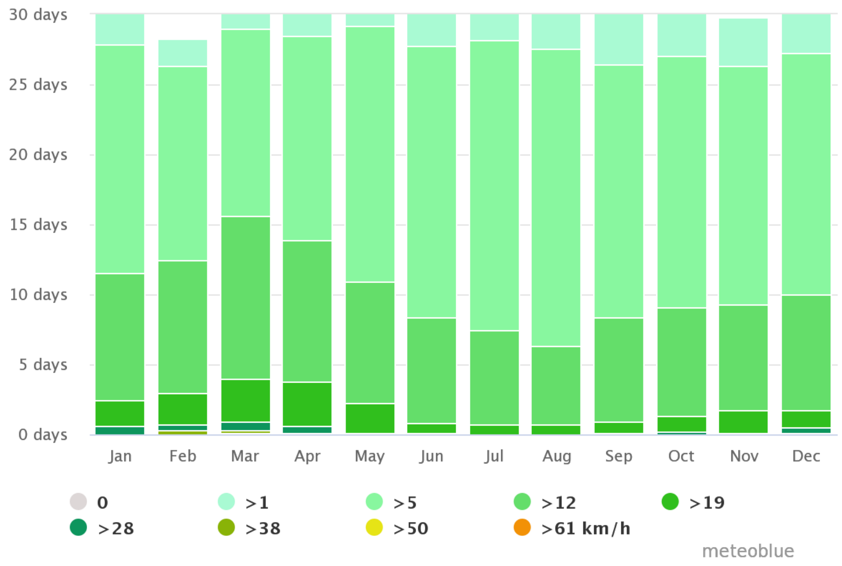

Figure 56. *Wind speed (from Meteoblue).*

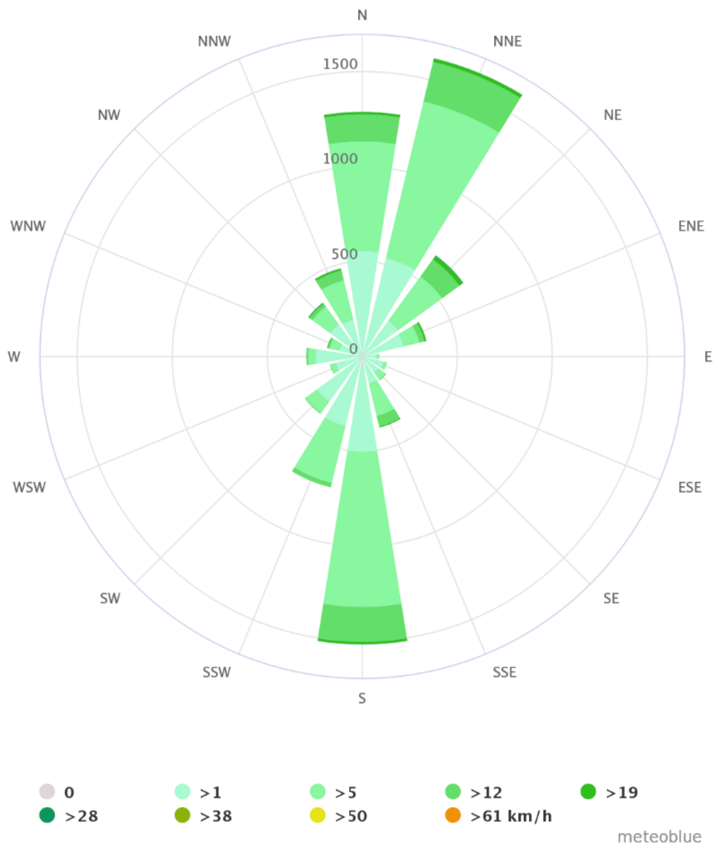

Figure 57. *Wind rose (from Meteoblue).*

7.2.4 Past floods' context in Rapallo

The peculiar morphology of Liguria region causes very localized precipitation events that, in some cases, are limited to single cities (Paliaga *et al.*, 2019; Paliaga, Faccini, *et al.*, 2020). In the last centuries, and particularly from the XX, most of the Italian and Mediterranean cities suffered an increase in both vulnerability and flash flood risk. This situation is particularly relevant for small catchments, which experienced: i) soil permeability reduction; ii) artificialization of drainage networks; iii) loss of natural spaces due to the uncontrolled urban sprawl and land-use changes both in floodplains and at basin scale.

For these reasons, Liguria region has historically been hit by numerous flooding events. In general, Liguria is a typical case in which urban sprawl seems to have the most decisive role in flooding events (Faccini *et al.*, 2015). Specifically, among the most damaging past events that occurred in Rapallo, two floods have been registered: one in 1911 and another in 1915[27] (see **Figure 58**). In September 1915, flash floods and landslides caused one of the most disastrous events in the area between Genoa, Rapallo and Chiavari. This event generated precipitation that reached approximately 400 mm in 3 hours. Similar events happened in October 1995 (around 250 mm of daily rain) and January 1996 (about 110 mm of daily rain), in Rapallo and Santa Margherita Ligure, respectively (Paliaga, Luino, Turconi, De Graff, *et al.*, 2020).

Figure 58. *Flood event of 1911 in Rapallo*[28].

In the recent decade, in the period between 2000 and 2019, a range of catastrophic events occurred in Italy, and specifically in the area surrounding Rapallo (Paliaga, Luino, Turconi, Marincioni, *et al.*, 2020). In November 2014, another flooding event strongly impacted Liguria, specifically the area of Levante, from Genoa to Rapallo. In the inland part of Rapallo municipality, landslide risk isolated the area[29].

[27] Accessed on November the 15th 2022: https://iltigullio.com/
[28] Accessed on November the 15th 2022: https://iltigullio.com/
[29] Accessed on November the 15th 2022: https://www.rainews.it/archivio-rainews/articoli/Alluvione-Liguria-in-ginocchio-Danni-e-soccorsi-anche-nel-Tigullio-b9a703bb-68f9-408e-a204-2b6882b7e36a.html

In October 29th, 2018, the 'Vaia' storm hit the coastal area of Rapallo, causing the destruction of the tourist port and the flooding of the city, particularly affecting the lowland areas near the shoreline (Bompani and Origone, 2018; Pedemonte *et al.*, 2018). **Figure 59** shows some of the boats marooned on the shore, in part of Rapallo city centre.

Two other strong events that were characterized by intense rainfall, floods, and landslides in this region occurred in October 2019 and November 2019 (Paliaga, Luino, Turconi, Marincioni, *et al.*, 2020).

Figure 59. *Flood event of 2018 in Rapallo (from Bompani and Origone (2018)).*

Chapter 8

InVEST modelling

This chapter is partly based on two publications Quagliolo, Comino and Pezzoli (2021a, 2021b).

The following sections introduce the modelling characteristics and data employed to perform simulations and vulnerability assessment. The data used are open-source and directly downloadable from either local/national geo-repositories (e.g. Geoportal Liguria, Arpa Liguria, SINANET, ISTAT for Italian case as well as EPIC WebGis Portugal, SNIG Portugal, INE Statistics Portugal for Portuguese cases), European (EUROSTAT, Copernicus, Global Human Settlement Layer), or Global sources. The use of openly available data is preferable for the objective of this research, as it facilitates future applications of the new flood impacts assessment.

8.1 Urban Flood Risk Mitigation model description

The Urban Flood Risk Mitigation Model is a recent module (2019) of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software version 3.9.0, and part of the tools of Natural Capital Project[30]. The description of the model is based on the guidelines available on the InVEST webpage (Sharp *et al.*, 2020). Particularly, this model considers the influence of built-up footprint on the different kinds of ecosystem services delivered by nature in the urban context. This model focuses on the ability of cities to reduce runoff generation due to extreme rainfall (such as cloudburst events), and thus limiting the potential flooding. Since natural infrastructures play a crucial role in reducing flooding events, this model considers the potential of permeable green areas to mainly reduce runoff while slowing surface flows and creating space for water (in floodplains or basins). Even if the biophysical quantification of runoff production in the built environment is quite difficult to estimate, due to the sewer systems and the dryness of the soil that can affect the water volume discharge, this model aims to perform this evaluation by using some empirical simplification (Salata *et al.*, 2021).

The main assumption of the model considers flood-prone areas as a result of the interaction between the permeable-impermeable surface layers (i.e., land use type) and the soil drainage (depending on the soil characteristics) which generates

[30] Available at https://naturalcapitalproject.stanford.edu/software/invest

the surface runoff during cloudburst events. For each pixel, the model output estimates the flood depth (i.e. the amount of water retained per pixel compared to the storm volumes) and, for each watershed, it calculates the potential economic damage by overlaying flood extent potential and built infrastructure information. This urban flood model uses the USDA (United States Department of Agriculture) Soil Conservation Service – "SCS runoff curve number" (SCS-CN) method to estimate runoff, which is based on the water balance equation of the rainfall. CN represents the potential maximum soil retention. The SCS-CN method has been developed for runoff volume estimation, growing in popularity in the last 50 years and seeing widespread use by public agency, local governments, and professionals (Eli and Lamont, 2010). Indeed, this method has been widely applied to small watersheds and urban catchments, and was adopted by the Basin Plan of Liguria Region (Banasik *et al.*, 2014). In general, this methodology (SCS-CN) is still commonly used in the large majority of environments and climate conditions (Lucas-Borja *et al.*, 2020). Despite its limitations, SCS-CN method is an accepted empirical method with limited data requirements and capable of determining approximately the effective conditions of the study areas.

By considering the runoff quantification mainly as a result of precipitation (P, in mm) received over the study area and based on land use and soil characteristics, this model solves the empirical calculations of the hydrological processes for estimation of water retention. The runoff production ($Q_{p,i}$) due to design storm depth (P) is estimated via the SCS-CN method using the potential maximum retention ($S_{max,i}$) and CN_i values on each pixel (i) (see Eq. 16).

$$Q_{p,i} = \begin{cases} \frac{(P-\lambda S_{max,i})^2}{P+(1-\lambda)S_{max,i}} & if \quad P > \lambda S_{max,i} \\ 0 & otherwise \end{cases} \tag{16}$$

The estimated runoff ($Q_{p,i}$) in Equation (16) is represented in mm as the design storm depth (P) and the potential retention ($S_{max,i}$). The initial abstraction ($\lambda\, S_{max,i}$) represents the rainfall depth needed to start runoff, also expressed in mm. For simplification, this model considers the factor λ as 0.2 times of $S_{max,i}$.

The empirical relation between $S_{max,i}$ and CN_i is provided in Equation (17). The hydrological behaviour of the area at the pixel level is manifested in terms of the CN values, which are based on the hydrologic soil group (HSG) and land use and soil characteristics.

$$S(mm)_{max,i} = \frac{25400}{CN_i} - 254 \tag{17}$$

Moreover, the model produces the runoff retention index per pixel (R_i), which is a ratio between the quantity of precipitation retained ($P - Q$) and the total precipitation (see Eq. 18) over the area of study.

$$R_i = 1 - \frac{Q_{p,i}}{P} \quad (18)$$

The runoff retained volume per pixel ($Q(m^3)_i$) is calculated in m^3 by multiplying the runoff retention index per pixel (R_i) (in mm) with the area of each pixel (m^2), as shown in Equation (19). Similarly, the runoff volume (or "flood volume") per pixel ($Q(m^3)_i$) is calculated in m^3 using Equation (20).

$$R(m^3)_i = R_i \times P \times Pixel\ area(m^2) \times 10^{-3} \quad (19)$$

$$Q(m^3)_i = Q_{p,i} \times Pixel\ area(m^2) \times 10^{-3} \quad (20)$$

The runoff retention index (R_i) is directly proportional to the direct economic avoided damage due to flooding. Since Green solutions (e.g., NBS) contribute to retention runoff, this model assumes that runoff retention index is also directly proportional to the mitigation services provided by these urban green solutions. Together with the biophysical evaluation of the runoff retention capacity of the urban areas, the InVEST model calculates the potential economic damage to the built infrastructure (in €) per watershed. This parameter is calculated by overlaying the flood extent potential information with the building footprint area. The potential damage estimation of the model does not consider the Flood Depth Damage function (DDF) because the Damage Loss Table values are not adjusted for the water depth (see section 8.1.2). The monetary valuation ($Affected.build$) of the damage per unit area (m^2) of the building type (as residential, commercial, industrial, etc.) is estimated by the model, and the cumulative potential economic damage of the study area is determined by summing up the individual damage caused to each building (see Eq. 21). If the entire area is flooded, $Affected.build$ represents the amount of infrastructure damage in € that would be done.

$$Affected.built = \sum_{watershed} a(b, W)\ d(b) \quad (21)$$

where:

- b is the building footprint in the set of built infrastructure B
- $a(b, W)$ is the area (m^2) of the building footprint that intersect the watershed W
- $d(b)$ is the damage value (from the Damage Loss Table – see section 8.1.2) for building (b) type.

Finally, the runoff retention service ($Service.built$) is represented by an indicator for each watershed as a product of runoff volume retained ($R(m^3)_i$) and flood affected built infrastructure ($Affected.build$) (see Eq. 21). $Service.built$ is expressed in €/m^3 even if it should be considered as an indicator which represents the avoided damage to built infrastructures (Eq. 22).

$$Service.built = Affected.build \sum_{watershed} R(m^3)_i \qquad (22)$$

The building damage calculation performed by the InVEST model showed aggregated values. To conduct a more detailed analysis of estimated built infrastructure damages, a value transfer method developed on GIS environment has been employed (see Section 10.2).

8.2 Urban Flood Risk Mitigation model: data input

Model inputs required:

- **Watershed vector or administrative boundaries (such as neighbourhoods)** delineating the areas of interest.
- **Numeric value of rainfall amount** for a single rainfall event (mm).
- **Soil Hydrological Group raster**.
- **Land Cover Map**.
- **Biophysical data table** containing values corresponding to each of the land use classes in the Land Cover Map.

How to identify the design rainfall value in a context of Climate Change?

The input on rainfall depth is represented by the measure of total rain (as constant) for a given storm event (numeric value of a single event typical of the study area). The focus of this research is to study pluvial related flash flood vulnerabilities in the context of urban Climate Change. Therefore, the rainfall event duration (i.e. the period of time during which rain falls) considered to identify the design storm corresponds to one hour. The flood damage assessment is strictly linked to the return period, or the frequency of recurrence, of a certain flood, which means the chance of occurrence of a storm of a given magnitude and duration in any year (as 50-years). The return period calculation strongly depends on the territorial context. For example, Hurford *et al.* (2012) showed how pluvial flooding in England causes most severe surface water flooding generally associated with rainfall intensity of less than 1-in-10-year return period.

According to the literature on statistical extreme rainfall investigation, GEV method has been used by several studies to perform quantification of climate change's influence on the spatial and temporal variability of meteorological events (Alexander *et al.*, 2006; Feng, Nadarajah and Hu, 2007; Fontolan *et al.*, 2019; Xavier *et al.*, 2020). The traditional design storm estimated through the intensity-duration-frequency (IDF) curves method, based on stationary extreme value theory (EVT) (i.e. the occurrence of extreme precipitation events is not expected to change over time), may not accurately represent climate change scenarios. Changes in the IDF relationships due to climate change have been observed in the Mediterranean city of Barcelona (Rodríguez *et al.*, 2014). Agilan and Umamahesh (2017) estimated a difference of rainfall intensity approximately 10 mm/h between traditional stationary IDF and non-stationary IDF approaches in an Indian urban catchment.

In the light of the above mentioned, this research considers the one hour-design rainfall event data provided for the 10, 50, and100-year return periods available for each study area respectively. To build both the base and future scenarios, the rainfall intensity-duration function (non-stationary IDF) for the city of Aveiro (see Brandão, Rodrigues and da Costa, 2001) and the rainfall depth-duration function (DDF) for the city of Rapallo (see ARPAL, 2013) have been created. Therefore, the reference values of rainfall for each return period implemented in this analysis are shown in **Table 9**, which refers to the base scenario. **Table 10** illustrates the rainfall amount for each return period by simulating Climate Change scenario 2050. Both tables provide the intensity of the precipitation, which means the depth of rainfall per unit of time (expressed as millimetres of rain per hour). The rainfall values reported are related to the two study cases: Aveiro (PT) and Rapallo (IT).

To develop the climate change scenarios, the data from the Swedish Meteorological and Hydrological Institute (SMHI)[31] was employed. The Service for Water Indicators in Climate Change Adaptation (SWICCA) scenarios of greenhouse gases are based on Representative Concentration Pathways (RCPs) developed for Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Intergovernmental Panel on Climate Change (IPCC). The moderate emission scenario RCP 4.5 has been selected for future climate simulation, in alignment with the Paris Agreement (2015)[32].

The mean precipitation value for each return period represents an average of rainfall variation within the mean ensemble range from the Hydrological Predictions for the Environment (E-hype)[33] model. In **Table 10**, the climate factors for flood simulations (near future, 2050) have been calculated for each return period in relation to the reference years, to finally derive the future design storm.

Table 9. *Design rainfall depth for each return period (Base scenario).*

	T = return period (1 hour duration)			Reference year
	10-years	**50-years**	**100-years**	
Aveiro (PT)	25.2 mm/h	31.9 mm/h	34.8 mm/h	*2001*
Rapallo (IT)	91 mm/h	133.5 mm/h	156 mm/h	*2013*

[31] https://hypeweb.smhi.se/
[32] Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf
[33] Accessed on 25th November 2021: https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change/

Table 10. *Design rainfall depth for each return period (Climate Change scenario - 2050).*

	T = return period (1 hour duration)		
	10-years	**50-years**	**100-years**
Aveiro (PT)	*8%*	*12%*	*14%*
	27.2 mm/h	35.7 mm/h	39.7 mm/h
Rapallo (IT)	*6%*	*6%*	*7%*
	96.5 mm/h	141.5 mm/h	166.9 mm/h

How to determine Hydrological Soil group raster?

Since the runoff evaluation is derived from the interaction of land use and soil characteristics through the employment of the SCS-CN method, the creation of two main databases is crucial for this model: data on land use and data on hydraulic conductivity of soils.

The first data is related to the hydrologic soil group (HSG). HSG is a group of soils having similar runoff potential under similar storm and cover conditions. Soil properties, without considering the slope of soil surface, are used to calculate HSGs through the assignment of these groups to soil map unit components. This procedure allows one to derive a soil's associated runoff curve number, which is used to estimate direct runoff or infiltration from excess rainfall. Indeed, HSGs are fundamental components of the USDA (United States Department of Agriculture) SCS-CN method for estimation of rainfall runoff. Soils have been essentially classified into four standard classes of hydrologic soil groups - A, B, C, and D - according to USDA classification (**Table 11**). To determine HSGs, it hydraulic conductivity (K) and soil depth should be considered (USDA - United States Department of Agriculture, 2009). This input represents essentially the saturated hydraulic conductivity of soils (Ksat mm/h), which means the ability of soils to be vertically drained of liquids when in a saturated state. In the literature, it is recognized that the hydraulic conductivity (K) depends on land-texture (soil's nature), which is strictly connected to the porosity of the soil: clay soils (impermeable soils) generally have a lower saturated hydraulic conductivity than sandy or gravelly soils (permeable soils), where the pores, less numerous but larger, facilitate the passage of big volumes of water (Abdelrahman, Natarajan and Hegde, 2016).

Table 11. *Hydrological soil groups according to USDA classification.*

Group A	Soils with low runoff potential and high rate of water transmission (more than 90% sand and less than 10% clay)
Group B	Soils with moderately low runoff potential and moderate rate of water transmission (between 10 to 20% clay and 50 to 90% sand)
Group C	Soils with moderately high runoff potential (between 20 to 40% clay and less than 50% sand)
Group D	Soils with high runoff potential and low rate of transmission (more than 40% clay and less than 50% sand)

8.3 Data input: case of Aveiro

The area of interest is the Municipality of Aveiro, and it considers the administrative boundaries and neighbourhood divisions instead of the watershed boundaries. **Figure 60** shows the 21 administrative neighborhoods identified for Aveiro, of which those highlighted in yellow constitute the city center (Alboi, Liceu, Beira-Mar, Carmo, Estação, Fonte Nova, Fórum, Gulbenkian, Santiago). This data has been generated with the knowledge of local experts using the information from the Aveiro Census 2011 (INE)[34]. Due to the limited availability of information regarding buildings for the damage assessment, two specific subdivisions (freguesias) within the municipality of Aveiro were selected: 'Glória e Vera Cruz' (city centre) and part of 'Esgueira' (industrial area).

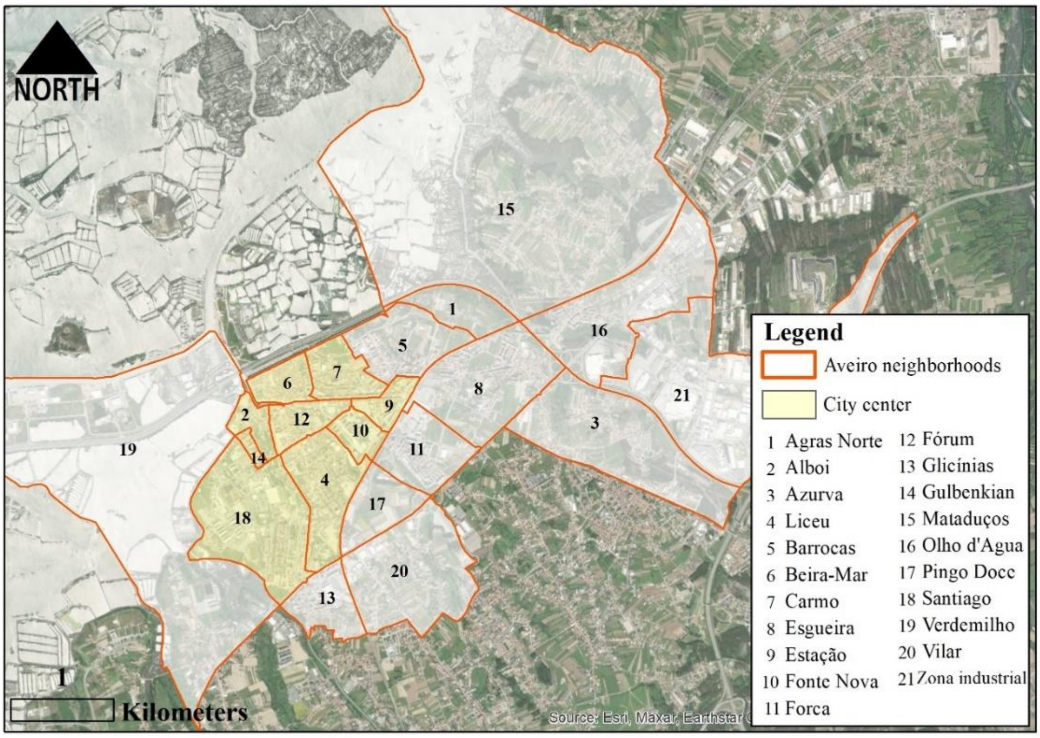

Figure 60. *Neighbourhoods in Aveiro city.*

To map the input data of soil conductivity, the 3D Soil Hydraulic database[35] of Europe at 250 m resolution has been consulted. This spatial soil hydraulic data has information at 7 soil depths (expressed in cm) divided in topsoil and subsoil. The saturated hydraulic conductivity (ks) in cm/day has been converted to μm/s. Then, the worst scenario was considered (when ks is the lowest) between two soil depth levels (60 and 100 cm). These values have been grouped in four classes (A, B, C and D) following the USDA criteria, as shown in **Table 12**.

[34] Accessed on 20th May 2022: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_base_dados
[35] Accessed on 21st May 2021: https://esdac.jrc.ec.europa.eu/content/3d-soil-hydraulic-database-europe-1-km-and-250-m-resolution

__Table 12.__ HSGs input data.

		Group A	Group B	Group C	Group D
Criteria for assignment of HSGs according to USDA	Saturated hydraulic conductivity of the least transmissive layer when a water impermeable soil is at a depth between 50 and 100 cm	>40 µm/s	[40;10] µm/s	[10;1] µm/s	<1 µm/s

Table 12 on HSGs with associated curve number has been linked to the input data on land use classification using the Land use and occupation map of Aveiro (COS-2018)[36]. This classification has been built around the USDA classes (USDA - United States Department of Agriculture, 2004).

To rank the 'urban districts' category in permeability classes according to USSDA classification, another dataset has been used. The imperviousness HRL (High resolution layer)[37] 2018, which is a database of 10 meters raster freely available on the Copernicus website, represents the spatial distribution of artificially sealed areas, including the level of sealing of the soil per area unit. The HRL 2018 has been employed to obtain the level of permeability of the urban districts.

To get 'urban open spaces' category according to USDA, the Normalised Difference Vegetation Index (NDVI) was employed. NDVI detects the consistency of vegetation by measuring the difference between near-infrared (which is reflected by vegetation) and red light (which is absorbed by the plant). This NDVI data was obtained by the cloud-free pixel-based composite data at global scale of four spectral bands (B2: Blue, B3: Green, B4: Red, B8: Near Infrared) created from the Sentinel-2 data for period January 2017 – December 2018. The composite data with a spatial resolution of 10 meters has been downloaded from Global Human Settlement Layer (GHSL)[38] of the European Commission. The employment of NDVI guided the definition of the good, fair or poor conditions of the 'urban open spaces' according to USDA classification. In that case, the Land use has been intersected with the NDVI dataset, and the average values of vegetation density for each class of 'urban open spaces' were estimated.

The 'impervious area' category, which represents the built-up footprint, has been calculated by overlaying the Land use and the Impervious Built-up (IBU –

[36] Accessed on 13th January 2021: https://snig.dgterritorio.gov.pt/rndg/srv/por/catalog.search#/search
[37] Accessed on 14th January 2021: https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness
[38] Accessed on 15th March 2021: https://ghsl.jrc.ec.europa.eu/download.php?ds=compositeS2

Copernicus, 2018)[39] datasets. IBU gives the information of building areas considered as a product of urban density and the highest levels of imperviousness in land use.

Regarding the 'agricultural lands' category, values were used that correspond as closely as possible to the USDA (USDA - United States Department of Agriculture, 2004) classification. The 'water bodies' category reflects the assumption of the model that this land use class cannot absorb water. Indeed, HSG values equal to zero correspond to areas where 100% of precipitation flows as runoff. **Table 13** represents the final biophysical table obtained with 25 land use classes associated to HSGs for Aveiro.

Table 13. *Biophysical table with land use and curve numbers (Aveiro).*

Cover description			*Curve numbers for hydrologic soil group*			
			A	**B**	**C**	**D**
Urban Open space	**1**	Poor condition (low NDVI)	68	79	86	89
	2	Fair condition (medium NDVI)	49	69	79	84
	3	Good condition (high NDVI)	39	61	74	80
Streets, roads & railways	**4**	Paved; curbs and storm sewers	98	98	98	98
	5	Gravel and open ditches	76	85	89	91
Impervious area	**6**	Buildings (dense urban)	98	98	98	98
Urban districts	**7**	(85% imp.)	89	92	94	95
	8	(72% imp.)	81	92	94	93
	9	(65% imp.)	77	85	90	92
	10	(38% imp.)	61	75	83	87
	11	(30% imp.)	57	72	81	86
	12	(25% imp.)	54	70	80	85
	13	(20% imp.)	51	68	79	84
	14	(12% imp.)	46	65	77	82
Water & Wetlands	**15**	Natural and artifical	0	0	0	0
Semiarid lands	**16**	Desert shrub	63	77	85	88
Agricultural lands	**17**	Brush - grass mixture	35	56	70	77
	18	Woods - grass combination	43	65	76	82
	19	Woods	36	60	73	79
	20	Areas without vegetation	68	79	86	89
	21	Pasture & grassland	49	69	79	84
	22	Farmstead - buildings & surrounding lots	59	74	82	86
	23	Fallow	74	83	88	90
	24	Row crop	64	75	82	85
	25	Meadow - continuous grass	30	58	71	78

[39] Accessed on 15th March 2021: https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/status-maps/impervious-built-up-2018

8.3 Data input: case of Rapallo

The area of interest is the Municipality of Rapallo, considering the administrative boundaries and neighbourhood divisions instead of the watershed boundaries (see **Figure 62**). A shapefile with neighbourhood boundaries does not exist for the Municipality of Rapallo. For this reason, this data has been generated with the help of local experts' knowledge by converting the information from **Figure 61** into a shapefile.

Figure 61. *Image on the subdivision of "antichi sestieri" for Rapallo Municipality (Source: https://it.wikipedia.org/wiki/Sestiere_(Rapallo)).*

A combination of different data has been employed to finally map the input data of soil conductivity. These maps are "Landscape Units" (Unità di Paesaggio - UDP)[40] and "Profili and Trivellate[13]" (2000), which contain information about the land-texture and the associated infiltration coefficient following the classification of Soil Taxonomy 99[41]. **Table 14** shows in the first line the USDA criteria used to easily convert soil conductivity into HSGs, while the second line represents our reclassification crossing the information about the type of soil (TS) and infiltration coefficient (CI). A "Landscape Units" map has been grouped in four classes (A, B, C and D) following the USDA criteria, as shown in **Table 14**. This analysis takes into account a maximum soil depth equal to one meter, which is the information provided by soil analysis of "Profili and Trivellate" map.

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[40] Accessed in September 2020: https://geoportal.regione.liguria.it/catalogo/mappe.html
[41] https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/class/taxonomy/

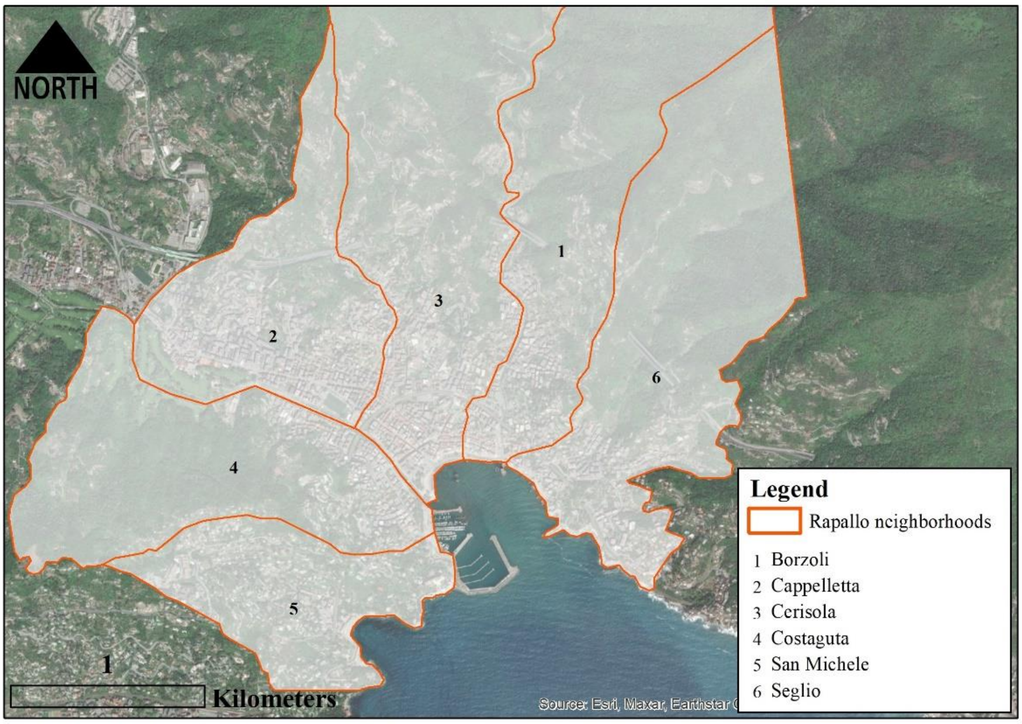

***Figure 62.** Neighbourhoods in Rapallo city.*

A combination of different data has been employed to generate a final soil conductivity input dataset. This includes the maps called "Landscape Units" (Unità di Paesaggio - UDP)[42] and "Profili and Trivellate[13]" (2000), which contain information about the land-texture and the associated infiltration coefficient following the classification of Soil Taxonomy 99[43]. **Table 14** shows, in the first line, the USDA criteria used to easily convert soil conductivity into HSGs, while the second line represents our reclassification crossing the information about the type of soil (TS) and infiltration coefficient (CI). The "Landscape Units" map has been grouped in four classes (A, B, C and D) following the USDA criteria, as shown in **Table 14**. This analysis takes into account a maximum soil depth equal to one meter, which is the information provided by soil analysis of "Profili and Trivellate" map.

[42] Accessed in September 2020: https://geoportal.regione.liguria.it/catalogo/mappe.html
[43] https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/class/taxonomy/

__Table 14.__ Construction of HSGs input data.

		Group A	Group B	Group C	Group D
Criteria for assignment of HSGs according to USDA	Saturated hydraulic conductivity of the least transmissive layer when a water impermeable soil is at a depth between 50 and 100 cm	>40 μm/s	[40;10] μm/s	[10;1] μm/s	<1 μm/s
Reclassification	Type of soil (TS) and infiltration coefficient (CI) grouped into four classes	TS = 10 CI = 999	TS = 5, 6 CI = 0,3 and 0,15	TS = 4 CI = 0,1	TS = 2, 3 CI = 0,07 and 0,05

Table 14 on HSGs with associated curve number has been connected to the input data on land use classification using the Land Cover Liguria (2019)[44]. This classification has been built around the USDA classes (USDA - United States Department of Agriculture, 2004). For the 'urban' category, the permeability classes of the different layers, according to USSDA classification, were ranked using another dataset. The national high resolution land consumption map (NHRLC)[45], which is a database of 10 meters resolution rasters produced yearly by the Italian Institute for Environmental Protection and Research (ISPRA) (freely accessible at the SINANET Portal) provides information (from satellite images) on sealed and artificial areas. The NHRLC was intersected with the land use data to achieve the classification of the urban districts, following the permeability. Regarding the 'agricultural lands' category, values were used that correspond as closely as possible to the classification of USDA (USDA - United States Department of Agriculture, 2004). As above described, the 'water bodies' category reflects the assumption of the model that this land use class cannot absorb water. Indeed, HSG values equal to zero correspond to areas where 100% of precipitation flows as runoff. **Table 15** represents the final biophysical table obtained with 24 land use classes associated to HSGs.

[44] Accessed in September 2020: https://geoportal.regione.liguria.it/catalogo/mappe.html
[45] Accessed in September 2020: http://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/consumo-di-suolo

__Table 15.__ Biophysical table with land use and curve numbers (Rapallo).

Cover description			*Curve numbers for hydrologic soil group*			
			A	**B**	**C**	**D**
Urban Open space	**1**	Poor condition (grass cover <50%)	68	79	86	89
	2	Fair condition (grass cover 50-75%)	49	69	79	84
	3	Good condition (grass cover >75%)	39	61	74	80
Streets, roads & railways	**4**	Paved; curbs and storm sewers	98	98	98	98
	5	Paved; open ditches	83	89	92	93
Impervious area	**6**	Paved open space & buildings (dense urban)	98	98	98	98
Urban districts	**7**	(85% imp.)	89	92	94	95
	8	(72% imp.)	81	92	94	93
	9	(65% imp.)	77	85	90	92
	10	(38% imp.)	61	75	83	87
	11	(30% imp.)	57	72	81	86
	12	(25% imp.)	54	70	80	85
	13	(20% imp.)	51	68	79	84
	14	(12% imp.)	46	65	77	82
Water bodies	**15**	Natural and artifical	0	0	0	0
Agricultural lands	**16**	Brush – grass mixture	35	56	70	77
	17	Woods – grass combination	43	65	76	82
	18	Woods	36	60	73	79
	19	Areas without vegetation	68	79	86	89
	20	Pasture & grassland	49	69	79	84
	21	Farmstead – buildings & surrounding lots	59	74	82	86
	22	Fallow	74	83	88	90
	23	Row crop	64	75	82	85
	24	Meadow – continuous grass	30	58	71	78

Chapter 9

Nature-based solutions scenarios design

This chapter provides a description of NBS scenarios to simulate urban flood adaptation. The adaptation scenarios are composed by single solutions. The future climate scenarios consider rainfall as the chancing variables. Further climate variables such as temperature, solar radiation, etc. were not considered in the future climate scenarios even if they are likely to impact the future urban waterflow and NBS performances.

The choice of NBS types is based on the type of analysis that will be developed. Indeed, the economic quantification of NBS effects is expressed in terms of flood losses as a result of damage to buildings and roads. For that reason, the implemented NBS will modify the building layer (by changing the cover of roofs) and roads layer (by changing a specific % of road coverage).

The next sections describe in detail the technical characteristics for selected NBS: Green roofs and Bioswales. Finally, a section dedicated to the description of the selected adaptation scenarios has been provided.

9.1 Green roofs

Green roofs are vegetative layers implemented on rooftops, with the intent to provide green space in urban areas for different purposes. They can contribute to mitigating negative effects that are typical of urban areas, caused especially by urban sealing, buildings, and heat emissions. Depending on the type of green roof and the plants used, green roofs may be modular or have drainage layers to mitigate flood events. All green roofs include a few important and common features, such as waterproofing and root repellent, to keep the host structure undamaged. Moreover, some positive effects associated with green roofs are associated with cooling and evapotranspiration, which lead to a reduction of the roof temperature itself as well as of the surrounding air. Maintenance is the most important part of the green roof top for both the plantation as well as the building (Mačiulytė *et al.*, 2018).

Green roofs are associated with residential buildings, hotels or underground parking. Installation, maintenance, and management effort (regular irrigation and fertilisation) leads to higher costs. Two typologies of green roofs exist: intensive, and extensive green roofs. Intensive roofs incorporate vegetation that are accessible for public or recreational purposes. Moreover, these roofs can include some different architectural elements, such as buildings or solar panels.

Extensive green roofs are characterized by a lighter weight system which requires minimum and less expensive maintenance/management than that of intensive systems. This kind of roofs, that are not accessible or are of limited access for public purposes, are partially characterised by steep slopes. These roofs implement more resistant plants that are generally well adapted to alpine environments/climate and tolerate different climate conditions (e.g., drought) and temperature variations.

Table 16 shows a description of main benefits and costs related to green roofs with a dedicated section to vegetation type.

Table 16. *General benefits, costs, and vegetation types of green roofs (adapted from Mačiulytė et al. (2018) and Regione Emilia-Romagna (2020)).*

<table>
<tr><td>Benefits</td><td>Costs</td></tr>
<tr><td>Enhanced biodiversity, human health and quality of life
Public access to green recreational areas
Storm water/rainwater management and quality increasing water retention
Improved air quality (pollution reduction)
Aesthetic value/visual attractiveness
Additional space (intensive roof)
Thermal performance/temperature reduction (air cooling and evapotranspiration)
Energy reduction for buildings (heating/cooling)
Reduction of noise/sound transmission
Habitat provision for urban wildlife
Reduced flood risk and slope stability
Beneficial for selected species with some specific plants
Carbon storage capacity</td><td>Costs vary significantly depending on the size, location and accessibility of the site, the types of plants, the type of structure, the design, the distances transport, the storage of materials on or offsite, the access for mobile cranes, access to goods lifts, the roof height, dimensions and load-bearing capacity, the roof construction, complexity of roof design including roof penetrations and the timing of project</td></tr>
<tr><td colspan="2">Vegetation type</td></tr>
<tr><td colspan="2">Appropriate vegetation type is made mainly by trees, shrubs, and perennials. The variety of species is strongly related to the underlayer depth and the microclimate condition. The extensive green roofs should implement perennials species (i.e., Sedum) which have some common aspects: they can regenerate, reproduce, tolerate adverse climate conditions (strong wind or drought), resist to the thermic and hydric stress, and need a few maintenance. The intensive green roofs can use different vegetation types a part of tall trees.</td></tr>
</table>

9.2 Bioswales

Water Sensitive Urban Design (WSUD) is an urban development paradigm aimed at reducing hydrological impacts of urban development on the environment. In practice, the WSUD integrates stormwater, groundwater water supply, and wastewater management to:

- protect existing natural features and ecological processes;
- maintain natural hydrologic behaviour of catchments;
- protect the surface and groundwater quality;
- reduce demand on the reticulated water supply system;
- minimise wastewater discharges to the environment.

Minimising impervious surfaces by using pervious roads and permeable concrete helps enhance the infiltration of stormwater in underlying surfaces, reducing runoff into sewerage systems and urban spaces, attenuating flood peaks, reducing the urban pollution load in runoff, as well as reducing the risk of damages due to drainage system failure by flooding (Mačiulytė *et al.*, 2018). Among the most common WSUD practices there are bioswales and rain gardens.

A bioswale is a vegetated, linear, and low sloped trench established along the roads in urban areas, with the objective of reducing flood risk during, or after, heavy rain events. They should be lower than the ground level and should be simple to construct. Bioswales absorb, store, and convey surface water runoff (draining from roadways), while removing pollutants and sediments as the water trickles through the vegetation and soil.

Two typologies of bioswales exist: dry and wet bioswales. The first type can be filled up only in case of rainfall event, while the second one always keeps a layer of water, in which specific plants can grow, such as riparian vegetation.

Table 17 shows a description of the main benefits and costs related to bioswales, with a dedicated section about vegetation type.

Table 17. *General benefits, costs, and vegetation types of bioswales (adapted from Mačiulytė et al. (2018) and Regione Emilia-Romagna (2020)).*

Benefits	Costs
• Remove pollution from the rainwater, and water quality improvement • Storm water storage management and control • Reduced flood risk • Reduction of air pollution and urban heat island effect • Habitat provision for wildlife • Potential re-use of water for irrigation	• Costs vary depending on size, site conditions and the type and size of the vegetation used. Annual maintenance costs include necessary pruning, mowing of the vegetation existing in the bioswale, periodical cleaning of the bioswale and control of inlet and outlet structures, enabling water flow management in the detention basin.

• Prevention of soil erosion • Increased biodiversity and pollination of the flora • Improved quality of life • Visually aesthetic blue and green recreation and multiple use areas	
Vegetation type	
The choice of the plants is strictly related to the climate condition of the intervention region. Trees are the most common and together with small bushes could reproduce natural hedges. In general, the vegetation species should tolerate periodic flooding alternated to dried seasons as well as the sediment and debris accumulation. Moreover, when used for draining impermeable surfaces the species should tolerate salt washing away from the roads during wintertime. To what concerns bioswales, the basal layer is made by privet, viburnum and grass. The intermediate layer is built by small trees as hazelnut trees or elder while the apical one is made by foliage of willows, snorts, plane trees or maples.	

9.3 NBS adaptation scenarios

The NBS adaptation scenarios are built on the above two described solutions (green roofs and bioswales). **Table 18** explains the matrix about the integrated climate (current and future) and adaptation scenarios (without and with NBS) employed in this research. **Figure 63** gives an overview of these adaptation scenarios by summarizing some technical information, the kind of intervention, and the implementation area at city level. Technical aspects, such as width and depth for bioswales or depths of substrate layer for green roofs, are characterized by average values calculated from three NBS projects and a guidelines reports about the city of Bologna (Italy): UNaLab[46], SOS4LIFE[47], Urban GreenUP[48] and SUDS Guidelines - Bologna city (Comune di Bologna *et al.*, 2018).

Table 18. *Definition of the integrated adaptation and climate scenarios.*

		Climate scenarios	
		Current climate	Future climate
Adaptation scenarios	No NBS	T0_NBS0	T1_NBS0
	Green roof	T0_NBS1	T1_NBS1
	Bioswale	T0_NBS2	T1_NBS2

NBS1 - Green roof simulates the effects of implementing green roofs on all buildings in the neighbourhoods that show the highest flood-related costs from the T0_NBS0 (current climate, no NBS) scenario results. In this way, it is possible to

[46] https://unalab.eu/en
[47] https://www.sos4life.it/
[48] https://www.urbangreenup.eu/

simulate the maximum benefits those neighbourhoods can get in terms of flood reduction by by implementing such solutions. For the purposes of this study, all instances of green roof simulation considered the application of this solution on the total roof area of the buildings selected for its implementation. The total simulated green roof area in Aveiro is 561,170 m^2, which corresponds to approximately 27% of the city's total building (roof) area in Aveiro city. For the Rapallo municipality, the scenario simulated 435,262 m^2 of green roof area, corresponding around 31% of the city's total building area (**Figure 63**).

NBS2 - Bioswale scenario simulates the effects of bioswales on all roads (except the highways) in the considered neighbourhoods, covering 20% of the road (SOS4LIFE project[49]). The total simulated bioswale area in Aveiro is 45,354 m^2, which corresponds to 3% of the city's total road area. For the city of Rapallo, this scenario simulated a total bioswale area of 55,207 m^2, corresponding to 11% of the city's total road area (**Figure 63**).

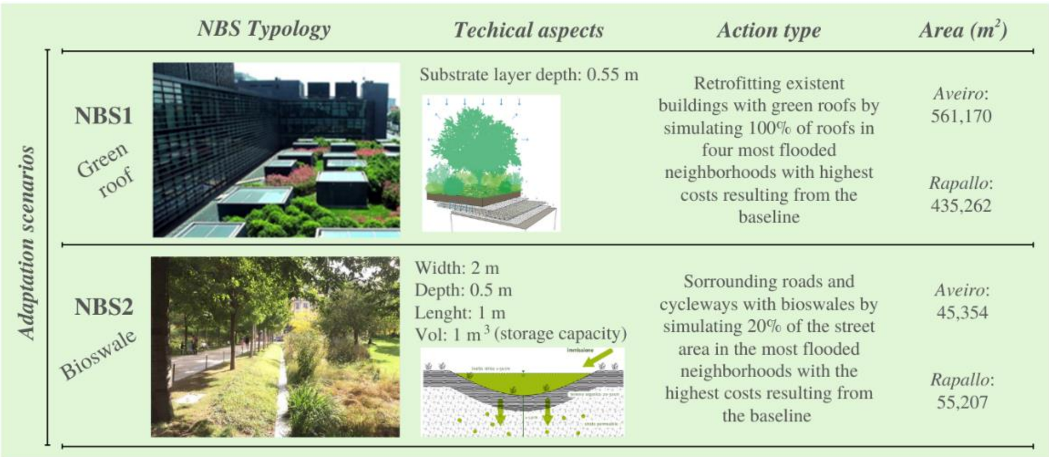

Figure 63. *Technical information and images of NBS scenarios (adapted from Mačiulytė et al. (2018) and Regione Emilia-Romagna (2020)).*

The neighbourhoods selected to implement the NBS are those that showed the most flooded areas and the greatest damages. **Figure 64** and **Figure 65** show the selected neighbourhoods for the city of Aveiro, where NBS1 and NBS2 scenarios have been implemented, respectively. Both figures show the spatial distribution of these NBS over the city center of Aveiro. NBS1 considers four neighbourhoods (Beira-Mar, Liceu, Forca and Santiago) as shown in **Figure 64**. NBS2 includes three neighbourhoods (Liceu, Forca and Santiago) because Beira-Mar has narrow streets where bioswales would not fit (**Figure 65**). **Figure 66** and **Figure 67** show the selected neighbourhoods for the city of Rapallo, to implement the NBS1 and NBS2 scenarios respectively. Both figures exhibit the spatial distribution of these NBS over Borzoli, Cappelletta and Cerisola neighbourhoods.

[49] https://www.sos4life.it/

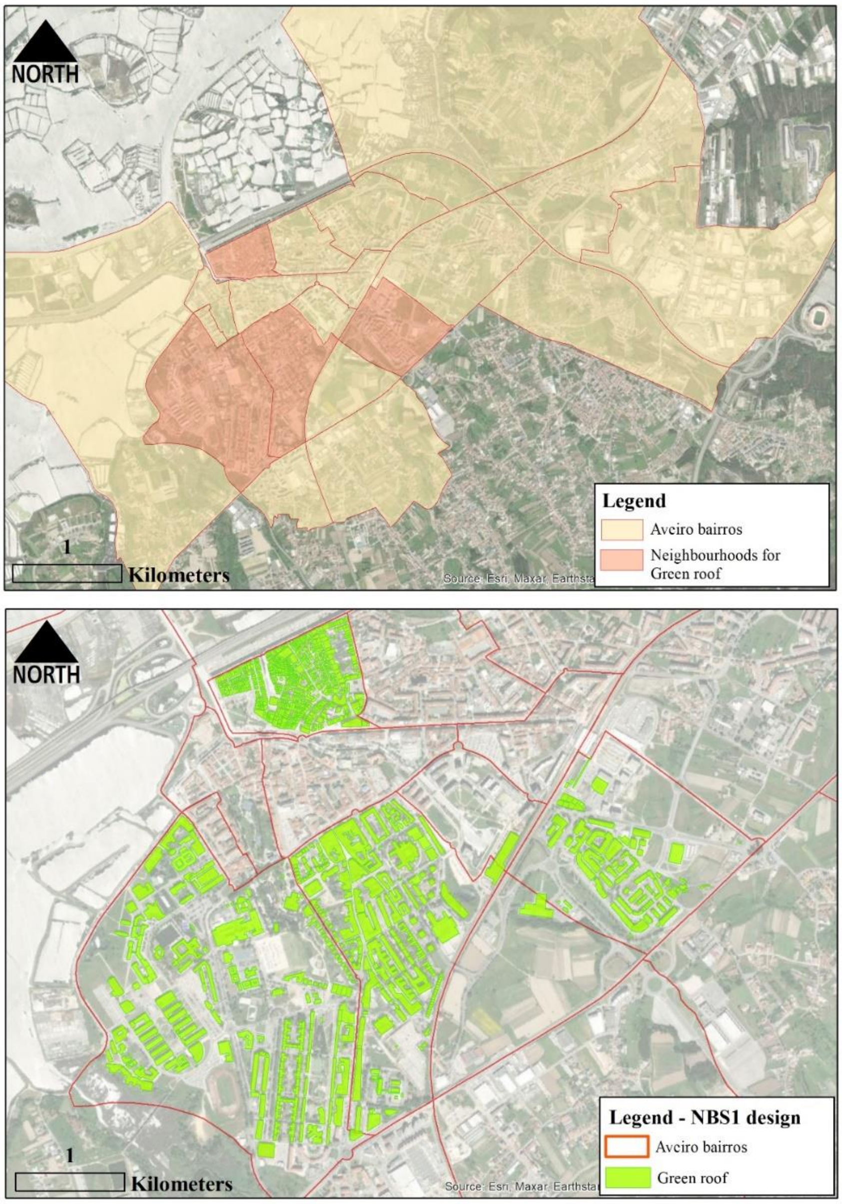

__Figure 64.__ Neighbourhoods for NBS2 implementation, and spatial distribution of green roofs over Aveiro city.

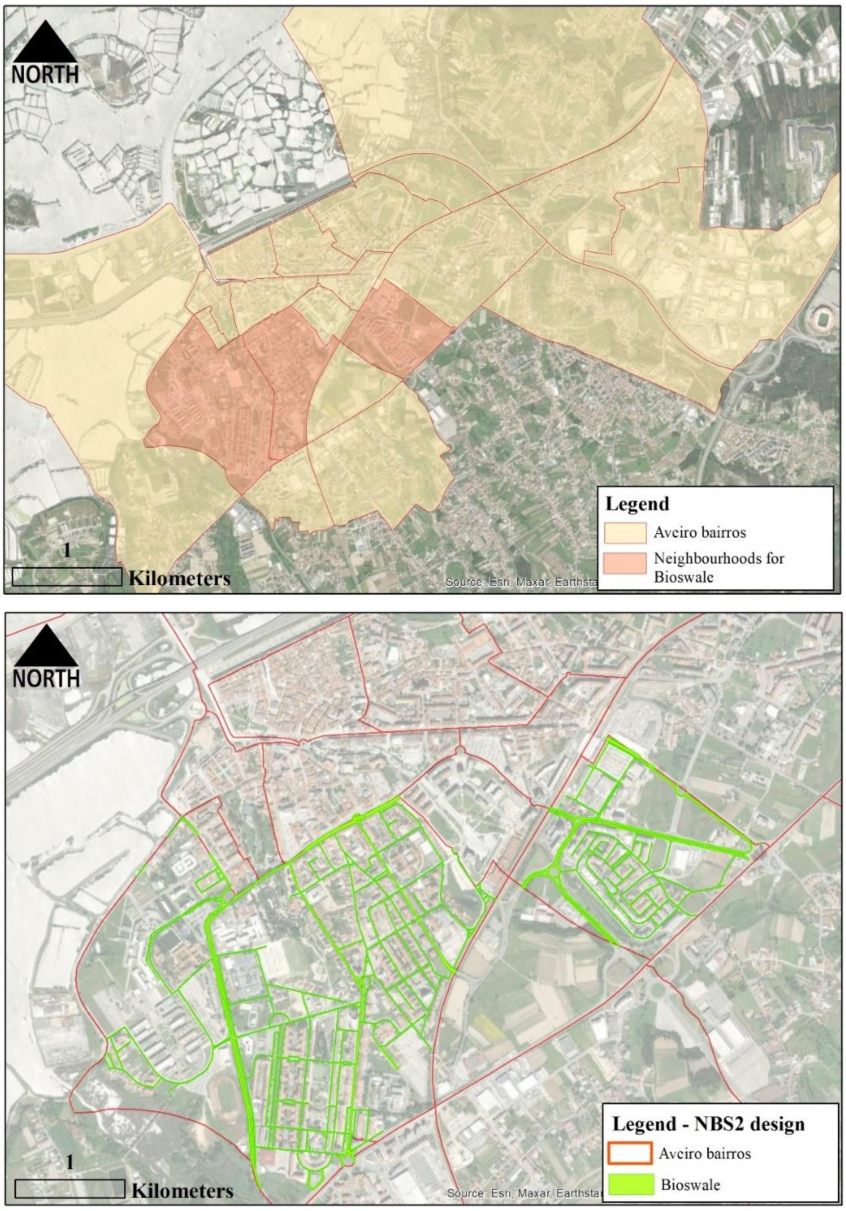

Figure 65. *Neighbourhoods for NBS2 implementation, and spatial distribution of bioswales over Aveiro city.*

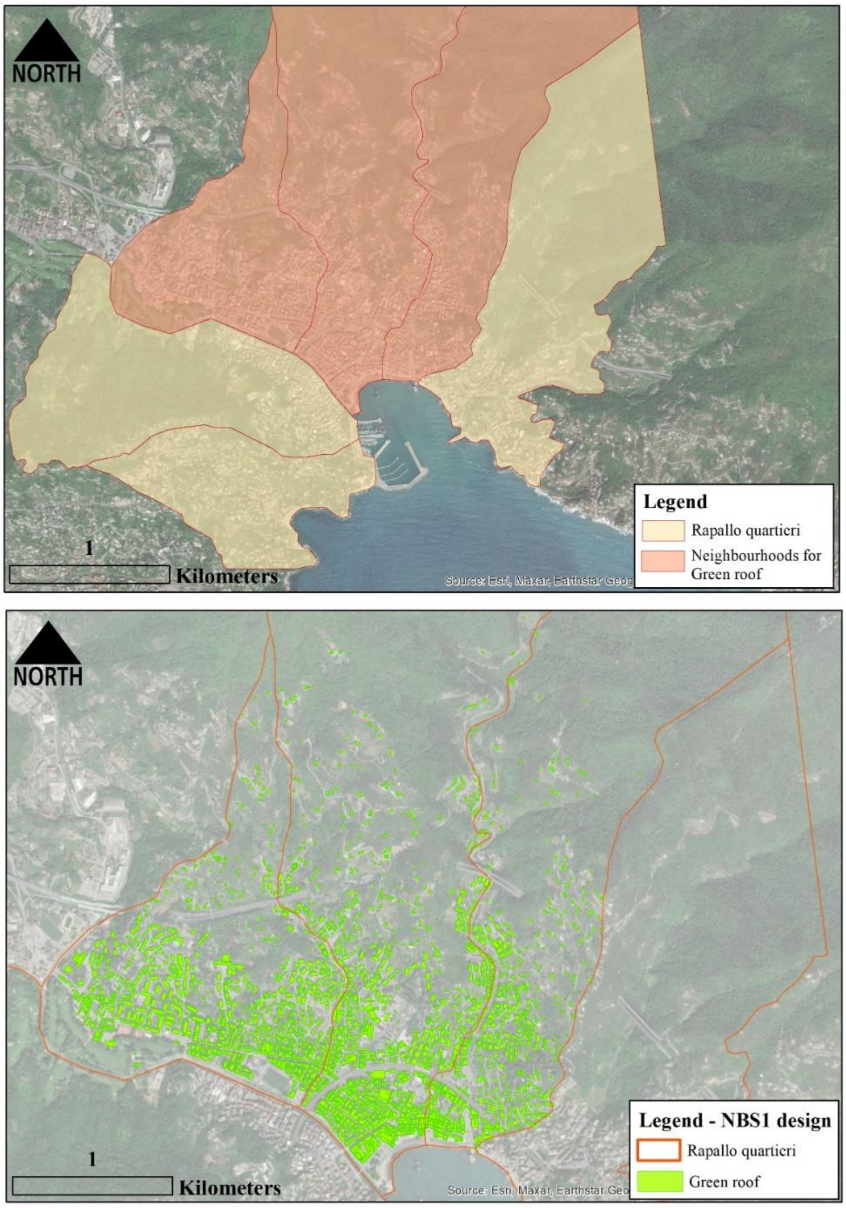

Figure 66. *Neighbourhoods for NBS1 implementation, and spatial distribution of green roofs over Rapallo city.*

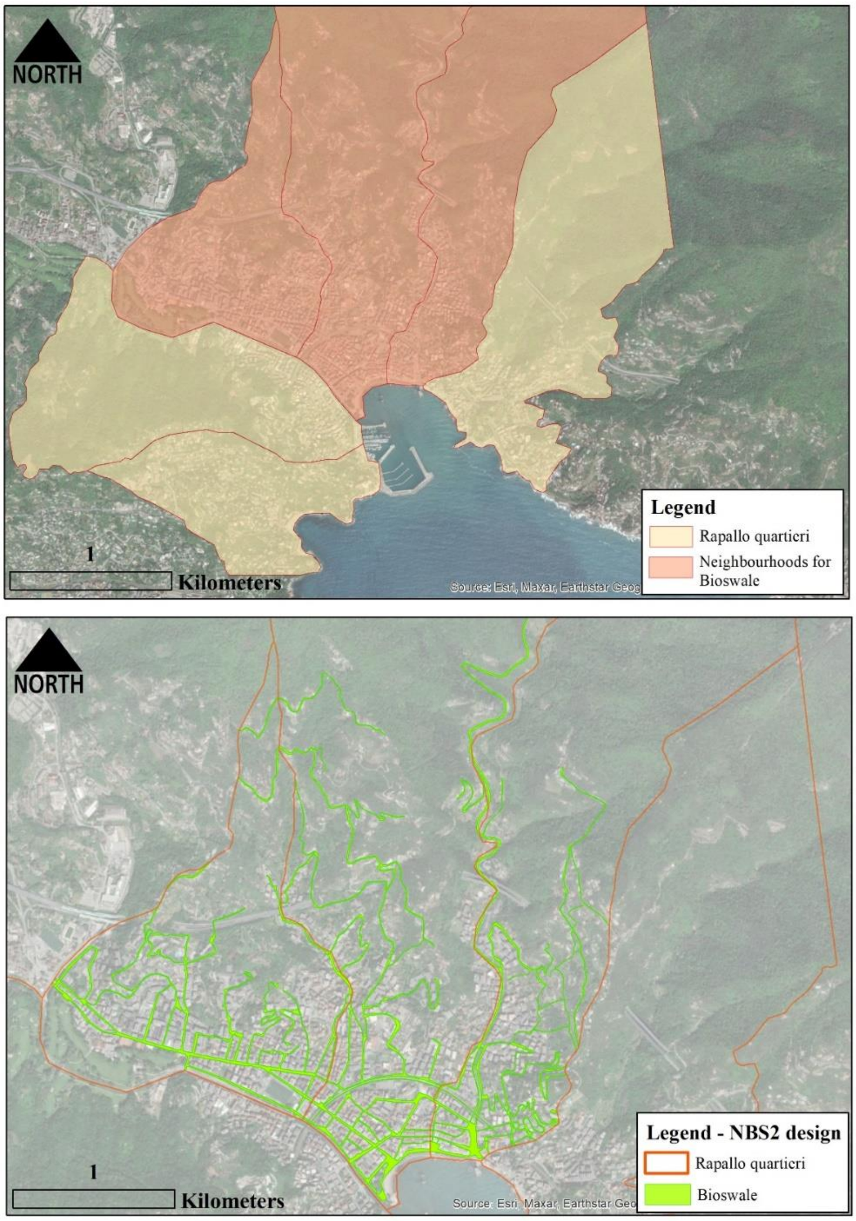

Figure 67. *Neighbourhoods for NBS2 implementation, and spatial distribution of bioswales over Rapallo city.*

Chapter 10

NBS costs and benefits

The following sections introduce the process to obtain NBS costs and benefits (in terms of avoided flooding costs) in order to conduct the cost-benefit analysis (CBA).

Cost-benefit analysis (CBA) is a relevant tool for decision making in urban planning by comparing different scenarios (Perman *et al.*, 2003; Boardman *et al.*, 2018; Locatelli *et al.*, 2020). Accurate CBA that considers disservices and co-benefits of green solutions in comparison to grey infrastructure are useful. To estimate NBS costs and benefits, a value transfer method has been employed. This method allows the use of value data and information from other similar contexts where primary ecosystem services evaluation has been conducted (Brander, 2013).

10.1 NBS cost calculation

In this section, the methodology for the implementation costs of green roofs and bioswales in Aveiro and Rapallo will be explained.

Implementation costs associated to NBS include both investment and maintenance costs. The investment costs consist of a single payment at the start of the project, and include planning costs, material costs, installation costs, and eventually roof reinforcement (for green roofs). The process of selecting the locations for such solutions constitute the planning costs, while the material costs consist of the costs for input materials. The installation costs are the costs for the installation itself. Sometimes a reinforcement of the structure that will host the green roof is needed to withstand the increased load of the green roof layer and its vegetation.

The maintenance costs are periodically and occur during the lifespan of the solutions. Some examples of maintenance costs are on-site inspections, fertilizer use, the replacement of plants, weeding and disease management, and water for irrigation (Mačiulytė *et al.*, 2018).

There are many variables influencing the costs of such measures, resulting in significant variations in costs of implementation for different locations. For instance, some relevant variables to take into account include the size, location and accessibility of the site, the types of plants used, the type of structure, the design, the distance for transport, etc. Specifically, costs associated to green roofs include the storage of materials on or off-site, the access for mobile cranes, access to good lifts, the roof height, dimensions and load-bearing capacity, the roof construction, as well as the complexity of roof design, including penetrations and the timing of the project (Mačiulytė *et al.*, 2018). Retrofits, which means installing a green roof on an existing building, where reinforcement measures are necessary to increase the structural capacity of a roof, may have high costs. However, studies have estimated the return on investment from green roofs (through energy savings) to be anywhere from zero to 20 years. The life expectancy of a waterproof membrane under a green roof is 40 years (compared to 17 years for a conventional roof); however, green roofs require regular maintenance and inspection (quarterly may be sufficient) actions to ensure they remain alive and functional[50].

Maintenance costs concerning the bioswales may be reduced using native grasses and plants that are already adapted to the area, requiring less water, no fertilizer, and infrequent mowing. If sediment is not removed periodically, a bioswale may eventually need to be restored to enable the proper flow. In general, bioswales do not require excessive maintenance. To ensure that a bioswale continues to operate effectively, it must be inspected periodically to ensure that the channel is adequately vegetated (without woody plant encroachment) and that there are no blockages (either from debris or sedimentation). Inspections should be performed annually and after any major storm event for bare soil, erosion, sediment and debris to be removed[51] (Mačiulytė *et al.*, 2018; Regione Emilia-Romagna, 2020).

The cost values found in literature range widely (e.g. Bianchini and Hewage, 2012; Feng and Hewage, 2018; Zhou and Arnbjerg-Nielsen, 2018; Locatelli et al., 2020). This CBA considers cost values derived from four NBS European projects: UNaLab, SOS4LIFE, Urban GreenUP and ThinkNature[52].

Given the large difference in cost values, three scenarios have been considered, consisting of the "Low" (minimum), "Medium" (average) and "High" (maximum) cost options (see **Table 19**). By examining different scenarios, it is possible to perform a sensitivity analysis to identify the degree of uncertainty on the predicted values (Boardman *et al.*, 2018). The unit costs considered (€/m^2) have been converted into the same year value (2020) using the consumer price index[53].

Table 20 reports the different ranges of total costs and annual costs calculated by considering the expected lifetime for both implemented solutions.

Also note that the annual maintenance costs of NBS correspond to, on average, 2.5% of the investment costs, according to the European projects evaluated. Alves *et al.* (2019), for instance, used 3% of the operation costs to derive the maintenance costs for green roofs. For this reason, in this research, maintenance costs have been derived annually from the implementation costs of green roofs and bioswales (see **Table 20**).

[50] *Naturally Resilient Communities* project. Accessed on 08h August 2022: https://nrcsolutions.org/green-roofs/
[51] *Naturally Resilient Communities* project. Accessed on 08h August 2022: https://nrcsolutions.org/bioswales/
[52] https://www.think-nature.eu/
[53] World Bank: https://databank.worldbank.org/source/world-development-indicators#

Table 19. *Green roof and bioswale lifetime and costs for Aveiro and Rapallo (in 2020 Euros, based on: UNaLab, SOS4LIFE, Urban GreenUP and ThinkNature).*

	Lifetime (years)	Type of cost	Lifetime cost (€/m²)	Annual cost (€/m²/year)[1]
Green roof	40	Investment	170 - 450	4.25 - 11.25
		Maintenaince		4.25 - 11.25
		Tot. Implementation		8.50 - 22.50
Bioswale	25	Investment	80 - 100	3.20 - 4.00
		Maintenaince		2.00 - 2.50
		Tot. Implementation		5.20 - 6.50

Note: [1]Annual investment costs are calculated using a time discount rate of 0%.

Table 20. *NBS costs options (€/m²/year) for Aveiro and Rapallo.*

	Cost option	Annual investment costs (€/m²/year)[2]	Annual maintenance cost (€/m²/year)
Green roof	Low	4.25	4.25
	Medium	7.75	7.75
	High	11.25	11.25
Bioswale	Low	3.20	2.00
	Medium	3.60	2.25
	High	4.00	2.50

Note: [2]Annual investment costs are calculated using a time discount rate of 0%.

To determine the annual investment costs (IC_t) of NBS (in €/year), the annuity payment calculation is used (Zerbe and Dively, 1994) (Eq. 23):

$$IC_t = \frac{P}{\left(\frac{1-\left(1/(1+r)^n\right)}{r}\right)} \tag{23}$$

where P is the present value of investment costs, r is the time discount rate, n is the lifetime of NBS, and t is the year.

The total annual costs (TC_t) of NBS implementation (in €/year) are given by the sum of the annual investment costs (IC_t) and annual maintenance costs (MC_t) for a NBS of specified area (a), such that (Eq. 24):

$$TC_t = a * (IC_t + MC_t) \tag{24}$$

For this study, a time discount rate of almost zero ($r = 0.001$) is applied to obtain insight in the maximum benefits from NBS implementation. Indeed, in the economics of climate change, the Stern Review advocates to consider time discount rate of almost zero (Stern, 2007). Given that the time discount rate is important to value future cost and benefit streams in present-day terms, this research performs a sensitivity analysis (see section *Results*). For this analysis, constant time discount rates are set at 2% and 4% (Gollier, 2008; Alves *et al.*, 2019).

10.2 NBS benefits

Assessing the expected annual damages (EAD) caused by flood events is conventionally done using flood depth-damage-functions (DDFs), by relating the floodwater depth and the corresponding damage factor for specific classes of infrastructure (Huizinga, de Moel and Szewczyk, 2017). Two assumptions have been made or this assessment method: the economic values of the assets are considered spatially homogeneous across the landscape; if part of the building shape is affected by flood it is assumed that the entire building is flooded accordingly.

This method represents the economic loss (in terms of absolute or relative values) as a function of the maximum water depth (Middelmann-Fernandes, 2010). Direct flood damages, related to the physical impacts on properties (buildings and infrastructures) in flooded areas, are estimated following four phases (Merz *et al.*, 2010; Roebeling *et al.*, 2011):

1. Firstly, the flooded area and flood depth for each of the scenarios are assessed using the InVEST Urban Flood Risk Mitigation (UFRM) model;
2. Second, the elements at risk (asset data) are categorized according to the classification based on economic sectors: residential, commercial, industrial and, infrastructures (roads) (see Section 10.2.1 and 10.2.2 for the city of Aveiro and Rapallo, respectively);
3. Third, the exposure of these asset categories (such as structures) to flooding is evaluated by intersecting the flood depth-maps with the assets using geographic information systems (GIS). Potential damage (D_i) to assets (i) is determined using the DDF from the Equation (25) (Davis and Skaggs, 1992; Huizinga, de Moel and Szewczyk, 2017):

$$D_i = \alpha H_i - \beta H_i^2 \tag{25}$$

with D_i the rate of damage to asset i (in % of the respective value v_i), and where H_i is the height of flood (in m) and i is the asset class.
The DDF are used to express the relation between the water depth and the max damages in Europe (see **Appendix B**). The Depth-damage functions differ between building types (residential, commercial and industrial) and roads by showing different curves. **Appendix B** also shows the strings used in GIS to apply the DDF curves and economic values related to the assets. The expected annual damage per return period ($EAD_{t,r}$) is obtained by multiplying the potential damage costs (i.e.

the damage to all flooded asset type values) and flood occurrence probability (i.e. the inverse of the flood return period; r), such that (Eq. 26):

$$EAD_{t,r} = \sum_i \left(D_i * F_{r,i} * v_i\right) * \frac{1}{r} \tag{26}$$

where D_i is the rate of damage to asset i, $F_{r,i}$ is the flooded area per return period r and asset i, v_i is the value of asset i, and $\frac{1}{r}$ is the annual probability of occurrence of a flooding event with return period r. Essentially, the total expected damage costs increase with higher flood-return periods. However, because this increase in total expected damage costs occurs at a decreasing rate, the annual damage costs decrease with increasing return periods. Although the total expected damage costs of less intense precipitation events are significantly lower, their frequent occurrence means that their cumulative damage exceeds the annual expected damage costs of more intense rainfalls;

4. Finally, the expected annual damage (over all return periods; EAD_t) is obtained by summing the expected annual damages per return period ($EAD_{t,r}$) over all return periods r, such that (Eq. 27):

$$EAD_t = \sum_r EAD_{t,r} \tag{27}$$

Hence, the expected annual damage is calculated for the situation without (NBS0) and with (NBS1; NBS2) nature-based solutions. The total annual benefit (TB_t) of NBS implementation (in €/year), corresponding to the total avoided flooding costs due to NBS implementation, is given by the difference between the expected annual damage without (NBS0) and with (NBS#) nature-based solutions, such that (Eq. 28):

$$TB_t = [EAD_t]_{NBS0} - [EAD_t]_{NBS\#} \tag{28}$$

10.2.1 Economic data input: case of Aveiro

Buildings and roads maps have been downloaded from Geofabrik Open Street Map (OSM) data[54]. Since the Municipality of Aveiro presented many missing buildings, and they came without classification (e.g. residential, commercial, etc.) from the OSM data, some steps were followed to produce the final building layer. Firstly, the InVEST model was run to identify the most vulnerable areas to flooding. The rainfall event considered is associated to a return period of 100-years (the worst scenario). This step enabled focusing on most critical areas, where all missing buildings have been drawn manually. Indeed, results showed that the 'Glória e Vera Cruz' 'freguesia' (parish) is the subdivision of the Aveiro Municipality that is most

[54] Accessed on 16th December 2020: http://download.geofabrik.de/

prone to flooding, and it is considered the city centre. 'Esgueira', which is the subdivision mainly related to the industrial part of the Municipality of Aveiro, has been included as it shows the highest values of runoff per pixel. Secondly, the classification of each building was conducted according to the 'Insituto Nacional de Estatística' (INE) [55], which built the dataset (point shapefile) from the Portuguese census of 2011. The INE classification includes three categories of buildings:

1. The building area is used for residential purposes;
2. The larger part of the building area is used for commercial purposes;
3. The larger part of the building area is used for residential purposes.

To re-classify the building layer, some assumptions have been taken in consideration (see **Table 21**). All the buildings without classification have been checked manually. Through that procedure, some buildings' categories have been re-adjusted based on real observation.

Table 21. *Rules to re-classify the building layer.*

Category 1	*Residential*	The first and the second categories from INE
Category 2	*Mixed (commercial & residential ratio)*	Sometimes two or more points from INE with different classifications were included in the same building. These mixed buildings were counted, and the global average classification ratio they displayed has been calculated, resulting in a class that is approximately 34.5% commercial and 65.5% residential in terms of value
Category 3	*Commercial*	The second category from INE. This class includes all public and recreational services (such as schools, university, hospitals, churches, etc.)
Category 4	*Industrial*	Buildings situated in areas with land use categorized as industrial

The road map has been re-classified by grouping the "street categories" following the OSM classes. Road category has been named Category 5 for the application in Aveiro. Since the bioswale design is related to the road's size, within this category, the final classification includes different types of roads in relation to their dimensions, re-classified as follows:

1. Large road: highway (with an average width of 12 m);
2. Medium road: primary, secondary and tertiary roads (with an average width of 10 m);
3. Small road: residential roads (with an average width of 5 m);
4. Cycleway (with an average width of 2 m).

The road width for each type of street has been determined by performing measurements using GIS satellite maps.

[55] Accessed on 5th May 2021: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_main

Real estate values for the residential building category were obtained from INE (Instituto Nacional de Estatística (INE), 2020) for the Aveiro district; however, values for commercial and industrial categories were not available in the INE database for the year of the study (2020). Huizinga et al. (2017) provided the values for these three classes of buildings for the year 2010 (€ (2010)/m^2). The relative difference between the median residential building value and the median values of the other two classes was calculated using the 2010 data. This operation resulted in two value factors (Residential/Commercial, and Residential/Industrial) which were then used in conjunction with the 2020 residential building values to estimate the values of the remaining two classes for the same year (€ (2020)/m^2). Lastly, the mixed category was calculated by multiplying the values of commercial and residential buildings with their respective weights in this class (34.5% and 65.5%, respectively). The economic data related to the road category are based on the full international construction costs data for Portugal, provided by Huizinga et al. (2017), which are updated using the consumer Price Index (CPI) for Portugal (year 2020) (World Bank, 2015).

The following table (**Table 22**) summarizes the building type and road category asset values in the city of Aveiro.

Table 22. *Asset values for the city of Aveiro (in 2020 Euros).*

	Value (€/m^2)	**Source**
Category 1	955	(Instituto Nacional de Estatìstica (INE), 2020)
Category 2	978	(Instituto Nacional de Estatìstica (INE), 2020) & (Huizinga, de Moel and Szewczyk, 2017)
Category 3	1,025	(Instituto Nacional de Estatìstica (INE), 2020) & (Huizinga, de Moel and Szewczyk, 2017)
Category 4	556	(Instituto Nacional de Estatìstica (INE), 2020) & (Huizinga, de Moel and Szewczyk, 2017)
Category 5	14	(Huizinga, de Moel and Szewczyk, 2017) & (World Bank, 2015)

10.2.2 Economic data input: case of Rapallo

The built infrastructure shapefile represents built infrastructure footprints. To map this input, the regional topographic geodatabase (BDTRE - 2013) has been accessed. To re-classify the building layer, some assumptions have been taken in consideration (see **Table 23**). All the buildings without classification have been checked manually. Through that procedure, some buildings' categories have been re-adjusted based on real observation.

Table 23. Re-classification of the building layer for Rapallo.

Category 1	*Residential*	This class includes residential buildings
Category 2	*Commercial*	This class includes all public, recreational, and other services (as schools, university, hospitals, churches, military, prisons, administrative, cultural and sports places etc.)
Category 3	*Industrial*	This class includes industrial buildings and energy production plants

The road map has been re-classified by grouping the "street categories" following the OSM classification. Road category has been named Category 4 for the application in Rapallo. Since the bioswale design is related to the road's size, within this category, the final classification includes different types of roads in relation to their dimensions, re-classified as follows:

1. Large road: highway (with an average width of 12 m);
2. Medium road: primary and secondary (with an average width of 10 m);
3. Small road: residential roads (with an average width of 5 m);
4. Cycleway (with an average width of 2 m).

The road width for each type of street has been determined by performing measurements using GIS satellite maps.

Lastly, the economic data related to those building assets are based on local information from 'Agenzia delle Entrate' (OMI) (Agenzia delle Entrate, 2021). Those values represent the average property estimates for the city of Genoa expressed in €/m^2 with the reference year 2021. The economic value (reference year 2010) associated to road class (category 4) from Huizinga, de Moel and Szewczyk (2017) has been updated using the consumer Price Index (CPI) for Italy (year 2020) (World Bank, 2015). The following table (**Table 24**) summarizes the building type and road category asset values in the city of Rapallo.

Table 24. Asset values for the city of Rapallo (in 2020 Euros).

	Value (€/m^2)	**Source**
Category 1	2,068	(Agenzia delle Entrate, 2021)
Category 2	1,333	(Agenzia delle Entrate, 2021)
Category 3	819	(Agenzia delle Entrate, 2021)
Category 4	22	(Huizinga, de Moel and Szewczyk, 2017) & (World Bank, 2015)

10.3 NBS partial cost-benefit analysis

To finally compare and assess the economic viability of NBS implementation in Aveiro and Rapallo, costs and benefits of green roofs and bioswales are combined. A CBA should include all the costs and benefits of the different NBS. Nevertheless, here, this research assumes as benefits only the avoided flood damages resulting from the implementation of the adaptation strategies. To develop this assessment, the annual benefit-cost ratio (BCR_t) and the annual net present value (NPV_t) (annuities) are calculated as performance indicators of CBA (Roebeling, 2003; Boardman *et al.*, 2018). BCR_t and $ANPV_t$ are calculated through Equations (29) and (30), respectively (Zerbe and Dively, 1994; Boardman *et al.*, 2018):

$$BCR_t = \frac{TB_t}{TC_t} \tag{29}$$

$$NPV_t = TB_t - TC_t \tag{30}$$

where an NPV_t < 0 and BCR_t < 1 imply that the project is not economically viable and an NPV_t > 0 an BCR_t > 1imply that the project is economically viable.

The CBA is performed by including three costs scenarios, Low, Medium, High (see section 10.1 -**Table 20**) to identify the degree of uncertainty as a sensitivity analysis. This analysis allows one to understand how different NBS costs could influence the results (Boardman *et al.*, 2018).

PART V - Results

Chapter 11

Biophysical and flood-damages assessment without NBS

This chapter shows scenarios without the implementation of NBS (NBS0). The following two sub-chapters represent the application on the city of Aveiro and the city of Rapallo.

This section aims at showing the most flooded areas in terms of flood depth (mm) resulting from the InVEST modelling analysis. These relate to the flood damages calculation on buildings and roads performed in GIS environment. This step allows the identification of the critical neighborhoods; thus it is useful to prioritize the intervention areas by combining the most flooded zones with the highest annual costs resulting from the damage estimates.

11.1 Case of Aveiro: NBS0 for current & future climate

This section presents the results for the scenarios without the implementation of NBS (NBS0). Firstly, the biophysical impacts for the current (T0) and future (T1) climate scenarios are presented (**Figure 68**, **Figure 69** and **Figure 70**). These figures present the water depth (mm) in terms of mean value per pixels (5x5m) for the city of Aveiro. The colour ramp denotes increasing flood depth for darker colour and the opposite for lighter and green colours.

The representation per pixel gives a more detailed overview by allowing identifying the strong positive correlation between the flood depth and the urbanisation level. Indeed, darker colours are evident in the most urbanized areas by delineating the city.

The differences between T0 and T1 for each return period are almost not visible in maps while the variation among return periods is quite evident (the colours increase of darkness when the return period is higher).

Indeed, compared to the 10-years return period event, the flood depth increases by a factor of 1.4 and 1.5 in respect to precipitation events with 50 and 100-years, respectively, both for T0 and T1. The portion of variation between the 10 and 50-years and, 10 and 100-years event is represented by 16%.

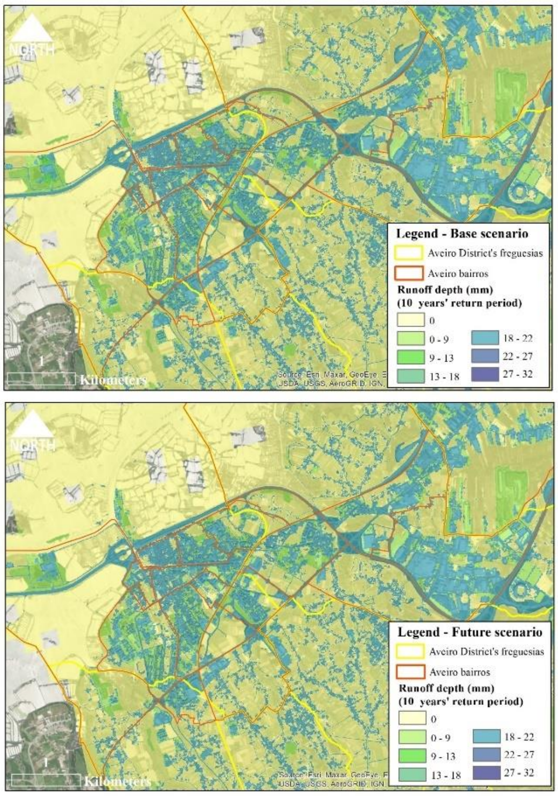

Figure 68. *Flood depth (mm) under 10-year return period per pixel for current & future scenarios (city of Aveiro).*

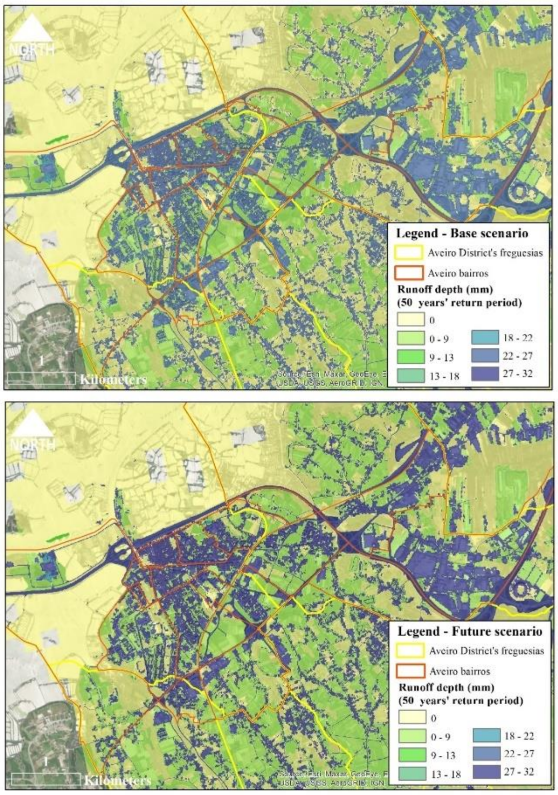

Figure 69. *Flood depth (mm) under 50-year return period per pixel for current & future scenarios (city of Aveiro).*

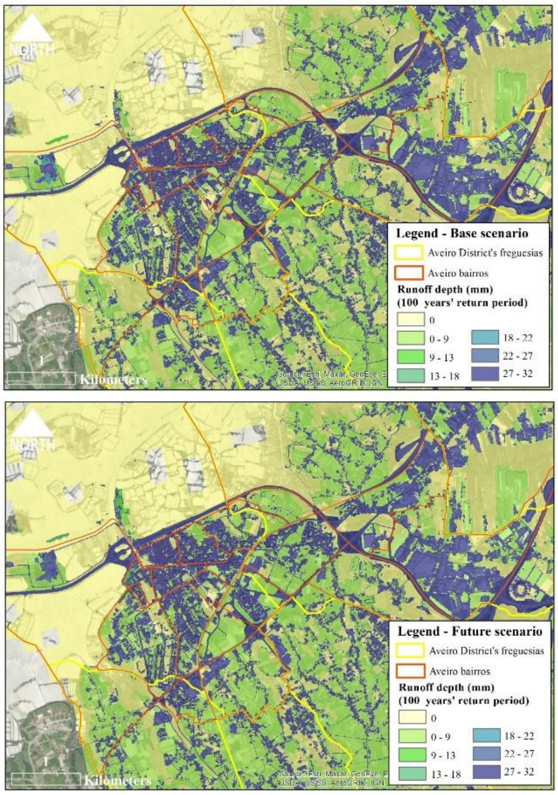

Figure 70. *Flood depth (mm) under 100-year return period per pixel for current & future scenarios (city of Aveiro).*

To consider the future implications in terms of adaptation policies, the model results have been elaborated in GIS to obtain flood indicator values at neighborhoods level. These final estimates represent a mean value of flood depth distributed on the entire neighborhood which allow to make comparisons and take decisions within the city scale.

Figure 71 presents the water depth (mm) in terms of mean value per neighborhoods as an indicator of flood severity. The biophysical impacts for the current (T0) and future (T1) climate scenarios show that the flood depth increases with higher return periods – on average by about 10% between T0 and T1 scenarios under all return periods (see **Figure 71**).

Compared to the 10-years return period event, flood depth is 40% and 50% larger for events with return periods of 50 and 100-years, respectively, both for T0 and T1. The neighborhoods of Beira Mar, Liceu, Forum, Gulbenkian, Carmo, Santiago and Zona industrial are the most flooded in the city.

Changes in flood depth (mm) are more visible between flood return periods in T0 and T1 (see **Table 25**).

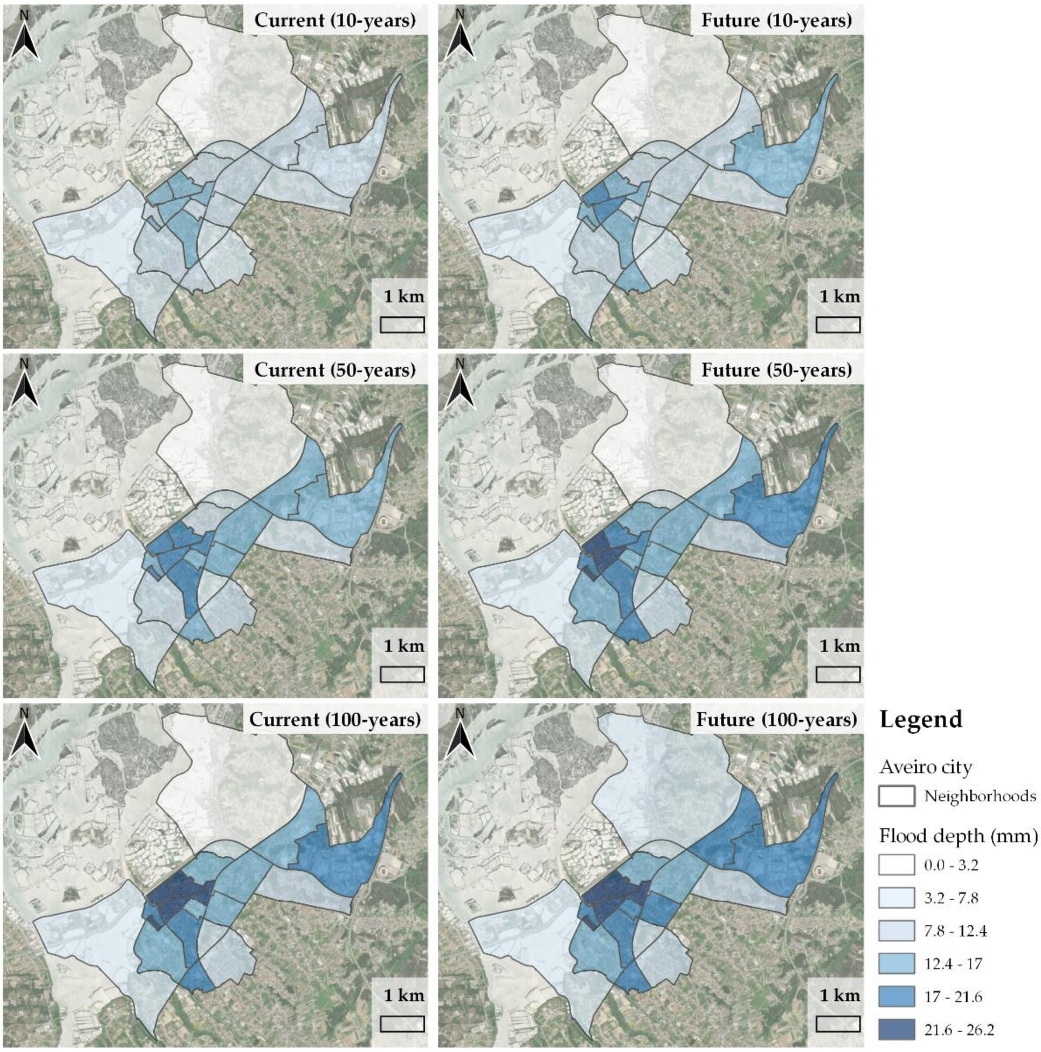

Figure 71. *Flood depth (mm) under 10, 50 and 100-year return periods as mean value per neighbourhood for current & future scenarios (city of Aveiro).*

Table 25. *Average values of flood depth (mm) under 10, 50 and 100-year return periods per neighbourhood for current & future scenarios (city of Aveiro).*

	Flood depth (mm)					
	Current climate			Future climate		
	10-years	50-years	100-years	10-years	50-years	100-years
Pingo Doce	5.21	7.07	7.98	5.74	7.88	8.94
Agras Norte	3.46	4.76	5.41	3.83	5.34	6.10
Verdemilho	3.16	4.34	4.88	3.51	4.82	5.41
Glicinias	11.84	15.87	17.67	13.03	17.48	19.44
Gulbenkian	15.17	20.22	22.44	16.67	22.21	24.60
Fonte Nova	10.81	14.56	16.23	11.91	16.06	17.86
Azurva	5.69	7.57	8.41	6.25	8.32	9.25
Alboi	11.81	15.85	17.63	13.00	17.44	19.37
Estaçao	14.30	19.53	21.87	15.83	21.63	24.17
Forum	16.14	21.55	23.93	17.75	23.68	26.25
Forca	10.47	14.22	15.93	11.56	15.75	17.63
Barrocas	8.76	11.94	13.39	9.69	13.24	14.82

Carmo	14.54	19.56	21.79	16.02	21.56	23.96
Olho d'Água	10.67	14.34	15.98	11.75	15.81	17.58
Beira-Mar	16.21	21.55	23.88	17.79	23.64	26.14
Vilar	5.83	7.80	8.71	6.41	8.62	9.65
Esgueira	9.80	13.29	14.88	10.82	14.71	16.46
Santiago	8.98	12.20	13.65	9.92	13.50	15.09
Zona industrial	11.48	15.47	17.24	12.66	17.05	18.98
Liceu	12.68	17.21	19.23	14.01	19.02	21.23

Although the expected total damage costs per event of less intense precipitation events (i.e. return periods of 10 years) are substantially lower, their frequent nature means that their cumulative damage exceeds the expected annual damage costs of an intense rainfall event (i.e. return period of 100 years; see **Table 26** for the current climate scenario and **Annex C** for the future climate scenario). Compared to 10-years return period, the expected annual flood costs are 78% and 88% lower for events with return periods of 50 and 100-years for T0 scenarios. On the other hand, compared to the 10-years return period event, the expected costs per event are 12% and 22% larger for events with return periods of 50 and 100-years, respectively, both for T0 and T1.

Table 26. *Expected annual damage costs (€/year) and expected total damage costs per event (€) of building and road under 10, 50 and 100-year return periods for current climate scenarios for the city of Aveiro.*

	Expected annual damage costs (€/year)			**Expected total damage costs per event (€/event)**		
	10-years	50-years	100-years	10-years	50-years	100-years
Pingo Doce	10,513	3,162	1,740	105,134	158,083	173,966
Agras Norte	11,662	2,734	2,290	116,621	136,675	229,005
Verdemilho	35,022	8,355	4,453	350,225	417,777	445,356
Glicinias	34,358	8,903	4,894	343,581	445,159	489,440
Gulbenkian	38,329	8,402	4,546	383,296	420,099	454,587
Fonte Nova	40,300	9,266	4,897	402,998	463,323	489,754
Azurva	66,362	14,926	9,065	663,618	746,293	906,468
Alboi	109,574	23,890	12,643	1,095,742	1,194,481	1,264,341
Estação	109,972	24,244	12,614	1,099,723	1,212,192	1,261,415
Forum	157,960	35,886	19,355	1,579,599	1,794,299	1,935,462
Forca	177,766	38,936	20,385	1,777,657	1,946,796	2,038,542
Barrocas	203,100	44,539	23,868	2,031,002	2,226,975	2,386,795
Carmo	222,843	49,444	25,791	2,228,427	2,472,190	2,579,134
Olho d'Água	223,222	49,590	25,999	2,232,224	2,479,512	2,599,869
Beira-Mar	232,572	51,061	26,819	2,325,720	2,553,049	2,681,860
Vilar	286,968	64,091	43,623	2,869,675	3,204,544	4,362,351
Esgueira	317,404	70,182	37,178	3,174,038	3,509,109	3,717,784
Santiago	313,416	71,446	39,914	3,134,165	3,572,283	3,991,438
Zona industrial	332,586	75,939	40,049	3,325,861	3,796,965	4,004,945
Liceu	484,226	105,668	55,474	4,842,258	5,283,383	5,547,379
Total (city)	**3,408,156**	**760,663**	**415,598**	**34,081,564**	**38,033,186**	**41,559,891**

Results for the expected annual flood damages to buildings and roads per neighborhood (€/year) for the current (T0) and future (T1) scenarios show that the damages are distributed across all neighborhoods in the city of Aveiro (see **Figure 72** and **Table 27**). However, some neighborhoods (Liceu, Santiago and Zona industrial) experience substantially more annual damages when compared to others. In the city center, Liceu is the neighborhood that is most affected by high annual damage costs (644,192 €/year) even if its area (582,416 m^2) is considerably smaller than, for example, Santiago (1,126,149 m^2) that faces lower annual damage costs (422,880 €/year). This is due to differences in, for instance, in NBS implementation area (in relation to the building' and road's area) and asset values (within each neighborhood). The total expected annual flood damage for the city of Aveiro is approximately € 4 million every year in T0_NBS0 scenario. Annual flood damages are 4% higher in the future climate scenario (2050) than in the current situation. The total building area of Aveiro (2,159,737 m^2) mostly consists of residential buildings (40%), followed by industrial (30%), commercial (26%) and mixed buildings (4%). The total road area of the city covers 1,487,578 m^2. In general, observed damages are expected to be higher in neighborhoods containing the largest areas of commercial buildings (which have a higher infrastructure value).

Table 27. *Expected flood damage (€/year) of building and road per neighbourhood (area in m^2) for current & future scenarios (city of Aveiro).*

		Tot. damages (€/year)	
	Area (m^2)	Current	Future
Pingo Doce	394,675	15,415	16,726
Agras Norte	338,050	16,686	18,885
Verdemilho	4,444,650	47,832	50,473
Glicinias	364,900	48,156	52,397
Gulbenkian	46,550	51,277	53,183
Fonte Nova	177,600	54,464	56,986
Azurva	1,385,750	90,352	96,291
Alboi	155,475	146,107	150,766
Estaçao	167,600	146,830	151,526
Forum	246,775	213,200	223,119
Forca	514,725	237,087	244,503
Barrocas	573,400	271,508	281,189
Carmo	319,575	298,078	308,263
Olho d'Água	1,309,000	298,811	309,289
Beira-Mar	218,325	310,452	320,544
Vilar	1,131,225	394,682	427,347
Esgueira	1,019,525	424,764	439,873
Santiago	1,188,725	424,777	447,618
Zona industrial	2,484,550	448,575	468,284
Liceu	614,475	645,367	665,192
Total (city)	**24,745,675**	**4,584,419**	**4,782,453**

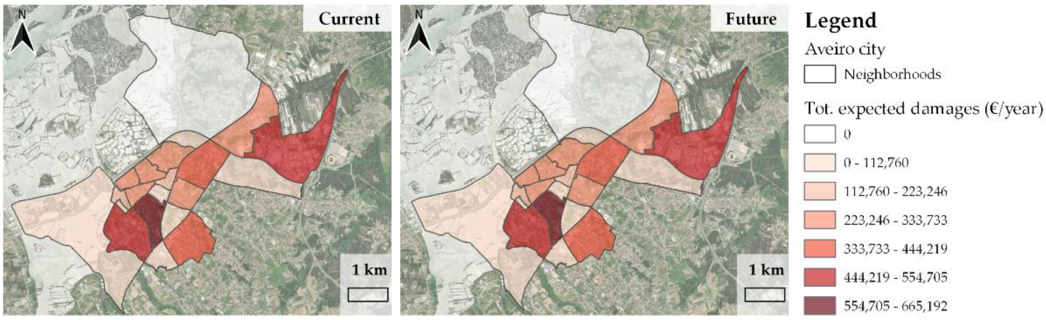

Figure 72. *Expected annual damage (€/year) of buildings and roads per neighbourhood for current & future scenarios (city of Aveiro).*

11.2 Case of Rapallo: NBS0 for current & future climate

This section presents the results for the scenarios without the implementation of NBS (NBS0). Firstly, the biophysical impacts are presented for the current (T0) and future (T1) climate scenarios (**Figure 73**, **Figure 74** and **Figure 75**). These figures present the water depth (mm) in terms of mean value per pixels (5x5m) for the city of Rapallo. The colour ramp denotes increasing flood depth for darker colour and the opposite for lighter and green colours. The representation per pixel gives a more detailed overview by allowing identifying the strong positive correlation between the flood depth and the urbanisation level. Indeed, darker colours are evident in the most urbanized areas by delineating the city.

The differences between T0 and T1 for each return period are almost not visible in maps while the variation among return periods is evident (the colours increase of darkness when the return period is higher). In respect to the simulation in the city of Aveiro, here, the flood depth varies hugely from 10 to 100-years flood events. As it is visible in **Figure 73**, the biggest part of Rapallo Municipality is covered by green and light blue colours during a 10-years event. Instead, **Figure 74** and **Figure 75** show not only darker colour which meant deeper flood depth. It is evident how the flooding area increases by showing wider darker blue covering the Municipality.

Indeed, compared to the 10-years return period event, the flood depth increases by a factor of 1.9 and 2.5 in respect to precipitation events with 50 and 100-years, respectively, both for T0 and T1. This means that a 100-years event shows a rising flood depth of almost three times of a 10-years event. The portion of flood depth variation between the 10 and 50-years and, 10 and 100-years event is represented by almost 60%. In respect to the case of Aveiro, the simulated flooding events in Rapallo prove an increasing delta of change in flood depth widely higher (16% in Aveiro compared to 56% in Rapallo) in relation to rising return periods. This difference can be explained by different climatic conditions in terms of precipitation amount.

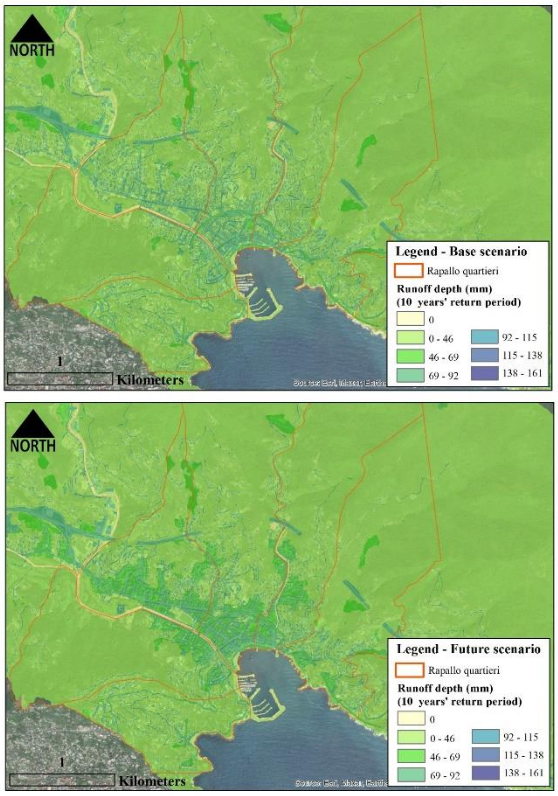

Figure 73. *Flood depth (mm) under 10-year return period per pixel for current & future scenarios (city of Rapallo).*

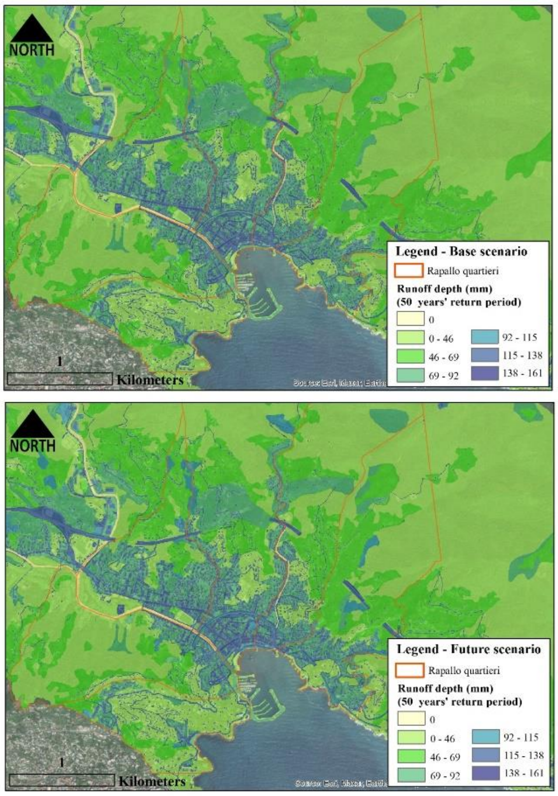

Figure 74. *Flood depth (mm) under 50-year return period per pixel for current & future scenarios (city of Rapallo).*

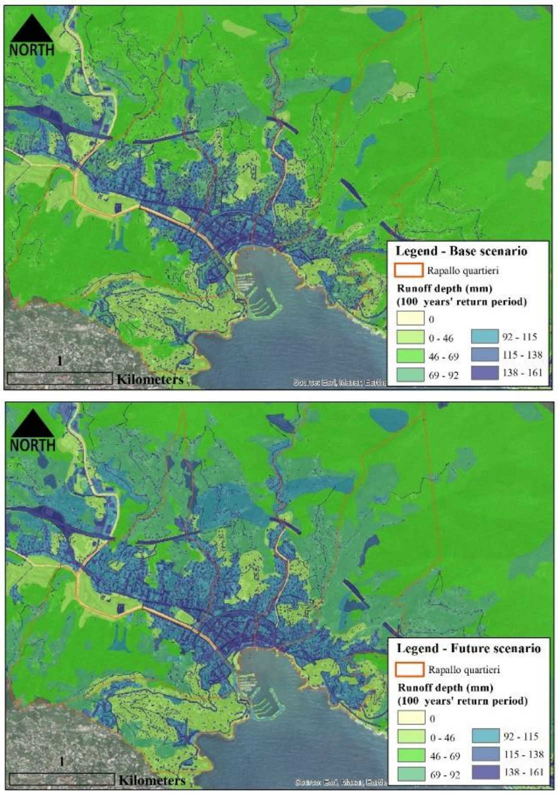

Figure 75. *Flood depth (mm) under 100-year return period per pixel for current & future scenarios (city of Rapallo).*

To consider the future implications in terms of adaptation policies, the model results have been elaborated in GIS to obtain flood indicator values at neighborhoods level. These final estimates represent a mean value of flood depth distributed on the entire neighborhood which allow to make comparisons and take decisions within the city scale.

Figure 76 presents the water depth (mm) in terms of mean value per neighborhoods as an indicator of flood severity. The biophysical impacts for the current (T0) and future (T1) climate scenarios show that the flood depth increases with higher return periods – on average by about 11% between T0 and T1 scenarios under all return periods expect for 50-years (10%). (see **Figure 76**). Compared to the 10-years return period event, the depth is 26% and 37% larger for events with return periods of 50 and 100-years, respectively – both for T0 and T1.

The neighborhood which shows the highest flood risk is Cappelletta followed by Cerisola and Borzoli (see **Figure 76**). Changes in flood depth are almost not visible from **Figure 76** because the difference from 10-years or 50-years to 100-years return period is great (**Table 28**). **Table 28** shows the average values of flood depth in mm per neighborhood in the city of Rapallo.

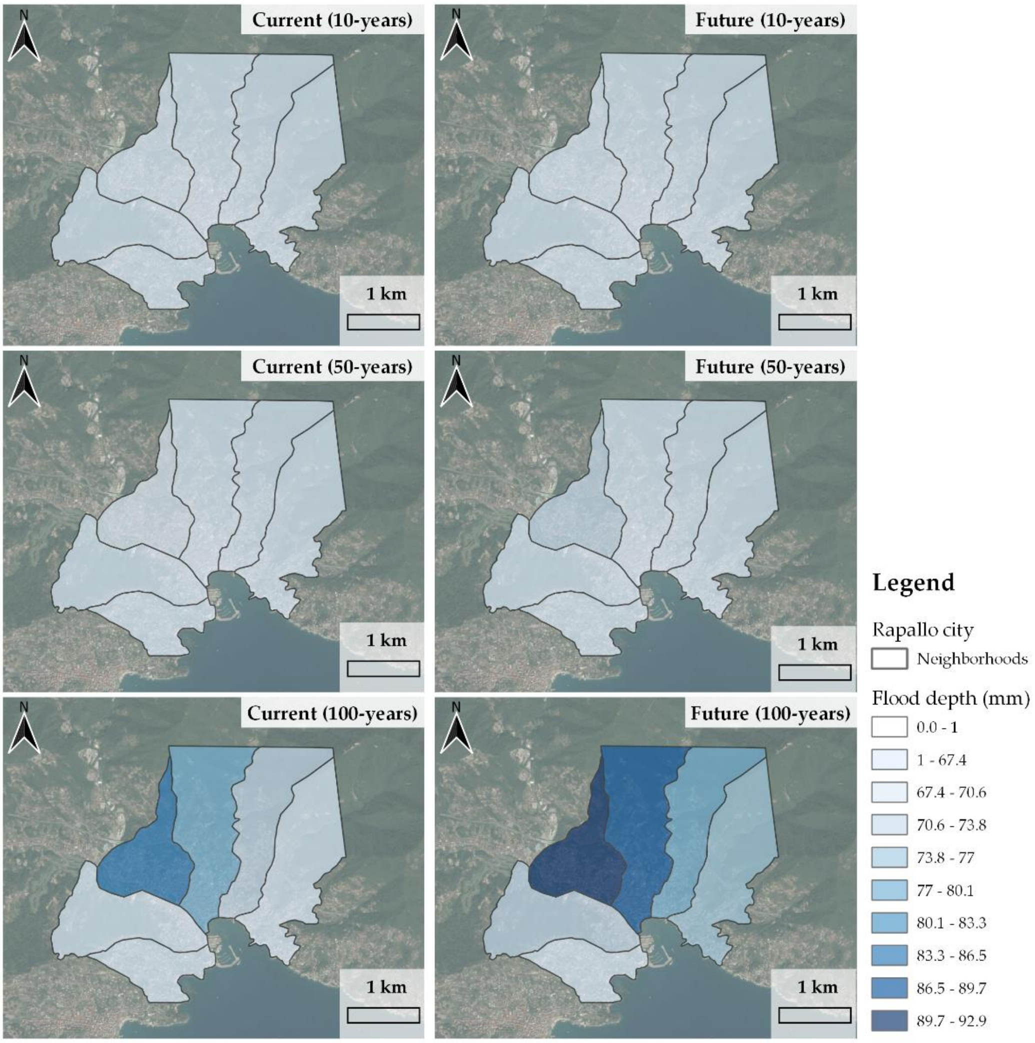

Figure 76. *Flood depth (mm) under 10, 50 and 100-year return periods per neighbourhood for current & future scenarios (city of Rapallo).*

Table 28. *Average values of flood depth (mm) under 10, 50 and 100-year return periods per neighbourhood for current & future scenarios (city of Rapallo).*

	Flood depth (mm)					
	Currrent climate			Future climate		
	10-years	50-years	100-years	10-years	50-years	100-years
San Michele	22.9	44.1	57.4	25.3	48.7	64.2
Costaguta	23.6	48.5	63.7	26.5	53.8	71.4
Cappelletta	38.4	67.6	84.5	41.9	73.5	92.9
Cerisola	32.7	61.5	78.4	36.2	67.4	86.8
Borzoli	27.7	54.7	70.9	30.9	60.4	79.0
Seglio	25.2	51.5	67.4	28.2	57.0	75.4

Although the expected total damage costs per event of less intense precipitation events (i.e. return periods of 10 years) are substantially lower, their frequent nature means that their cumulative damage exceeds the expected annual damage costs of an intense rainfall event (i.e. return period of 100 years; see **Table 29** for the current climate scenario and **Annex C** for the future climate scenario). Compared to 10-years return period, the expected annual flood costs are 70% and 82% lower for events with return periods of 50 and 100-years for T0 scenarios. On the other hand, compared to the 10-years return period event, the expected costs per event are 51% and 78% larger for events with return periods of 50 and 100-years, respectively, both for T0 and T1.

Table 29. *Expected annual damage costs (€/year) and expected total damage costs per event (€) of building and road under 10, 50 and 100-year return periods for current climate scenarios for the city of Rapallo.*

	Expected annual damage costs (€/year)			**Expected total damage costs per event (€/event)**		
	10-years	50-years	100-years	10-years	50-years	100-years
San Michele	450,142	136,359	80,548	4,501,424	6,817,960	8,054,785
Costaguta	488,971	148,168	87,421	4,889,713	7,408,381	8,742,055
Cappelletta	1,072,072	324,055	190,965	10,720,719	16,202,740	19,096,456
Cerisola	1,176,566	355,296	209,337	11,765,663	17,764,805	20,933,670
Borzoli	584,866	177,095	104,460	5,848,659	8,854,744	10,445,971
Seglio	566,610	171,924	101,485	5,666,104	8,596,182	10,148,534
Total (city)	**4,339,228**	**1,312,896**	**774,215**	**43,392,282**	**65,644,812**	**77,421,471**

Results for the expected annual flood damages to buildings and roads per neighborhood (€/year) for the current (T0) and future (T1) scenarios show that the damages are distributed across two main neighborhoods in the city of Rapallo (see **Figure 77** and **Table 30**). One of these two neighborhoods with the highest flood costs, named Cerisola, is representative of the city center in Rapallo.

As a result, Cerisola is the neighborhood that is most affected by high annual damage costs even if its area (1,932,522 m^2) is not the widest within Rapallo Municipality. Indeed, Seglio (1,998,034 m^2) has the biggest area among all the neighborhoods but considerably lower damage costs: Seglio simulated damages for 840,019 €/year while Cerisola shows damages of 1,741,199 €/year in T0 (896,148 €/year and 1,856,193 €/year in T1, respectively). This is due to differences in, for instance, in NBS implementation area (in relation to the building' and road's area) and asset values (within each neighborhood).

The total expected annual flood damages for the city of Rapallo are approximately € 6 million every year in T0_NBS0 scenario and almost € 7 million in T1_NB0 scenario (see **Table 30**). Annual flood damages are between 6-7% higher in the future climate scenario (2050) than in the current situation.

The total building area of Rapallo (1,401,361 m^2) mostly consists of residential buildings (91%), followed by commercial (5%) and industrial (4%). The total road area of the city consists of 193,087 m^2. As expected, observed damages become massive in neighborhoods containing the largest areas of residential buildings, which have the higher infrastructure value (€/m^2) in the city of Rapallo. Hence, in order, Cerisola has the biggest residential area (36% on the total building area) followed by Cappelletta neighborhood (35% on the total building area) at city level.

The same situation for the percentage of road distributed across the neighborhoods, Cerisola has a larger area (23% on the total road area) followed by Cappelletta (21% on the total road area) at city scale.

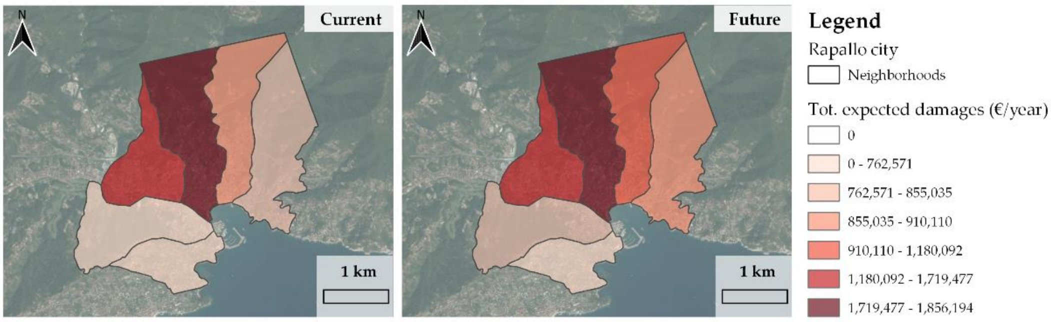

Figure 77. *Expected annual damages (€/year) of buildings and roads per neighbourhood for current & future scenarios (city of Rapallo).*

Table 30. *Expected flood damage (€/year) of building and road per neighbourhood (area in m^2) for current & future scenarios (city of Rapallo).*

		Tot. damages (€/year)	
	Area (m^2)	Current	Future
San Michele	868,984	667,049	711,397
Costaguta	1,531,831	724,559	772,806
Cappelletta	1,186,299	1,587,091	1,692,133
Cerisola	1,932,522	1,741,199	1,856,193
Borzoli	1,569,769	866,420	924,070
Seglio	1,998,034	840,019	896,148
Total (city)	**9,087,442**	**6,426,339**	**6,852,750**

Chapter 12

Biophysical and flood-damages assessment with NBS: city of Aveiro

This chapter presents NBS scenarios implementation for the city of Aveiro. Firstly, the biophysical impacts of NBS simulations are presented for the current (T0) and future (T1) climate scenarios. Secondly, the flood damages reduction on buildings due to green roofs (NBS1 – section 12.1) and on roads due to bioswales (NBS2 – section 12.2), named NBS benefits, are developed for T0 and T1. Lastly, the economic viability of NBS scenarios is presented by combining NBS costs and benefits.

To better highlight the positive or negative variation among various scenarios, with and without NBS, difference maps are elaborated.

12.1 NBS1: biophysical impacts and economic viability

This first section is about the flood mitigation benefits derived from NBS1 (green roofs) simulation. Results for water volume retained (%) due to green roof (NBS1) installation show, as expected, the largest variations in neighborhoods where green roofs are implemented (see **Figure 78**)[56]. The results present a slight improvement between the current and future climate (**Table 31**). In average, the water volume retained is of 4% under 10-years events and 3% under 50-years and 100-years return periods between current and future scenarios at city level. This means that, when return periods are bigger, higher is the flood reduction benefit.

Moreover, water volume retained improves by 9% for 10-years return period, 10% for 50-years and 11% for 100-years events under both current and future climate. Looking at neighborhood level, water volume retained is usually observed in neighborhoods with larger areas of NBS1 implementation. However, maximum water volume retained occurs in Beira-Mar neighborhood (92,986 m^2) even if the largest green roof area has been implemented in Santiago (209,630 m^2). The reason Beira-Mar presents the largest water volume retained is because it is the neighborhood with the largest relative area of implementation, with green roofs covering 45% of the neighborhood's total area. Liceu follows with 32% of NBS1 surface coverage while Santiago and Forca present lower values (19% and 15%, respectively).

[56] Note that the change in water volume retained can exceed 100% because the amount of water retained with NBS can be (several times) larger than the water retained without NBS.

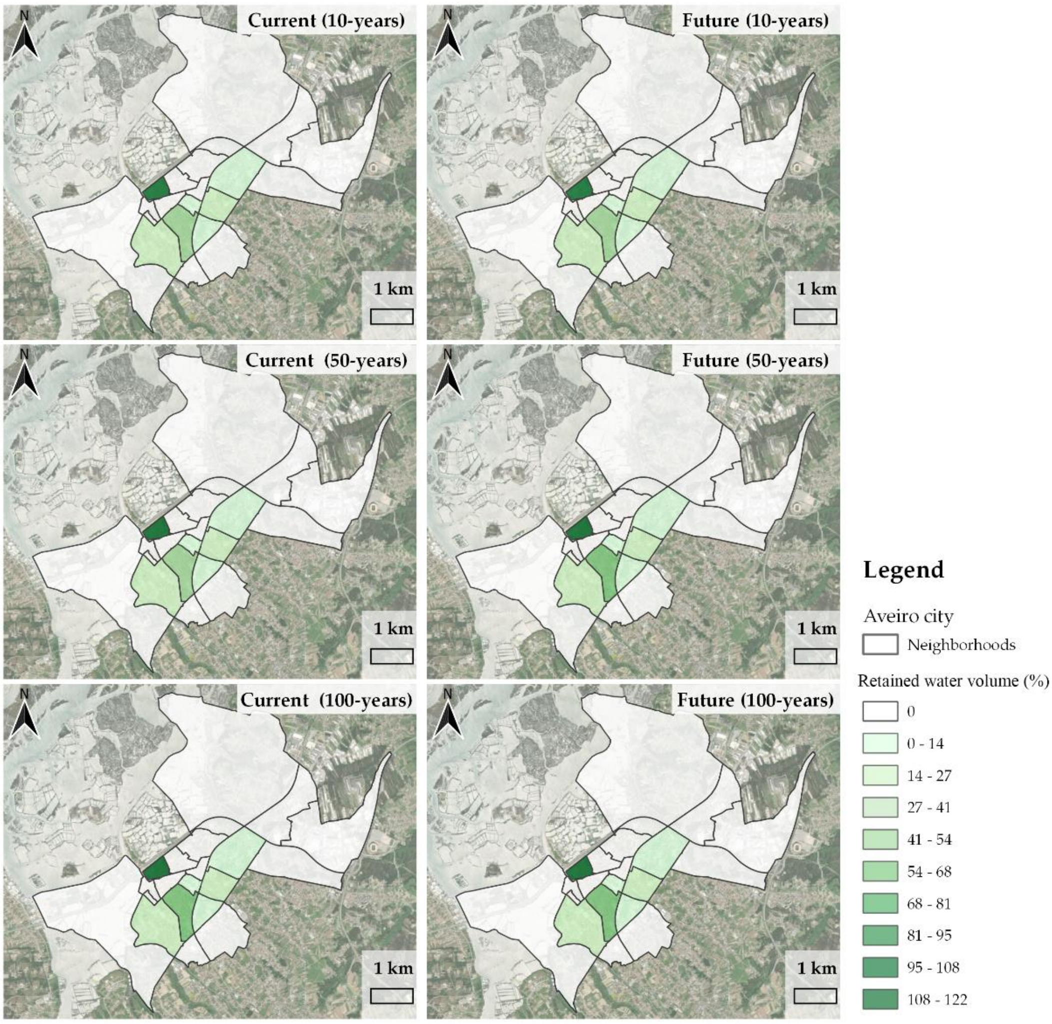

Figure 78. *Green roofs percentual differences (NBS1-NBS0) in retained water volume (%) for 10, 50 and 100-year return periods per neighbourhoods under current & future climate (city of Aveiro).*

Table 31. *Green roofs percentual differences (NBS1-NBS0) in retained water volume (%) for 10, 50 and 100-years return periods per neighbourhood under current & future climate (city of Aveiro).*

	Current climate			Future climate		
	10-years	50-years	100-years	10-years	50-years	100-years
Beira-Mar	96.48%	111.36%	116.93%	101.26%	116.37%	121.94%
Liceu	46.26%	52.70%	55.25%	48.28%	54.99%	57.61%
Forca	17.88%	19.89%	20.69%	18.52%	20.61%	21.44%
Santiago	20.10%	22.03%	22.76%	20.72%	22.69%	23.43%

This second part is about the NBS1 annual costs and benefits estimated in monetary terms. The following table (**Table 32**) shows the avoided costs every year due to the implementation of green roofs (€/year) for each neighborhood. The city of Aveiro can save every year from € 1,475,617 in the current scenario (T0) to

1,530,402 in the future scenario (T1) due to green roofs. In other words, approximately 90% of the expected flooding costs can be abolished every year.

Table 32. *Expected annual flood costs (€/year) for NBS0 and NBS1 with the annual avoided costs (€/year) per neighborhood (city of Aveiro).*

	NBS0: Expected damage costs (€/year)		**NBS1**: Expected damage costs (€/year)		Avoided costs (€/year)	
	Current	Future	Current	Future	Current	Future
Beira-Mar	310,452	320,544	33,540	34,640	276,370	285,311
Liceu	645,367	665,192	43,869	45,237	600,323	618,663
Forca	237,087	244,503	17,123	17,723	218,539	225,216
Santiago	424,777	447,618	42,494	44,321	380,385	401,213
Total (city)	**1,617,683**	**1,677,857**	**137,026**	**141,921**	**1,475,617**	**1,530,402**

Results for annual flood mitigation benefits from green roofs (NBS1) show that the Liceu neighborhood experiences the highest benefits while Forca presents the lowest benefits (see **Table 33**). Total green roof benefits increase, on average by 4% from T0 to T1 scenarios at city level.

NBS1 annual costs are given for three scenarios (Low, Medium and High; see **Table 33**). Neighborhoods with higher NBS1 costs correspond, self-evidently, to larger green roof implementation areas. Note, however, that largest costs and benefits of NBS1 do not always coincide across neighborhoods, due to differences in NBS1 implementation area (and thus NBS1 implementation costs; largest in Santiago) and asset values (and thus flood mitigation benefits from NBS1; largest in Liceu).

Table 33. *Green roof annual benefits and costs (€/year) from T0_NBS1 and T1_NBS1 scenarios with Low, Medium and High costs' scenarios per neighbourhood (city of Aveiro).*

	Annual benefits (avoided costs (€/year))			**Annual costs** (€/year)		
	Current	Future	Variation (base & future)	Low	Medium	High
Beira-Mar	276,370	285,311	+3%	743,887	1,487,773	2,045,688
Liceu	600,323	618,663	+3%	1,484,662	2,969,325	4,082,821
Forca	218,539	225,216	+3%	583,772	1,167,544	1,605,374
Santiago	380,385	401,213	+5%	1,677,039	3,354,078	4,611,857
Total (city)	**1,475,617**	**1,530,402**	+4%	**4,489,360**	**8,978,720**	**12,345,740**

The third part is to assess the economic viability of the NBS1 scenario, using the annual net present value (NPV) and annual benefit-cost ratio (BCR) (see **Table 34** and **Table 35**). Results show that all the annual NPV (€/year) and all BCR index are smaller than 1 as shown – even considering the Low cost scenario – implying that NBS1 are not economically viable from a flood mitigation perspective alone. The Forca neighborhood shows the most favorable (i.e. least negative NPV) results, given the relatively small area of NBS1 implementation (and, thus, low implementation costs) and relatively large, considering the area of NBS1 implementation, flood mitigation benefits (protecting higher-value assets). The Santiago neighborhood shows the lowest NPV in both NBS1 scenarios, mainly due the large NBS1 implementation costs (i.e. corresponding to the largest areas of NBS1 implementation) and relatively low flood mitigation benefits (protecting lower-value assets). However, Liceu followed by Beira-Mar and Forca neighborhoods have the highest BCR index (**Table 35**).

In the future scenario (T1), NBS1 scenario is more economically viable than in the current scenario (T0).

Table 34. *Green roof annual NPV (€/year) per neighbourhood for NBS1 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Annual NPV (€)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
Beira-Mar	-467,516	-458,576	-1,211,403	-1,202,463	-1,769,318	-1,760,378
Liceu	-884,340	-865,999	-2,369,002	-2,350,661	-3,482,499	-3,464,158
Forca	-365,233	-358,557	-949,005	-942,329	-1,386,834	-1,380,158
Santiago	-1,296,654	-1,275,826	-2,973,693	-2,952,865	-4,231,472	-4,210,644
Total (city)	**-3,013,743**	**-2,958,957**	**-7,503,102**	**-7,448,317**	**-10,870,122**	**-10,815,337**

Table 35. *Green roof annual BCR index per neighbourhood for NBS1 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Annual BCR	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
Beira-Mar	0.37	0.38	0.18	0.19	0.13	0.14
Liceu	0.4	0.41	0.2	0.21	0.14	0.15
Forca	0.37	0.38	0.18	0.19	0.13	0.14
Santiago	0.22	0.24	0.11	0.12	0.08	0.09

Finally, a sensitivity analysis on the time discount rate is performed to assess the uncertainty associated with future values (2% in **Table 36** and 4% in **Table 37**). Results for the variations in discount rates (2% and 4%) show that the NPVs change significantly if the discount rate used is 2% or 4%. As expected, the NPVs and BCRs decrease with an increase in the discount rate for all costs scenarios. For the city of Aveiro, the NPVs decrease by between 26-34% when the discount rate increases from 0% to 2%; similarly, the NPVs decrease by between 58-75% when the discount rate increases from 0% to 4%.

Table 36. *Green roof annual NPV (€/year) and BCR for NBS1 with 2% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Total (city)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
NPV	-4,391,121	-4,336,336	-9,232,786	-9178001	-14,068,840	-14,014,055
BCR	0.25	0.26	0.14	0.14	0.09	0.10

Table 37. *Green roof annual NPV (€/year) and BCR for NBS1 with 4% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Total (city)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
NPV	-5,723,629	-5,668,844	-11,662,652	-11,607,867	-17,596,065	-17,541,279
BCR	0.20	0.21	0.11	0.12	0.08	0.08

12.2 NBS2: biophysical impacts and economic viability

This first section is about the flood mitigation benefits derived from NBS2 (bioswale) simulation. Results for water volume retained (%) due to bioswale (NBS2) installation show, as expected, the largest variations in neighborhoods where bioswales are implemented (see **Figure 79)**[57]. The results present a slight improvement between the current and future climate (**Table 38**).

Moreover, water volume retained improves by 4% for 10-years return period, 3% for 50-years and 100-years events under both current and future climate. This means that, when return periods are bigger, higher is the flood reduction benefit. Looking at neighborhood level, water volume retained is usually observed in neighborhoods with larger areas of NBS2 implementation. However, maximum water volume retained occurs in the Liceu neighborhood (12,602 m^2) even if the largest bioswale area has been implemented in Santiago (18,880 m^2) followed by Forca (13,873 m^2). The reason Liceu presents the largest retention capacity improvement is because it is the neighborhood with the largest relative area of implementation, with bioswales covering 64% of the road total area within the neighborhood.

Table 38. *Bioswales percentual differences (NBS2-NBS0) in retained water volume (%) for 10, 50 and 100-years return periods per neighbourhood under current & future climate (city of Aveiro).*

	Current climate			Future climate		
	10-years	50-years	100-years	10-years	50-years	100-years
Liceu	12.08%	13.67%	14.29%	12.58%	14.23%	14.87%
Forca	13.36%	14.78%	15.34%	13.81%	15.28%	15.86%
Santiago	7.21%	7.89%	8.14%	7.43%	8.11%	8.36%

[57] Note that the change in water volume retained can exceed 100% because the amount of water retained with NBS can be (several times) larger than the water retained without NBS.

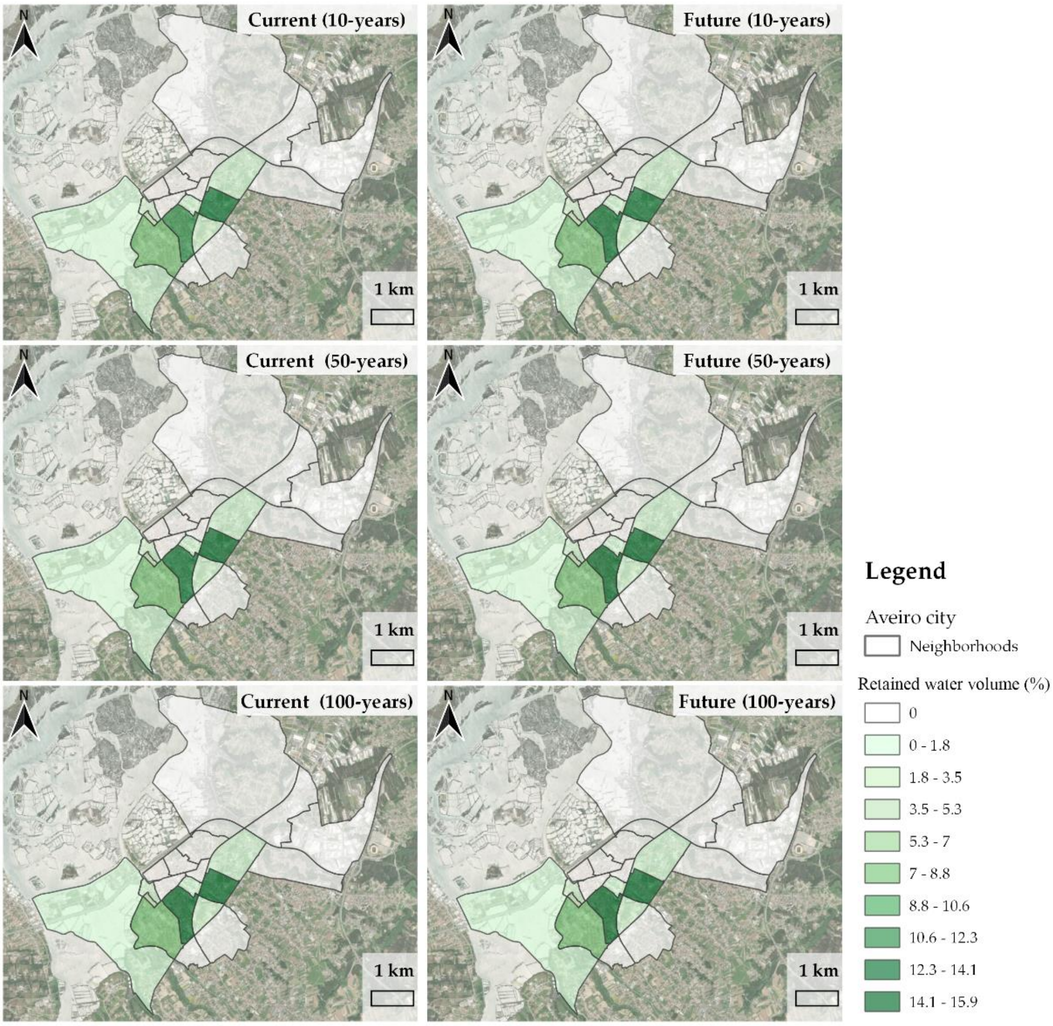

Figure 79. *Bioswales percentual differences (NBS2-NBS0) in retained water volume (%) for 10, 50 and 100-year return periods per neighbourhood under current & future climate (city of Aveiro).*

This second part is about the NBS2 annual costs and benefits estimated in monetary terms. To what concerns the NBS2 costs and benefits estimated in economic terms, the following table showing the avoided costs every year due to the implementation of bioswales (€/year) has been presented (**Table 39**). The city of Aveiro can save every year from € 2,956 in the current scenario (T0) to 3,242 in the future scenario (T1) due to bioswales. In other words, only 0.18% of the expected flooding costs can be abolished every year due to bioswales implementation.

Results for annual flood mitigation benefits from bioswales (NBS2) that the Santiago neighborhood experiences the highest benefits while Liceu presents the lowest benefits (see **Table 40**). Total bioswale benefits increase, on average by 10% from T0 to T1 scenarios at city level.

NBS2 annual costs are given for three scenarios (Low, Medium and High; see **Table 40**). Neighborhoods with higher NBS2 costs correspond, self-evidently, to larger bioswale implementation areas. Note, however, that largest costs and benefits of NBS2 do not always coincide across neighborhoods, due to differences in NBS2 implementation area (and thus NBS2 implementation costs; largest in Santiago) and asset values (and thus flood mitigation benefits from NBS2; largest in Liceu).

Table 39. *Expected annual flood costs (€/year) for NBS0 and NBS2 with the annual avoided costs (€/year) per neighborhood (city of Aveiro).*

	NBS0: Expected damage costs (€/year)		**NBS2**: Expected damage costs (€/year)		Avoided costs (€/year)	
	Current	Future	Current	Future	Current	Future
Liceu	645,367	665,192	348	384	826	906
Forca	237,087	244,503	574	630	850	933
Santiago	424,777	447,618	615	678	1,281	1,405
Total (city)	**1,617,683**	**1,677,857**	**1,537**	**1,692**	**2,957**	**3,244**

Table 40. *Bioswale annual benefits and costs (€/year) from T0_NBS2 and T1_NBS2 scenarios with Low, Medium and High costs' scenarios per neighbourhood (city of Aveiro).*

	Annual benefits (avoided costs (€/year))			**Annual costs** (€/year)		
	Current	Future	Variation (base & future)	Low	Medium	High
Liceu	826	906	+10%	63,008	75,609	88,211
Forca	850	933	+10%	69,363	83,236	97,108
Santiago	1,281	1,405	+10%	94,399	113,279	132,159
Total (city)	**2,957**	**3,244**	**+10%**	**226,770**	**272,124**	**317,478**

The third part is to assess the economic viability of the NBS2 scenario, using the annual net present value (NPV) and annual benefit-cost ratio (BCR) (see **Table 41** and **Table 42**). Results show that all the annual NPV (€/year) and all BCR index are smaller than 1 as shown – even considering the Low cost scenario – implying that NBS2 are not economically viable from a flood mitigation perspective alone. The Liceu neighborhood shows the most favorable (i.e. least negative NPV) results, given the relatively small area of NBS2 implementation (and, thus, low implementation costs) and relatively large, considering the area of NBS2 implementation, flood mitigation benefits (protecting higher-value assets). The Santiago neighborhood shows the lowest NPV in both NBS2 scenarios, mainly due the large NBS2 implementation costs (i.e. corresponding to the largest areas of NBS2 implementation) and relatively low flood mitigation benefits (protecting lower-value assets). A peculiar situation is presented in **Table 42**, where BCR indices are all very little and for all the neighborhoods is the same value.

In the future scenario (T1), both NBS2 scenarios are more economically viable than in the current scenario (T0).

Table 41. *Bioswale annual NPV (€/year) per neighbourhood for NBS2 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Annual NPV (€)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
Liceu	-62,182	-62,101	-74,783	-74,703	-87,385	-87,304
Forca	-68,513	-68,430	-82,385	-82,303	-96,258	-96,175
Santiago	-93,118	-92,995	-111,998	-111,875	-130,878	-130,754
Total (city)	**-223,813**	**-223,526**	**-269,167**	**-268,880**	**-314,521**	**-314,234**

Table 42. *Bioswale annual BCR index per neighbourhood for NBS2 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Annual BCR	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
Liceu	0.01	0.01	0.01	0.01	0.01	0.01
Forca	0.01	0.01	0.01	0.01	0.01	0.01
Santiago	0.01	0.01	0.01	0.01	0.01	0.01

Finally, a sensitivity analysis on the time discount rate is performed to assess the uncertainty associated with future values (2% in **Table 43** and 4% in **Table 44**). Results for the variations in discount rates (2% and 4%) show that the NPVs change significantly if the discount rate used is 2% or 4%. As expected, the NPVs and BCRs decrease with an increase in the discount rate for all costs scenarios. For the city of Aveiro, the NPVs decrease by between 17-18% when the discount rate increases from 0% to 2%; similarly, the NPVs decrease by 37% when the discount rate increases from 0% to 4%.

Table 43. *Bioswale annual NPV (€/year) and BCR for NBS2 with 2% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Total (city)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
NPV	-273,595	-273,308	-308,164	-307,877	-342,733	-342,446
BCR	0.01	0.01	0.01	0.01	0.01	0.01

Table 44. *Bioswale annual NPV (€/year) and BCR for NBS2 with 4% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Aveiro).*

Total (city)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
NPV	-320,006	-319,720	-360,377	-360,091	-400,747	-400,461
BCR	0.01	0.01	0.01	0.01	0.01	0.01

Chapter 13

Biophysical and flood-damages assessment with NBS: city of Rapallo

This chapter presents NBS scenarios implementation for the city of Rapallo. Firstly, the biophysical impacts of NBS simulations are presented for the current (T0) and future (T1) climate scenarios. Secondly, the flood damages reduction on buildings due to green roofs (NBS1 – section 13.1) and on roads due to bioswales (NBS2 – section 13.2), named NBS benefits, are developed for T0 and T1. Lastly, the economic viability of NBS scenarios is presented by combining NBS costs and benefits.

To better highlight the positive or negative variation among various scenarios, with and without NBS, difference maps are elaborated.

13.1 NBS1: biophysical impacts and economic viability

This first section is about the flood mitigation benefits derived from NBS1 (green roofs) simulation. Results for water volume retained (%) due to green roof (NBS1) installation show, as expected, the largest variations in neighborhoods where green roofs are implemented (see **Figure 80**)[58]. The results present a slight improvement between the current and future climate (**Table 45**). In average, the flood depth reduces of 2% under all return periods between current and future scenarios at city level.

Moreover, water volume retained improves by 14% for 10-years return period, 17% for 50-years and 18% for 100-years events under both current and future climate. This means that, when return periods are bigger, higher is the flood reduction benefit. Looking at neighborhood level, water volume retained is usually observed in neighborhoods with larger areas of NBS1 implementation. However, maximum water volume retained occurs in Cappelletta neighborhood (165,168 m^2) even if the highest green roof area has been implemented in Cerisola (182,486 m^2). The reason Cappelletta presents the largest retention capacity is because it is the neighborhood with the largest relative area of implementation, with green roofs covering 42% of the neighborhood's total area. Cerisola follows with 38% of NBS1 surface coverage.

[58] Note that the change in water volume retained can exceed 100% because the amount of water retained with NBS can be (several times) larger than the water retained without NBS.

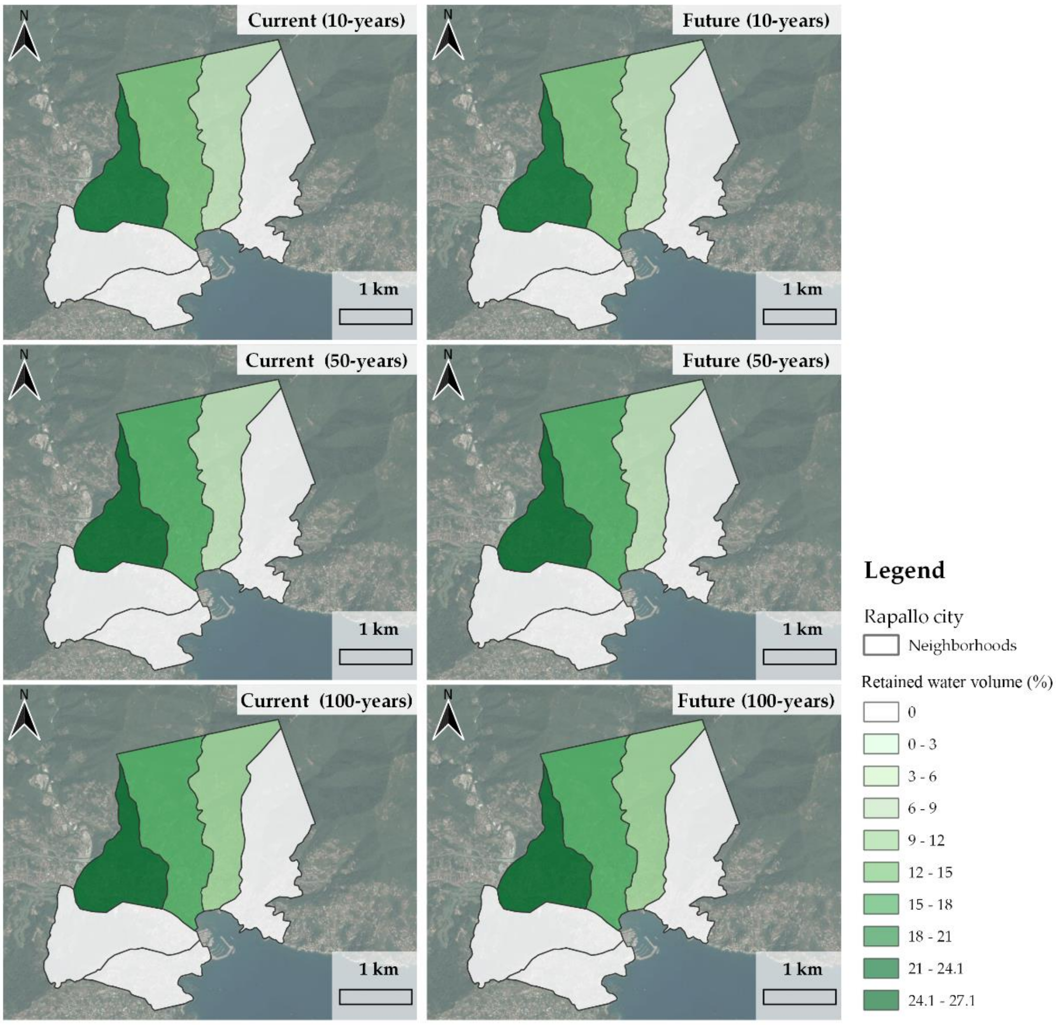

Figure 80. *Green roofs percentual differences (NBS1-NBS0) in retained water volume (%) for 10, 50 and 100-year return periods per neighbourhood under current & future climate (city of Rapallo).*

Table 45. *Green roofs percentual differences (NBS1-NBS0) in retained water volume (%) for 10, 50 and 100-years return periods per neighbourhood under current & future climate (city of Rapallo).*

	Current climate			Future climate		
	10-years	50-years	100-years	10-years	50-years	100-years
Cappelletta	21.64%	25.13%	26.48%	22.18%	25.64%	27.06%
Cerisola	13.59%	15.92%	16.88%	13.94%	16.27%	17.30%
Borzoli	7.55%	8.76%	9.26%	7.74%	8.95%	9.47%

This second part is about the NBS1 annual costs and benefits estimated in monetary terms. The following table (**Table 46**) shows the avoided costs every year due to the implementation of green roofs (€/year) for each neighborhood. The city of Rapallo can save every year from € 3,683,227 in the current scenario (T0) to 3,899,827 in the future scenario (T1) due to green roofs. In other words, approximately 89% of the expected flooding costs can be erased every year.

Table 46. *Expected annual flood costs (€/year) for NBS0 and NBS1 with the annual avoided costs (€/year) per neighborhood (city of Rapallo).*

	NBS0: Expected damage costs (€/year)		**NBS1**: Expected damage costs (€/year)		Avoided costs (€/year)	
	Current	Future	Current	Future	Current	Future
Cappelletta	1,574,832	1,679,069	171,256	192,502	1,403,576	1,486,567
Cerisola	1,728,087	1,842,160	199,460	223,833	1,528,626	1,618,326
Borzoli	857,664	914,658	106,640	119,725	751,023	794,933
Total (city)	**4,160,583**	**4,435,887**	**477,356**	**536,060**	**3,683,227**	**3,899,827**

Results for annual flood mitigation benefits from green roofs (NBS1) show that the Cerisola neighborhood experiences the highest benefits while Borzoli presents the lowest benefits (see **Table 47**). Total green roof benefits increase, on average by 6% from T0 to T1 scenarios at city level.

NBS1 annual costs are given for three scenarios (Low, Medium and High; see **Table 47**). Neighborhoods with higher NBS1 costs correspond, self-evidently, to larger green roof implementation areas. Note, however, that the largest costs and benefits of NBS1 do not always coincide across neighborhoods, due to a few differences.

Generally, what the data shows is that NBS1 benefits in biophysical terms and in economic terms do not present a linear relation within the neighborhoods. Thus, this difference is connected to the way the employed modelling works. The soil types have a strong influence on these kinds of differences among neighborhoods across the city of Rapallo. Cappelletta has the largest portion of soil, which is characterized by the highest capacity of infiltration, and, for this reason, it shows the greater improvements in flood depth.

On the other hand, Cerisola neighborhood has the highest NBS1 benefits in economic terms. This situation is directly related to the total area of green roof implemented in this neighborhood, as above-mentioned. Cerisola has also high costs which are due to the economic values of the assets present in such neighborhood. Indeed, almost 37% of the total residential buildings in Rapallo which have the highest economic values, are located in Cerisola neighborhood.

Table 47. *Green roof annual benefits and costs (€/year) from T0_NBS1 and T1_NBS1 scenarios with Low, Medium and High costs' scenarios per neighbourhood (city of Rapallo).*

	Annual benefits (avoided costs (€/year))			**Annual costs** (€/year)		
	Current	Future	Variation (base & future)	Low	Medium	High
Cappelletta	1,403,576	1,486,567	+6%	1,321,348	2,642,696	3,633,708
Cerisola	1,528,626	1,618,326	+6%	1,459,893	2,919,787	4,014,707
Borzoli	751,023	794,933	+6%	700,852	1,401,705	1,927,345
Total (city)	**3,683,227**	**3,899,827**	**+6%**	**3,482,093**	**6,964,188**	**9,575,760**

The third part is to assess the economic viability of the NBS1 scenario, using the annual net present value (NPV) and annual benefit-cost ratio (BCR) (see **Table 48** and **Table 49**). Results show that all the annual NPV (€/year) are negative except for the Low costs scenario, as shown in **Table 48**. The same situation in **Table 49**, where only for the Low cost scenario the BCR are bigger than 1. This means that when considered the Low cost scenario, the benefits exceed the costs every year – implying that NBS1 are economically viable from a flood reduction perspective alone. The Cappelletta neighborhood shows the most favorable (i.e. least negative NPV) results, given the relatively small area of NBS1 implementation (and, thus, low implementation costs) and relatively large, considering the area of NBS1 implementation, flood mitigation benefits (protecting higher-value assets). Further, Cerisola neighborhood showed great potential in reducing flood costs thanks to green roofs (the major economic benefit at city level). However, the BCR index is the smallest at city level because Cerisola covers 43% of the total NBS1 costs at city scale, followed by Cappelletta with 38% and Borzoli with 20% (**Table 49**).

In the future scenario (T1), NBS1 scenario is more economically viable than in the current scenario (T0).

Table 48. *Green roof annual NPV (€/year) per neighbourhood for NBS1 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Annual NPV (€)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
Cappelletta	82,228	165,218	-1,239,119	-1,156,129	-2,230,131	-2,147,141
Cerisola	68,732	158,433	-1,391,160	-1,301,460	-2,486,081	-2,396,380
Borzoli	50,170	94,080	-650,682	-606,772	-1,176,321	-1,132,412
Total (city)	**201,132**	**417,732**	**-3,280,962**	**-3,064,362**	**-5,892,534**	**-5,675,934**

Table 49. *Green roof annual BCR index per neighbourhood for NBS1 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Annual BCR	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
Cappelletta	1.06	1.13	0.53	0.56	0.39	0.41
Cerisola	1.05	1.12	0.52	0.55	0.38	0.4
Borzoli	1.07	1.13	0.4	0.57	0.39	0.41

Finally, a sensitivity analysis on the time discount rate is performed to assess the uncertainty associated with future values (2% in **Table 50** and 4% in **Table 51**). Results for the variations in discount rates (2% and 4%) show that the NPVs change significantly if the discount rate used is 2% or 4%. As expected, the NPVs and BCRs decrease with an increase in the discount rate for all costs scenarios. For the city of Aveiro, the NPVs decrease by between 33-531% when the discount rate increases from 0% to 2%; similarly, the NPVs decrease by between 78-1045% when the discount rate increases from 0% to 4%.

Table 50. *Green roof annual NPV (€/year) and BCR for NBS1 with 2% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Total (city)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
NPV	-867,208	-650,608	-4,622,563	-4,405,963	-8,373,565	-8,156,965
BCR	0.81	0.86	0.44	0.47	0.31	0.32

Table 51. *Green roof annual NPV (€/year) and BCR for NBS1 with 4% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Total (city)	**Low**		**Medium**		**High**	
	Current	Future	Current	Future	Current	Future
NPV	-1,900,745	-1,684,145	-6,507,247	-6,290,647	-11,109,396	-10,892,796
BCR	0.66	0.70	0.36	0.38	0.25	0.26

13.2 NBS2: biophysical impacts and economic viability

This first section is about the flood mitigation benefits derived from NBS2 (bioswale) simulation. Results for water volume retained (%) due to bioswale (NBS2) installation show, as expected, the largest variations in neighborhoods where bioswales are implemented (see **Figure 81**)[59]. The results present a slight improvement between the current and future climate (**Table 52**).

Moreover, water volume retained improves by 6% for 10-years return period, 7% for 50-years and 100-years events under both current and future climate. This means that, when return periods are bigger, higher is the flood reduction benefit. Looking at neighborhood level, water volume retained is usually observed in neighborhoods with larger areas of NBS2 implementation. However, maximum water volume retained occurs the Cappelletta neighborhood (21,233 m^2) even if the largest bioswale area has been implemented in Borzoli (18,176 m^2) followed by Cerisola (15,256 m^2). Indeed, about 23% of the total road area in the Borzoli neighborhood is covered by bioswales while Cerisola has approximately 13% of bioswales.

Table 52. *Bioswale percentual differences (NBS2-NBS0) in retained water volume (%) for 10, 50 and 100-year return periods per neighbourhood under current & future climate (city of Rapallo).*

	Current Base climate			Future climate		
	10-years	50-years	100-years	10-years	50-years	100-years
Cappelletta	8.78%	10.15%	10.69%	8.99%	10.35%	10.91%
Cerisola	5.20%	5.93%	6.22%	5.31%	6.04%	6.35%
Borzoli	4.30%	4.94%	5.20%	4.40%	5.04%	5.32%

[59] Note that the change in water volume retained can exceed 100% because the amount of water retained with NBS can be (several times) larger than the water retained without NBS.

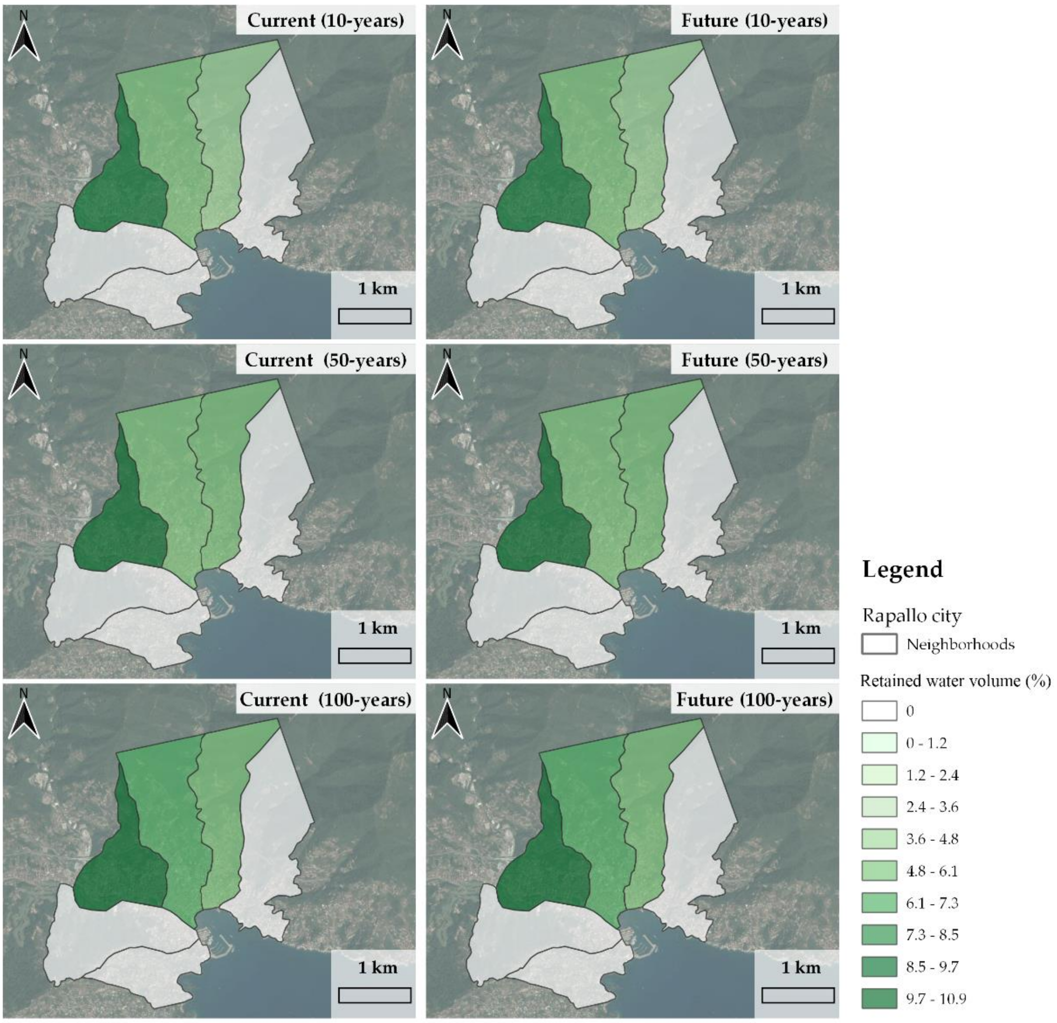

Figure 81. *Bioswale percentual differences (NBS2-NBS0) in retained water volume (%) for 10, 50 and 100-year return periods per neighbourhood under current & future climate (city of Rapallo).*

This second part is about the NBS2 annual costs and benefits estimated in monetary terms. To what concerns the NBS2 costs and benefits estimated in economic terms, the following table showing the avoided costs every year due to the implementation of bioswales (€/year) has been presented (**Table 53**). The city of Rapallo can save every year from € 20,564 in the current scenario (T0) to 21,847 in the future scenario (T1) due to bioswales. In other words, about 60% of the expected flooding costs in Rapallo can be erased every year.

Results for annual flood mitigation benefits from bioswales (NBS2) that the Cerisola neighborhood experiences the highest benefits while Borzoli presents the lowest benefits (see **Table 54**). Total bioswale benefits increase, on average by 6% from T0 to T1 scenarios at city level.

NBS2 annual costs are given for three scenarios (Low, Medium and High; see **Table 54**). Neighborhoods with higher NBS2 costs correspond, self-evidently, to larger bioswale implementation areas. Note, however, that largest costs and benefits of NBS2 do not always coincide across neighborhoods, due to differences in NBS2 implementation area (and thus NBS2 implementation area; largest in Cappelletta), asset values (and thus flood mitigation benefits from NBS2; largest in Cerisola) and soil type (and thus infiltration capacity of soil due to NBS2; larger in Cerisola).

Table 53. *Expected annual flood costs (€/year) for NBS0 and NBS2 with the annual avoided costs(€/year) per neighborhood (city of Rapallo).*

	NBS0: Expected damage costs (€/year)		**NBS2**: Expected damage costs (€/year)		Avoided costs (€/year)	
	Current	Future	Current	Future	Current	Future
Cappelletta	12,258	13,065	4,776	5,140	7,482	7,924
Cerisola	13,112	14,034	5,383	5,838	7,728	8,195
Borzoli	8,756	9,412	3403	3,685	5,353	5,726
Total (city)	**34,126**	**36,511**	**13,562**	**14,663**	**20,564**	**21,847**

Table 54. *Bioswale annual benefits and costs (€/year) from T0_NBS2 and T1_NB21 scenarios with Low, Medium and High costs' scenarios per neighbourhood (city of Rapallo).*

	Annual benefits (avoided costs (€/year))			**Annual costs** (€/year)		
	Current	Future	Variation (base & future)	Low	Medium	High
Cappelletta	7,482	7,924	+6%	93,584	112,301	131,018
Cerisola	7,728	8,195	+6%	106,166	127,399	148,632
Borzoli	5,353	5,726	+7%	76,283	91,539	106,796
Total (city)	**20,564**	**21,847**	**+6%**	**276,033**	**331,239**	**386,446**

The third part is to assess the economic viability of the NBS2 scenario, using the annual net present value (NPV) and annual benefit-cost ratio (BCR) (see **Table 55** and **Table 56**). Results show that all the annual NPV (€/year) and all BCR index are smaller than 1 as shown – even considering the Low cost scenario – implying that NBS2 are not economically viable from a flood mitigation perspective alone. The Borzoli neighborhood shows the most favorable (i.e. least negative NPV) results, given the relatively small area of NBS2 implementation (and, thus, low implementation costs) and relatively large, considering the area of NBS2 implementation, flood mitigation benefits (protecting higher-value assets). The Cerisola neighborhood shows the lowest NPV in both NBS2 scenarios, mainly due the large NBS2 implementation costs (i.e. corresponding to the largest areas of NBS2 implementation) and relatively low flood mitigation benefits (protecting lower-value assets Concerning the results of the BCR index, Cappelletta neighborhood has the highest values followed by Cerisola and Borzoli that present almost the same values (see **Table 56**).

In the future scenario (T1), NBS2 scenario is more economically viable than in the current scenario (T0).

Table 55. *Bioswale annual NPV (€/year) per neighbourhood for NBS2 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Annual NPV (€)	Low		Medium		High	
	Current	Future	Current	Future	Current	Future
Cappelletta	-86,102	-85,659	-104,819	-104,376	-123,536	-123,093
Cerisola	-98,437	-97,970	-119,671	-119,203	-140,904	-140,436
Borzoli	-70,930	-70,557	-86,186	-85,813	-101,443	-101,070
Total (city)	**-255,469**	**-254,187**	**-310,676**	**-309,393**	**-365,883**	**-364,599**

Table 56. *Bioswale annual BCR index per neighbourhood for NBS2 with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Annual BCR	Low		Medium		High	
	Current	Future	Current	Future	Current	Future
Cappelletta	0.08	0.09	0.07	0.07	0.06	0.06
Cerisola	0.07	0.08	0.06	0.06	0.05	0.06
Borzoli	0.07	0.08	0.06	0.06	0.05	0.05

Finally, a sensitivity analysis on the time discount rate is performed to assess the uncertainty associated with future values (2% in **Table 57** and 4% in **Table 58**). Results for the variations in discount rates (2% and 4%) show that the NPVs change significantly if the discount rate used is 2% or 4%. As expected, the NPVs and BCRs decrease with an increase in the discount rate for all costs scenarios. For the city of Aveiro, the NPVs decrease by between 18-19% when the discount rate increases from 0% to 2%; similarly, the NPVs decrease by between 39-40% when the discount rate increases from 0% to 4%.

Table 57. *Bioswale annual NPV (€/year) and BCR for NBS2 with 2% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Total (city)	Low		Medium		High	
	Current	Future	Current	Future	Current	Future
NPV	-316,066	-314,783	-358,145	-356,862	-400,224	-398,941
BCR	0.06	0.06	0.05	0.06	0.05	0.05

Table 58. *Bioswale annual NPV (€/year) and BCR for NBS2 with 4% discount rate with three cost scenarios (Low, Medium and High) under current and future conditions (city of Rapallo).*

Total (city)	Low		Medium		High	
	Current	Future	Current	Future	Current	Future
NPV	-372,560	-371,278	-421,701	-420,418	-470,841	-469,559
BCR	0.05	0.06	0.05	0.05	0.04	0.04

PART VI – Discussion and future perspectives

Chapter 14

Critical discussion and reflections

The following chapter concerns the discussion of the results obtained from this research by comparing the two case studies, to reflect on both their differences and communalities. Attention is given to the utility of 'improving by doing' thanks to the development of the proposed evaluation method. Moreover, some critical reflections on strengths and weaknesses of this research, and particularly on the employed methodology, have been provided. This chapter also illustrates some simplifications and limitations of the model.

14.1 Main findings

Figure 82 and **Figure 83** represent a synthesis of the effects in monetary terms of all scenarios considered in the current and future situation for Aveiro and Rapallo cases, respectively. Specifically, EAD (as the result of the sum of buildings and roads damages), NBS costs and benefits (for NBS1 and NBS2 scenarios) have been investigated. It is evident how EAD for the city of Rapallo (around € 6 million yearly) are considerably higher than for Aveiro (around € 4 million yearly) in a situation without intervention (NBS0). One reason for this large difference could be related to different real estate values between the two cities (which are larger in Rapallo). Thus, it directly influences the economic evaluation, as it is a damage assessment of assets. Concerning the NBS1 costs, the values range between € 4 million and € 12 million for Aveiro, and between € 2.5 million and € 9.5 million for Rapallo in the case of green roof implementation (yearly values). With bioswales, NBS2 costs show less variation between the two cases (both less than € 1 million yearly). The motivation is related to the different percentage of NBS area implemented in both cities. Finally, the benefits present diverse values among the two cities. Avoided building damage costs due to green roofs (benefits) in Aveiro total are approximately € 3.1-3.2 million every year (for current and future scenario) while for Rapallo the benefits are approximately € 2.7-3.0 million every year (for current and future scenario). An explanation is given by the fact that the amount of precipitation per flood return period for Rapallo is higher than for Aveiro. Indeed, the benefits in terms of flood reduction increase when the amount of precipitation increases, and vice versa. Avoided roads damage costs due to bioswales (benefits) in Aveiro are around € 4.5-4.7 million every year while for Rapallo the benefits are approximately € 6.4-6.8 million every year.

In general, these differences related to the CBA analysis results from the two study cases might be explained by differing soil types which differ between Aveiro and Rapallo. This aspect can strongly influence the benefit estimation because it is connected to the infiltration capacity of the soil.

Results from the sensitivity analysis show that the scenarios with the highest NPVs are the same in all cases, even with a change in the values of the NPV. The scenarios that provide a higher NPV are the same even considering the uncertainty of the future, meaning that the model considered is robust. Generally, larger investments to implement NBS (such as for green roofs) are less attractive when the discount rate is higher because initial investment costs weigh relatively more than the (more discounted) future benefits. In addition, when the lifespan of a project is larger (e.g. about 40 years for green roofs), a lower weight is given to future values due to higher discount rate.

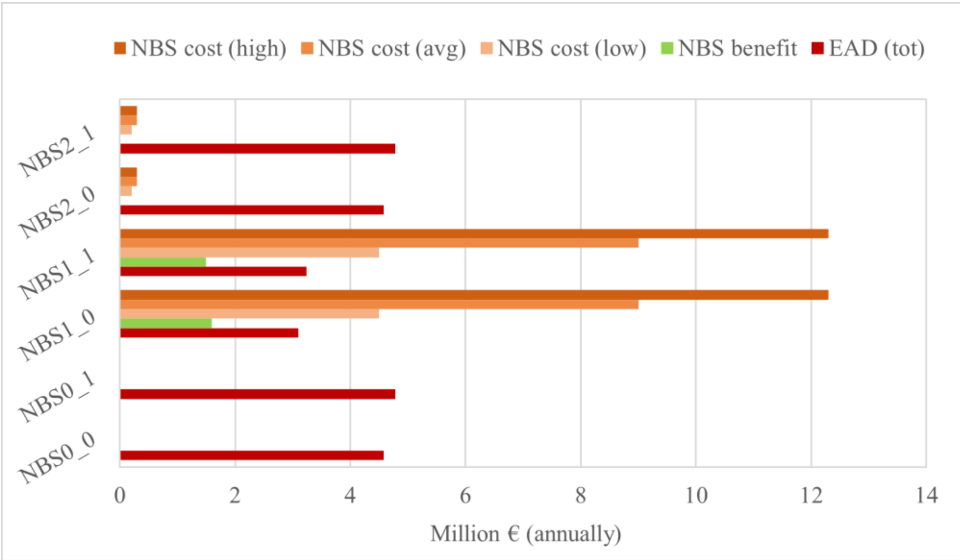

Figure 82. *Total expected annual damages (buildings & roads), benefits and costs for NBS0 (no NBS), NBS1 (green roof) and NBS2 (bioswale) without (_0) and with (_1) climate change for the city of Aveiro.*

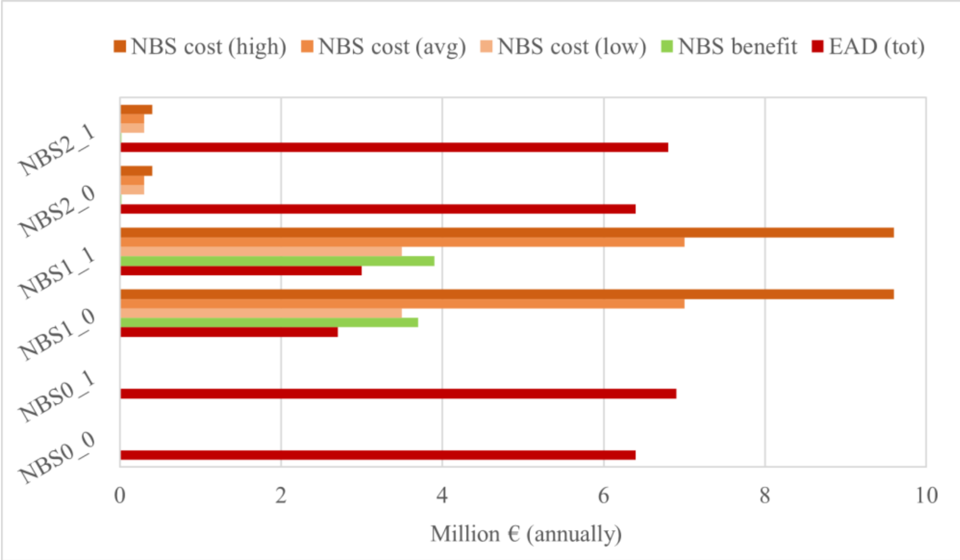

Figure 83. *Total expected annual damages (buildings & roads), benefits and costs for NBS0 (no NBS), NBS1 (green roof) and NBS2 (bioswale) without (_0) and with (_1) climate change for the city of Rapallo.*

As mentioned in the literature review section (*Chapter 3*), a few studies assess NBS impacts in an integrated way, especially by combining the biophysical and economic effects.

Several previous studies focused on assessing urban flood mitigation through NBS implementation (Lee, Hyun and Choi, 2013; Rozos, Makropoulos and Maksimović, 2013; Ramírez, Qi and Xiaobo, 2016; Boelee *et al.*, 2017; Jackisch and Weiler, 2017; Mei *et al.*, 2018; Fenner *et al.*, 2019; Yao *et al.*, 2020; Rosa and Pappalardo, 2020; Costa *et al.*, 2021; Salata *et al.*, 2021; Nguyen *et al.*, 2021). For example, in line with Costa et al. (2021), who assessed the effectiveness of reducing the flood depth by implementing various NBS scenarios (such as green roofs, green parking and water storage in the streets), the present research shows that green roofs implementation can be effective for flood control during rainfall events with low to high probability of occurrence. Moreover, both works proved that flood reduction improves with higher return periods when water depth is considered as proxy for flooding. Rosa and Pappalardo (2020) and Yao et al. (2020) state that NBS for flood reduction are highly context-specific, and that their spatial behaviour depends on different aspects (such as land use, hydrological system, demographic paths, NBS typology, etc.).

Comparing literature avoided flooding cost literature results is still difficult because studies focusing on flood mitigation often employ distinct methods, and they don't assess the same types of NBS. Some previous studies worked on avoided flooding costs in terms of damage calculation, or NBS benefits, in urban areas (Webber, Fu and Butler, 2018; Bertilsson *et al.*, 2019; Alves *et al.*, 2020; Bennink, 2022). A different method was used by Jenkins et al. (2017), which focused their interest on the interaction between flood insurance in the United Kingdom and surface water flood risk management. However, some researches showed important findings on flood mitigation benefits of NBS which might be interesting to point out. Alves et al. (2020) showed that the maximum damage reduction achieved by applying a combination of green and grey solutions is of 50% of the total flood damage value; they also found that green roofs only lead to an annual saving of approximately 32%. This is in line with the results of this study for the city of Aveiro, which show a reduction of annual flood damages to buildings and roads of 32% and 31%, with green roof implementation, under the current and future climate scenarios, respectively. In relative terms, the flood mitigation benefits associated to the bioswale implementation reduced annual flood damage costs by 0.1% in the current scenario and future scenario. As for Rapallo, the values are higher, with the scenarios showing a yearly reduced annual flood damage costs to buildings and roads of 65% for green roofs, and 0.3% for bioswales scenarios. In general, it is hard to make comparisons among different cases because the values are expressed in relative terms, and it is always strictly context-specific.

Few studies assessed the economic viability of NBS implementation by combining costs and benefits of NBS in cities (Mei *et al.*, 2018; Velasco *et al.*, 2018; Alves *et al.*, 2019, 2020; Locatelli *et al.*, 2020). For example, a study on the cost-effectiveness of Green Infrastructures (GI) for flood mitigation showed a higher cost-effectiveness for vegetated swales when compared to green roofs implementation (Mei *et al.*, 2018). The result of the present research demonstrates the opposite, with green roofs providing larger net-benefits than bioswales. Locatelli et al. (2020) showed that most of the NPV for NBS (green roofs, permeable pavements, detention ponds, infiltration trenches and bioretention cells) are negative, even when multiple co-benefits of NBS are considered. They were able to achieve a positive NPV only when low costs scenarios were considered.

Even though the present research shows that costs outweigh benefits for both NBS scenarios in the city of Aveiro, it is important to point out that, for the case of green roofs, the benefits contribute to between 11% and 32% of the NBS annual implementation costs every year in the current situation (range of 12% - 34% in the future situation). For the Rapallo case, NPV resulted in positive values for the low-cost scenario of green roofs; for the high-cost scenario of green roofs the benefits contribute to 38% of the NBS1 implementation costs in the current situation (40% in the future situation). For NBS2, the NPV are negative even for the Rapallo case; the values related to the benefits contribution to NBS costs range from 7% to 5% in the current situation (8% to 6% in the future). Consequently, the economic viability of NBS should, ideally, be based on the multiple ecosystem service benefits and co-benefits from NBS.

Few studies assessed multiple benefits of NBS under different climate conditions (Debele *et al.*, 2019). One study that worked on future climate scenarios (Velasco *et al.*, 2018), argued that green roofs simulated a higher net-benefit in the pessimistic climate scenario in relation to the optimistic climate scenario. Results of the present research showed the same situation, by proving a more beneficial NBS effect in the future scenarios. This condition may be representative of climate change influencing pluvial flood events. Indeed, what emerged from this research is the result of a moderate future climate scenario (RCP4.5). Thus, benefits and

NPV could increase if other, more extreme, future scenarios are considered (such as RCP6 and RCP8.5).

From a biophysical perspective, the simulations show that both green roofs and bioswales have positive effects in terms of flood mitigation benefit. However, the high degree of variation in the impacts of ecosystems on hydrology (depending, for instance, on ecosystem type, location, climate, etc.) generates difficulties in reaching generalized assumptions about NBS. Green roofs, for example, can increase water retention according to their type, size, age, etc. (Salata, 2023). From the economic point of view, the results obtained show that NBS assessment should be based on the multiple ecosystem services and values from NBS. Indeed, economically evaluating only the flood mitigation service is reductive, and does not accurately reflect the value of the full range of benefits provided by NBS.

14.2 Adaptation through a NBS perspective

This research focused on urban climate adaptation through a NBS and ecosystem services perspective. Nowadays, this topic continues to present uncertainties, especially due to the need of an evaluation framework for ecosystem services provided by NBS which also includes future climate scenarios to support urban adaptation planning. To enhance a successful implementation of NBS, identifying and understanding barriers is crucial (Sarabi *et al.*, 2020).

Due to the lack of monetary valuation of environmental resources, NBS still lack standards for their development and integration into urban adaptation planning. Firstly, there is a need for upgrading municipal, regional and national legislations to support long-term policies for successful implementation of NBS (Sarabi *et al.*, 2020). Supportive regulations are crucial to reduce the investment risks and encouraging collaboration between the private and public sectors (i.e. by means of public-private partnership) (Langemeyer *et al.*, 2020). Hence, their implementation is possible with a broad active collaboration and coordination between policy makers and stakeholders, promoting the integration of the multiple impacts, benefits and costs of NBS in all levels of the policy domain. Why is that particularly important? A lack of policy coherence can lead to inaction when one agency sees adaptation as the responsibility of another. Especially in the private sector, there is a common perception that greening (i.e. NBS) entails high costs, although its benefits (both economic and social) make it a good investment (Feng and Hewage, 2018; Grant, 2018; D'Antonio, 2019; Vause, Dawkins and Zaman, 2021). Thus, a way to increase the public awareness on the importance of NBS, and then to stimulate their uptake, can be the combination of command-and-control as regulations and market-based strategies as financial strategies (Mees *et al.*, 2013). In the field of urban planning, an incentive can be in the form of *"a payment, discount or reduction on fees or a concession, which is offered by the planning authority, public utility, or occasionally an NGO, on condition that a particular green infrastructure quantum is provided"* (Grant, 2018).

Some examples about practical applications of those kinds of incentives have been shown hereafter (Mees *et al.,* 2013; Grant, 2018). The Municipalities of The Hague and Amsterdam (The Netherlands) offer a subsidy to small businesses for green roofs and living walls aiming at achieving climate change adaptation and air quality improvement. The city of Hamburg (Germany) was the first to adopt a green roof strategy, in the 1980s, which provides a subsidy covering up to 60% of installation costs. In the United States, several cities offer financial incentives, such as Austin (Texas), Seattle (Washington), Milwaukee (Wisconsin), Nashville (Tennessee), New York City, Philadelphia (Pennsylvania), Palo Alto (California), Portland (Oregon) and Syracuse (New York). In these cities, the common approach is to offer subsidies that can cover up to 50% of installation and maintenance costs of green roofs. Singapore and the city of Nagoya (Japan) offer subsidies covering up to 50% of installation costs, both for green roofs and living walls. The city of Hamburg (Germany) combines financial incentives for voluntary installations with regulation for compulsory installation of green roofs in new local plans. Other examples include the Municipality of Bologna (Italy), which developed an instrument with which private companies can decrease their carbon footprint by paying for local afforestation and thus generate environmental and social benefits for the community, or the city of Amsterdam (Netherlands), which established a public green fund that doubled private investment in greening the city (European Environmental Agency (EEA), 2021b).

A strong barrier for NBS uptake is associated to the fact that, for instance, bioswales or permeable pavements involve the public dimension. Hence, it is more difficult to establish an accepted measure of payment for NBS from the population. Lack of regulations and incentives for green roofs may limit their implementation among property owners. For the above-mentioned reasons, strengthening the knowledge and the commitment about co-benefits that NBS can provide, such as mitigation of climate change, aesthetic improvement, biodiversity enhancement, energy savings etc., is important to increase the NBS uptake (López Maciel, 2019; Roggero, 2020). Despite the growing evidence that natural habitats provide more benefits in terms of avoided losses from climate change-related impacts, large and systematic investments in NBS are missing (Xie, Bulkeley and Tozer, 2022).

14.3 Strengths and empirical knowledge

The proposed assessment framework for climate change adaptation measures was among the first attempts to adopt and integrate different evaluation spheres through spatially explicit evaluation.

The overall results of the biophysical and economic assessment show potential to support decision-making within urban spatial planning that integrates NBS and climate concern into current and future policies. The specific results of the biophysical and damage assessment help understand the patterns and magnitude of climate change-related flood impacts, and promote the prioritization of intervention actions designed with context-specificity in mind. Certainly, this research shows that NBS have a good performance for a medium-term adaptation (2050) under a moderate emission scenario (RCP 4.5).

Scenario analysis of NBS simulation is an effective way to spatially visualise the effectiveness of different adaptation options. It shows how developing comparative analysis among different NBS scenarios helps to make trade-off decisions, and also small interventions rather than a single dominant intervention.

This study also shows how simple open-source and free tools can help policy makers at the local level develop decision support systems to design adaptation actions. Still, the practical application to the case studies in Portugal and Italy proves the replicability to other similar regions. Considering that NBS impact assessments are of general interest to the scientific community and policymakers committed to climate change adaptation, this methodological application can be used as a guide for future development.

Despite the uncertainty in the scenarios, the results of this study can be employed for future urban NBS development strategies; further research will be dedicated to comparing different contexts.

14.4 Limitations and weaknesses

This study has been affected by some limitations. First, the key weakness of this study is the non-inclusion of multiple co-benefits in the analysis. The NBS benefits considered in this research are limited to avoided monetary losses resulting from flood risk mitigation service. As a result, by not including multiple co-benefits of NBS in the impact assessment, the potential and multifunctionality of such solutions is underestimated.

Second, another limitation is related to the direct flood damage assessment that did consider the structure though not the content value of the property. By forgoing the value of building contents, the potential damages are underestimated and, thus, so are the potential benefits of NBS. For example, a study conducted on assessing the cultural and regulating ecosystem service values of green/blue solutions in the city of Aveiro (Portugal) highlighted a potential underestimation of flood damages equal to 15% (Roebeling *et al.*, 2011).

The third limitation of the current study refers to the uncertainty associated with the quantitative assessment of the flood impacts (biophysical assessment). This uncertainty results from the modelling tool that simulates the biophysical effects of urban floods. The use of the InVEST Flood Risk Mitigation model, due to the lack of original, high resolution and site-specific data, can be the main cause of incongruencies found in flood risk maps. Indeed, the strong limitation of the InVEST model (based on the SCS-CN method) is that it does not take into consideration important data, such as DTM, flow velocity, drainage network and sewage system. The hydrological soil group raster is a worldwide database with 250 m resolution, and is often too wide to capture the variation of the soil within the urban system. Moreover, InVEST is not explicitly designed to account for specific features of NBS (such as the vegetation type) and thus it was necessary to make assumptions and approximations to manage the modelling of the adaptation simulations. Another uncertainty refers to the rainfall (for all the considered return periods). The values considered in this study come from dated reports: 2001 for the Portuguese case study and 2013 for the Italian one. Thus, the considered precipitation events may not properly represent extreme rainfall events typically used to describe the influence of climate change influence. Another limitation of this research lies in the usage of only one future climate scenario (RCP 4.5), which does not allow a complete estimation of the possible benefits of NBS under the wider range of possible future climate conditions. The choice to consider RCP4.5 was due to the more moderate nature of this scenario. Alternatives point towards extremer scenarios (RCP 8.5) in 2100. However, some authors argue that RCP 8.5 is a very unlikely scenario while other point out that there is a 35% probability of exceeding the RCP 8.5 scenario (Christensen et al., 2018; Peters and Hausfather, 2020).

Fourth, the time discount rate was, implicitly, considered to be equal to zero (r = 0.001). The choice to consider a strong prescriptive discounting has been driven by the nature of this research in the field of climate change adaptation. Indeed, a low discount rate (almost zero) is justified in policy evaluation to preserve ecosystem services and biodiversity as precautionary investment that secures future human wellbeing, reducing potentially catastrophic and irreversible effects. Right-based ethics suggest that is morally wrong to impose substantial and uncompensated risks on posterity. The Stern Review advocates to consider time discount rate of zero in the economics of climate change (Stern, 2007). Although the applied time discount rate in environmental-economic analyses is generally below 4% and, in addition, that it is argued that they ought to decline over time (down to 2%; see (Arrow *et al.*, 2014)), a low interest rate prioritizes investments with large initial investments and/or outlays. The sensitivity analyses developed with discount rate rates of 2% and 4% as well as on the costs shows, however, that it has no impact on the prioritization of NBS across neighborhoods.

Lastly, limits on NBS costs calculation exist. This study employs NBS costs as aggregated values from the existent recent literature on this recent topic. There is often a lack of data on some specific NBS. Hence, the values are not context-specific, and it can lead to rough estimates on investment and maintenance costs.

Chapter 15

Conclusion and future perspectives

This work presents a method to integrate biophysical NBS effects with related economic benefits to conduct a cost-benefit analysis of flood risk mitigation. To achieve this goal, monetary values of flood damages to buildings and roads, as well as benefits and costs of NBS, namely green roofs and bioswales, have been assessed. The NBS performance assessment has been simulated for rainfall events with return periods of 10, 50 and 100 years, considering both current and future climate scenarios. The application of this approach has been developed for different study cases.

This thesis integrates a variety of multi- and inter-disciplinary notions and methods in climate change adaptation. This research considers the effectiveness of adaptation strategies, namely NBS, to cope with a situation where climate change impacts cannot be avoided. Specifically, the goal was the development of a methodology to include monetary analysis of benefits with present and future climate scenarios into cost-benefit analysis for flood risk mitigation measures. This research, performed through spatial analysis and modelling approaches in a quantitative perspective, intends to contribute towards improving the knowledge needed to support urban planning for climate resilient cities, as well as towards a more comprehensive understanding of the effects of NBS on climate change adaptation. Studies such as this are extremely important, as they strengthen the knowledge-base and act as a foundation for urban climate change adaptation planning.

Despite the mentioned uncertainties and constraints of this research, results have shown similar values of costs and benefits found in previous works, although comparisons between different environments are context-specific and, thus, difficult to conduct.

15.1 Contribution to scientific method

This research contributes to the existing body of knowledge on NBS for climate change adaptation in three different ways.

First, it enriches the literature on economic losses from climate change-related floods. Uncertainty about climate change is, in itself, a barrier to adaptation action. By better understanding climate change impacts, not only from a biophysical perspective, but also from an economic perspective, and making that information available, decision-makers may make more informed decisions to boost adaptation.

Second, it advances systematic evaluation methodologies for climate change adaptation effectiveness benefits of solutions. This study provides quantification of the NBS impacts as set by the European Union (EU) Adaptation Strategy on adaptation to climate change[60] adopted in 2021. The EU Adaptation Strategy describes how the EU can adapt to the impacts of climate change and become climate resilient by 2050 with an important focus on NBS. To this end, an integrated methodology comprising four key steps is adopted. These consist of i) integrating climate change impacts on precipitation events for the case studies considering the most recent IPCC climate change scenarios (RCP); ii) quantifying changes in flooding impacts arising from NBS implementation; iii) monetizing these impacts; and iv) assessing the economic viability of such solutions.

Third, it proves the potential of a locally adapted holistic approach to assess NBS impacts of urban flood risk. The application of this method to two different case studies does not intend to provide precise cost and benefit estimates. Rather, the aim is to provide evidence of the replicability of such assessment methods to other cities.

15.2 Policy implications

The link between adaptation and its operationalisation must be acknowledged if the intent is to help urban planners in the face of climate change impacts (EIP-AGRI Focus Group, 2022). Therefore, policy implications should lead towards increasing the capability of those who must make decisions under climate changes uncertainties by increasing the freedom of actions. This is especially relevant in the context of NBS adaptation, where inter-and trans-disciplinarity entails a systemic and holistic perspective on major societal challenges.

This research explores how this holistic approach can be adopted in the spatial planning process by developing a planning support system that shows that nature in cities can be an ‘asset’ rather than a ‘cost’. Through the application of urban Ecosystem Accounting (EA), it will help decision-makers in cities to scale up NBS by increasing investments.

Four main key points can be highlighted as policy implications to address adoption of NBS in different urban contexts. Firstly, NBS implementation is a very context-specific process in the definition of the objectives, risk assessment and climate regions, as well as roadmaps. Identifying the specific actors involved, and how they are interconnected, as well as recognizing social, cultural, physical, environmental, and institutional frameworks, gives more complexity to this process (Raymond *et al.*, 2017; Mačiulytė *et al.*, 2018). Thus, replicability and upscaling of NBS is good when the implementation approach is tailored to local conditions. Second, in comparison with some engineered approaches (where benefits may be fewer but more intuitive and well documented), the multiple benefits of NBS may be less visible

[60] Accessed on 10th January 2023: https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en

and understood. This barrier is mainly related to the perception among some policy makers that nature is not a real part of the solution to address the complex environmental and social challenges of cities. Indeed, environmental features in cities are often seen as 'cost' rather than as an investment in assets. To understand and evaluate all the benefits of NBS, context-specific information, distribution of all benefits over space, time and various stakeholders in society, as well as comparisons tailored with the context and the kind of intervention, are needed. On the other hand, engineered solutions may produce benefits that are delivered immediately after construction is completed, while NBS may require time to mature and deliver a wider range of benefits across different stakeholders. If urban planners are not used to assessing solutions such as NBS, which deliver various benefits across multiple agendas, it would be difficult to recognize their full contribution and, thus, limit a wider uptake of NBS. Third, strictly connected to the previous consideration, NBS are often undervalued because their multiple benefits are not considered. Barriers in evaluating these benefits are linked to non-market values of natural resources and, thus, their full contribution to society is rarely identified. Finally, spatially assessing the multiple benefits and relative monitoring and maintenance costs of NBS is essential to have information for local actors directly involved. The knowledge of who should pay supports the creation of financial mechanisms to promote NBS uptake.

At this point, a further consideration is needed. CBA analysis provides a method for making direct comparisons among alternative adaptation scenarios by assessing the relative efficiency of the alternatives. However, how does one normalize the operationalisation of NBS scenarios in urban planning? One solution may be to define three categories of intervention linked to the criticalities presented by the NBS biophysical-economic assessment (Alemaw, Chaoka and Tafesse, 2020; Comune di Milano, 2020):

- Direct intervention of private citizens, which foresee a small transformation within the city (e.g. green roof on a private building);
- Direct intervention of private citizens, which pay for small transformations within the city for public work (e.g. rain garden);
- Indirect intervention of public sector, which expects transformations within the city (e.g. bioswale).

15.3 Future research

An obvious choice for further research from the narrow perspective of this PhD thesis would be an extended and broader analysis of the range of NBS co-benefits.

Future work should also focus on simulating multiple combinations of different NBS to be able to find the most efficient solution, maximizing benefits and minimizing costs (Alves *et al.*, 2019). In addition, this work, and most of the publications examined, analyzed the benefits provided by NBS. However, it is recognized that NBS might have negative impacts, so called dis-benefits or co-costs (such as increasing housing market pricing), which should be quantified and included in the assessment when comparing different adaptation alternatives (Zhou *et al.*, 2013; Alves *et al.*, 2020). Thus, further development of such wider assessment could be beneficial from a planning perspective.

Further work is also needed on the economic evaluation methods for NBS co-benefits, such as aesthetics enhancement, biodiversity improvement, and recreation. Nowadays, economic evaluation methods are insufficient to represent all NBS co-benefits in cities, considering that many benefits are challenging to assess in economic terms (McPhearson *et al.*, 2015). An improvement on economic representation of these benefits will help to encourage further application of NBS in urban spaces.

Lastly, future improvement on biophysical modelling of the flood impacts should be performed, especially by considering the integration of compound flooding hazard (coastal and urban flood) in coastal cities. Through sea-level rise projections and storm surge data employment, future climate change scenarios can be considered in a compound flooding perspective.

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Appendix A

Table 59. *List of selected studies for the systematic literature review.*

Reference	Authors	Title	Year	Journal
(Connop *et al.*, 2016)	Connop S., Vandergert P., Eisenberg B., Collier M.J., Nash C., Clough J., Newport D.	Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure	2016	Environmental Science and Policy
(Senosiain, 2020)	Senosiain J.L.	Urban regreeneration: Green urban infrastructure as a response to climate change mitigation and adaptation	2020	International Journal of Design and Nature and Ecodynamics
(Karamouz and Heydari, 2020)	Karamouz M., Heydari Z.	Conceptual Design Framework for Coastal Flood Best Management Practices	2020	Journal of Water Resources Planning and Management
(Chan *et al.*, 2018)	Chan F.K.S., Griffiths J.A., Higgitt D., Xu S., Zhu F., Tang Y.-T., Xu Y., Thorne C.R.	"Sponge City" in China—A breakthrough of planning and flood risk management in the urban context	2018	Land Use Policy
(Boelee *et al.*, 2017)	Boelee E., Janse J., Le Gal A., Kok M., Alkemade R., Ligtvoet W.	Overcoming water challenges through nature-based solutions	2017	Water Policy
(Alves *et al.*, 2018)	Alves A., Gómez J.P., Vojinovic Z., Sánchez A., Weesakul S.	Combining co-benefits and stakeholders perceptions into green infrastructure selection for flood risk reduction	2018	Environments
(Duy *et al.*, 2018)	Duy P.N., Chapman L., Tight M., Linh P.N., Thuong L.V.	Increasing vulnerability to floods in new development areas: evidence from Ho Chi Minh City	2018	International Journal of Climate Change Strategies and Management
(Bertilsson *et al.*, 2019)	Bertilsson L., Wiklund K., de Moura Tebaldi I., Rezende O.M., Veról A.P., Miguez M.G.	Urban flood resilience – A multi-criteria index to integrate flood resilience into urban planning	2019	Journal of Hydrology
(Sörensen and Emilsson, 2019)	Sörensen J., Emilsson T.	Evaluating flood risk reduction by urban blue-green infrastructure using insurance data	2019	Journal of Water Resources Planning and Management

(O'Donnell, Lamond and Thorne, 2017)	O'Donnell E.C., Lamond J.E., Thorne C.R.	Recognising barriers to implementation of Blue-Green Infrastructure: a Newcastle case study	2017	Urban Water Journal
(El Hattab *et al.*, 2020)	El Hattab M.H., Theodoropoulos G., Rong X., Mijic A.	Applying the systems approach to decompose the SuDS decision-making process for appropriate hydrologic model selection	2020	Water
(O'Sullivan *et al.*, 2012)	O'Sullivan J.J., Bruen M., Purcell P.J., Gebre F.	Urban drainage in Ireland - embracing sustainable systems	2012	Water and Environment Journal
(Ramírez, Qi and Xiaobo, 2016)	Ramírez J.I., Qi K., Xiaobo L.	Sustainable stormwater management in Yinchuan New Town	2016	Water Practice and Technology
(Dong, Guo and Zeng, 2017)	Dong X., Guo H., Zeng S.	Enhancing future resilience in urban drainage system: Green versus grey infrastructure	2017	Water Research
(Hasala, Supak and Rivers, 2020)	Hasala D., Supak S., Rivers L.	Green infrastructure site selection in the Walnut Creek wetland community: A case study from southeast Raleigh, North Carolina	2020	Landscape and Urban Planning
(Kunapo *et al.*, 2018)	Kunapo J., Fletcher T.D., Ladson A.R., Cunningham L., Burns M.J.	A spatially explicit framework for climate adaptation	2018	Urban Water Journal
(Butt *et al.*, 2018)	Butt N., Shanahan D.F., Shumway N., Bekessy S.A., Fuller R.A., Watson J.E.M., Maggini R., Hole D.G.	Opportunities for biodiversity conservation as cities adapt to climate change	2018	Geo: Geography and Environment
(Pimentel-Rodrigues and Silva-Afonso, 2018)	Pimentel-Rodrigues C., Silva-Afonso A.	Adaptation measures to climate change. Integration of green roofs with rainwater harvesting systems	2018	WSEAS Transactions on Environment and Development
(Schubert *et al.*, 2017)	Schubert J.E., Burns M.J., Fletcher T.D., Sanders B.F.	A framework for the case-specific assessment of Green Infrastructure in mitigating urban flood hazards	2017	Advances in Water Resources
(Zidar *et al.*, 2017)	Zidar K., Belliveau-Nance M., Cucchi A., Denk D., Kricun A., O'Rourke S., Rahman S., Rangarajan S., Rothstein E., Shih J., Montalto F.	A framework for multifunctional green infrastructure investment in Camden, NJ	2017	Urban Planning
(Xie *et al.*, 2017)	Xie J., Chen H., Liao Z., Gu X., Zhu D., Zhang J.	An integrated assessment of urban flooding mitigation strategies for robust decision making	2017	Environmental Modelling and Software

(I.M. Voskamp and Van de Ven, 2015)	Voskamp I.M., Van de Ven F.H.M.	Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events	2015	Building and Environment
(Farrugia, Hudson and McCulloch, 2013)	Farrugia S., Hudson M.D., McCulloch L.	An evaluation of flood control and urban cooling ecosystem services delivered by urban green infrastructure	2013	International Journal of Biodiversity Science, Ecosystem Services and Management
(Rozos, Makropoulos and Maksimović, 2013)	Rozos E., Makropoulos C., Maksimović Č.	Rethinking urban areas: An example of an integrated blue-green approach	2013	Water Science and Technology: Water Supply
(Xie *et al.*, 2019)	Xie X., Qin S., Gou Z., Yi M.	Engaging professionals in urban stormwater management: the case of China's Sponge City	2020	Building Research and Information
(Bu *et al.*, 2020)	Bu J., Peng C., Li C., Wang X., Zhang Y., Yang Z., Cai Y.	A method for determining reasonable water area ratio based on flood risk and cost-effectiveness in Rainy City	2020	Environmental Earth Sciences
(Wu *et al.*, 2020)	Wu H.-L., Cheng W.-C., Shen S.-L., Lin M.-Y., Arulrajah A.	Variation of hydro-environment during past four decades with underground sponge city planning to control flash floods in Wuhan, China: An overview	2020	Underground Space (China)
(Lancia *et al.*, 2020)	Lancia M., Zheng C., He X., Lerner D.N., Andrews C., Tian Y.	Hydrogeological constraints and opportunities for "Sponge City" development: Shenzhen, southern China	2020	Journal of Hydrology: Regional Studies
(Rubinato *et al.*, 2019)	Rubinato M., Nichols A., Peng Y., Zhang J.-M., Lashford C., Cai Y.-P., Lin P.-Z., Tait S.	Urban and river flooding: Comparison of flood risk management approaches in the UK and China and an assessment of future knowledge needs	2019	Water Science and Engineering
(O'Donnell *et al.*, 2020)	O'Donnell E.C., Thorne C.R., Yeakley J.A., Chan F.K.S.	Sustainable Flood Risk and Stormwater Management in Blue-Green Cities; an Interdisciplinary Case Study in Portland, Oregon	2020	Journal of the American Water Resources Association
(Lawson *et al.*, 2014)	Lawson E., Thorne C., Ahilan S., Allen D., Arthur S., Everett G., Fenner R., Glenis V., Guan D., Hoang L., Kilsby C., Lamond J., Mant J., Maskrey S., Mount N., Sleigh A., Smith L., Wright N.	Delivering and evaluating the multiple flood risk benefits in Blue-Green cities: An interdisciplinary approach	2014	WIT Transactions on Ecology and the Environment

(Kirshen *et al.*, 2020)	Kirshen P., Borrelli M., Byrnes J., Chen R., Lockwood L., Watson C., Starbuck K., Wiggin J., Novelly A., Uiterwyk K., Thurson K., McMann B., Foster C., Sprague H., Roberts H.J., Bosma K., Jin D., Herst R.	Integrated assessment of storm surge barrier systems under present and future climates and comparison to alternatives: a case study of Boston, USA	2020	Climatic Change
(Lafortezza *et al.*, 2018)	Lafortezza R., Sanesi G.	Nature-based solutions: Settling the issue of sustainable urbanization	2019	Environmental Research
(McClymont *et al.*, 2020)	McClymont K., Fernandes Cunha D.G., Maidment C., Ashagre B., Vasconcelos A.F., Batalini de Macedo M., Nóbrega dos Santos M.F., Gomes Júnior M.N., Mendiondo E.M., Barbassa A.P., Rajendran L., Imani M.	Towards urban resilience through Sustainable Drainage Systems: A multi-objective optimisation problem	2020	Journal of Environmental Management
(Hanson, Wickenberg and Alkan, 2020)	Hanson H.I., Wickenberg B., Alkan Olsson J.	Working on the boundaries—How do science use and interpret the nature-based solution concept?	2020	Land Use Policy
(Watkin *et al.*, 2019)	Watkin L.J., Ruangpan L., Vojinovic Z., Weesakul S., Torres A.S.	A framework for assessing benefits of implemented nature-based solutions	2019	Sustainability
(Sutton-Grier and Sandifer, 2019)	Sutton-Grier A.E., Sandifer P.A.	Conservation of Wetlands and Other Coastal Ecosystems: a Commentary on their Value to Protect Biodiversity, Reduce Disaster Impacts, and Promote Human Health and Well-Being	2019	Wetlands
(Huang *et al.*, 2020)	Huang, YJ; Tian, Z; Ke, Q; Liu, JG; Irannezhad, M; Fan, DL; Hou, MF; Sun, LX	Nature-based solutions for urban pluvial flood risk management	2020	Water
(Gunasekara *et al.*, 2018)	Gunasekara R., Pecnik G., Girvan M., De La Rosa T.	Delivering integrated water management benefits: The North West Bicester development, UK	2018	Proceedings of the Institution of Civil Engineers: Water Management

(Diaz-Nieto, Lerner and Saul, 2016)	Diaz-Nieto J., Lerner D.N., Saul A.J.	Least-cost path analysis to identify retrofit surface-water conveyance solutions	2016	Journal of Hydrologic Engineering
(Jenkins *et al.*, 2017)	Jenkins K., Surminski S., Hall J., Crick F.	Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model	2017	Science of the Total Environment
(Li, Uyttenhove and Van Eetvelde, 2020)	Li L., Uyttenhove P., Van Eetvelde V.	Planning green infrastructure to mitigate urban surface water flooding risk – A methodology to identify priority areas applied in the city of Ghent	2020	Landscape and Urban Planning
(Alves *et al.*, 2019)	Alves A., Gersonius B., Kapelan Z., Vojinovic Z., Sanchez A.	Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management	2019	Journal of Environmental Management
(Fenner *et al.*, 2019)	Fenner R., O'Donnell E., Ahilan S., Dawson D., Kapetas L., Krivtsov V., Ncube S., Vercruysse K.	Achieving urban flood resilience in an uncertain future	2019	Water
(Webber, Fu and Butler, 2018)	Webber J.L., Fu G., Butler D.	Rapid surface water intervention performance comparison for urban planning	2018	Water Science and Technology
(Moore *et al.*, 2016)	Moore T.L., Gulliver J.S., Stack L., Simpson M.H.	Stormwater management and climate change: vulnerability and capacity for adaptation in urban and suburban contexts	2016	Climatic Change
(Zellner *et al.*, 2016)	Zellner M., Massey D., Minor E., Gonzalez-Meler M.	Exploring the effects of green infrastructure placement on neighborhood-level flooding via spatially explicit simulations	2016	Computers, Environment and Urban Systems
(Cook, 2007)	Cook E.A.	Green site design: Strategies for storm water management	2007	Journal of Green Building
(L. Li *et al.*, 2020)	Li L., Collins A.M., Cheshmehzangi A., Chan F.K.S.	Identifying enablers and barriers to the implementation of the Green Infrastructure for urban flood management: A comparative analysis of the UK and China	2020	Urban Forestry and Urban Greening
(Y. Li *et al.*, 2020)	Li Y., Li H.X., Huang J., Liu C.	An approximation method for evaluating flash flooding mitigation of sponge city strategies – A case study of Central Geelong	2020	Journal of Cleaner Production
(Brink *et al.*, 2016)	Brink E., Aalders T., Ádám D., Feller R., Henselek Y., Hoffmann A., Ibe K., Matthey-Doret A., Meyer M., Negrut	Cascades of green: A review of ecosystem-based adaptation in urban areas	2016	Global Environmental Change

	N.L., Rau A.-L., Riewerts B., von Schuckmann L., Törnros S., von Wehrden H., Abson D.J., Wamsler C.			
(Ellis and Lundy, 2016)	Ellis J.B., Lundy L.	Implementing sustainable drainage systems for urban surface water management within the regulatory framework in England and Wales	2016	Journal of Environmental Management
(Everard and McInnes, 2013)	Everard M., McInnes R.	Systemic solutions for multi-benefit water and environmental management	2013	Science of the Total Environment
(Im, 2019)	Im J.	Green streets to serve urban sustainability: Benefits and typology	2019	Sustainability
(Liu *et al.*, 2016)	Liu W., Chen W., Feng Q., Peng C., Kang P.	Cost-Benefit Analysis of Green Infrastructures on Community Stormwater Reduction and Utilization: A Case of Beijing, China	2016	Environmental Management
(Locatelli *et al.*, 2020)	Locatelli L., Guerrero M., Russo B., Martí nez-Gomariz E., Sunyer D., Martí nez M.	Socio-economic assessment of green infrastructure for climate change adaptation in the context of urban drainage planning	2020	Sustainability
(Porse, 2014)	Porse E.	Risk-based zoning for urbanizing floodplains	2014	Water Science and Technology
(Yu, 2013)	Yu C.	Sustainable urban drainable systems for management of surface water	2013	Design and Management of Sustainable Built Environments
(Sharma and Kansal, 2013)	Sharma D., Kansal A.	Sustainable city: A case study of stormwater management in economically developed urban catchments	2013	Mechanism Design for Sustainability: Techniques and Cases
(Watkins and Charlesworth, 2014)	Watkins S., Charlesworth S.M.	Sustainable Drainage Systems - Features and Designs	2014	Water Resources in the Built Environment: Management Issues and Solutions
(Coupe *et al.*, 2014)	Coupe S.J., Faraj A.S., Nnadi E.O., Charlesworth S.M.	Integrated Sustainable Urban Drainage Systems	2013	Water Efficiency in Buildings: Theory and Practice

(Nasr and Shmroukh, 2020)	Nasr M., Shmroukh A.N.	Gray-to-Green Infrastructure for Stormwater Management: An Applicable Approach in Alexandria City, Egypt	2020	Advances in Science, Technology and Innovation
(Kalantari *et al.*, 2018)	Kalantari Z., Ferreira C.S.S., Keesstra S., Destouni G.	Nature-based solutions for flood-drought risk mitigation in vulnerable urbanizing parts of East-Africa	2018	Current Opinion in Environmental Science and Health
(Saleh and Weinstein, 2016)	Saleh F., Weinstein M.P.	The role of nature-based infrastructure (NBI) in coastal resiliency planning: A literature review	2016	Journal of Environmental Management
(Venkataramanan *et al.*, 2020)	Venkataramanan V., Lopez D., McCuskey D.J., Kiefus D., McDonald R.I., Miller W.M., Packman A.I., Young S.L.	Knowledge, attitudes, intentions, and behavior related to green infrastructure for flood management: A systematic literature review	2020	Science of the Total Environment
(Hobbie and Grimm, 2020)	Hobbie S.E., Grimm N.B.	Nature-based approaches to managing climate change impacts in cities	2020	Philosophical Transactions of the Royal Society B: Biological Sciences
(Faivre *et al.*, 2018)	Faivre N., Sgobbi A., Happaerts S., Raynal J., Schmidt L.	Translating the Sendai Framework into action: The EU approach to ecosystem-based disaster risk reduction	2018	International Journal of Disaster Risk Reduction
(Morris *et al.*, 2018)	Morris R.L., Konlechner T.M., Ghisalberti M., Swearer S.	From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence	2018	Global Change Biology
(Aerts, 2018)	Aerts J.C.J.H.	A review of cost estimates for flood adaptation	2018	Water

Appendix B

Damage functions

Figure 84, **Figure 85**, **Figure 86** and **Figure 87** present the graphical damage functions adapted by Huizinga, de Moel and Szewczyk (2017), where x represents the water depth (m) and the y is the damage factor. This report provides country-specific data for different economic sectors. For each country, the data contain land-use (economic sector) specific values for the average maximum damage per m^2.

The depth damage curves are usually presented as a set of points rather than an expression. These curves were converted to functions by fitting a third-degree polynomial. The maximum depth is usually an established depth for which the building might suffer disastrously failure and therefore considered totally lost. These values are usually systematically obtained from regression analysis of damage values identified in literature (Huizinga, de Moel and Szewczyk, 2017).

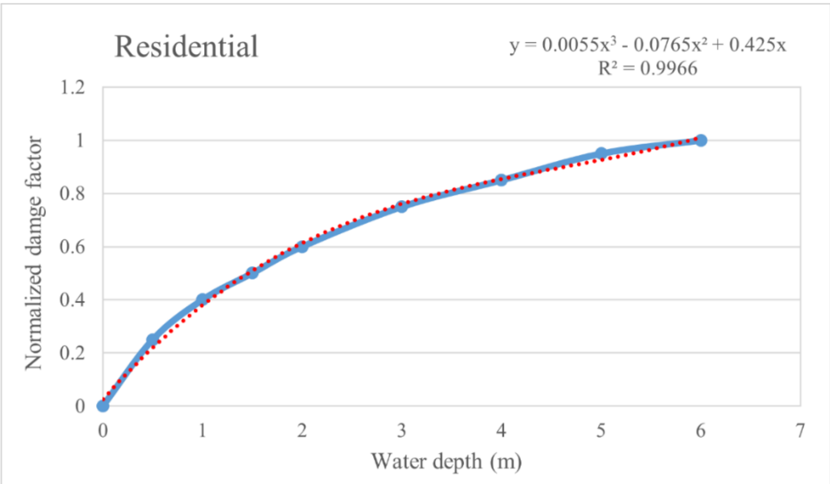

Figure 84. *Damage function for residential buildings.*

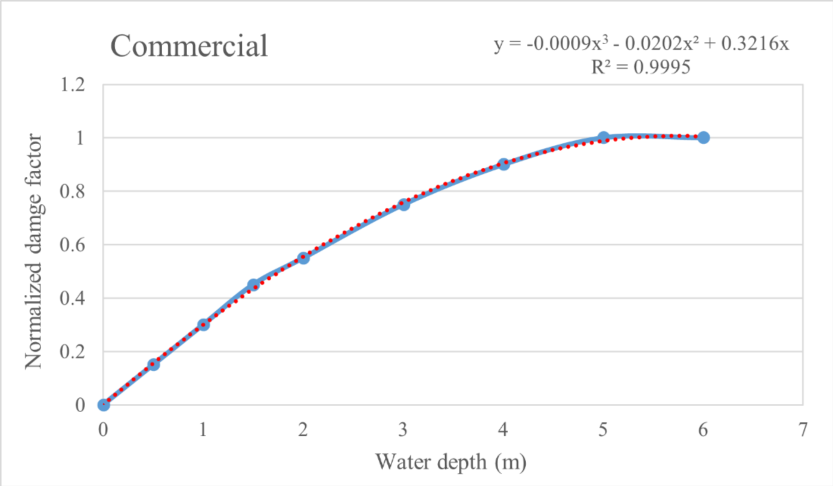

Figure 85. *Damage function for commercial buildings*

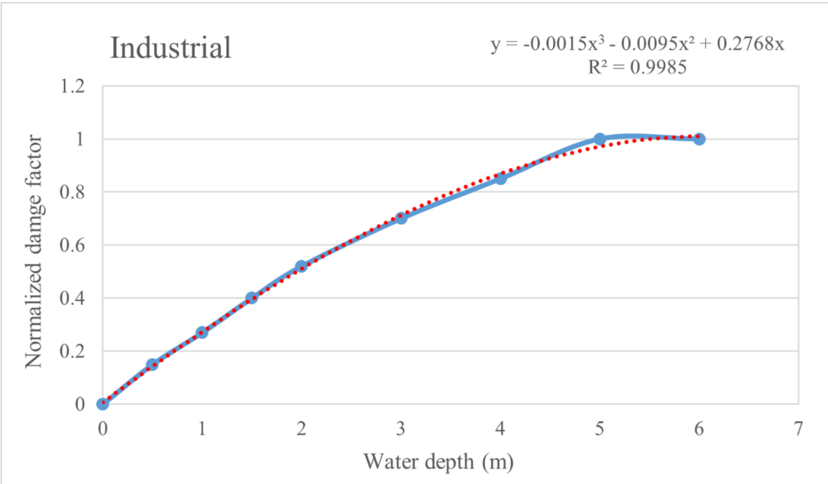

Figure 86. *Damage function for industrial buildings*

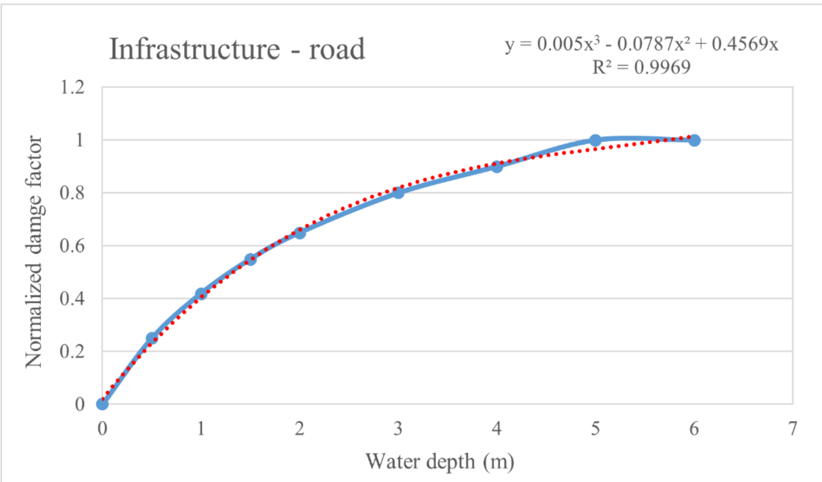

Figure 87. *Damage function for roads*

The following strings have been used in GIS to apply the DDF curves for both study cases. “VALUE” stands for the water depth, while “Type” represents the category (see Chapter 10). For the case of Portugal, “Type”=1 is residential, “Type”=2 is mixed (65.5% residential & 34.5% commercial), “Type”=3 is commercial, “Type”=4 is industrial, and “Type”=5 is road:

```
if( "Type"=1,(0.0055*("VALUE"^3)-0.0765*("VALUE"^2)+0.425*("VALUE"),
(if( "Type"=2,(((0.0055*("VALUE"^3)-0.0765*("VALUE"^2)+0.425*("VALUE")*0.655)+((-
0.0009*("VALUE"^3)-0.0202*("VALUE"^2)+0.3216*("VALUE")*0.345)),
(if( "Type"=3,(-0.0009*("VALUE"^3)-0.0202*("VALUE"^2)+0.3216*("VALUE"),
(if( "Type"=4,(-0.0015*("VALUE"^3)-0.0095*("VALUE"^2)+0.2768*("VALUE"),
(if( "Type"=5,(0.005*("VALUE"^3)-0.0787*("VALUE"^2)+0.4569*("VALUE"), 0 ))))))))
```

For the case of Italy, “Type”=1 is residential, “Type”=2 is commercial, “Type”=3 is industrial, and “Type”=4 is road:

```
if( "Type"=1,(0.0055*("VALUE"^3)-0.0765*("VALUE"^2)+0.425*("VALUE"),
(if( "Type"=2,(-0.0009*("VALUE"^3)-0.0202*("VALUE"^2)+0.3216*("VALUE"),
(if( "Type"=3,(-0.0015*("VALUE"^3)-0.0095*("VALUE"^2)+0.2768*("VALUE"),
(if( "Type"=4,(0.005*("VALUE"^3)-0.0787*("VALUE"^2)+0.4569*("VALUE"), 0 )))))))
```

To calculate the economic values of the assets (buildings and roads), the constructions values (€/m^2) have been employed differentiated for each category. Those values have been provided by the JRC report (Huizinga, de Moel and Szewczyk, 2017) and updated with the real estate values for each city considered. For Portugal, the following string shows the application in GIS:

```
if("Type"=1, 955,
(if("Type"=2, 979.02,
(if("Type"=3, 1024.60,
(if("Type"=4, 555.66,
(if("Type"=5, 14.18, 0)))))))))
```

For Italy, the following string shows the application in GIS:

```
if("Type"=1, 2068,
(if("Type"=2, 1333,
(if("Type"=3, 819,
(if("Type"=4, 21.92, 0)))))))
```

Appendix C

Damage costs for NBS0

Table 60 shows the future climate scenario for the city of Aveiro in terms of expected annual damage costs (€/year) and expected total damage costs per event (€). Compared to 10-years return period, the expected annual flood costs decrease by 77% and 88% for events with return periods of 50 and 100-years for T1 scenarios. On the opposite, compared to the 10-years return period event, the expected costs per event is 17% and 23% larger for events with return periods of 50 and 100-years, respectively, for T1.

Table 60. *Expected annual damage costs (€/year) and expected total damage costs per event (€) of building and road under 10, 50 and 100-year return periods for future climate scenarios for the city of Aveiro.*

	Expected annual damage costs (€/year)			**Expected total damage costs per event (€/event)**		
	10-years	50-years	100-years	10-years	50-years	100-years
Pingo Doce	11,406	3,452	1,868	114,064	172,579	186,834
Agras Norte	11,978	4,570	2,337	119,780	228,508	233,676
Verdemilho	36,907	8,847	4,720	369,067	442,328	471,976
Glicinias	37,378	9,697	5,322	373,784	484,839	532,212
Gulbenkian	39,423	9,058	4,702	394,230	452,910	470,182
Fonte Nova	42,093	9,740	5,152	420,930	487,025	515,203
Azurva	68,821	18,054	9,416	688,206	902,715	941,573
Alboi	112,507	25,197	13,062	1,125,068	1,259,860	1,306,153
Estação	113,308	25,126	13,092	1,133,080	1,256,311	1,309,158
Forum	164,343	38,515	20,261	1,643,427	1,925,760	2,026,115
Forca	182,780	40,617	21,106	1,827,796	2,030,848	2,110,648
Barrocas	208,822	47,560	24,806	2,088,223	2,378,009	2,480,649
Carmo	230,078	51,361	26,824	2,300,780	2,568,044	2,682,393
Olho d’Água	230,477	51,778	27,034	2,304,775	2,588,880	2,703,363
Beira-Mar	239,336	53,432	27,776	2,393,356	2,671,620	2,777,606
Vilar	295,428	86,988	44,932	2,954,279	4,349,380	4,493,193
Esgueira	327,236	74,055	38,583	3,272,360	3,702,726	3,858,258
Santiago	326,413	79,427	41,777	3,264,134	3,971,364	4,177,724
Zona industrial	346,555	79,678	42,052	3,465,546	3,983,914	4,205,153
Liceu	497,298	110,544	57,350	4,972,975	5,527,198	5,735,016
Total (city)	**3,522,586**	**827,696**	**432,171**	**35,225,860**	**41,384,816**	**43,217,083**

Table 61 shows the future climate scenario for the city of Rapallo in terms of expected annual damage costs (€/year) and expected total damage costs per event (€). Compared to 10-years return period, the expected annual flood costs decrease by 70% and 82% for events with return periods of 50 and 100-years for T1 scenarios. On the opposite, compared to the 10-years return period event, the expected

costs per event is 51% and 80% larger for events with return periods of 50 and 100-years, respectively, for T1.

Table 61. *Expected annual damage costs (€/year) and expected total damage costs per event (€) of building and road under 10, 50 and 100-year return periods for future climate scenarios for the city of Rapallo.*

	Expected annual damage costs (€/year)			**Expected total damage costs per event (€/event)**		
	10-years	50-years	100-years	10-years	50-years	100-years
San Michele	479,679	145,155	86,563	4,796,792	7,257,756	8,656,280
Costaguta	521,252	157,672	93,882	5,212,516	7,883,620	93,88,234
Cappelletta	1,142,482	344,685	204,967	11,424,824	17,234,227	20,496,700
Cerisola	1,253,592	377,925	224,676	12,535,925	18,896,266	22,467,613
Borzoli	623,403	188,499	112,168	6,234,033	9,424,952	11,216,841
Seglio	604,146	182,995	109,008	6,041,459	9,149,749	10,900,777
Total (city)	**4,624,555**	**1,396,931**	**831,264**	**46,245,549**	**69,846,570**	**83,126,445**

Appendix D

Courses - Hard & Soft skills

Hard skills

- (01SDJRS) **Earth climate and climate change** (h. 20) – score 33.33
- (01QTZRS) **Geomatics and gis for environmental application and regional planning** (h. 30) – score 50.00
- (01RGKRS) **Multicriteria analysis and strategic assessment** (h. 10) – score 16.67
- (01ULSRS) **Psychology of urban life** (h. 10) – score 13.33
- (01TBWRS) **Sustainable urban forms: a quantitative and qualitative perspective** (h. 15) – score 20.00
- (01SDERS) **Urban planning for climate change** (h. 15) – score 20.00

Soft skills

- (02LWHRS) **Communication** (h. 5) – score 6.67
- (01UNVRS) **Navigating the hiring process: CV, tests, interview** (h. 2) – score 2.67
- (01RISRS) **Public speaking** (h. 5) – score 6.67
- (01SYBRS) **Research integrity** (h. 5) – score 6.67
- (01SWQRS) **Responsible research and innovation, the impact on social challenges** (h. 5) – score 6.67
- (01UNXRS) **The new Internet Society: entering the black-box of digital innovations** (h. 6) – score 8.00
- (01UNXRS) **Thinking out of the box** (h. 1) – score 1.33
- (01SWPRS) **Time management** (h. 2) – score 2.67
- (External activity) **Winter School – Research Methodology in social science, urban studies and spatial planning** (h. 10) – score 10.00

List of publications

- (*Under major review*) Quagliolo C.; Roebeling P., Matos F., Pezzoli A. and Comino E. (2023). Pluvial flood adaptation using Nature-Based Solutions: an integrated biophysical-economic assessment. In: *Science of the Total Environment*.
- Quagliolo C.; Roebeling P., Mendonça P., Pezzoli A. and Comino E. (2022). Integrating biophysical and economic assessment: Review of Nature-Based Adaptation to urban flood extremes. In: *Urban Science* 6:55. https://doi.org/10.3390/urbansci6030053
- Assumma V., Quagliolo C., Comino E. and Mondini G. (2022). Definition of an Integrated Theoretical Framework to Assess the NBS Suitability in Flood Risk Areas. In: *Gervasi O. et al. (eds.): Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol 13380. Springer, Cham.* https://doi.org/10.1007/978-3-031-10542-5_16.
- Quagliolo C., Assumma V., Comino E., Mondini G. and Pezzoli A. (2022). An Integrated Method to Assess Flood Risk and Resilience in the MAB UNESCO Collina Po (Italy). In: *F. Calabrò et al. (eds.): New Metropolitan Perspectives. NMP 2022, LNNS 482, pp. 1–11, 2022. Springer Nature Switzerland AG 2022.* https://doi.org/10.1007/978-3-031-06825-6_243.
- Quagliolo C., Comino E. and Pezzoli A. (2021). Nature-based simulation to address Climate Change-related flooding. Preliminary insights on a small-sized Italian City. In: *Gervasi O. et al. (eds.): ICCSA 2021, LNCS 12955, pp. 1–10, 2021. Springer Nature Switzerland AG 2021.* https://doi.org/10.1007/978-3-030-87007-2_39.
- Quagliolo C., Comino E. and Pezzoli A. (2021) Experimental Flash Floods Assessment Through Urban Flood Risk Mitigation (UFRM) Model: The Case Study of Ligurian Coastal Cities. In: *Front. Water* 3:663378. https://doi.org/10.3389/frwa.2021.663378.
- Quagliolo, C., Pezzoli, A., Comino, E., Bagliani, M. (2021). The Relation Between Coastal Flood Risk and Ecosystem Services Affecting Coastal Tourism: A Review of Recent Assessments. In: *Baumeister, J., Bertone, E., Burton, P. (eds.) SeaCities. Cities Research Series. Springer, Singapore.* https://doi.org/10.1007/978-981-15-8748-1_8.
- Assumma, V., Bottero, M., Datola, G., Pezzoli, A., Quagliolo, C. (2021). Climate Change and Urban Resilience. Preliminary Insights from an Integrated Evaluation Framework. In: *Bevilacqua C., Calabrò F., Della Spina L. (eds) New Metropolitan Perspectives. NMP 2020. Smart Innovation, Systems and Technologies, vol 178. Springer, Cham*. https://doi.org/10.1007/978-3-030-48279-4_63.
- Latini, G., Bagliani, M., Orusa, T. (2020). Lessico e Nuvole: le parole del cambiamento climatico - II ed., Università di Torino. In: *Zenodo*. http://doi.org/10.5281/zenodo.4276945.

- ❖ Qi, Y., Chan, F., Thorne, C., O'Donnell, E., Quagliolo, C., Comino, E., Pezzoli, A., Li, L., Griffiths, J., Sang, Y., Feng, M. (2020). Addressing Challenges of Urban Water Management in Chinese Sponge Cities via Nature-Based Solutions. In: *Water*, 10, 2788. https://doi.org/10.3390/w12102788.
- ❖ Quagliolo, C., Pezzoli, A., Ignaccolo, R., Davila José Luis, S. (2020). Time-lagged inverse distance weighting for air temperature analysis in an equatorial urban area (Guayaquil, Ecuador). In: *Meteorological Applications*, pp. 1-16. https://doi.org/10.1002/met.1938.
- ❖ Brunetta, G., Assumma, V., Quagliolo, C., Biccheri, G. (2019). The indicators for measuring the socio-economic vulnerability for territorial resilience. In *AISU Conference 2019*, 11-13 Sep, Bologna (Italy).

Project involvement

- ❖ **UNaLab – Urban Nature Lab** - Working Group headed by the University of Aveiro (Prof. Peter Roebeling) for Work package 3.
- ❖ **INCCA – Integrated Coastal Climate Change Adaptation for Resilient Communities** (Universidade de Aveiro; Faculdade de Ciências da Universidade de Lisboa)
- ❖ **LESSICO E NUVOLE – Le parole del cambiamento climatico** (Università degli Studi di Torino; Agorà Scienza: Sezione Valorizzazione della Ricerca e Public Engagement della Direzione Ricerca e Terza Missione - Università degli Studi di Torino; UniToGO: UniTo Green Office – Università degli Studi di Torino)

Visiting period

University of Aveiro (CESAM - Centre for Environmental and Marine Studies) - Aveiro (Portugal) - Supervisor: *Dr. Peter Roebeling* (Assistant Researcher and Professor):

- ❖ 31st October – 23rd December 2020
- ❖ 1st March – 31st May 2021
- ❖ 31st October – 25th May 2022
- ❖ 1st September – 6th December 2022