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Pluvial flood adaptation using nature-based solutions: An integrated biophysical-economic assessment

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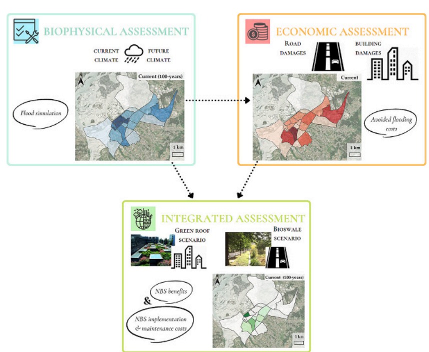
HIGHLIGHTS

- Biophysical-economic NBS impact assessment aids urban adaptation planning.
- Model simulations show green roofs perform better than bioswales.
- NBS performance is more promising under RCP 4.5 than under the current climate.
- NBS benefits can be enlarged if other co-benefits are considered.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally, flood events are considered the costliest natural hazard. Changes in precipitation patterns and large areas of impervious surfaces in urban environments are increasing the sensitivity of these systems to runoff production. At the same time, projected global sea-level rise may further increase the frequency of compound flooding due to simultaneous storm surge, sea-level rise and pluvial runoff that cause vast socio-economic and ecological impacts to coastal cities. In this context, over the last decade, the role of Nature-Based Solutions (NBS) has been recognised to support climate change adaptation by addressing ideas of multi-functionality, non-linearity and heterogeneity in urban design. Thus, increasing awareness about NBS benefits increases the willingness to accept these solutions. However, empirical evidence of NBS effectiveness at the urban catchment scale is still subject to debate. This study develops a spatial biophysical-economic framework that allows for the integrated assessment of NBS flood risk mitigation impacts, costs and benefits in the face of climate change, combining the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, benefit transfer methods and Geographic Information System (GIS) tools. Specifically, the InVEST Urban Flood Risk Mitigation model was used to assess the biophysical impacts of NBS on urban pluvial flood risk, benefit-transfer methods were used to evaluate the economic implications of such solutions, and GIS was used to integrate and map biophysical impacts and economic implications. For the case of the coastal lagoon city of Aveiro (Portugal), NBS scenarios of green

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roofs and bioswales under current and future climate conditions were assessed. The main findings of this study show that green roofs scenarios would save 32 % of the flood damages to buildings and infrastructures every year, while bioswales help save only 0.1 %. Moreover, green roofs implementation provides larger benefits in the future climate scenario (representative concentration pathway – RCP – 4.5). The findings confirm the extent to which knowledge on NBS benefits and costs is partial and uncertain, thus requiring constant progress through biophysical-economic assessment to support an evolutive decision making process in climate adaptation planning.

1. Introduction

Among all natural disasters, climate change-related flooding is considered the most damaging in urban areas (Alves et al., 2020; European Environmental Agency (EEA), 2012; Middelmann-Fernandes, 2010; Rosenzweig et al., 2019). Especially, extreme rainfall events and local storms lead to pluvial flooding in many cities when runoff production exceeds the drainage capacity of the urban system (Costa et al., 2021; Houston et al., 2011). A pluvial (or urban) flood refers to the runoff exceedance to the urban drainage system, during high-intensity and short- duration precipitation events (Miller and Hutchins, 2017). In general, and historically, urban drainage systems have had a limited hydraulic capacity, capable of coping primarily with low magnitude precipitation events, such as a 10-year return period rainfall events (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 over the last decades (Pagano et al., 2019; Zhou et al., 2013), 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 and, thus, flood adaptation measures should be flexible and multifunctional – in particular considering local spatial variability within the urban environment (Voskamp et al., 2021).

The International Union for Conservation of Nature and Natural Resources (IUCN) pioneered the concept of Nature-Based Solutions (NBS) 20 years ago. In 2015, NBS became the core of the European Commission (EC) research and innovation program. EC 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 Commission, 2015). In this view, NBS offer a new perspective by providing a range of benefits (e.g. provisioning, regulating and cultural services; social cohesion and inclusion; health and well-being; etc.) while addressing complex urban challenges and mitigating disturbances caused by climate extremes (Frantzeskaki et al., 2019; Kabisch et al., 2017; Liu et al., 2016; Ommer et al., 2022). Increasing evidence on NBS effectiveness in dealing with urban-environmental issues, such as assessing provided benefits, can better inform evidence-based decisions for climate adaptation (Alves et al., 2020; Zölch et al., 2018). Examples of NBS for urban stormwater management include green roofs, bioswales, ponds, basins, buffer and filter strips, rain gardens as well as permeable pavements that can increase the retention, evaporation, and infiltration of stormwater before it reaches sewage systems (see e.g. Kõiv-Vainik et al., 2022).

However, designing and evaluating long-term adaptation strategies is still a complex challenge (Aerts, 2018). More attention is often 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). Moreover, economic analysis of NBS (co-) benefits can have a relevant influence on decision-making allowing to visualize its financial effects (European Environment Agency (EEA), 2016). Benefits of flood adaptation strategies are expressed as the avoided "expected annual damage" (EAD) achieved by the implementation of NBS (Aerts et al., 2014; Haer et al., 2017). To date, few studies partly assess the biophysical (e.g. flood risk and damage) and economic (i.e. monetary costs and benefits) impacts of NBS for flood risk mitigation, and the employed methods are diverse. Indeed, an integrated methodological framework explaining how to assess NBS impacts, costs and benefits is still missing (Price, 2021). Moreover, a small portion of studies considers climate change data when conducting integrated scenario-based analysis with NBS adaptation scenarios (Boelee et al., 2017; Dong et al., 2017; Locatelli et al., 2020; Matos and Roebeling, 2022; Moore et al., 2016). Contemplating the complexity of urban adaptation, scenario-based assessment is a crucial tool for addressing trade-offs in climate change research – aiding policymakers to visualize and identify near- and long-term impacts in a context of future uncertainties to inform the design of adaptation measures (Magalhães Filho et al., 2022; Riahi et al., 2017). Recently, modelling software solutions have started to incorporate tools to assess these impacts in the context of green solutions (Matos and Roebeling, 2022). One such example is the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software, which is a suite of models used to map and estimate the value of services obtained from nature, containing functions to assess benefits such as pollination, water quality, temperature regulation, coastal erosion, flood mitigation, among others (Sharp et al., 2020).

There is a lack of synthesis regarding the evidence on the effectiveness of NBS for climate change adaptation, and particularly in comparison with other alternatives (Chausson et al., 2020; Costa et al., 2021). Determining the effectiveness of NBS to better integrate such solutions into urban planning should be performed by in-depth analysis aimed at demonstrating the multiple costs and (co-) benefits of NBS for present and future climate (Quagliolo et al., 2022). Further, knowledge on how costs and benefits are distributed across stakeholders should also be addressed (Hobbie and Grimm, 2020). While Ecosystem Services (ES) are often cited in planning documents as indicators to estimate the impacts of urban transformations on the environment, it is quite difficult to find common analytical biophysical assessments that generate practical implementation at parcel-based functional zoning in regulating spatial planning (Costanza et al., 1997).

The objective of this study is to develop a spatial biophysical-economic framework that allows for the integrated assessment of NBS flood risk mitigation impacts, costs and benefits in the face of climate change. To this end, a combination of InVEST model, benefits transfer methods and GIS tools were employed First, a flood risk assessment was conducted to assess the biophysical performance of NBS through the employment of the InVEST Urban Flood Risk Mitigation model. This model was chosen due to its ability to simulate urban impacts of flooding using less highly specific data input, making it versatile and easy to adopt by non-expert users, at the cost of reduced precision and complexity when compared with dedicated hydrological simulation software. Secondly, a value transfer method was used to assess NBS costs and benefits. Value transfer allows the use of (e.g. monetary) value data from other similar contexts where primary ecosystem service evaluations have been conducted (Brander, 2013). NBS scenarios of green roofs and bioswales under current and future climate conditions have been performed for the case study of the coastal lagoon city of Aveiro (Portugal). By mapping the expected impacts, costs and benefits of different NBS across different locations under current and future climate conditions, it supports urban planners in the development of climate change adaptation strategies.

2. Materials and methods

2.1. Application: the city of Aveiro (Portugal)

The city of Aveiro (Fig. 1) is a coastal lagoon urban area located on the Northwest Atlantic coast of Portugal. The municipality of Aveiro has an area of almost 200 km^2 representing one of the most populous cities in the Centre Region of Portugal (population density 414 inhabitants/km^2) (Instituto Nacional de Estatística - INE, 2023). For the present study, the neighborhood scale is used to generate practical implementation at the parcel level, in line with the functional zoning that regulates spatial urban planning (Salata et al., 2020). **Fig. A.1.** – **Annex A** 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).

Located in front of the Ria de Aveiro coastal lagoon, Aveiro is part of a fragile ecosystem that is strongly influenced by both natural and anthropogenic factors modified by climate change. The Ria de Aveiro has been widely studied in different scientific fields (biology, physics, environment, etc.). Through the application of hydrodynamic and morphodynamic models, it was found that the area is strongly influenced by tidal action, while the wind and wave stresses on the lagoon water levels are smaller in comparison (Dias, 2001; de Lima, 2018; Ribeiro et al., 2021). 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.

Pluvial flooding events in Aveiro are caused by high water levels in the Ria de Aveiro lagoon in combination with intense rainfall events in the city (Roebeling et al., 2014). Moreover, the impervious areas for the Municipality of Aveiro (approximately 21.8 % in 2018) show a positive trend over the period 2012–2018 – with urbanization uptake of about 61 % onto agricultural areas and 32 % onto natural areas (Copernicus, 2018).

In this context, the extension of urban flood area is expected to increase under climate change scenarios when more frequent and intense rainfall events as well as mean sea-level rise for the region are foreseen (Lopes et al., 2013).

Overflow from the city channels occurred several times during its history, even after the installation of a flood control system in 1985 (sluices and flood gates at the city entrance) to prevent ocean water intrusion. Indeed, since this moment, the frequency of flooding events has decreased, and similarly, the resulting waterflow volume has reduced. However, the city of Aveiro is still affected by pluvial flooding events in the lowest-lying areas of the city, of which the most adverse tend to occur when high freshwater inflows and high sea levels coincide (Baptista Borges, 2013; de Lima, 2018).

2.2. Methodological framework

The spatial biophysical-economic framework that allows for the integrated assessment of NBS flood risk mitigation impacts, costs and benefits consists of three stepwise-integrated phases, as shown in Fig. 2. First, the biophysical assessment uses the Urban Flood Risk Mitigation model part of the Integrated InVEST software developed by the Natural Capital Project,[1] as to identify the areas most susceptible to flooding in terms of flood depth. Second, by intersecting the generated inundation maps with the asset layers, buildings and roads at risk are identified. Finally, the economic assessment is developed using the value transfer method (Brander, 2013), as to estimate the costs of NBS (construction and maintenance) and the benefits of flood risk mitigation (avoided flooding costs). By employing flood-depth damage functions, the expected costs of the assets at risk and the annual cost of flooding were calculated. The NBS impact assessment was developed by integrating climate (current and future predictions) and adaptation (green roofs and bioswales) scenarios (see Sections 2.2.1 and 2.2.2, respectively), so as to obtain the different benefits (i.e. the expected annual flood risk mitigation benefits) for current/future climate and NBS scenarios.

2.2.1. Biophysical assessment: InVEST modelling

The Urban Flood Risk Mitigation (UFRM) model is a recent (2019) product of InVEST. Particularly, this spatial model focuses on the ability of cities to reduce runoff generation during to rainfall events. Even if the biophysical quantification of runoff production in the built environment is difficult to estimate, mainly due to the complexity of sewer systems and soil infiltration capacity, this model attempts to do it by using some empirical simplifications (Quagliolo et al., 2021; 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 (land use type) and soil drainage (related to the soil characteristics) layers which generate runoff during rainfall events (Sharp et al., 2020). As a hydrological model, runoff production is estimated by the USDA (United States Department of Agriculture) Soil Conservation Service – “SCS runoff curve number” (SCS-CN) method, using the potential maximum retention and curve number values on each pixel (Lucas-Borja et al., 2020; Xu et al., 2020). In addition, the model estimates soil water retention, which is considered useful to establish comparisons between scenarios where differences in runoff production are not clearly visible. The model spatial resolution is 5 m × 5 m pixels. **Table A.1 – Annex A** shows the specific data needed for the InVEST-UFRM model.

Different scenarios of one hour-design storms are considered by including short, medium, and long (10, 50 and 100 years) flood return periods (i.e. the frequency of recurrence of a certain flood event, such as 50-years). Current scenarios (2001) are given by intensity-duration-frequency (IDF) curves created for Portugal (Brandão et al., 2001). The corresponding design storms, equivalent to rainfall intensity (rainfall amount per unit of time, such as mm/h), are 25.2 mm/h (10-years), 31.9 mm/h (50-years) and 34.8 mm/h (100-years). To obtain the future (2050) design storm events, climate projections from the Swedish Meteorological and Hydrological Institute (SMHI)[2] were employed. The Service for Water Indicators in Climate Change Adaptation (SWICCA)[3] scenarios of greenhouse gases are based on Representative Concentration Pathways (RCPs) developed for the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Intergovernmental Panel on Climate Change (IPCC). The moderate emission scenario RCP 4.5 (i.e. without overshoot pathway to 4.5 W/m^2 in radioactive forcing – 650 ppm CO_2 equivalent – and stabilization after 2100; sea level rise will be on average 0.47 m between 2081 and 2100) was selected for future climate simulation. The choice to use a moderate emission scenario such as RCP 4.5 for the present study is justified by the fact that for the first half of the century (up to 2050), the differences in annual precipitation between emission scenarios RCP 4.5 and RCP 8.5 are minimal in Portugal (see Lima et al., 2023). The future precipitation values were calculated by estimating a mean of the average percentual changes in rainfall between the current and future scenarios for each return period. Each of these average change values was derived from an ensemble provided by the Hydrological Predictions for the Environment (*E*-hype) model (SMHI, 2021). The rainfall amounts increase by 8 %, 12 % and 14 % from the

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

[2] https://hypeweb.smhi.se/

[3] https://climate.copernicus.eu/water-indicators-climate-change-adaptation

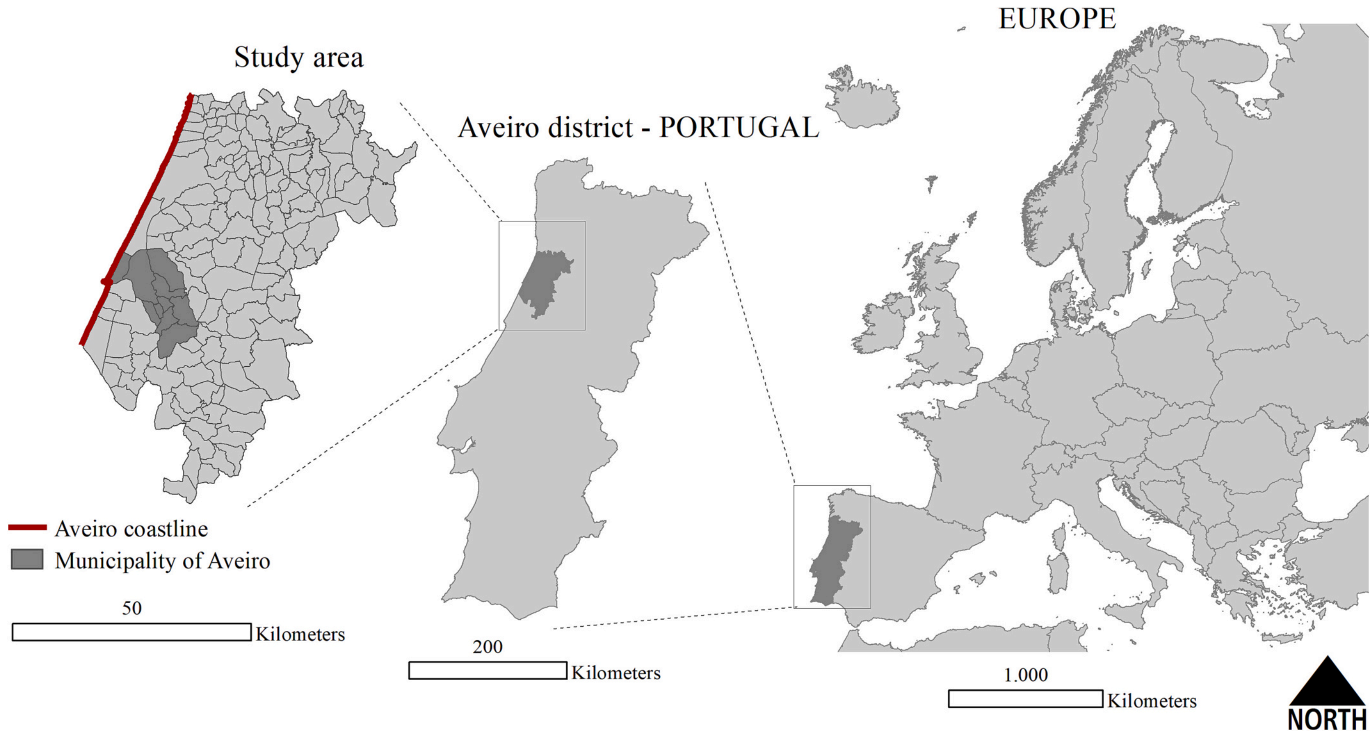

Fig. 1. Map of the study area – municipality of Aveiro (Portugal).

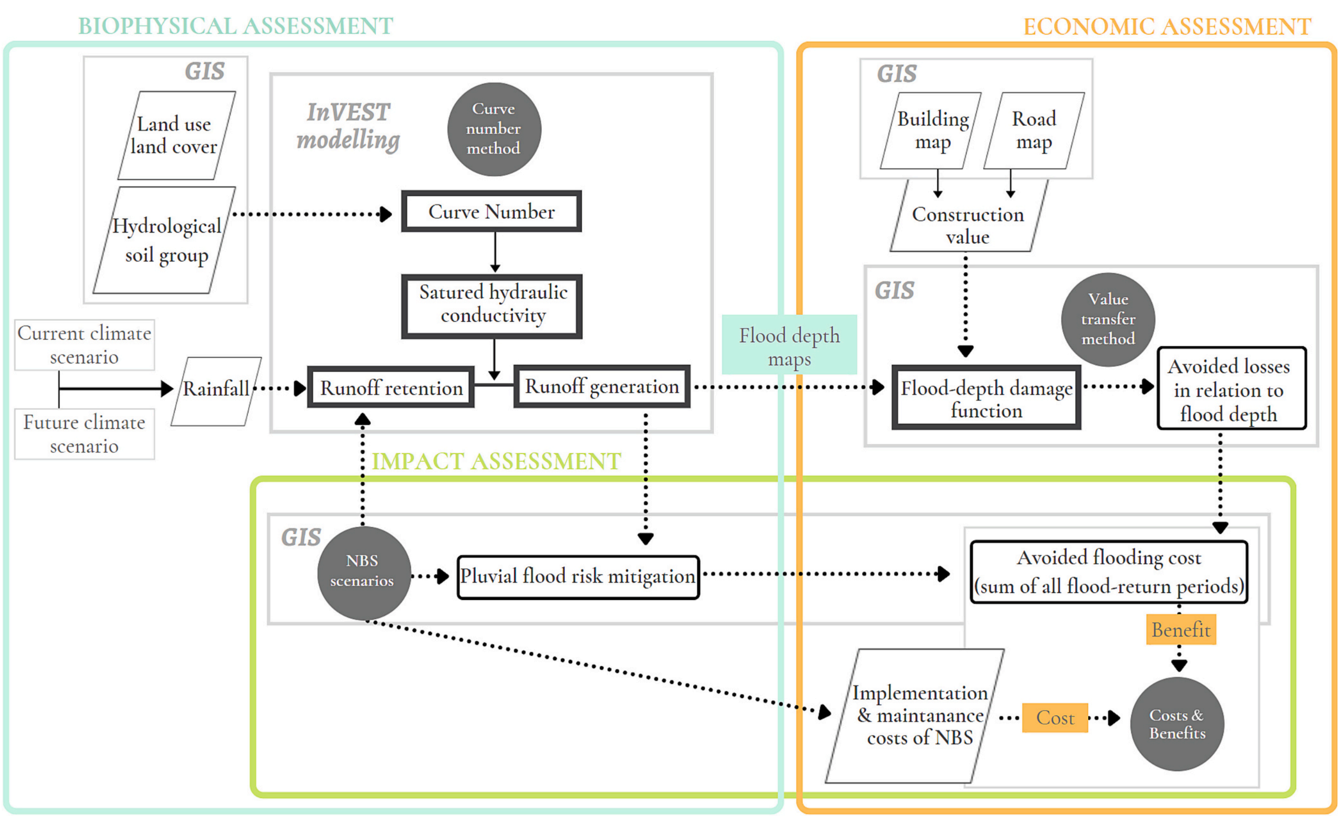

Fig. 2. Methodological framework. The results from the biophysical assessment (blue) are used to perform the economic assessment (orange), then the outcomes of both steps are used in the impact assessment (green).

current (2001) to the future (2050) climate scenario for, respectively, 10-years, 50-years and 100-years return period events. The final design storms for the future climate scenario (2050) are 27.2 (10-years), 35.7 mm/h (50-years) and 39.7 mm/h (50-years). The reference years for current (2001) and future (2050) scenarios were decided based on the data that was available at the time the study was conducted.

2.2.2. NBS scenario design

The NBS adaptation scenarios include implementation of green roofs and bioswales. Green roofs are vegetative multi-layered compositions implemented on rooftops, with specific retention capacity, substrate and vegetation. They can contribute to mitigating negative effects related to urban sealing and heat emissions, by increasing carbon sequestration, saving energy, reducing heat island effects, increasing evapotranspiration, improving air quality and biodiversity, and raising aesthetic values (Mačiulytė et al., 2018). In continuous urbanized areas, green roofs are considered among the best solutions to control stormwater runoff (Kõiv-Vainik et al., 2022). Bioswales are vegetated, linear, and low sloped trenches established along roads in urban areas, with the main objective of reducing flood risk during, or after, heavy rainfall events. They absorb, store, and convey surface water (draining from roadways) and thus delaying runoff peaks and flow velocity while removing pollutants and sediments as the water trickles through the vegetation and soil (Gavrić et al., 2019; Mačiulytė et al., 2018).

The matrix showing the integrated climate (T0 = current, 2001, climate; T1 = future, 2050, climate) and adaptation scenarios (NBS0 = without NBS; NBS1 or NBS2 = with NBS) employed in this study, was defined as follows:

- T0_NBS0 (Current climate & No NBS)
- T0_NBS1 (Current climate & Green roof)
- T0_NBS2 (Current climate & Bioswale)
- T1_NBS0 (Future climate & No NBS)
- T1_NBS1 (Future climate & Green roof)
- T1_NBS2 (Future climate & Bioswale)

The choice to simulate these two specific NBS for the present research is justified by the fact that green roofs and bioswales are among the main NBS considered to address flooding issues in urban areas of Portugal (see e.g. Arnsteg et al., 2022). Moreover, this choice has been driven by the need to model NBS at building and infrastructure scale, as the damage calculations were conducted on flood risk mitigation service to the mentioned assets. 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 report about the city of Bologna (Italy): UNaLab,[4] SOS4LIFE,[5] Urban GreenUP[6] and SUDS Guidelines – Bologna city (Comune di Bologna et al., 2018).

The green roof scenario simulates the effects of implementing green roofs on all buildings in the neighborhoods that show the highest flood-related costs from the T0_NBS0 (current climate; no NBS) scenario results. In this way, it is possible to assess the maximum benefits for those neighborhoods in terms of flood reduction that can be obtained by implementing NBS. For the purpose of this study, green roofs are implemented on the total roof area of buildings in the considered neighborhoods. The total simulated green roof area is 561,170 m^2, which corresponds to 27 % of the city's total building (roof) area in Aveiro city. Similarly, bioswales are implemented on all roads in the considered neighborhoods, covering 20 % of the road (SOS4LIFE project[7]). The total simulated bioswale area is 45,354 m^2, which corresponds to 3 % of the city's total road area.

2.2.3. Economic assessment: NBS costs and benefits

2.2.3.1. NBS costs. To estimate NBS costs, a value transfer method was employed. Implementation costs of green roofs and bioswales 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 roof reinforcement (for green roofs). The process of selecting the locations for such solutions constitutes the planning costs, while the material costs consist of the expense for input materials. The installation costs are the costs for the installation itself. Sometimes, reinforcement actions are required in order to prepare a structure to withstand the increased load of the green roof layer, thus adding reinforcement costs to the total. The maintenance costs are periodic and occur during the entire lifespan of the NBS. Some examples of maintenance costs are on-site inspections, fertilizer use, the replacement of plants, weeding, disease management, and water for irrigation (Mačiulytė et al., 2018). Maintenance costs concerning the bioswales may be reduced by employing 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. Inspections should be performed annually and after any major storm event for bare soil, erosion, sediment and debris to be removed (Mačiulytė et al., 2018; Regione Emilia-Romagna, 2020).

The NBS cost values found in literature broadly differ (i.e. Bianchini and Hewage, 2012; Locatelli et al., 2020; Zhou and Arnbjerg-Nielsen, 2018; Feng and Hewage, 2018). This research considers cost values derived from four NBS European projects: UNaLab, SOS4LIFE, Urban GreenUP and ThinkNature.[8] Given the large difference in cost values, three scenarios have been considered, consisting of the "Low" (minimum), "Medium" (average) and "High" (maximum) cost options. 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 (World Bank, 2022). Table 1 reports the different ranges of total costs and annual costs calculated by considering the expected lifetime for both implemented solutions.

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:

$$TC_t = a^*(IC_t + MC_t) \tag{1}$$

where the annual investment costs are calculated as the average investment costs over the lifetime of the NBS. Also note that the annual

Table 1
Green roof and bioswale lifetime and costs (in 2020 Euros, based on: UNaLab, SOS4LIFE, Urban GreenUP and ThinkNature).

	Lifetime (years)	Type of cost	Lifetime cost (€/m^2)	Annual cost (€/m^2/year)
Green roof	40	Investment	170–450	4–11
		Maintenaince		3–12
		Total		7–23
Bioswale	25	Investment	80–100	3–4
		Maintenaince		2–3
		Total		5–7

4 https://unalab.eu/en
5 https://www.sos4life.it/
6 https://www.urbangreenup.eu/
7 https://www.sos4life.it/
8 https://www.think-nature.eu/

maintenance costs of NBS correspond to, on average, 2.5 % of the investment costs of NBS (estimated value from the following projects: UNaLab, SOS4LIFE, Urban GreenUP and ThinkNature).

2.2.3.2. NBS benefits. To estimate NBS benefits, a value transfer method was employed. 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 et al., 2017). 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, were estimated following four phases (Merz et al., 2010; Roebeling et al., 2014):

1. Firstly, the flooded area and flood depth for each of the scenarios were assessed using the InVEST Urban Flood Risk Mitigation (UFRM) model;
2. Second, the elements exposed to risk (asset data) were categorized according to the classification based on economic sectors: residential, commercial, industrial and, infrastructure. Building and road maps were obtained from Geofabrik Open Street Map (OSM) (Geofabrik, 2020). Buildings were classified according to the Portuguese 'Instituto Nacional de Estatística' (INE) in 4 categories: residential, commercial, mixed (34.5 % commercial and 65.4 % residential), and industrial. Roads have been grouped in 4 types (big, medium, small and cycleway) by following the OSM classes (Instituto Nacional de Estatística - INE, 2021).

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 cost data for Portugal provided by Huizinga et al. (2017), which were updated using the consumer Price Index (CPI) for Portugal (year 2020) (World Bank, 2015). **Table A.2 – Annex A** summarizes the building type and road category asset values in the city of Aveiro.

3. Third, the exposure of the asset categories (as structures) to flooding were evaluated by intersecting the flood depth maps with the assets using geographic information systems (GIS). Potential damage (D_i) to assets (i) was determined using the DDF (Davis and Skaggs, 1992) based on data from Huizinga et al. (2017) and fitting the quadratic function:

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

with D_i the rate of damage to asset i (in % of the respective value v_i), where H_i is the height of flood (in m) and i is the asset class, and where α and β are parameter estimates.

The expected annual damage per return period ($EAD_{t,r}$) was obtained by multiplying the expected total damage costs per event (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:

$$EAD_{t,r} = \sum_i (D_i * F_{r,i} * v_i) * \frac{1}{r} \tag{3}$$

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 the asset i, and $\frac{1}{r}$ is the probability of occurrence of a flooding event with return period r.

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

$$EAD_t = \sum_r EAD_{t,r} \tag{4}$$

Hence, the expected annual damage was calculated for the situation without (NBS0) and with (NBS1; NBS2) nature-based solutions.

The total annual benefits (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:

$$TB_t = [EAD_t]_{NBS0} - [EAD_t]_{NBS\#} \tag{5}$$

3. Results

3.1. NBS0 scenario: current and future climate

This section presents the results for the scenarios without the implementation of NBS (NBS0). 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 Fig. 3). 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 Beira Mar, Liceu, Forum, Gulbenkian, Carmo, Santiago and Zona industrial are the areas most susceptible to flooding in the city of Aveiro.

Although the expected total damage costs for events of less intense precipitations (i.e. return periods of 10 years) are substantially lower, their high frequent nature means that their cumulative damage exceeds the expected annual damage costs of a more intense rainfall event (i.e. return period of 100 years; see Table 2). Compared to a 10-years return period event, 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.

Results for the expected annual flood damages to buildings and roads per neighborhood (€/year) for the current (T0) and future (T1) scenarios show their distribution across all neighborhoods in the city of Aveiro (see Table 3). However, some neighborhoods (Liceu, Santiago and Zona industrial) show 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 extension (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 flood depths and asset values across neighborhoods. The total expected annual flood damage for the city of Aveiro is approximately € 4 million per year in the T0_NBS0 scenario. Annual flood damages are 4 % higher in the future climate scenario (2050) than in the current situation (2001). 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,

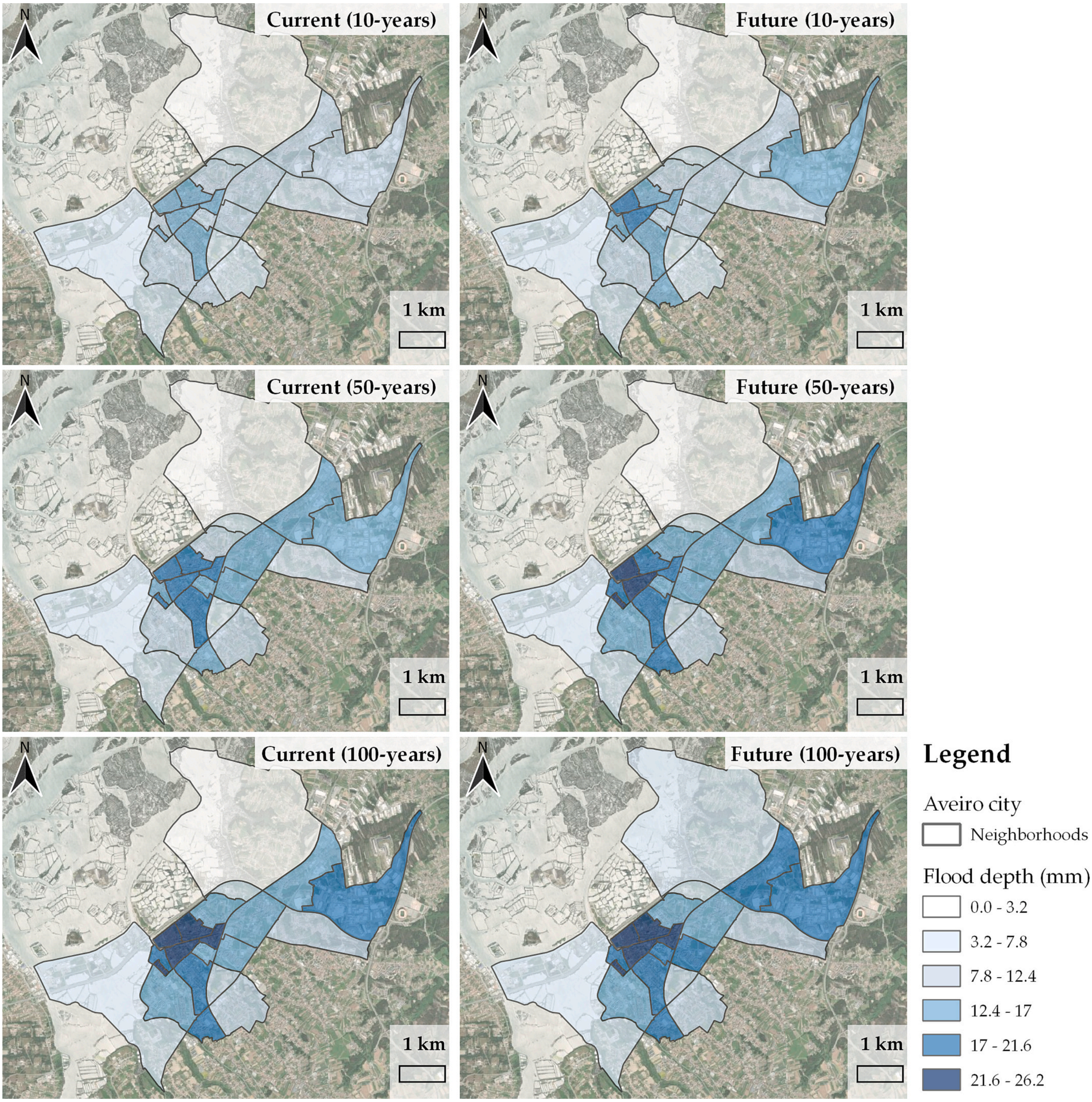

Fig. 3. Flood depth (in mm) under 10, 50 and 100-year return periods as mean value per neighborhoods for current (left) and future (right) scenarios.

Table 2
Expected total damage costs per event (€) and expected annual damage costs (€/year) of building and road for current and future climate scenarios at city scale.

	Expected total damage costs per event (€/event)			Expected annual damage costs (€/year)		
	10-years	50-years	100-years	10-years	50-years	100-years
Current scenario	34,081,564	38,033,186	41,559,891	3,408,156	760,663	415,598
Future scenario	35,225,860	41,384,816	43,217,083	3,522,586	827,696	432,171

Table 3
Expected flood damage (€/year) to buildings and roads per neighborhoods under current and future climate scenarios (with percentual variation in parenthesis).

Neighborhood	Current	Future	
Pingo Doce	15,415	16,726	(+9 %)
Agras Norte	16,686	18,885	(+13 %)
Verdemilho	47,832	50,473	(+6 %)
Glicinias	48,156	52,397	(+9 %)
Gulbenkian	51,277	53,183	(+4 %)
Fonte Nova	54,464	56,986	(+5 %)
Azurva	90,352	96,291	(+7 %)
Alboi	146,107	150,766	(+3 %)
Estação	146,830	151,526	(+3 %)
Forum	213,200	223,119	(+5 %)
Forca	237,087	244,503	(+3 %)
Barrocas	271,508	281,189	(+4 %)
Carmo	298,078	308,263	(+3 %)
Olho d'Água	298,811	309,289	(+4 %)
Beira-Mar	310,452	320,544	(+3 %)
Vilar	394,682	427,347	(+8 %)
Esgueira	424,764	439,873	(+4 %)
Santiago	424,777	447,618	(+5 %)
Zona industrial	448,575	468,284	(+4 %)
Liceu	645,367	665,192	(+3 %)
Total (city)	4,584,419	4,782,453	(+4 %)

observed damages are higher in neighborhoods containing the largest areas of commercial buildings (which have a higher infrastructure value).

3.2. NBS1 and NBS2: current and future scenarios

3.2.1. Biophysical results

Results for flood depth reduction due to green roof (NBS1) installation show that neighborhoods in which green roofs are implemented have the largest variations in retained water volume (see Table 4). The results demonstrate, also, a slight improvement between the current and future climate. Soil water retention increases 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 the neighborhood scale, increases in retained water volume are usually observed in neighborhoods with larger areas of NBS implementation. However, largest increases in water retention are observed in the Beira-Mar neighborhood (92,986 m^2), even if the largest green roof area has been implemented in Santiago (209,630 m^2). Reasonably, Beira-Mar presents the largest increase in retained water volume (up to over 120 %; i.e. retention capacity more than doubles) because it is the neighborhood with the largest relative area of green roof implementation, with green roofs covering 45 % of the total neighborhood area. Liceu follows with 32 % of NBS surface coverage, while Santiago and Forca present lower values (19 % and 15 %, respectively).

Results for flood depth reduction due to bioswale (NBS2) installation show, as expected, that neighborhoods in which bioswales are implemented receives the largest variations (see Table 4). The results also demonstrate a slight improvement between the current and future climate. Soil water retention increases by 4 % for 10-years return period, 3 % for 50-years and 100-years events under both current and future climate. Again, increases in retained water volume are observed in neighborhoods with larger areas of NBS implementation. However, the largest increases in water retention (up to 15 %) are observed 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 increase in retained water volume is because it is the neighborhood with the largest relative area of bioswale implementation, with bioswales covering 64 % of the total road area within the neighborhood.

3.2.2. Economic findings

Results for green roofs (NBS1) show that the Liceu neighborhood obtains the highest (up to almost 620 k€/year) and the Forca neighborhood the lowest (up to about 225 k€/year) flood mitigation benefits (see Table 5). Total green roof benefits in Aveiro amount to ~1.5 m€/year, and increase on average by 4 % from the current situation (T0) to the future climate (T1) scenarios. For the bioswale scenario (NBS2), the Santiago neighborhood presents the highest (up to about 1.4 k€/year) and the Liceu neighborhood the lowest (up to about 0.9 k€/year) flood mitigation benefits (see Table 5). Total bioswale benefits in Aveiro amount to ~3.2 k€/year, and increase by 10 % from the current situation (T0) to the future climate (T1) scenarios. Hence, flood mitigation benefits from bioswales are a fraction (less than 0.5 %) of those from green roofs.

NBS annual costs are given for three scenarios (Low, Medium and High; see Table 5). Results for green roofs (NBS1) show that largest annual costs are observed in the Santiago neighborhood (as of 1.6 m€/year) and lowest for the Forca neighborhood (as of ~0.6 m€/year). Total green roof costs in Aveiro amount to, at least, ~4.5 m€/year. Results for bioswales (NBS2) show that largest annual costs are, also, observed in the Santiago neighborhood (as of 94 k€/year) and lowest for the Liceu neighborhood (as of 63 k€/year). Total bioswale costs in Aveiro amount to, at least, ~225 k€/year. Hence, bioswale costs are a fraction (about 5 %) of those for green roofs. Neighborhoods with higher NBS costs correspond, self-evidently, to larger green roof and bioswale implementation areas.

The largest costs and benefits of NBS do not always coincide across neighborhoods, due to differences in NBS implementation area (and thus NBS annual costs; largest in the Santiago neighborhood) and asset values (and thus flood mitigation benefits from NBS; largest in the Liceu neighborhood). Even though the present research shows that costs outweigh benefits for both NBS scenarios, it is important to claim that, in the case of green roofs, the benefits contribute to between 11 % to 32 % of the NBS annual costs every year under current climate conditions (range of 12 % to 34 % under future climate conditions). In the case of

Table 4
Percentual differences (NBS1-NBS0 and NBS2-NBS0) in retained water volume (%) of green roofs and bioswales, respectively, for 10, 50 and 100-years return periods per neighborhood under current and future climate scenarios.

	Current climate			Future climate		
	10-years	50-years	100-years	10-years	50-years	100-years
NBS1 scenario (green roof)						
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 %
NBS2 scenario (bioswale)						
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 %

Table 5
Annual benefits and costs (in €/year), for neighborhood, of green roofs and bioswales, respectively, under current and future climate scenarios and considering Low, Medium and High cost scenarios.

	Annual benefits (avoided costs (€/year))			**Annual costs** (€/year)		
	Current	Future	Variation (current & future)	Low	Medium	High
NBS1 scenario (green roof)						
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**
NBS2 scenario (bioswale)						
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**

bioswales, the benefits contribute to between 0.9 % to 1.3 % of the NBS annual costs every year under current climate conditions (range of 1 % to 1.4 % under future climate conditions).

4. Discussion

4.1. Comparing results with previous studies

From a biophysical perspective, the simulations show that the pluvial flooding risk is distributed across all the neighborhoods in the city of Aveiro. Additionally, the pluvial flooding risk increases in the face of climate change (RCP 4.5; 2050). Both green roofs and bioswales have positive effects in terms of flood reduction given their capacity to store rainwater. However, green roofs are more effective than bioswales in reducing pluvial flooding risk. In general, NBS water retention is larger under high return period events as well as under future climate scenarios, which are characterized by more intense rainfall. From an economic perspective, albeit higher return period events imply larger total damage costs than lower return period events, lower return period events imply higher annual damage costs than higher return period events. Results show large annual building and road damage costs, which increase in the face of climate change. Green roofs provide larger benefits than bioswales; both NBS provide the largest benefits under the less intense – yet more costly – lower return period flooding events. Comparing benefits and costs, results show that NBS costs outweigh their benefits – suggesting that NBS are unlikely to be cost-beneficial when only taking into account flood mitigation benefits.

Previous studies focused on assessing urban flood mitigation through NBS implementation (Boelee et al., 2017; Costa et al., 2021; Fenner et al., 2019; Jackisch and Weiler, 2017; Lee et al., 2013; Mei et al., 2018; Nguyen et al., 2021; Ramírez et al., 2016; La Rosa and Pappalardo, 2020; Rozos et al., 2013; Salata et al., 2021; Yao et al., 2020). For example, in line with Costa et al. (2021), who assessed the effectiveness of reducing flood depth by implementing various NBS scenarios (such as green roofs, green parking and water storage on 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 by NBS improves with higher return periods when water depth is considered a proxy of flooding. La Rosa and Pappalardo (2020) and Yao et al. (2020) state that NBS for flood reduction are highly context-specific, and their spatial behavior depends on different aspects (such as land use, hydrological system, demographic paths, NBS typology, etc).

Comparing avoided flooding cost literature results is still difficult because studies focusing on flood mitigation often employ distinct methods, and they do not assess the same types of NBS. Some previous studies worked on avoided flooding costs in terms of damage calculation in urban areas (Alves et al., 2020; Bennink, 2022; Bertilsson et al., 2019; Webber et al., 2018). A different method was used by Jenkins et al. (2017), who focused on the interaction between flood insurance and surface water flood risk management in the United Kingdom. However, some researches showed important findings on flood mitigation benefits from 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 50 % of the total flood damage value; they also found that green roofs lead to an annual saving of approximately 32 %. This is in line with the results of this study, which show a reduction in annual flood damages of 32 % and 31 %, with green roof implementation under the current and future climate scenarios, respectively.

One study that worked on future climate scenarios (Velasco et al., 2018), argued that green roofs provided higher net-benefits in the pessimistic climate scenario in relation to the optimistic climate scenario. Results of the present research showed the same result, indicating that NBS provided larger flood mitigation benefits in the future scenarios. This is due to the NBS ability to store additional water during the more intense rainfall events that characterize high return-periods and scenarios including future climate conditions. As more flood damages are mitigated in these scenarios, the benefits of NBS are larger. Indeed, what emerged from this research is the result of the moderate future climate scenario (RCP4.5) and, thus, benefits could increase if other, more extreme future scenarios were to be considered (such as RCP8.5).

4.2. Limitations, recommendations and future perspectives

Firstly, the biophysical assessment presents some limitations, for instance regarding the data used in the InVEST model. The hydrological soil group raster is a worldwide database with 250 m resolution, and is often too wide to capture the variation in soils within the urban system. Moreover, the ability of InVEST to simulate pluvial floods is imperfect, as it does not consider essential inputs for flood estimates, such as the elevation of the terrain. The flood estimate by the InVEST model is expressed in terms of flood depth only, without considering water flow and drainage (grid-based model) and flood velocity – leading to an underestimation of potential flood damage costs. Furthermore, this InVEST model 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. The choice to use UFRM-InVEST modelling for the biophysical assessment was mainly associated with the free and open-source nature of the software.

Another limitation of this study lies in the usage of only one future climate scenario (RCP 4.5), which does not allow for 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 more extreme scenarios (RCP 8.5) in 2100. However, some authors argue that RCP 8.5 is a very unlikely scenario while others point out that there is a 35 % probability of exceeding the RCP 8.5 scenario (Christensen et al., 2018; Peters and Hausfather, 2020). Given the more intense rainfall events under e.g. RCP 8.5, it can be expected that NBS water retention, flood mitigation impacts and benefits are larger under more extreme climate scenarios.

Limits and uncertainties are also nested in the economic assessment. The NBS benefits considered in this analysis are limited to avoided monetary losses resulting from flood risk mitigation – i.e. the direct flood damage to the structure of the property while excluding the contents value. By forgoing the contents value, 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., 2014). Among the limitations observed in this study, the NBS cost calculation should be underlined. This study employs NBS costs as aggregated values from the existing literature on this recent topic. There is often a lack of data on some specific NBS; hence, the values are not context-specific and, thus, are ballpark estimates for investment and maintenance costs.

Despite these limitations, this research explores how this approach can be adopted in the adaptation process to support cities in the assessment and adoption of NBS to reduce pluvial flooding. Two key points can be highlighted as policy recommendations to address adoption of NBS in different urban contexts. Firstly, NBS implementation is a very context-specific process – namely in the definition of the objectives, risk assessment, climate regions and roadmaps (Mačiulytė et al., 2018; Raymond et al., 2017). Hence, replicability and upscaling of NBS is strong when the implementation approach is tailored to local conditions. The framework developed in the present study can, thus, be used as a primary means of assessing potential NBS impacts, costs and benefits, in an inexpensive, spatially-explicit manner. Nevertheless, a secondary, deeper, exploration of the subject using more complex models is recommended when planning large-scale NBS adoption actions. Second, a barrier exists that is 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, the environmental features in cities are often treated as 'costs' rather than as an investment in assets. This can hinder NBS adoption, as these solutions are costly, and may require time to mature and deliver a wider selection of benefits across different stakeholders. Additionally, NBS are often undervalued because their multiple benefits are not considered. Barriers in evaluating these benefits are often a consequence of natural resources and services not having direct market values, thus, their full contribution to society is rarely identified. By assessing the economic value of flood mitigation services provided by NBS, which have no direct market value, this study helps overcome such barriers.

The perception of NBS benefits can be improved if other co-benefits of these solutions are considered. Economic valuation methods are still insufficient to represent all NBS co-benefits in cities, considering that many benefits are challenging to assess in economic terms (Elmqvist et al., 2015). We argue that evaluating a single ecosystem service from these solutions does not accurately reflect the value of the full range of benefits they can provide, resulting in an underestimation of values and benefits. As the present study only assesses flood mitigation benefits without considering other co-benefits, the focus is placed on comparing NBS impacts, benefits and costs and, thus, putting more emphasis on NBS benefits, rather than performing a partial Cost-Benefit Analysis (CBA). Further work is needed on economic valuation methods for NBS co-benefits, such as aesthetics enhancement, biodiversity improvement and recreation, among others. As such, one recommendation for future studies regarding the improvement of this framework would be to include more ES in the assessment process. This should be done in a way that does not impact the framework's overall simplicity and ease of adoption for practitioners with limited access to specific data and/or software. Additionally, the validity of this NBS assessment methodology can be reinforced by applying this framework to more settings characterized by different climatic, land use, and socioeconomic conditions.

5. Conclusions

This work presents a method to integrate biophysical and economic impacts of NBS for pluvial flood risk adaptation in the face of climate change – including a comparative analysis of flood risk mitigation impacts, costs and benefits of green roofs and bioswales for the case of Aveiro (Portugal). 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 (2001) and future (RCP 4.5) climate scenarios. This approach has been applied to the Aveiro case study without the intent to provide precise cost and benefit data. The aim is to prove the potential of a locally adapted approach to assess NBS impacts for urban flood risk mitigation.

Results for Aveiro show that NBS water retention is larger under high return period events as well as under future climate scenarios, while green roofs are more effective than bioswales in reducing pluvial flooding risk. Lower return period events imply higher annual damage costs than higher return period events and, thus, green roofs provide larger flood mitigation benefits than bioswales that, notably, are larger under future climate conditions. NBS are unlikely to be cost-beneficial when only taking into account flood mitigation benefits, as NBS costs outweigh their flood mitigation benefits.

This study goes beyond previous studies by quantitively assessing NBS flood mitigation impacts, costs and benefits through a combination of adaptation and climate change scenarios (rather than only adaptation scenarios) and, by spatially representing the obtained estimates at the neighborhood scale (rather than city scale). This methodological framework may be used as a guide on how to replicate a spatial biophysical-economic assessment of NBS implementation to reduce urban pluvial flood impacts and costs. Despite the uncertainty in the scenarios, the results of this study can be employed for the development of urban NBS development strategies, as it provides insight in the areas that are most prone to and bear the largest cost of flooding as well as which NBS can best be employed to mitigate flooding impacts and costs. Further research will be dedicated to compare different contexts, paying attention to the local differences associated with the design of flood return periods.

CRediT authorship contribution statement

Conceptualization, C.Q. and P.R.; methodology, C.Q. and P.R.; formal analysis, C.Q., P.R., E.C. and F.M.; data curation, C.Q., P.R., E.C. and F.M.; writing—original draft preparation, C.Q.; writing—review and editing, P.R., E.C., A.P. and F.M.; visualization, C.Q.; supervision, P. R., E.C. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Aerts, J.C.J.H., 2018. A review of cost estimates for flood adaptation. Water (Switzerland) 10. https://doi.org/10.3390/w10111646.
Aerts, J.C.J.H., Botzen, W.J.W., Emanuel, K., Lin, N., De Moel, H., Michel-Kerjan, E.O., 2014. Evaluating flood resilience strategies for coastal megacities. Science (80-.) 344, 473–475. https://doi.org/10.1126/science.1248222.
Alves, A., Vojinovic, Z., Kapelan, Z., Sanchez, A., Gersonius, B., 2020. Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation. Sci. Total Environ. 703, 134980 https://doi.org/10.1016/j.scitotenv.2019.134980.
Arnsteg, A., Glinski, J., Marijauskaite, P., Nitschke, A., Olsson, M., Pierre, A., Rosenquist Ohlsson, L., van der Vleuten, S., Pilesjö, P., 2022. Flood modelling and proposed blue-green solutions – a case study in Lisbon, Portugal. Agil. GIScience Ser. 3, 1–9. https://doi.org/10.5194/agile-giss-3-53-2022.
Baptista Borges, C.S., 2013. Benefícios da infraestrutura verde/azul para o controlo de cheias. Universidade de Aveiro.
Bennink, C., 2022. Flood-mitigation Impacts, Costs and Benefits From Green Roofs in Urban Areas: A Cross-city Comparison. Wageningen University and Research.
Bertilsson, L., Wiklund, K., de Moura Tebaldi, I., Rezende, O.M., Veról, A.P., Miguez, M. G., 2019. Urban flood resilience – a multi-criteria index to integrate flood resilience into urban planning. J. Hydrol. 573, 970–982. https://doi.org/10.1016/j.jhydrol.2018.06.052.
Bianchini, F., Hewage, K.N., 2012. Probabilistic social cost-benefit analysis for green roofs: a lifecycle approach. Build. Environ. 58, 152–162.
Boardman, A.E., Greenberg, D.H., Vining, A.R., Weimer, D.L., 2018. Cost-benefit Analysis. Concepts and Practice, Fifth. ed. Cambridge University Press, New York, USA. https://doi.org/10.4324/9781315387420-4.
Boelee, E., Janse, J., Le Gal, A., Kok, M., Alkemade, R., Ligtvoet, W., 2017. Overcoming water challenges through nature-based solutions. Water Policy 19, 820–836.
Brandão, C., Rodrigues, R., da Costa, J.P., 2001. Análise de fenómenos extremos. Precipitações intensas em Portugal Continental, Lisboa.
Brander, L.M., 2013. Guidance Manual on Value Transfer Methods for Ecosystem Services. UNEP, Nairobi, Kenya. https://doi.org/10.1016/j.jss.2008.05.016.
Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C.A.J., Kapos, I., Roe, D., Smith, A., Woreniecki, S., Seddon, N., 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob. Chang. Biol. 26, 6134–6155.
Christensen, P., Gillingham, K., Nordhaus, W., 2018. Uncertainty in forecasts of long-run economic growth. Proc. Natl. Acad. Sci. U. S. A. 115, 5409–5414. https://doi.org/10.1073/pnas.1713628115.
Comune di Bologna, European Investment Bank, Atkins, Iridra, 2018. Linee guida sull'adozione di tecniche di drenaggio urbano sostenibile per una città più resiliente ai cambiamenti climatici.
Copernicus, 2018. Urban Atlas change 2012-2018 [WWW document]. URL. https://land.copernicus.eu/local/urban-atlas.
Costa, S., Peters, R., Martins, R., Postmes, L., Keizer, J.J., Roebeling, P., 2021. Effectiveness of nature-based solutions on pluvial flood hazard mitigation: the case study of the city of Eindhoven (the Netherlands). Resources 10. https://doi.org/10.3390/resources10030024.
Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.
Davis, S.A., Skaggs, L.L., 1992. Catalog of Residential Depth-Damage Functions Used by the Army Corps of Engineers in Flood Damage Estimation.
de Lima, P.M.T., 2018. Avaliação da Vulnerabilidade e do Risco de Cheia Urbana na Cidade de Aveiro. Universidade de Aveiro.
Dias, J.M., 2001. Contribution to the Study of the ria de Aveiro Hydrodynamics. Universidade the Aveiro.
Dong, X., Guo, H., Zeng, S., 2017. Enhancing future resilience in urban drainage system: green versus grey infrastructure. Water Res. https://doi.org/10.1016/j.watres.2017.07.038.
Elmqvist, T., Setälä, H., Handel, S.N., van der Ploeg, S., Aronson, J., Blignaut, J.N., Gómez-Baggethun, E., Nowak, D.J., Kronenberg, J., de Groot, R., 2015. Benefits of restoring ecosystem services in urban areas. Curr. Opin. Environ. Sustain. 14, 101–108. https://doi.org/10.1016/j.cosust.2015.05.001.
European Commission, 2015. Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities. Publications Office of the European Union, Luxembourg. https://doi.org/10.2777/765301.
European Environment Agency (EEA), 2016. Urban Adaptation to Climate Change in Europe 2016. Transforming Cities in a Changing Climate.
European Environmental Agency (EEA), 2012. Urban Adaptation to Climate Change in Europe - Challenges and Opportunities for Cities Together with Supportive National and European Policies, EEA Report. Luxembourg. https://doi.org/10.2800/41895.
Feng, H., Hewage, K.N., 2018. Economic benefits and costs of green roofs. In: Pérez, G., Perini, K.B.T.-N.B.S., for U. and B.S. (Eds.), Nature Based Strategies for Urban and Building Sustainability. Butterworth-Heinemann, pp. 307–318. https://doi.org/10.1016/B978-0-12-812150-4.00028-8.
Fenner, R., O'Donnell, E., Ahilan, S., Dawson, D., Kapetas, L., Krivtsov, V., Ncube, S., Vercruysse, K., 2019. Achieving urban flood resilience in an uncertain future. Water 11.
Frantzeskaki, N., McPhearson, T., Collier, M.J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., Van Wyk, E., Ordóñez, C., Oke, C., Pintér, L., 2019. Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making. Bioscience 69, 455–466. https://doi.org/10.1093/biosci/biz042.
Gavrić, S., Leonhardt, G., Marsalek, J., Viklander, M., 2019. Processes improving urban stormwater quality in grass swales and filter strips: a review of research findings. Sci. Total Environ. 669, 431–447. https://doi.org/10.1016/j.scitotenv.2019.03.072.
Geofabrik, 2020. OpneStreetMap data extracts [WWW document]. URL. http://download.geofabrik.de/ (accessed 12.16.20).
Haer, T., Botzen, W.J.W., Zavala-Hidalgo, J., Cusell, C., Ward, P.J., 2017. Economic evaluation of climate risk adaptation strategies: cost-benefit analysis of flood protection in Tabasco, Mexico. Atmósfera 30, 101–120. https://doi.org/10.20937/ATM.2017.30.02.03.
Hobbie, S.E., Grimm, N.B., 2020. Nature-based approaches to managing climate change impacts in cities. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 375.
Houston, D., Werrity, A., Bassett, D., Geddes, A., Hoolachan, A., McMillan, M., 2011. Pluvial (Rain-Related) Flooding in Urban Areas: The Invisible Hazard. Joseph Rowntree Foundation, York.
Huizinga, J., de Moel, H., Szewczyk, W., 2017. Global Flood Depth-damage Functions. Methodology and the Database With Guidelines. Joint Research Centre (JRC). https://doi.org/10.2760/16510.
Instituto Nacional de Estatística - INE, 2021. Statistics Portugal [WWW document]. URL. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_main (accessed 5.5.21).
Instituto Nacional de Estatística - INE, 2023. Statistics Portugal [WWW document]. URL. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&userLoadSave=Load&userTableOrder=9956&tipoSeleccao=1&context (accessed 5.11.23).
Instituto Nacional de Estatística (INE), 2020. Indicadores [WWW document]. URL. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0009595&contexto=bd&selTab=tab2 (accessed 11.3.21).
Jackisch, N., Weiler, M., 2017. The hydrologic outcome of a low impact development (LID) site including superposition with streamflow peaks. Urban Water J. 14, 143–159. https://doi.org/10.1080/1573062X.2015.1080735.
Jenkins, K., Surminski, S., Hall, J., Crick, F., 2017. Assessing surface water flood risk and management strategies under future climate change: insights from an agent-based model. Sci. Total Environ. 595, 159–168.
Kabisch, N., Korn, H., Stadler, J., Bonn, A., 2017. Nature-Based Solutions to Climate Change Adaptation in Urban Areas - Linkage Between Science, Policy and Practice. Springer Nature, Cham, Switzerland. https://doi.org/10.1007/978-3-319-56091-5_8.
Kõiv-Vainik, M., Kill, K., Espenberg, M., Uuemaa, E., Teemusk, A., Maddison, M., Palta, M.M., Török, L., Mander, Ü., Scholz, M., Kasak, K., 2022. Urban stormwater retention capacity of nature-based solutions at different climatic conditions. Nat.-Based Solut. 2, 100038 https://doi.org/10.1016/j.nbsj.2022.100038.
La Rosa, D., Pappalardo, V., 2020. Planning for spatial equity - a performance based approach for sustainable urban drainage systems. Sustain. Cities Soc. 53, 101885.
Lee, J., Hyun, K., Choi, J., 2013. Analysis of the impact of low impact development on runoff from a new district in Korea. Water Sci. Technol. 68, 1315–1321. https://doi.org/10.2166/wst.2013.346.
Lima, D.C.A., Bento, V.A., Lemos, G., Nogueira, M., Soares, P.M.M., 2023. A multi-variable constrained ensemble of regional climate projections under multi-scenarios for Portugal – part I: an overview of impacts on means and extremes. Clim. Serv. 30 https://doi.org/10.1016/j.cliser.2023.100377.
Liu, W., Chen, W., Feng, Q., Peng, C., Kang, P., 2016. Cost-benefit analysis of green infrastructures on community stormwater reduction and utilization: a case of Beijing, China. Environ. Manag. 58, 1015–1026.
Locatelli, L., Guerrero, M., Russo, B., Martinez-Gomariz, E., Sunyer, D., Martinez, M., 2020. Socio-economic assessment of green infrastructure for climate change adaptation in the context of urban drainage planning. Sustainability 3792, 1–18.
Lopes, C.L., Plecha, S., Silva, P.A., Dias, J.M., 2013. Influence of morphological changes in a lagoon flooding extension: case study of Ria de Aveiro (Portugal). J. Coast. Res. 1158–1163.
Lucas-Borja, M.E., Bombino, G., Carrà, B.G., D'agostino, D., Denisi, P., Labate, A., Plaza-Alvarez, P.A., Zema, D.A., 2020. Modeling the soil response to rainstorms after wildfire and prescribed fire in mediterranean forests. Climate 8, 1–20. https://doi.org/10.3390/cli8120150.

Mačiulytė, E., Cioffi, M., Zappia, F., Duce, E., Ferrari, A., Batinga de Mendoca, M.F.K., Loriga, G., Suška, P., Vaccari Paz, B.L., Zangani, D., Bult, P.H., 2018. Business Models & Financing Strategies, UNaLab Report.

Magalhães Filho, L.N.L., Roebeling, P., Costa, L., de Lima, L., 2022. Ecosystem services values at risk on the Atlantic coastal zone due to sea-level rise and socioeconomic development. SSRN Electron. J. 58 https://doi.org/10.2139/ssrn.4137891.

Matos, F.A., Roebeling, P., 2022. Modelling impacts of nature-based solutions on surface water quality: a rapid review. Sustain. 14, 1–17. https://doi.org/10.3390/su14127381.

Mei, C., Liu, J., Wang, H., Yang, Z., Ding, X., Shao, W., 2018. Integrated assessments of green infrastructure for flood mitigation to support robust decision-making for sponge city construction in an urbanized watershed. Sci. Total Environ. 639, 1394–1407. https://doi.org/10.1016/j.scitotenv.2018.05.199.

Merz, B., Kreibich, H., Schwarze, R., Thieken, A., 2010. Review article "assessment of economic flood damage.". Nat. Hazards Earth Syst. Sci. 10, 1697–1724. https://doi.org/10.5194/nhess-10-1697-2010.

Middelmann-Fernandes, M.H., 2010. Flood damage estimation beyond stage-damage functions: an Australian example. J. Flood Risk Manag. 3, 88–96. https://doi.org/10.1111/j.1753-318X.2009.01058.x.

Miller, J.D., Hutchins, M., 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. J. Hydrol. Reg. Stud. 12, 345–362. https://doi.org/10.1016/j.ejrh.2017.06.006.

Moore, T.L., Gulliver, J.S., Stack, L., Simpson, M.H., 2016. Stormwater management and climate change: vulnerability and capacity for adaptation in urban and suburban contexts. Clim. Chang. 138, 491–504. https://doi.org/10.1007/s10584-016-1766-2.

Nguyen, H.D., Fox, D., Dang, D.K., Pham, L.T., Viet Du, Q.V., Nguyen, T.H.T., Dang, T.N., Tran, V.T., Vu, P.L., Nguyen, Q.H., Nguyen, T.G., Bui, Q.T., Petrisor, A.I., 2021. Predicting future urban flood risk using land change and hydraulic modeling in a river watershed in the central province of Vietnam. Remote Sens. 13, 1–24. https://doi.org/10.3390/rs13020262.

Ommer, J., Bucchignani, E., Leo, L.S., Kalas, M., Vranić, S., Debele, S., Kumar, P., Cloke, H.L., Di Sabatino, S., 2022. Quantifying co-benefits and disbenefits of nature-based solutions targeting disaster risk reduction. Int. J. Disaster Risk Reduct. 75 https://doi.org/10.1016/j.ijdrr.2022.102966.

Pagano, A., Pluchinotta, I., Pengal, P., Cokan, B., Giordano, R., 2019. Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: a participatory system dynamics model for benefits and co-benefits evaluation. Sci. Total Environ. 690, 543–555. https://doi.org/10.1016/j.scitotenv.2019.07.059.

Peters, G.P., Hausfather, Z., 2020. Emissions - the "business as usual" story is misleading. Nature 577, 618–620.

Price, R.A., 2021. Nature-based Solutions (NbS) – What are They and What are the Barriers and Enablers to Their Use? K4D Help. Report. Inst. Dev. Stud. https://doi.org/10.19088/K4D.2021.098.

Quagliolo, C., Comino, E., Pezzoli, A., 2021. Experimental flash floods assessment through urban flood risk mitigation (UFRM) model: the case study of Ligurian coastal cities. Front. Water 3, 1–16. https://doi.org/10.3389/frwa.2021.663378.

Quagliolo, C., Roebeling, P., Mendonça, R., Pezzoli, A., Comino, E., 2022. Integrating biophysical and economic assessment: review of nature-based adaptation to urban flood extremes. Urban Sci. 6, 1–23.

Ramírez, J.I., Qi, K., Xiaobo, L., 2016. Sustainable stormwater management in Yinchuan New Town. Water Pract. Technol. 11, 469–479. https://doi.org/10.2166/wpt.2016.051.

Raymond, C.M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M.R., Geneletti, D., Calfapietra, C., 2017. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environ. Sci. Pol. 77, 15–24. https://doi.org/10.1016/j.envsci.2017.07.008.

Regione Emilia-Romagna, 2020. Liberare il suolo. Linee guida per migliorare la resilienza ai cambiamenti climatici negli interventi di rigenerazione urbana.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Ribeiro, A.S., Lopes, C.L., Sousa, M.C., Gomez-Gesteira, M., Dias, J.M., 2021. Flooding conditions at aveiro port (Portugal) within the framework of projected climate change. J. Mar. Sci. Eng. 9 https://doi.org/10.3390/jmse9060595.

Roebeling, P.C., Teotónio, C., Saraiva, M., Rocha, J., Baptista, C., Fidélis, T., Martins, F., Jacob, A., 2014. Assessing the benefits from combined urban parks and retention basins using the SULD decision support tool: a case study for the city of Aveiro (Portugal). In: Bridging the Implementation Gap of Accessibility Instruments and Planning Support Systems, pp. 1–16.

Rosenzweig, B., Ruddell, B.L., McPhillips, L., Hobbins, R., McPhearson, T., Cheng, Z., Chang, H., Kim, Y., 2019. Developing knowledge systems for urban resilience to cloudburst rain events. Environ. Sci. Pol. 99, 150–159. https://doi.org/10.1016/j.envsci.2019.05.020.

Rozos, E., Makropoulos, C., Maksimović, Č., 2013. Rethinking urban areas: an example of an integrated blue-green approach. Water Sci. Technol. Water Supply 13, 1534–1542. https://doi.org/10.2166/ws.2013.140.

Salata, S., Giaimo, C., Alberto Barbieri, C., Garnero, G., 2020. The utilization of ecosystem services mapping in land use planning: the experience of LIFE SAM4CP project. J. Environ. Plan. Manag. 63, 523–545. https://doi.org/10.1080/09640568.2019.1598341.

Salata, S., Ronchi, S., Giaimo, C., Arcidiacono, A., Pantaloni, G.G., 2021. Performance-based planning to reduce flooding vulnerability insights from the case of Turin (north-West Italy). Sustainability 13, 1–25.

Sharp, R., Douglass, J., Wolny, S., Arkema, K., Bernhardt, J., Bierbower, W., Chaumont, N., Denu, D., Fisher, D., Glowinski, K., Griffin, R., Guannel, G., Guerry, A., Johnson, J., Hamel, P., Kennedy, C., Kim, C.K., Lacayo, M., Lonsdorf, E., Mandle, L., Rogers, L., Silver, J., Toft, J., Verutes, G., Vogl, A.L., Wood, S., Wyatt, K., 2020. InVEST 3.9.0. user's guide. The Natural Capital Project [WWW document] (URL). https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/index.html.

SMHI, 2021. SMHI hypeweb [WWW document]. URL. https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change/ (accessed 11.25.21).

Sörensen, J., Mobini, S., 2017. Pluvial, urban flood mechanisms and characteristics – assessment based on insurance claims. J. Hydrol. 555, 51–67. https://doi.org/10.1016/j.jhydrol.2017.09.039.

Velasco, M., Russo, B., Cabello, Termes, M., Sunyer, D., Malgrat, P., 2018. Assessment of the effectiveness of structural and nonstructural measures to cope with global change impacts in Barcelona. J. Flood Risk Manag. 11, S55–S68. https://doi.org/10.1111/jfr3.12247.

Voskamp, I.M., de Luca, C., Polo-Ballinas, M.B., Hulsman, H., Brolsma, R., 2021. Nature-based solutions tools for planning urban climate adaptation: state of the art. Sustain. 13, 1–17. https://doi.org/10.3390/su13116381.

Webber, J.L., Fu, G., Butler, D., 2018. Rapid surface water intervention performance comparison for urban planning. Water Sci. Technol. 77, 8.

World Bank, 2015. World development indicators [WWW document]. URL. https://databank.worldbank.org/source/world-development-indicators# (accessed 7.16.22).

World Bank, 2022. World development indicators [WWW document]. URL. https://databank.worldbank.org/source/world-development-indicators# (accessed 5.16.22).

Xu, C., Rahman, M., Haase, D., Wu, Y., Su, M., Pauleit, S., 2020. Surface runoff in urban areas: the role of residential cover and urban growth form. J. Clean. Prod. 262, 121421 https://doi.org/10.1016/j.jclepro.2020.121421.

Yao, L., Wu, Z., Wang, Y., Sun, S., Wei, W., Xu, Y., 2020. Does the spatial location of green roofs affects runoff mitigation in small urbanized catchments? J. Environ. Manag. 268, 110707 https://doi.org/10.1016/j.jenvman.2020.110707.

Zhou, Q., Arnbjerg-Nielsen, K., 2018. Uncertainty assessment of climate change adaptation options using an economic pluvial flood risk framework. Water (Switzerland) 10. https://doi.org/10.3390/w10121877.

Zhou, Q., Panduro, T.E., Thorsen, B.J., Arnbjerg-Nielsen, K., 2013. Adaption to extreme rainfall with open urban drainage system: an integrated hydrological cost-benefit analysis. Environ. Manag. 51, 586–601. https://doi.org/10.1007/s00267-012-0010-8.

Zölch, T., Wamsler, C., Pauleit, S., 2018. Integrating the ecosystem-based approach into municipal climate adaptation strategies: the case of Germany. J. Clean. Prod. 170, 966–977. https://doi.org/10.1016/J.JCLEPRO.2017.09.146.