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Valuing the contribution of green roofs to pluvial flood risk mitigation: A cost-benefit analysis

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ABSTRACT

Cities in the 21st century face increasing pressures from population growth, urban sprawl, and emissions, while flood-related challenges exacerbated by climate change strongly intensify their vulnerabilities. Consequently, urban global change is becoming an urgent necessity globally. Nature-based solutions (NBS) have gained increasing attention as valuable sources of ecosystem services, which can also address these multiple societal challenges. Green roofs are widely used for stormwater management and treatment in compact urban environments. However, to date, most research has been conducted regarding green roof costs or flood risk mitigation benefits at a citywide scale; while local administrations need more evidence on the economic viability of green roofs that may increase the willingness to consider these nature-based solutions. Hence, the objective of this study is to develop and apply a spatially explicit assessment of flood risk mitigation impacts (biophysically – water depth), costs and benefits of NBS (economically – implementation costs, avoided damage costs, net present values and benefit-cost ratios) under current (2013) and future (2050; RCP 4.5) climate conditions – with a case study for green roofs in Rapallo (Italy). The spatial biophysical-economic approach integrates the InVEST Urban Flood Risk Mitigation model (spatial resolution: 5 m × 5 m), benefit transfer methods, and geographic information systems into a cost-benefit analysis. Results show that flood risks under current (2013) climate conditions imply significant building damage costs (~6.5 million €/yr for Rapallo), that these costs increase when considering future (2050) climate conditions (by about 7 %), and that NBS (green roofs) implementation can reduce these costs (by almost 90 %). Moreover, green roofs result to be economically viable from a flood mitigation perspective alone when considering Low NBS costs, while flood mitigation benefits contribute to, respectively, 87 % and 63 % of the green roof annual implementation costs when considering Medium and High NBS costs. Finally, results show that the economic viability of green roofs differs across neighbourhoods – hence allowing for the economic prioritization of green roof implementation across neighbourhoods. By quantitively assessing NBS impacts, costs, and benefits at the neighbourhood level, this study supports the decision on the most viable locations for the implementation of NBS for flood risk mitigation – highlighting the need for spatial assessment studies to support urban NBS development strategies.

1. Introduction

Climate change threatens ecosystems and society worldwide, requiring communities to adapt and mitigate impacts. Extreme events, such as heat waves, heavy precipitation, floods, storms, droughts, storm surges, and slow-onset events (e.g. coastal erosion) have significant negative impacts on the economy and human health, both directly and indirectly (European Environmental Agency (EEA), 2021). With the growing phenomenon of urbanization comes an increase in impermeabilized surface areas and a subsequent increase in stormwater runoff, peak flows, and pollutant transport (Davis., 2008; Fletcher et al., 2013). In addition to the reduced infiltration and drainage capacity, the high density of population and assets makes urban environments vulnerable to pluvial flooding events (Berndtsson et al., 2019; Jongman et al.,

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2012). Urban floods are natural hazard events with high economic impacts (Rözer et al., 2016), resulting in elevated costs escalating globally (Ashley et al., 2005; Barredo, 2009; Meyer et al., 2013). Their effects are expected to continue to increase with the growing impacts of climate change (Cardona et al., 2012; Olsson & Foster, 2014).

Ecosystems provide flexible ways to support climate change adaptation and mitigation (Voskamp et al., 2021). For this purpose, nature-based solutions (NBS) represent the primary source of ecosystem services (ES) for urban areas (Langemeyer et al., 2020). Copied from and inspired by nature, NBS provides a range of ecosystem services (provisioning, regulating and maintenance, and cultural) while also improving social cohesion and human well-being by mimicking the complex processes of nature (European Commission, 2015; Frantzeskaki et al., 2019; Kabisch et al., 2017; Ommer et al., 2022).

Nature-based green roofs are considered among the best solutions to control stormwater flows (Kõiv-Vainik et al., 2022). Green roofs are multi-layered systems implemented on rooftops, increasing water retention capacity using vegetative elements (López-Maciel et al., 2023; Mačiulytė et al., 2018a; Quagliolo et al., 2023). Green roofs can take various forms, commonly classified as extensive, semi-intensive, and intensive green roofs. These categories primarily differ in depth, vegetation types, and the level of maintenance required (Abass et al., 2020). Beyond their visual appeal, green roofs are essential in mitigating complex urban environmental challenges from building density, surface sealing, and heat waves (Essuman-Quainoo & Jim, 2023). They provide physiological and functional benefits (Eisenberg & Polcher, 2019), making them an interesting urban NBS, especially in land-scarce urban areas (Teotónio et al., 2021). A well-implemented green roof can extend the roof's longevity, reduce energy consumption, minimize noise, and enhance the value of the property (Mendonça et al., 2023; Teotónio et al., 2021; Zhang & He, 2021). From a public urban perspective, they reduce urban heat islands, manage stormwater, enhance biodiversity, create new amenity spaces, and foster job creation (Eisenberg & Polcher, 2019; Yahya et al., 2020). Despite the potential benefits, there is still much to study about the disservices associated with NBS and green roof implementation (Haase et al., 2014, 2017). Poorly spatially distributed NBS can foster social inequality, by attracting high-income households and displacing lower-income households (gentrification) – potentially enhancing urban sprawl, increasing inequalities and reducing access to public amenities (Bockarjova et al., 2020; Rita Mendonça et al., 2024; Rumbach et al., 2022).

Despite these benefits, green roofs can encounter adoption barriers, including financial, structural, knowledge and information, technical, and climatic factors (López-Maciel et al., 2023; Mahdiyar et al., 2020). A common barrier to the adoption of green roofs concerns their potential high implementation and long-term maintenance costs and, therefore, are not the preferred NBS among urban planners (Berto et al., 2020; Oberti & Plantamura, 2018; Roy et al., 2008). From a structural perspective, and depending on the area, many existing buildings could lack the load-bearing capacity needed to support the green roofs (see e.g. Doğmuşöz, 2023). In terms of knowledge and technical capacity it is documented that the lack of awareness among developers, architects and building owners about the co-benefits, but also the maintenance needed for green roofs, implies potential barriers for their implementation (Doğmuşöz, 2023; López-Maciel et al., 2023). The lack of regulations and incentives, especially for small green roofs, hinders widespread implementation (Roggero, 2020). Then, in the absence of mandates or subsidies, private building owners could deprioritize green-roof adoption (López-Maciel et al., 2023). In this regard, consistent policy implementation emerges as a global barrier, as city planners often struggle to engage private property owners when financial costs outweigh the benefits. Consequently, incentives and policies for green infrastructure adoption positively affect green roof implementation (Liberalesso et al., 2020). However, having incentives is not sufficient; a limited diffusion of green infrastructure, such as green roofs, poses challenges, particularly among potential adopters and the private sector, even in countries with a high gross domestic product (Cirrincione et al., 2021; Tabatabaee et al., 2019). For instance, a study developed for private property owners across the city of Eindhoven (The Netherlands) concluded that the intention to implement green roofs on their properties was relatively low for the population despite the fact that the local government provided financial incentives to facilitate green roofs implementation (López-Maciel et al., 2023). As a social and institutional factor we can conclude that even where benefits are known, green roof adoption is slow due to limited and inconsistent integration of NBS in urban planning policies (see Di Pirro et al., 2023).

Strategic keys to achieving widespread implementation of NBS in urban planning consist of comprehensive knowledge about designing and maintaining NBS as well as quantifying their impact, costs and benefits (Alves et al., 2020; Kõiv-Vainik et al., 2022; Mendonça et al., 2024; Ommer et al., 2022). An increased demand arises for a reliable economic assessment that quantifies costs and benefits across various case studies (European Commission, 2021; Veerkamp et al., 2021). In this view, increasing evidence (both biophysical and economic) on the effectiveness of NBS for flood risk mitigation in a spatially explicit way, together with their multiple functions, services and values (i.e. aesthetic improvement, human well-being enhancement, air quality regulation, etc.) to face climate and societal-related challenges, can help decision-makers perform cost-benefit assessments (Alves et al., 2020; Quagliolo et al., 2023; Zölch et al., 2018). The biophysical evaluation of ecosystem services and the respective economic valuation of NBS are crucial for urban sustainable development policies (Bouraoui et al., 2012). Spatial biophysical assessments, and particularly flood risk inundation maps, are developed using hydrological modelling tools, such as, HEC-RAS (Rangari et al., 2019), MIKE Urban (Bisht et al., 2016), ANUGA (Issermann & Chang, 2020), Infoworks ICM (Costa et al., 2021), 2D and 3D hydrodynamic models (Rong et al., 2020), and 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 land use, topography, stream networks, sewer systems, digital elevation models and building maps, are crucial (Bulti & Abebe, 2020). However, the benefit of such complex flood modelling is not satisfied when there is a lack of proper data (Afifi et al., 2019). Instead of expecting models to quantify the biophysical performance of a system accurately, the added value of simplified, less data-demanding, flood risk assessment models is the possibility to: i) obtain a spatial assessment, thus understanding the location of vulnerable areas, ii) use the output to estimate simulated adaptation alternatives (such as NBS), and iii) understand the range of costs and benefits related to these adaptation alternatives (Salata et al., 2022). Modelling software solutions such as the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), have started to incorporate modules to map and assess the multiple impacts, costs and benefits obtained from nature in the context of green solutions and NBS (Matos & Roebeling, 2022; Quagliolo et al., 2023; Sharp et al., 2020).

This study performs a spatially explicit assessment of flood risk mitigation impacts, costs, and benefits of NBS for the case of green roofs in Rapallo (Italy). To this end, an integrated three-stepwise approach is developed. Firstly, the biophysical assessment is created by employing the InVEST-UFRM (Urban Flood Risk Mitigation) model (Sharp et al., 2020) to identify flood areas, flood depths and buildings at risk for different flood return periods (10, 50 and 100 years) under current (2013) and future (2050; Representative Concentration Pathway – RCP – 4.5) climate and NBS adaptation (green roof) scenarios. Secondly, the economic assessment is developed using value transfer methods (Brander, 2013) and flood-depth damage functions (Huizinga et al., 2017), to estimate the costs (investment and maintenance) and benefits (avoided flooding costs) of NBS for flood risk mitigation. Finally, a cost-benefit analysis (CBA) is performed by equating NBS flood risk mitigation costs and benefits and carrying-out a sensitivity analysis on NBS implementation costs and discount rates (for which most significant variations are observed). The above-mentioned analyses are performed at a fine spatial scale (5 m × 5 m) as to take into account biophysical and economic heterogeneity. However, for participatory urban planning purposes (in line with the functional zoning that regulates spatial urban planning) as well as privacy issues, results are aggregated and presented at the neighbourhood scale (Locatelli et al., 2020; Quagliolo et al., 2022; Senosiain, 2020).

2. Materials and methods

2.1. The city of Rapallo (Italy): socio-economic aspects and flooding issues

Rapallo is a coastal city in the metropolitan area of Genoa within the Liguria Region in Italy (Fig. 1). The municipality is located at 44.4°N 8.94°E, about 25 km^2 southeast of Genoa, in the Tigullo Gulf. Liguria covers 2 % (5418 km^2) of the Italian territory, while the population density of the region is almost 287 inhabitants/km^2 (Quagliolo et al., 2021). Rapallo is recognized mainly for its tourist activities. Considering the orography of the territory and that more than 50 % of the territory is covered by forest, the coastline, particularly the Metropolitan area of Genoa, shows the highest population density values in the Region (population of 850.000 in the metropolitan area). The Region went through rapid urbanization in coastal areas, combined with a population that has doubled in a relatively 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. Fig. A.1. – Annex A shows the 6 administrative neighbourhoods identified for Rapallo (Borzoli, Cappelletta, Cerisola, Costaguta, San Michele, and Seglio).

Rapallo lies 3 m above sea level, mainly extending through a lowland between Boate and San Francesco streams (see the Hydrographic Basins map in Fig. 1). It covers one major natural watershed linked to the Boate stream and seven smaller basins. A narrow coastal zone with hills and steep mountains inland characterizes Rapallo (see the Digital Terrain model – DTM map in Fig. 1). Because of this steep topography behind the city, the catchment area has a particular drainage system. A range of watercourses has historically been incorporated into the urban area through the city's expansion processes. These processes did not consider the rising runoff volume, especially during extreme events. Therefore, the town is plagued by frequent flooding (Paliaga, Luino, Turconi, Marincioni, & Faccini, 2020).

The peculiar morphology of the Liguria region causes very localized precipitation events that, in some cases, are limited to single cities (Paliaga et al., 2019; Paliaga, Faccini, Luino, Roccati, & Turconi, 2020). Over the last centuries, particularly from the XX century, most 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) reduction in soil permeability, ii) artificialization of drainage networks, iii) loss of natural spaces due to uncontrolled urban sprawl, and iv) land-use changes in floodplains and river basin.

For these reasons, numerous flooding events have historically hit the Liguria region. In general, Liguria is a typical case in which urban sprawl has the most decisive role in flooding events (Faccini et al., 2015). Specifically, two floods have been registered among the most damaging past events in Rapallo: one in 1911 and another in 1915. In September 1915, flash floods and landslides caused one of the most disastrous events between Genoa, Rapallo, and Chiavari. This rainfall event generated precipitation that reached approximately 400 mm in 3 h. 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, & Faccini, 2020). Between 2000 and 2019, a range of catastrophic events occurred in Italy, specifically in the area surrounding Rapallo (Paliaga, Luino, Turconi, Marincioni, & Faccini, 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. In October 2018, the 'Vaia' storm hit the coastal region of Rapallo, causing the destruction of the tourist port and the flooding of the city, particularly affecting the lowland areas near the shoreline (Bompani & Origone, 2018; Pedemonte et al., 2018). Two other storm events characterized by intense rainfall, floods, and landslides in this region occurred in October 2019 and November 2019 (Paliaga, Luino, Turconi, Marincioni, & Faccini, 2020).

2.2. Integrated biophysical and economic impact assessment

The spatial biophysical-economic assessment comprises an integrated three-stepwise approach (see Fig. 2). First, the biophysical assessment employs the Urban Flood Risk Mitigation (UFRM) module of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Sharp et al., 2020) to identify flood areas and depths for different flood return periods (10, 50 and 100 years) under current (2013) and future (2050; RCP 4.5) climate and NBS (green roof) scenarios. By intersecting these inundation maps with the asset layers, buildings at risk are identified. Second, the economic assessment employs value transfer methods (Brander, 2013) and flood-depth damage functions (Huizinga et al., 2017), to estimate the costs (investment and maintenance) and benefits (avoided flooding costs) of NBS for flood risk mitigation. Third, a CBA combines the flood risk mitigation costs and benefits of NBS. The robustness of the model is verified through a sensitivity analysis on costs and discount rates, for which most significant variations are observed. The NBS impact assessment is developed by integrating current (2013) and future (2050; RCP 4.5) climate conditions and NBS adaptation scenarios (green roofs).

2.2.1. Biophysical assessment: InVEST modelling

The biophysical assessment uses the Urban Flood Risk Mitigation (UFRM) module of the Integrated InVEST model (Sharp et al., 2020) developed by the Natural Capital Project[1] to identify flood areas and depths. The UFRM module focuses on the ability of cities to limit potential flooding during rainfall events. This spatial module considers flood-prone areas produced by stormwater runoff, because of the interaction of permeable-impermeable surfaces (land use type) and soil drainage (soil characteristics) layers (Quagliolo et al., 2021; Salata et al., 2021; Sharp et al., 2020). Runoff production is estimated by the USDA (United States Department of Agriculture) Soil Conservation Service – "SCS runoff curve number" (SCS-CN) method (Lucas-Borja et al., 2020; Xu et al., 2020), using the potential maximum retention and curve number values for each pixel (spatial resolution: 5 m × 5 m). More details about the InVEST-UFRM model are available in Quagliolo et al. (2021), (2023) and Salata et al. (2021) Table A.1 – Annex A shows the data and sources for the InVEST-UFRM model.

Rainfall events are considered by including one-hour-design storms under 10-, 50- and 100-year flood return periods (i.e., the frequency of recurrence of a specific flood event). Due to the lack of detailed data on design storms for the city of Rapallo, the current (2013) climate design storm events are based on rainfall depth-duration functions from the nearest city: Genoa (ARPAL, 2013). The design storms, equivalent to rainfall intensity (rainfall amount per unit of time; in mm/h), are 91 mm/h (10-years), 133.5 mm/h (50-years) and 156 mm/h (100-years). The future (2050) climate design storm events for Italy are derived from climate projections from the Swedish Meteorological and Hydrological Institute (SMHI)[2] and the Service for Water Indicators in Climate Change Adaptation (SWICCA)[3] greenhouse gas emission scenarios, which are

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

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

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

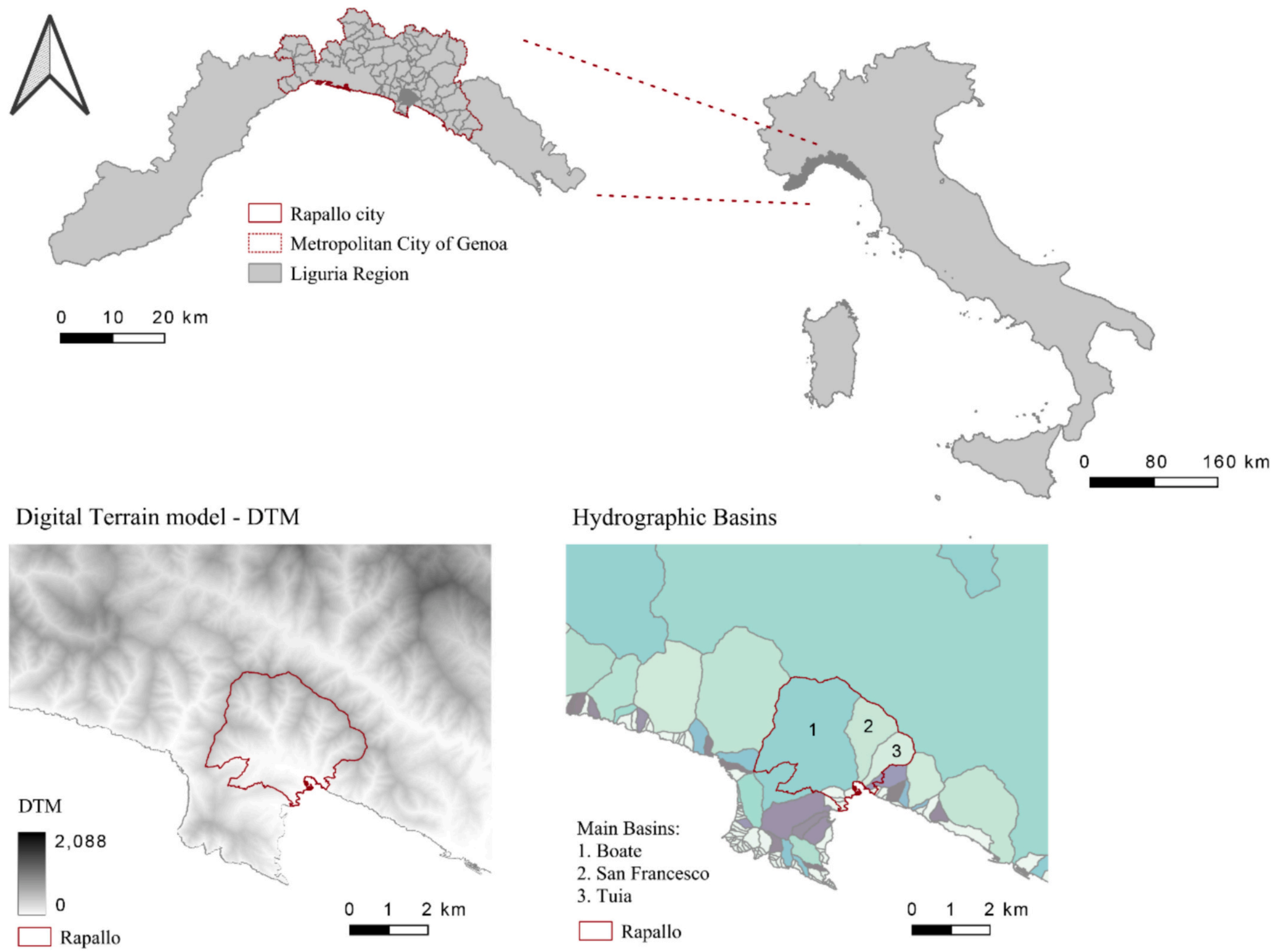

Fig. 1. Study area.

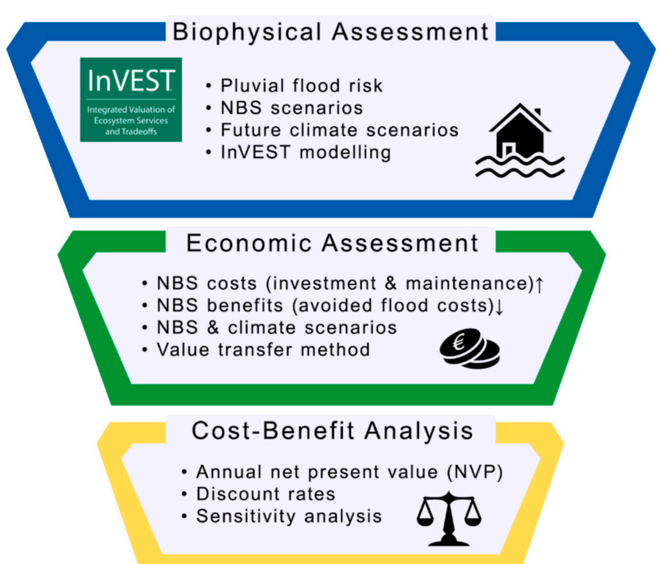

Fig. 2. Three-stepwise integrated spatial biophysical-economic assessment approach.

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 RCP 4.5 is chosen for future (2050) climate simulation, which considers a pathway without overshoot to 4.5 W/m2 in radioactive forcing and stabilization after 2100 (650 ppm CO2 equivalent), and with sea level rise being, on average, 0.47 m between 2081 and 2100. The moderate emission RCP 4.5 is selected for the present study, because for the first half of the century (up to 2050) the differences in average annual precipitation between RCP 4.5 and RCP 8.5 are minimal in Italy (Faggian, 2021; San José et al., 2016). The future (2050) climate precipitation values are calculated by estimating the mean of the average percentual changes in rainfall between the current (2013) and future (2050) climate projections for each return period. Each average change value is derived from an ensemble provided by the Hydrological Predictions for the Environment (*E*-hype) model (SMHI, 2021). Rainfall amounts increase by 6 % for the 10- and 50-year return period events and by 7 % for the 100-year return period events from the current (2013) to the future (2050) climate. The final design storms for the future climate (2050) are 96.5 mm/h (10 years), 141.5 mm/h (50 years), and 166.9 mm/h (100 years). The reference year for the current (2013) climate was chosen based on the data availability when the study was conducted.

2.2.2. Economic assessment: NBS costs and benefits

The economic evaluation is developed using value transfer methods

(Brander, 2013) and flood depth-damage-functions (Huizinga et al., 2017) to estimate the costs (investment and maintenance) and benefits (avoided flooding costs) of NBS. This method allows using value data and information from similar contexts where primary ecosystem service evaluations have been conducted (Brander, 2013).

2.2.2.1. NBS costs. Implementation costs of NBS include investment and maintenance costs. Investment costs consist of a single payment at the start of the project, associated with planning (i.e. process of selecting the locations for such solutions), materials (i.e. expenses for input materials), construction (i.e. installation itself), and roof reinforcement (i.e. to prepare the structure to withstand the increased load of the green roof layer). Maintenance costs are periodic and occur during the lifespan of the NBS (e.g. on-site inspections, the replacement of plants, weeding, disease management, and water for irrigation) (Mačiulytė et al., 2018b).

NBS costs are based on those from four European NBS projects (UNaLab, SOS4LIFE, Urban GreenUP and ThinkNature; see Quagliolo et al., 2023). As the literature on cost values broadly differs, a sensitivity analysis is performed: "Low" (minimum), "Medium" (average), and "High" (maximum) NBS costs are examined to identify the degree of uncertainty on the predicted values (Boardman et al., 2018). The considered unit costs (in €/m^2) are converted into the same year value (2020) using the consumer price index (World Bank, 2022). Table 1 reports the different ranges of total and annual costs calculated by considering the expected lifetime for green roofs.

The total annual costs (TC_t) of NBS implementation (in €/year) are calculated by summing the annual investment costs (IC_t) and annual maintenance costs (MC_t) for the NBS area (a):

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

where the annual investment costs are estimated as the average investment costs over the lifetime of the NBS, and the yearly maintenance costs correspond to 2.5 % of the investment costs (estimated value from the four European NBS projects). In line with Stern (2007), a time discount rate of almost zero ($r = 0.001$) is applied to obtain insight in the maximum benefits of NBS implementation.

2.2.2.2. NBS benefits. NBS benefits are defined as the avoided flooding costs due to green roof implementation. For this reason the focus of this study is on building damage assessment (building structure and contents), which represents a significant part of tangible damage costs from pluvial floods (see e.g. Mobini et al., 2021). The expected annual damages (EAD) caused by flood events are assessed by employing flood depth-damage-functions (DDFs), which relate floodwater depth and corresponding damage factor (building structure and contents) for specific classes of infrastructure (Middelmann-Fernandes, 2010; Huizinga et al., 2017). Direct flood damages to buildings are estimated following four steps (Merz et al., 2010; Roebeling et al., 2014; see Quagliolo et al., 2023):

1. The flood area and depth maps for each scenario are assessed using the InVEST-UFRM model.

Table 1
Green roof lifetime, investment, and maintenance costs (in 2020 Euros; based on UNaLab, SOS4LIFE, Urban GreenUP, and ThinkNature; adapted from Quagliolo et al., 2023).

Lifetime (years)	Type of cost	Lifetime cost (€/m^2)	Annual NBS costs (€/m^2/year)		
			Low	Medium	High
40	Investment	170–450	4.0*	7.5*	11.0*
	Maintenance		3.0	7.5	12.0
	Total		7.0	15.0	23.0

* Annual investment costs are calculated using a time discount rate of 0 %.

2. The elements potentially at risk (building map) are obtained from the regional topographic geodatabase (Regione Liguria, 2013) and categorized by economic sector (residential, commercial, and industrial). Building structure values (in 2020 Euros) for the three categories are obtained from "Agenzia delle Entrate" (Agenzia delle Entrate, 2021) for the Metropolitan area of Genoa: residential (2068 €/m^2), commercial (1333 €/m^2) and industrial (819 €/m^2). Corresponding building contents values are estimated at 50 % (for residential), 100 % (for commercial) and 150 % (for industrial) of the building structure values (Huizinga et al., 2017).
3. Buildings at risk of flooding are assessed by intersecting the flood area and depth maps with the building layers using geographic information systems (GIS). Potential damage (D_i) to assets (i) is assessed using the DDF (Davis & Skaggs, 1992) based on data from Huizinga et al. (2017) and fitting the quadratic function as follows:

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

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

The expected annual damage per return period ($ED_{t,r}$) is obtained by multiplying the expected total damage costs per event (i.e. the damage to all flooded building category values) and flood occurrence probability (i.e. the inverse of the flood return period; r):

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

where D_i is the rate of damage to building category i, $F_{r,i}$ is the flooded area per return period r and building category i, v_i is the value of the building category 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; ED_t) is calculated by the sum of the expected annual damages per return period ($ED_{t,r}$) over all return periods r:

$$ED_t = \sum_r ED_{t,r} \tag{4}$$

The expected annual damage is calculated for the baseline and NBS scenarios. The total annual benefits (TB_t) of NBS implementation (in €/year), corresponding to the total avoided flooding costs, is given by the difference between the expected annual damage without (Baseline) and with (Green roof) nature-based solutions:

$$TB_t = [ED_t]_{Baseline} - [ED_t]_{Green\ roof} \tag{5}$$

2.2.3. Cost-benefit analysis

Cost-benefit analysis (CBA) is a relevant tool for decision-making in urban planning by comparing different scenarios (Boardman et al., 2018; Locatelli et al., 2020; Perman et al., 2003). This CBA focuses on quantifying and monetizing some elements, including costs and benefits related to NBS implementation (Pouso et al., 2018; TEEB, 2009). To compare and assess the economic viability of NBS, the annual benefit-cost ratio (BCR_t) and annual net present value (NPV_t) are calculated (Boardman et al., 2018; Zerbe & Dively, 1994):

$$BCR_t = TB_t / TC_t \tag{7}$$

$$NPV_t = TB_t - TC_t \tag{8}$$

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

In addition to the sensitivity analysis on NBS costs (see Section 2.2.2.1), a sensitivity analysis is performed on discount rates to assess the robustness of the model results. Given that the time discount rate is essential to value future cost and benefit streams in present-day terms, this research performs a sensitivity analysis on time discount rates for 0 %, 2 %, and 4 % (Alves et al., 2020; Gollier, 2008).

2.3. Scenario design

The NBS scenario entails green roofs – i.e. vegetative multi-layered rooftop compositions, with specific substrate, vegetation and retention capacity – that contribute, among others, to mitigating negative effects related to urban sealing through water retention and evapotranspiration (Mačiulytė et al., 2018a). Green roofs are considered among the best solutions to control stormwater flow in continuous urbanized areas (see e.g. (Arnsteg et al., 2022; Kõiv-Vainik et al., 2022). The combined climate conditions and NBS adaptation scenarios assessed in this study are the following:

- Baseline (Baseline_2013): current climate (2013) without NBS
- Business-as-usual (BAU_2050): future climate (2050) without NBS
- Nature-based solutions (NBS_2050): future climate (2050) with NBS (green roofs)

The NBS (green roof) simulation is performed on all buildings in those neighbourhoods that show the highest flood-related costs for the Baseline_2013 scenario (100 % coverage) (see Fig. 4) – namely 165,168 m^2 of green roofs in Cappelletta, 182,487 m^2 of green roofs in Cerisola and 87,607 m^2 of green roofs in Borzoli. To simulate the NBS (green roofs) in the InVEST-UFRM model, technical aspects (namely vegetation and substrate type and depth) are characterized based on average values calculated from three NBS projects (UNaLab, SOS4LIFE and Urban GreenUP) and a SUDS guidelines report for Bologna (Italy; (Comune di Bologna et al., 2018).

3. Results

3.1. Biophysical results

This section presents the biophysical results for the Baseline_2013, BAU_2050, and NBS_2050 scenarios. The biophysical impacts for the Baseline_2013 scenario show that flood depths vary between 27 mm (10-year return period) and 85 mm (100-year return period), and are expected to increase by about 11 % under the BAU_2050 scenario (see Table 2 and Fig. 3). The flood depth increases with higher return periods: compared to the 10-year return period event, flood depth is 26 % and 37 % larger for events with return periods of 50 and 100 years, respectively – both for the Baseline_2013 and BAU_2050 scenarios. The Cappelletta, Cerisola, and Borzoli neighbourhoods are most susceptible to flooding – particularly considering the 100-year return period event (see Fig. 3).

Compared to the BAU_2050 scenario, results for the NBS_2050 scenario show that flood depths reduce, on average, by 24 % for 10 years, 18 % for 50 years, and 16 % for 100-year return period events (see Table 2). Most considerable reductions in flood depth values are generally observed in neighbourhoods with larger green roof implementation areas. However, the most significant flood risk reductions are observed in the Cappelletta neighbourhood, which shows a decrease in flood depth of over 29 % under the 10-year return period event – even if the largest green roof area has been implemented in Cerisola (182,487 m^2). Cappelletta shows the most significant flood depth reduction because it is the neighbourhood with the largest relative area of green roof implementation (with green roofs covering 42 % of the total neighbourhood area; Cerisola follows with green roofs covering 38 % of the neighbourhood's area).

3.2. Economic results

Annual green roof implementation costs are given for Low, Medium and High NBS costs (see Table 3). At the city level, the total green roof area implemented corresponds to 435,262 m^2, representing approximately 30 % of the building area in Rapallo. Neighbourhoods with higher green roof implementation costs correspond, self-evidently, to larger green roof implementation areas. Cerisola shows a range of annual green roof implementation costs that vary between 1.5 and 4.0 million €/year (182,487 m^2 of green roofs), followed by Cappelletta (1.3 to 3.6 million €/year; 165,168 m^2) and Borzoli (0.7 to 1.9 million €/year; 87,607 m^2).

The total expected annual flood damage costs to buildings in Rapallo are estimated at almost 6.5 million €/year in the Baseline_2013 scenario, and are expected to increase by 7 % (to over 6.9 million €/year) under the BAU_2050 scenario (see Table 4). Albeit flood damage costs to buildings for the Baseline_2013 scenario are distributed across all neighbourhoods in the city of Rapallo (see Fig. 4), the highest annual flood damage costs are observed in Cerisola (2.7 million €/year; flooded area of 1,932,522 m^2), Cappelletta (2.4 million €/year; flooded area of 1,186,299 m^2) and Borzoli (1.3 million €/year; flooded area of 1,569,769 m^2). Differences in flood damage costs are due to differences in flood depths (most significant in Cappelletta, ranging between 38.4 and 84.5 mm in the Baseline_2013; see Table 2), affected building area (largest in Cerisola; 182,487 m^2), and building values (highest in Cerisola; 358 million €) across neighbourhoods. The total building area of Rapallo (1,401,361 m^2) consists primarily of residential buildings (91 %), followed by commercial (5 %) and industrial (4 %) buildings. Damage costs are highest in neighbourhoods with the largest share of residential building areas (which have a higher value: 2068 €/m^2 for residential, versus 1333 €/m^2 for commercial and 819 €/m^2 for industrial).

Compared to the BAU_2050 scenario, results for the NBS_2050 scenario show that expected annual flood damage costs are reduced by 88 % (see Table 3) – i.e., yearly flood risk mitigation benefits from green roofs in Rapallo amount to 6.1 million €/year. At the neighbourhood level, flood risk mitigation benefits are greatest in Cerisola (2.5 million €/year), followed by Cappelletta (2.3 million €/year) and Borzoli (1.2 million €/year). This is explained by the significant expected flood damage costs in Cerisola and Cappelletta under the BAU_2050 scenario (2.9 and 2.6 million €/year, respectively) and the large green roof implementation area in Cerisola and Cappelletta under the NBS_2050

Table 2
Average flood depth (mm) by neighbourhood under 10, 50, and 100-year return periods for the Baseline_2013, BAU_2050, and NBS_2050 scenarios.

	Flood depth (mm)								
	Baseline_2013			BAU_2050			NBS_2050		
	10-yrs	50-yrs	100-yrs	10-yrs	50-yrs	100-yrs	10-yrs	50-yrs	100-yrs
Cappelletta	38.4	67.6	84.5	41.9	73.5	92.9	29.8	56.1	72.8
Cerisola	32.7	61.5	78.4	36.2	67.4	86.8	27.7	55.3	73.0
Borzoli	27.7	54.7	70.9	30.9	60.4	79.0	25.8	53.1	70.7

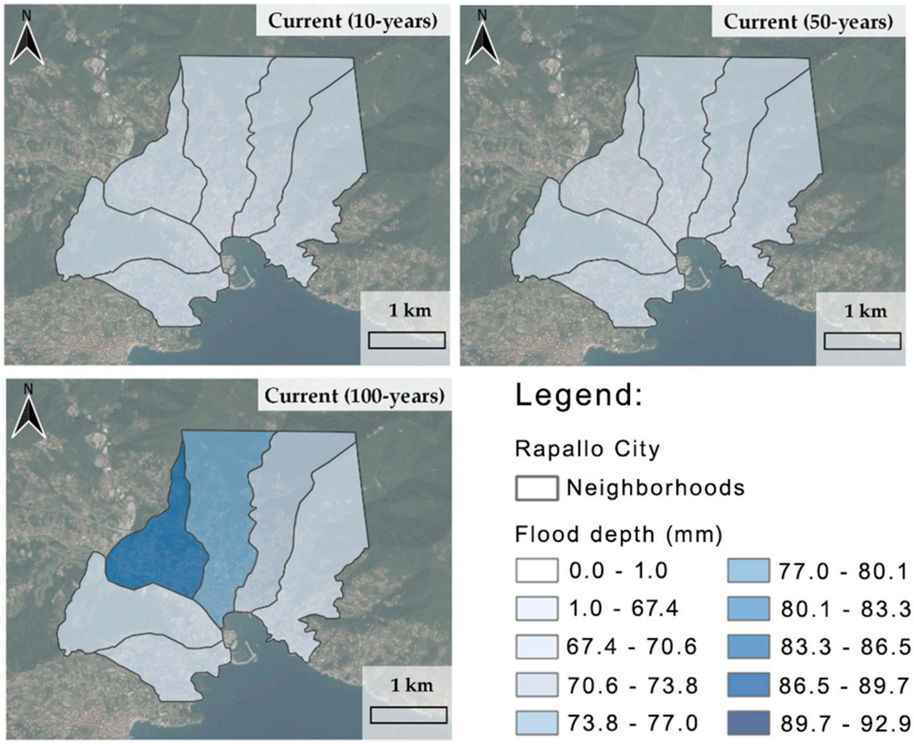

Fig. 3. Average flood depth (mm) by neighbourhood under 10, 50, and 100-year return periods for the Baseline_2013 scenario.

Table 3
Implementation area (m^2) and annual implementation costs (€/year) by neighbourhood for Low, Medium, and High NBS costs.

	Area	NBS costs (€/year)		
	(m^2)	Low	Medium	High
Cappelletta	165,168	1,321,348	2,642,696	3,633,708
Cerisola	182,487	1,459,893	2,919,787	4,014,707
Borzoli	87,607	700,852	1,401,705	1,927,345
Total	435,262	3,482,093	6,964,188	9,575,760

Table 4
Expected annual flood damage costs and NBS mitigation benefits (€/year) by neighbourhood for Baseline_2013, BAU_2050, and NBS_2050 scenarios.

	Expected flood damage costs (€/year)			NBS flood mitigation benefits (€/year)*	
	Baseline_2013	BAU_2050	NBS_2050	Total	per m^2
Cappelletta	2,428,536	2,589,279	296,856	2,292,423	13.88
Cerisola	2,727,663	2,907,719	353,305	2,554,415	14.00
Borzoli	1,314,845	1,402,220	183,545	1,218,675	13.91
Total	6,471,044	6,899,218	833,705	6,065,513	13.94

* Based on comparison between the BAU_2050 and NBS_2050 scenario.

scenario (182,487 m^2 and 165,168 m^2, respectively). Flood mitigation benefits per unit area differ slightly across neighbourhoods, varying between 13.88 €/m^2/yr in Cappelletta and 14.00 €/m^2/yr in Cerisola, due to differences in flood depths and value of assets across neighbourhoods.

3.3. Economic viability

This section assesses the economic viability of the NBS_2050 scenario using the annual net present value (NPV) and annual benefit-cost ratio (BCR) (see Table 5). Results show that the annual NPV (€/year) is positive under Low NBS costs (+2.6 million €/year), with largest NPV observed for the Cerisola and Cappelletta neighbourhoods (highest expected flood damage costs and green roof implementation areas) and the smallest NPV observed for the Borzoli neighbourhood (smallest expected flood damage costs and green roof implementation area). Hence, under Low NBS costs, green roofs are economically viable from a flood mitigation perspective alone. Albeit differences are small, the BCR results show that the economic viability of green roofs differs across neighbourhoods (see Table 5). Under Low NBS costs, Cerisola is the neighbourhood that shows the largest BCR (1.750) and, hence, from an economic perspective could be prioritized for green roof implementation.

On the other hand, the annual NPV (€/year) is negative under Medium and High NBS costs (−0.9 and −3.5 million €/year, respectively). Most negative NPV are observed for neighbourhoods with the largest green roof implementation areas (Cerisola and Cappelletti). Hence, under Medium and High NBS costs, green roofs are not economically viable from a flood mitigation perspective alone. Albeit the BCR is smaller than 1 for all neighbourhoods, Cerisola remains the neighbourhood with the largest BCR (0.875 and 0.636 under Medium and Low costs, respectively).

3.4. Sensitivity analysis

Finally, a sensitivity analysis on NBS costs and time discount rates is performed to assess the uncertainty associated with future values. The time discount rates employed for this assessment are 0 %, 2 %, and 4 %. Results for the variation in NBS costs show that all NPV are positive under Low NBS costs and that the NPV become negative under Medium and High NBS costs (see Table 6). The NPV decreases with an increase in the time discount rate for all NBS costs as the present value of future NBS flood mitigation benefits decrease while the present value NBS investment costs remain unchanged.

Hence, when Low NBS costs are considered, green roofs are economically viable from a flood mitigation perspective alone.

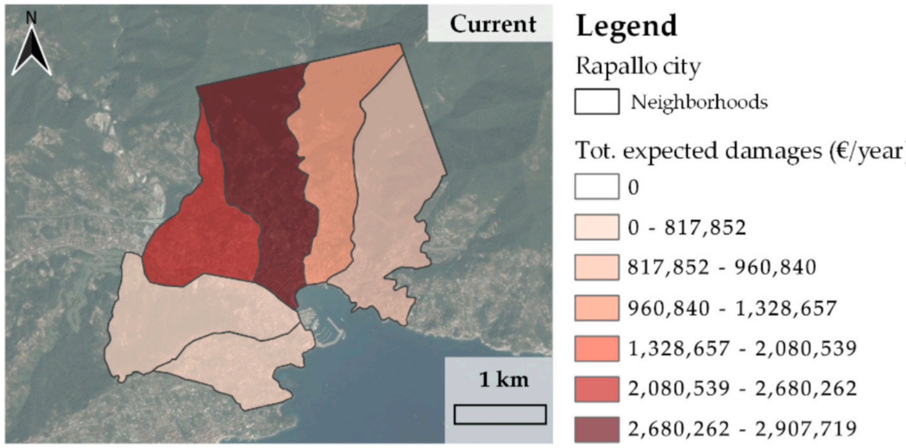

Fig. 4. Expected annual flood damage costs (in €/year) by neighbourhood for the Baseline_2013 scenario.

Table 5
Annual net present value (NPV; €/year) and benefit-cost ratio (BCR) by neighbourhood for Low, Medium, and High NBS costs.

	Low NBS costs		Medium NBS costs		High NBS costs	
	Annual NPV (€/yr)	Annual BCR	Annual NPV (€/yr)	Annual BCR	Annual NPV (€/yr)	Annual BCR
Cappelletta	971,075	1.735	−350,273	0.867	−1,341,285	0.631
Cerisola	1,094,522	1.750	−365,372	0.875	−1,460,292	0.636
Borzoli	517,823	1.739	−183,030	0.869	−708,670	0.632
Total	2,583,420	1.742	−898,675	0.871	−3,510,247	0.633

Table 6
Annual net present value (NPV; €/year) for 0 %, 2 %, and 4 % discount rates and Low, Medium, and High NBS costs.

Annual NPV (€/year)	Low NBS costs	Medium NBS costs	High NBS costs
Discount rate 0 %	2,583,420	−898,675	−3,510,247
Discount rate 2 %	1,515,078	−2,240,277	−5,991,279
Discount rate 4 %	481,541	−4,124,961	−8,727,110

4. Discussion

The biophysical results show that pluvial flood risk is distributed across all neighbourhoods in Rapallo, and especially among the three central neighbourhoods (Cappelletta, Cerisola, and Borzoli). Moreover, flood depth increases (by over 10 %) under future (2050) climate conditions (RCP 4.5) and without NBS. NBS (green roofs) have a positive influence on reducing flood risk in environments with predominately sealed surfaces due to their capacity to store rainwater. Notably, flood depths decrease (by between 15 % to 25 %) under future (2050) climate conditions and with NBS (green roofs), while noting that the amount of water stored by green roofs is larger under high return period events and future (2050) climate conditions – in line with results from the studies by Biasin et al. (2023) and Di Pirro et al. (2022). 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 conclusions about the water retention capacity of NBS. Green roofs can increase water retention according to type, size, age, etc. ((Salata, 2023), so their efficacy depends on design and implementation.

From an economic perspective, results show that flood risks under current (2013) climate conditions imply significant annual building damage costs (~6.5 million €/yr for Rapallo), and these costs increase when considering future (2050) climate conditions (by about 7 %) while NBS (green roofs) can reduce these flood damage costs (by almost 90 %). Green roofs provide the largest annual flood risk mitigation benefits under less intense flooding events, because (and despite being less damaging) lower intensity rainfall events are far more frequent and, hence, their cumulative costs add-up to values that surpass the average annual costs of higher intensity (and more damaging) rainfall events – in line with Quagliolo et al. (2023). Our study also shows, however, that green roof implementation costs differ widely across various sources – with considered investment costs (CAPEX) ranging between 170 and 450 €/m^2 (lifetime 40 years) and maintenance costs (OPEX) ranging between 3.0 and 12.0 €/m^2/yr. These values are around those used by Alves et al. (2020; CAPEX+OPEX = ~12€/m^2/yr), Locatelli et al. (2020; CAPEX = ~80€/m^2 and OPEX = ~2.3 €/m^2/yr), Teotónio et al. (2018; CAPEX = ~21-98 €/m^2 and OPEX = ~0.5-12.1 €/m^2/yr) and Biasin et al. (2023; CAPEX = ~78€/m^2 and OPEX = 55 €/m^2/yr).

Comparing benefits and costs, results show that green roof benefits outweigh their costs when considering Low NBS costs (NPV of +2.6 million €/yr for Rapallo) – in line with Locatelli et al. (2020: Barcelona case study); while green roof costs outweigh their benefits when considering Medium (NPV of −0.9 million €/yr for Rapallo) and High (NPV of −3.5 million €/yr for Rapallo) NBS costs – in line with Biasin et al. (2023; Turin case study) and Locatelli et al. (2020: Badalona case study). Note, however, that under Medium and High NBS costs, flood risk mitigation benefits contribute to, respectively, 87 % and 63 % of the green roof annual implementation costs. Other hydrological-economic studies, which consider hybrid scenarios (i.e. combined green roof, other nature-based and grey solution scenarios), found similar results (see Alves et al., 2020; Velasco et al., 2018). Finally, BCR results show that the economic viability of green roofs differs across neighbourhoods – thus allowing for the economic prioritization of green roof implementation across neighbourhoods. Hence, depending on the context in which green roofs are implemented (such as climate conditions, soil characteristics, impermeabilization, assets/values at risk and implementation costs), green roofs can be either or not economically viable from a flood risk mitigation perspective alone.

It is argued that economically evaluating NBS flood risk mitigation services alone is reductive as it does not consider other ecosystem services and values (i.e. co-benefits) provided by NBS, such as temperature and air quality regulation, water quality regulation, biodiversity improvement, aesthetics and recreation. Alves et al. (2020), Biasin et al. (2023), Locatelli et al. (2020) and Velasco et al. (2018) assess NBS flood-risk mitigation benefits using spatially-explicit hydrological-economic approaches, while only Alves et al. (2020) and Locatelli et al. (2020) also consider NBS co-benefits using non-spatially explicit approaches (namely unit values and value transfer). Other studies assess NBS flood risk mitigation benefits and co-benefits using purely non-spatially explicit approaches (Claus & Rousseau, 2012; Mahdiyar et al., 2016; Teotónio et al., 2018). Although a wide range of co-benefits are provided by NBS, their integration into the decision-making process is limited due to the challenging monetization of the full range of ecosystem services. Additionally, the economic valuation methods are insufficient to represent all of them (Elmqvist et al., 2015). However, various business models have been identified that can facilitate an extended and broader monetization of NBS co-benefits. Some examples of business models are presented within EU NBS projects such as NATURVATION (Toxopeus, 2019) and GrowGreen (Trinomics & IUCN, 2019), while the European Investment Bank discusses the state-of-play and way forward to invest in NBS (European Investment Bank et al., 2023) and the European Business and Biodiversity Platform gives an overview of various case studies (Directorate General for Environment et al., 2024).

Self-evidently, the economic viability of NBS increases when also NBS co-benefits are considered (see Alves et al., 2020; Locatelli et al., 2020) and, hence, further research on the multiple spatially/context-specific ecosystem services and values provided by NBS is needed. This study contributes to previous studies by, first, assessing the flood-risk mitigation cost and benefits from NBS under current and future climate conditions using hydrological-economic approaches. To the knowledge of the authors, only Locatelli et al. (2020) and Velasco et al. (2018) did so before. Second, this study shows how open-source hydrological models (such as InVEST-UFRM) can be used to perform such hydrological-economic assessments – this in contrast with Locatelli et al. (2020) and Velasco et al. (2018) that use commercial hydrological models (namely InfoWorks ICM). Finally, none of the above-mentioned studies performed their NBS cost and/or benefit assessments at the neighbourhood scale – which is essential from a spatial planning perspective to prioritize NBS interventions across neighbourhoods (see e.g. (Locatelli et al., 2020; Quagliolo et al., 2022; Senosiain, 2020).

Some caveats remain. First, we used a time discount rate equal to zero – thus giving more weight to future benefits from NBS. In the field of climate change adaptation research, a zero/low discount rate is justified in policy evaluation to preserve ecosystem services and biodiversity as a prudent investment that secures future human well-being and reduces potentially catastrophic and irreversible effects (Dasgupta, 2021). Right-based ethics suggest that imposing substantial and uncompensated risks on posterity is morally wrong (Dasgupta, 2021; OECD, 2006; Stern, 2007). The Stern Review advocates considering a time discount rate of zero in the economics of climate change (Stern, 2007). Nevertheless, the sensitivity analysis with respect to time discount rate shows that even at positive time discount rates, green roofs can be economically viable from a flood mitigation perspective alone when considering Low NBS costs. Second, we did not consider co-benefits from NBS – thus underestimating the total future benefits of NBS. The focus of this study was on assessing, in a spatially/context-specific fashion, the flood risk mitigation costs and benefits from NBS as to prove the potential of a locally adapted approach to assess the economic viability of NBS for urban flood risk mitigation. We argue that when considering co-benefits in future studies, associated co-benefits should (when applicable) also be assessed in a spatially/context-specific fashion as (co-) benefits of NBS are highly context specific (see e.g. Van Zanten et al., 2023). Third, this study employs NBS costs derived from recent literature on this topic. There is often a lack of data on some specific NBS. Hence, the values are not context-specific, and can lead to rough estimates of investment and maintenance costs. Nevertheless, the sensitivity analysis with respect to NBS implementation costs (Low; Medium; High) shows that it does not impact the prioritization of green roofs across neighbourhoods. Finally, the assumption of 100 % green roof coverage, is useful to identify theoretical maximum benefits, but it is important to compare with most urban contexts which in practice do not reach this degree of implementation. Table 7 illustrates that, even in leading cities with robust regulatory and financial support such as Basel and Toronto, green roof adoption rarely exceeds 40–50 % of suitable surfaces (Dong et al., 2020; Zurich University of Applied Sciences Wädenswil (ZHAW), 2020). In many other cases, especially where adoption is voluntary or incentives are weak, coverage remains below 10 %. These disparities suggest that assuming universal adoption in Rapallo overestimates both flood mitigation potential and projected economic returns.

To enhance policy relevance, future analyses should be calibrated to local conditions from different case studies, including regulatory frameworks, public support, and technical capacity. An approach, grounded in the experiences of comparable cities, can offer a clearer view of cost-benefit trajectories under partial implementation. Additionally, observed adoption patterns indicate that large-scale rollout requires sustained policy commitment, targeted subsidies, and visible demonstration projects. Integrating such grounded assumptions into planning models would promote more actionable insights for municipalities.

5. Conclusions

This study presents a cost-benefit analysis (CBA) of the flood risk mitigation impacts, costs and benefits of NBS (green roofs) under future (2050) climate conditions for the city of Rapallo in Italy. Specifically, the InVEST-UFRM model is used to assess the biophysical effects of NBS on flood levels during rainfall events of different return periods and climate conditions, and the respective damages to buildings (structure and contents) are estimated. Benefit-transfer methods are used to assess the economic impacts of green roofs, and a CBA is performed by applying a constant time discount rate (equal to zero to obtain upper-bound estimates) to evaluate the economic viability of such solutions.

By quantitatively assessing green roof impacts, costs, and benefits at the neighbourhood level, this study shows the need for spatial assessment studies to support urban NBS development strategies. Specifically, this analysis provides insights into the most flooded neighbourhoods and, in parallel, the neighbourhoods that are expected to incur largest flood damage costs – thus supporting the decision on the most viable neighbourhoods for the implementation of NBS for flood risk mitigation. Finally, the CBA, one of the essential tools for assessing the economic value of NBS projects, helps urban planners justify implementing such solutions (Hekrle et al., 2023).

This study presents an integrated spatial biophysical-economic approach to assess the economic viability of NBS for urban flood risk mitigation in the face of climate change, which decision-makers and urban planners can use to weigh financial costs and benefits (Dasgupta, 2021; TEEB, 2009). Hence, decision-makers obtain a better understanding on the balance between what they spend and what they gain from implementing NBS and thus managing smarter decisions. This is important considering that economic assessments nowadays are insufficient to fully capture the benefits related to green roofs and NBS in cities, as many significant benefits are challenging to assess economically (Elmqvist et al., 2015). It is imperative to continue refining

Table 7
Adoption coverage of green roofs in different cities (derived from Dong et al. (2020)).

Country	City	Green roofs' adoption level
Switzerland	Basel	5.71 m^2 per person (the largest in the world)
Canada	Toronto	50 ha installed (2009–2018)
Japan	Tokyo	134.5 ha installed by 2015
USA	Portland	15.8 ha installed by 2015

economic valuation techniques to fully grasp the various (co-) benefits of NBS. Hence, further work must be conducted on spatially/context-specific valuation methods for multiple (co-) benefits of NBS, such as biodiversity improvements, temperature regulation, air and water purification, health benefits, aesthetics and real-estate valuation, and recreation and well-being.

CRediT authorship contribution statement

Carlotta Quagliolo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Roebeling:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Pezzoli:** Writing – review & editing. **Fábio André Matos:** Writing – review & editing, Data curation. **Max López-Maciel:** Writing – review & editing. **Elena Comino:** Writing – review & editing, Data curation.

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Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2025.106405.

Data availability

Data will be made available on request.

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