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Nature-based solutions for watershed management: An investigation on water-related ecosystem services delivery at multiple spatial scales

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ABSTRACT

The expansion of urban areas, driven by population growth and economic activities, places significant pressure on water resources, affecting both quality and quantity. Furthermore, climate change alters rainfall patterns, leading to more frequent and intense events in many cities. This increases the risk of flooding and water pollution, as drainage systems become more frequently exceeded and impervious surfaces rise.

In this context, Nature-Based Solutions (NBS) offer a way to address urban and societal challenges by mimicking natural processes like infiltration and evapotranspiration, thereby promoting the Ecosystem Services (ES) delivery. This research aims to identify the most effective NBS combination to tackle urban flooding challenges, by assessing the “water flow regulation” and “water quality regulation” ES.

Using hydrological modelling and ES assessments in the Seveso River watershed in Northern Italy, the study found that combining NBS for stormwater management with river restoration significantly reduces peak flow rates, discharged volumes, flooded areas and pollution, also improving the river ecological quality. Different NBS scenarios were evaluated across various spatial scales, demonstrating their ability to enhance ES. The results highlight NBS multifunctionality, not only improving “water flow regulation” and “water quality regulation” services, but also providing multiple co-benefits.

1. Introduction

The growth of urban areas poses a significant challenge for the future of the planet (Castelli et al., 2017). Cities are at the forefront of global changes, affecting urban ecosystems and societies, and face various pressures (Frantzeskaki et al., 2016). Urban residents confront serious issues such as air pollution, reduced access to green spaces, and health and socio-environmental justice concerns (Kabisch and Haase, 2014). Water-related challenges are particularly crucial, as water is essential for environmental and overall quality of life, from direct consumption to various human activities, and for maintaining biodiversity and ecosystems (Raymond et al., 2017). Indeed, the expanding urban population, alongside pollution and economic activities, places immense strain on water resources, impacting both quality and availability (Raymond et al., 2017). Climate change is expected to worsen these issues by altering rainfall patterns and temperature regimes, with many regions experiencing increased frequency of intense rainfall and prolonged dry spells (Praskievicz and Chang, 2009; Braud et al., 2013; Raymond et al., 2017; Moosavi et al., 2021). The rise of impervious surfaces due to urban development reduces infiltration and evapotranspiration (Walsh et al., 2005; Braud et al., 2013), leading to runoff that can exceed urban sewer systems capacity and increase flood risks for cities near rivers and coastlines (Castelli et al., 2017). Urban runoff can also harm water quality by introducing excess nutrients and sediments, causing eutrophication (Fletcher et al., 2013; McGrane, 2016). Furthermore, over the past two centuries, activities such as channelization, dam construction,

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Abbreviations: NBS, Nature-Based Solutions; CSOs, Combined Sewer Overflows; NDC, Northwest Diversion Channel; RP, Return Period; MQI, Morphological Quality Index; FFI, Fluvial Functionality Index; PP, Permeable Pavement; RG, Rain Gardens; GR, Green Roofs; SW, Swales; BIO, Bio-Retention Areas; RPD, Relative Percentage Difference; USEPA-SWMM, United States Environmental Protection Agency Stormwater Management Model; TSS, Total Suspended Solids; CICES, Common International Classification of Ecosystem Services; DTM, Digital Terrain Model; IDF, Intensity-Duration-Frequency; WFD, Water Framework Directive.

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and pollution have severely degraded urban river environments, impacting their morphology, ecology, and water quality (Merril and Gregory, 2007; Poff et al., 2007; Rahel, 2007; Wohl and Merritts, 2007; Bouska et al., 2010; Vörösmarty et al., 2010) and altering their capacity to offer drinking water, aesthetic value, recreation, and health benefits (Tvedt and Coopey, 2006; Grizzetti et al., 2016; Ekka et al., 2020). These changes have resulted in altered water regimes, erosion, and reduced natural self-regulation and purification abilities of rivers (Guerrero et al., 2018), diminishing the value of the benefits they provide to human well-being (Thorp et al., 2006; Grabowski and Gurnell, 2016).

Sustainable watershed and stormwater management, aimed at responsibly using resources to maintain water quantity and quality for future generations (Brown, 2003), is a key urban challenge (Raymond et al., 2017; Adem Esmail and Suleiman, 2020), addressed (despite some controversies in the implementation, see Voulvoulis et al., 2017) in European legislation, notably the Water Framework Directive (WFD European Commission, 2000) and the Floods Directive (European Commission, 2007). Traditionally, watershed and stormwater management have focused on risk management, using engineered solutions to channel runoff from urban areas downstream and prevent damage (Urbonas and Stahre, 1993; Barrow, 1998; Woods-Ballard et al., 2007; Moosavi, 2017). However, the ongoing growth of urban areas has made this approach impractical for protecting water resources (Albert et al., 2021; Moosavi et al., 2021). Since the 2000s, there has been a global shift towards a more holistic approach to water management, supported by initiatives like Sponge Cities, Water Sensitive Cities, and Daylighting rivers (Wild et al., 2011; Qiao et al., 2020; Fogarty et al., 2021; Yin et al., 2021; Carvalho et al., 2022; Fu et al., 2023). Such initiatives aim to restore the hydrological cycle in urban areas and enhance flood resilience by mimicking natural processes such as accumulation, infiltration, and evapotranspiration (Ballard et al., 2015).

These nature-based approaches tackle various environmental challenges (i.e. reducing urban runoff, enhancing water quality, restoring aquatic biodiversity) while offering numerous benefits to the society, economy and ecological systems (Moosavi et al., 2021). Due to their focus on multiple objectives and practical solutions through the use of nature and natural processes, the term “Nature-Based Solutions” (NBS) has become widely adopted (European Commission, 2015; European Commission, 2000; Moosavi et al., 2021; Tsatsou et al., 2023). NBS address issues like climate change, food and water security, disaster risk, human health, and socio-economic development (Lafortezza and Sanesi, 2019), through a combination of ecological, social and engineering approaches (Remme et al., 2024). As Remme et al. (2024) highlight, NBS are closely tied to the concept of Ecosystem Services (ES), which refer to the benefits ecosystems provide to human well-being (McVittie and Hussain, 2013; Geneletti et al., 2020). As Babí Almenar et al. (2018) point out, “ES are defined as flows (e.g. carbon sequestration, water purification) generated by ecosytems, as a result of ecological processes and exchanges of information (e.g. genetic information, visual appreciation of natural features)”. NBS influence the flow of these services (i.e. movement and distribution of benefits provided by natural ecosystems to humans and other ecosystem components, see Remme et al., 2024) by modifying the ecosystem’s functioning or by altering how people interact with the ecosystem (Babí Almenar et al., 2021; Remme et al., 2024). In this context, ES act as a mechanism through which NBS tackle urban challenges. The identification of which ES are targeted by NBS is fundamental to address these challenges (Khoshkar et al., 2020; Adams et al., 2023). Urban planning should be guided by ES assessment, as it helps identify solutions that target human benefits and support biodiversity (Costanza et al., 1997; Loomis et al., 2000; Wilkinson et al., 2013; Costanza, 2020). However, the integration of ES assessments into real-world policy remains a challenge and, in some cases, the original NBS projects are modified and adapted to altered objectives and new contingencies (Suleiman et al., 2020a; Suleiman et al., 2020b).

According to Harrison et al. (2018), ES assessment methods are typically categorized into biophysical, socio-cultural, and economic approaches. Biophysical methods quantify ES using models such as hydrological or ecological systems. Socio-cultural methods capture individual or collective preferences through stakeholder inputs, while economic methods express the value of ES in monetary terms. Over the years, effort has been made to propose and refine methodologies (see also SI Section S7), from the Millenium Ecosystem Assessment and the Economics of Ecosystems and Biodiversity (TEEB) classification to the Common International Classification of Ecosystem Services (CICES) (MA, 2005; Haines-Young and Potschin, 2012; McVittie and Hussain, 2013).

However, previous studies mainly provide a qualitative assessment of ES (Geneletti et al., 2020), lacking a quantitative framework to identify the optimal conversion scenario with NBS in urban watersheds. In this paper, we make an effort to quantify water-related ES, presenting a conceptual analysis and real-case application of the effectiveness of NBS for river restoration — reinstating natural processes that shape river landscapes and reducing human pressures (Wohl et al., 2005) — and stormwater management as integrated solutions to enhance the targeted ES.

Specifically, tested on the Seveso River watershed in Northern Italy, this approach aims to study the “water flow regulation” and “water quality regulation” ES and their potential enhancement derived from several NBS scenarios. ES were quantitatively assessed using indexes derived from hydrological simulation techniques. The solutions were applied across various spatial scales, from micro (community scale) to large scale (river watershed management), to identify the optimal combination of NBS types and spatial scales to address the target urban challenge. This application highlights the multifunctionality of NBS, extending their use beyond stormwater management to enhance a broader range of ES, such as improving river ecological quality, pollution control, carbon removal, and social benefits (Finewood et al., 2019).

2. Materials and methods

2.1. Study area

The Seveso River watershed is located in the north-western part of the Lombardy Region. The river originates near Como and flows towards Milan, where it is fully enclosed underground from the Ornato Street culvert to the Redefossi Channel (Fig. 1a). Further details about the Seveso River watershed and the specific areas selected for stormwater management at smaller scales are provided in the Supplementary Information (SI, Section S1).

The Seveso River has been selected as the pilot watershed due to its history of frequent flooding and poor environmental and water quality (Becciu et al., 2018; Ceppi et al., 2022; Gambini et al., 2024). To mitigate flooding, the Northwest Diversion Channel (NDC) was constructed in the 1950s; however, its effectiveness has diminished over time due to continued urban expansion (Becciu et al., 2018). In the municipalities of Bresso, Cormano, and Cusano Milanino, areas with high, medium, or low flood risk account for 26.5 % of the total land area. Additionally, around $9.4 \bullet 10^6$ m^2 in Milan also fall within these flood risk zones (Fig. 1e). Water quality, as assessed by the Water Framework Directive (WFD; European Commission, 2000), remains poor both chemically and ecologically. The Fluvial Functionality Index (FFI; Ispra, 2007), which identifies degraded sections needing protection, consistently ranks the area below the “sufficient” level (Fig. 1f), both for the left and the right banks.

The proposed NBS for river restoration are situated along a 2-km stretch of the river, upstream of the culvert, in the municipalities of Cormano and Bresso. This area is the only suitable location for NBS before the river is diverted underground (Fig. 1b). These interventions are part of the Seveso River Action Plan, though their implementation is currently delayed due to a lack of funding (CAP Holding, oral communication).

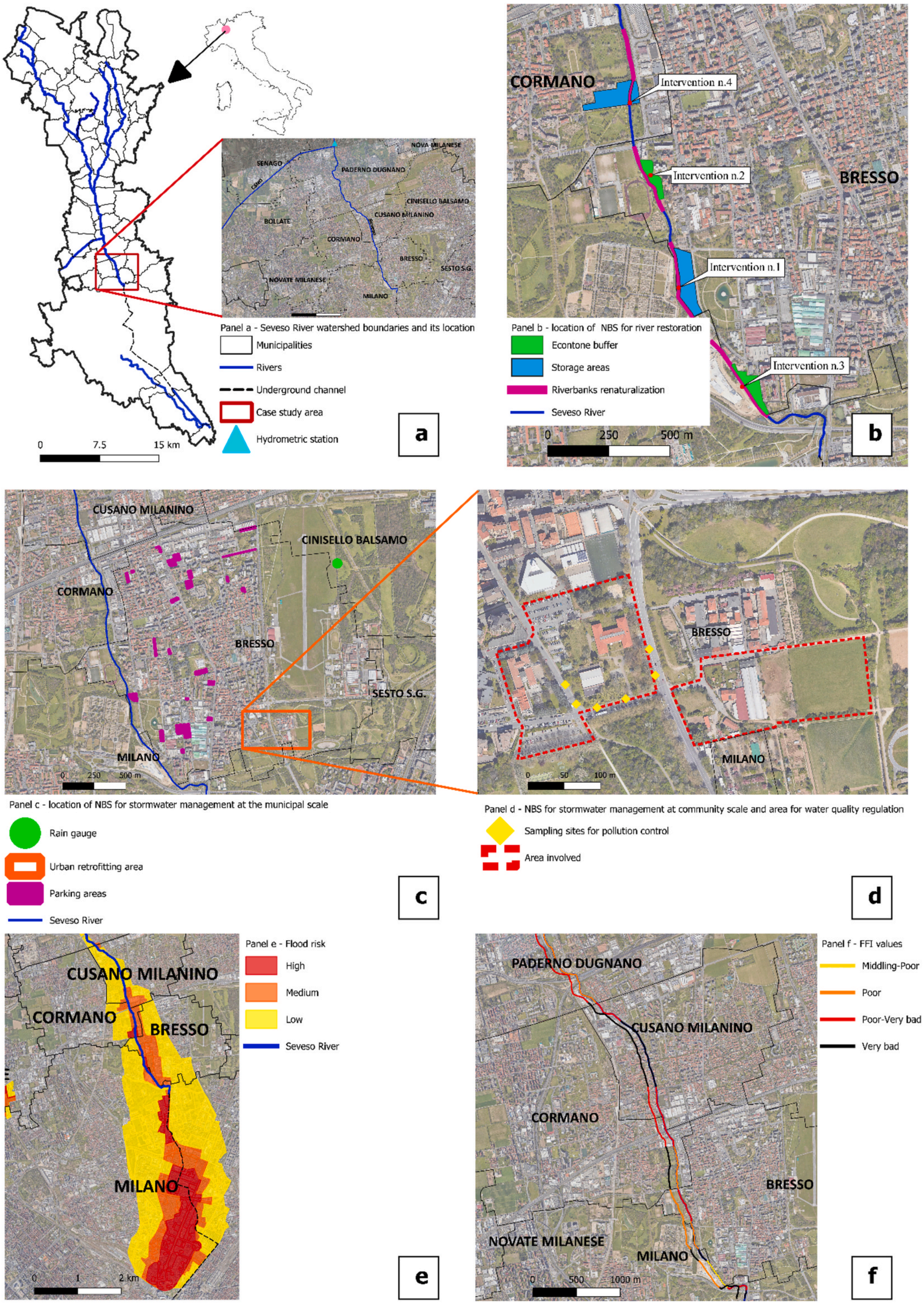


Fig. 1. Study area: Seveso River watershed boundaries and its location (Panel a); location of NBS for river restoration (Panels a and b); location of NBS for stormwater management at the municipal scale (Panel c) and community scale (Panel d) in Bresso municipality; Flood risk in the case study area (Panel e); FFI values for Seveso River in the case study area (Panel f).

For stormwater management, NBS were implemented at two spatial scales. At the municipal scale (Bresso) (Fig. 1c), a parking de-sealing with permeable pavement (PP) intervention was carried out (see Section 2.2). At the community scale (Fig. 1d), various NBS combinations (Section 2.2, Table 1) were applied in a redevelopment project, where new buildings are expected to increase the impervious surface area by approximately 5 %. This project involves the municipality of Bresso, water utilities CAP Holding, and Parco Nord, and is currently in the design phase.

The NBS for river restoration are located in high and medium flood risk areas, while the NBS for stormwater management are situated in medium and low flood risk zones (Fig. 1e), upstream of the higher-risk area in Milan. The effects of these integrated strategies were evaluated by considering the total area involved in both river restoration and stormwater control interventions.

Table 1
NBS for stormwater management at municipal and community spatial scale. NBS Footprint represents the physical surface occupied by the NBS, while NBS spatial ratio is the surface area occupied by NBS (NBS footprint) divided by the total intervention area.

Spatial scale	ID	Scenario	NBS Footprint [m^2]	Impervious area [m^2]	Total Area [m^2]	Impervious rate [%]	NBS spatial ratio [%]
Municipal	MSA	Municipal current state	N.A.	$1.3 \bullet 10^6$	$1.6 \bullet 10^6$	81.0	N.A.
	SDS	De-sealing (PP)	64,000	$1.3 \bullet 10^6$			4
Community	SA	Current state	N.A.	23,290	57,400	40.6	N.A.
	SB	New developments without control systems	N.A.	25,894		45.1	N.A.
	S1	PP only (all parking area)	5,929	19,965		34.8	10
	S2	BIO only (10 % of impervious area)	2,589	25,894		45.1	5
	S3	RG only (10 % of impervious area)	2,589	25,894		45.1	5
	S4	PP, GR, BIO, RG	9,446	17,713		30.9	16
	S5	only detention pond	1,600	25,894		45.1	3
	S6	PP, GR, BIO, RG, SW + detention pond	11,246	17,713		30.9	20

2.2. *Nature-based solutions planning*

Reconnecting floodplains in the southern part of the watershed was initially proposed as part of the river restoration plan to assess its potential benefits for flood risk mitigation, particularly in reducing the potentially flooded areas.

The proposed interventions involve the creation of three natural flood storage areas (see Fig. 1b). The first area, approximately 20,000 m^2, is located in Cormano and is currently fenced off and abandoned. The second area, around 3,500 m^2, is situated opposite the first and is currently used as a waste deposit site, which will undergo de-sealing. The third area, covering approximately 18,000 m^2 in Bresso, includes a public park and another waste deposit site, both of which will also be subject to de-sealing (Fig. 1b). In total, four types of interventions are planned: riverbank consolidation and renaturalization, diversification of riverbed morphology, and enhancement of riparian vegetation through the creation of ecotonal buffers, covering an area of 41,500 m^2. A detailed description of these interventions, with a particular focus on water quality and other ES, is provided in the SI (Section S2), highlighting the additional benefits they can offer.

For stormwater management, the conversion scenario at the municipal scale (parking de-sealing with permeable pavements PP) involves all the Bresso car parks identified through satellite image (See Table 1). A total area covered by parking lots and equal to 64,000 m^2 (corresponding to 4 % of the total municipal area considered of 160 ha) was converted to PP.

The interventions proposed at community scale, in a total area of 57,400 m^2 involved PP, rain gardens (RG), green roofs (GR), swales (SW), bio-retention areas (BIO) and a detention pond. Table 1 reports the eight different scenarios considered.

As for NBS footprint, which represents the physical surface occupied by the NBS, S4 derives from the sum of the areas of PP (5,929 m^2), GR (2,252 m^2) and BIO/RG (1,265 m^2) evaluated on the 5–10 % of the remaining impervious area; the size in S5 is exactly the size of the detention pond; S6 derives from the sum of the NBS proposed in S4, the detention pond (1,600 m^2) and SW (200 m^2).

A detailed description of the two interventions proposed (parking de-sealing with PP and combined NBS for stormwater controls) is available in the SI (Section S3).

2.3. *ES impact assessment of NBS scenarios*

In this research, the main focus is on the assessment of water-related ES of the CICES classification, for the groups of “water flow regulation” and “water quality regulation” (Table S11 in the SI), delivered by several NBS scenarios, to addresses the urban challenge of stormwater. The two considered ES groups both fall under the umbrella of the target ES (i.e. the primary ES we want to address) stormwater retention, primarily aimed at reducing the risk of flooding in urban areas through NBS, and consequently improving runoff infiltration and storage, as well as enhancing pollution control, reducing the transport of nutrients, and sediments (Remme et al., 2024). The two considered ES groups have been chosen since they are the most critical for all the watershed in very densely populated urban areas. The “water flow regulation” category includes services like runoff attenuation and water storage. Runoff attenuation is directly linked to fluvial and pluvial flood control, while infiltration controls with low release promote groundwater recharge and evapotranspiration. By coupling storage with infiltration, NBS help restore the natural water cycle that is altered in urban areas, where infiltration and evaporation rates decrease. Traditional detention tanks, on the other hand, do not achieve this restoration (Marchioni and Becciu, 2015; Marchioni et al., 2021a; Raimondi et al., 2022a,b, 2023).

In terms of “water quality regulation” services, NBS help reduce pollutant loads through filtration in permeable pavements (PP), sediment retention in swales (SW), and river restoration techniques. These processes enhance water quality through filtration and deposition (Marchioni et al., 2016; Marchioni et al., 2022).

For the ES assessment, an ecosystem indicator was defined to evaluate the capacity or potential of the ecosystem to deliver a service. Ecosystem indicators are divided into two main categories: i) demand indicators, which measure the societal need for ecosystem services, and ii) service indicators, which assess the ecosystem’s contribution to providing actual benefits that meet human needs (Veerkamp et al., 2021). Service indicators can reflect either the supply or flow of benefits and may be derived through empirical methods, modelling, or experimental approaches. Table 2 outlines the water-related ES indicators that were quantitatively assessed in this study.

The ES indicators for “water flow regulation” can be estimated using rainfall-runoff models and one-dimensional steady flow models (Section 2.3.1.). Specifically, for assessing fluvial peak flow attenuation resulting from river restoration interventions, the chosen indicator is the reduction in flooded area, expressed as the Relative Percentage Difference (RPD) between current and conversion scenarios. For NBS for stormwater management, peak flow and lag time are used to measure runoff peak flow attenuation. Additionally, the reduction in flooded areas is also employed as the indicator of the effectiveness of the integrated strategy combining NBS for both river restoration and stormwater management.

Water storage is especially important when applying NBS to mimic natural processes. In a natural environment, such processes manage significant volumes of stormwater through interception, small-scale depression storage, and infiltration. These mechanisms help to reduce surface runoff while also promoting groundwater recharge and evapotranspiration. The water storage indicators are the volume reduction before and after the conversion and the Stormwater Capture index (SWcapture). These indicators were evaluated for both spatial resolution (municipal and community scale). The volume reduction indicator checks if the placement of NBS would positively increase the efficiency in managing stormwater volume, while the stormwater capture index (SWcapture) links rainfall and runoff volume and can relate to the water

Table 2
Service indicator estimated quantitatively from the conversion scenarios.

Service Group	Service type	NBS group	Service indicator	Method	Spatial resolution	Contrast	Temporal resolution
Water flow regulation	Fluvial peak flow attenuation	River restoration (RR) alone + Coupled RR and stormwater	Flooded area reduction, RPD	One-dimensional steady flow model	Southern part of the watershed	Before and after conversion	Design-storm, Continuous simulation
	Runoff peak flow attenuation	Stormwater	Peak flow, Lag-time	Rainfall-runoff model	Municipal and community	Before and after conversion	Design-storm, Continuous simulation
	Water storage	Stormwater	Volume reduction		Municipal and community	Before and after conversion	Design-storm, Continuous simulation
			Stormwater Capture		Municipal and community	Rainfall/runoff	Continuous simulation
Water quality regulation	Filtration and deposition	Stormwater	Load removal	Pollutant build-up/wash-off model	Community	Before and after conversion	Design-storm, event-based
	Water conditions	River restoration	River ecological quality improvement	Fluvial Functionality Index (IFF)	Southern part of the watershed	Before and after conversion	N.A.

N.A.: not applicable.

cycle, indicating the parcel of the stormwater that does not translate into runoff.

SWcapture (Equation (1) ranges from 0 to 1 where for zero runoff the stormwater capture is equal to 1 as the entire rainfall is managed on-source (entirely captured). The index is 0 when the entire rainfall translates into runoff.

$$SW_{capture} = 1 - \frac{V}{P \bullet S} \tag{1}$$

where P represents the total precipitation, S the drained area and V the stormwater volume measured at the outlet.

For “water quality regulation”, “filtration and deposition” services (Table 2) were assessed by modelling the load removal capacity from the structures, with load removal being the selected indicator. The “water conditions” are assessed through the indicator “river ecological quality improvement” (See Section 2.3.2).

Except for water storage, all the ES indicators are compared before and after conversion scenarios with NBS. The temporal resolution, when applicable, includes design-storm, used for flood risk assessment correlating the storm events with a Return Period (RP), and continuous simulation (i.e. a simulation for the entire selected period including dry and wet days) for a typical hydrological year (2015) and for two months in 2014 (November and December) when multiple combined storms were recorded. Although water storage indicators were evaluated for both design-storm and continuous simulation scenarios, the latter is considered more significant: while design-storm analysis helps assess storm probability levels and flood risk, continuous simulation provides a more comprehensive view of the overall rainfall patterns essential for restoring the water cycle.

Table 3 shows the online data source for the “water flow regulation” and “water quality regulation” assessment.

Finally, a cost-benefit analysis was conducted to assess the economic sustainability of NBS for water quality and water flow regulation, compared to traditional approaches, taking into account energy savings and CO_2 emission reductions. The goal is to provide the essential information to assist Bresso municipality in selecting the most effective solution (Section S6).

2.3.1. “Water flow regulation” ES assessment

2.3.1.1. River restoration: One-dimensional steady flow model. A one-dimensional steady flow model was used to model the fluvial peak flood attenuation. The Hec-Ras one-dimensional steady flow model (Brunner, 1995) was used to derive the flood map. The Manning roughness coefficients for each cross section and land use were chosen following literature criteria (Cowan, 1956; Chow, 1959; Arcement and Schneider, 1989). The Ornato street culvert constitutes the downstream boundary condition and has been defined with an opening of 4x2 m and a maximum admissible flow rate equal to 35 $m^3 s^{-1}$ (Watershed Management Authority, oral communication).

Table 3
Data sources for river restoration and stormwater management models.

Data	**Data source**
Bresso car parks Satellite image	https://www.geoportale.regione.lombardia.it
Geometric characteristics of the cross sections along the entire course of the Seveso	https://www.adbpo.gov.it(https://www.geoportale.regione.lombardia.it)
Digital Terrain Model (DTM) of the Lombardy Region, with a 20x20 m resolution	https://www.geoportale.regione.lombardia.it
Land use geographic data	https://www.geoportale.regione.lombardia.it
Flood hydrograph upstream of the NDC were extracted for 10, 100, and 500-years RP	https://www.adbpo.gov.it
Continuously measured flow rates at the hydrometric station in the municipality of Paderno Dugnano, for the period 19 June 2014 – 5 November 2019	https://www.arpalombardia.it
IDF (Intensity-Duration-Frequency) curve parameters for Bresso municipality	https://idro.arpalombardia.it
Registered rainfall data for Cinisello Balsamo municipality (Fig. 1c)	https://www.arpalombardia.it
Current state Fluvial Functional Index (FFI)	https://flanet.org

Two floodable areas have been designed in Hec-Ras, one on the left side proceeding downstream (hydropraphic left) and one on the right side (hydrographic right) and south of the culvert by using road and railway embankments as limits visible in the satellite image, and by including the districts commonly affected by flooding (Fig. 1e). A green embankment structure, with a height of 1 m, was modeled to distinguish between the storage areas and the designated floodable zones. In the three storage areas (Fig. 1b), the riverbank is lowered to allow the river to expand once the culvert reaches its maximum drainage capacity. To ensure the areas can fully drain after a flood and restore their reservoir capacity for future events, a gate has been installed in each area. The gate opens when the water level in the storage area exceeds that of the nearest section. For each 10, 100, and 500-years RP, 24-hours duration, two simulations were carried out, one that represents the current state and one that considers the three storage areas and their simultaneous functioning. As input data, the hydrographs upstream of the NDC, provided by the Autorità di Bacino Distrettuale del Fiume Po (AdbPo), were reduced by 30 $m^3 s^{-1}$ at each time step for each RP, assuming that the bypass NDC operates fully during flood periods.

The flow rates measured at Paderno Dugnano were recalculated to account for the flow derived from the NDC, before carrying out our four additional continuous simulations, referred to particularly relevant events that caused flooding and damage in the northern part of Milan: 23 June – 14 July 2014 and 3 – 27 November 2014, characterized by a maximum flow with a 100-years RP; 31 July – 8 August 2016 characterized by two peaks five days apart; 19 June – 7 July 2018 with a peak flow rate of 63 $m^3 s^{-1}$, corresponding to an RP lower than 10 years.

The design-storm selection was based on storm events analyzed in the Flood Management Plan by the Watershed Management Agency. These events are considered the reference design-storm for the Seveso Watershed. The recorded storm events matched those that caused flooding in Milan and were widely reported in the media, facilitating the acquisition of data for model calibration.

Calibration was carried out comparing the results from simulations with the flood maps from the regional Watershed Management Agency and media information about registered flood events in Milan.

2.3.1.2. Stormwater management: Rainfall-runoff model. The United States Environmental Protection Agency Stormwater Management Model (USEPA-SWMM) rainfall-runoff routing model (Rossman, 2010) was utilized to estimate the "water flow regulation" indicators for the stormwater NBS, specifically peak flow attenuation and lag time. The Low Impact Development (LID) section of the model was used to account for the NBS proposed, each represented by multiple overlapping layers. The layers can be three or four depending on NBS typology. The first layer is a surface layer capable of supporting vegetation, followed by a second layer of engineered soil, designed with specific characteristics to facilitate water infiltration and partial treatment. The third layer functions as a storage layer. For permeable pavements (PP), an additional flooring layer is included. The study involved the following stormwater control measures: green roofs (GR), rain gardens (RG), bio-retention areas (BIO), permeable pavements (PP), and swales (SW). For each of these measures, the parameters (such as layer thicknesses, slopes, vegetation coverage, etc.) were sourced from the literature (Ngan, 2012; Stormwater Management Guidebook, 2013; Ballard et al., 2015) and are provided in the SI (Section S3). A lumped model was used for the municipal scale, while a semi-distributed model was employed for the community scale, enabling the assessment of lag time for the design-storm events. As regard temporal resolution, the simulations for the municipal scale (parking de-sealing with PP) and for the community scale (NBS combination scenarios) interventions were conducted considering the following design-storms: 1-hour Chicago storm and a 24-hours constant-rainfall-intensity storm with 2, 10, 50, 100-years RT, with the IDF (Intensity-Duration-Frequency) curve parameters for Bresso municipality. Additionally, the continuous simulation for the typical hydrological year 2015, as well as for the period from November to December 2014, incorporated data from the nearest rain gauge located in the municipality of Cinisello Balsamo (Fig. 1c). This gauge recorded a total rainfall depth of 756 mm and a maximum rainfall intensity of 90 mm h^{-1}.

For the rainfall-runoff simulations, which assess both peak flow and volume within the water flow service, short-duration storm events with higher intensity were chosen to highlight peak flow, while longer events, which yield larger storm volumes, were selected to verify the storage capacity of the structures.

Since this study conducts an initial sensitivity analysis using an analytical approach to aid in design optimisation, the lack of measured data for model calibration and validation did not present a significant limitation. The primary aim was to compare scenarios to identify a preliminary optimal solution, which can subsequently undergo further data-driven evaluation.

2.3.1.3. Coupled river restoration and stormwater NBS. The integrated effect of NBS for river restoration and stormwater management was studied combining the results of the previous analyses, where the hydrographs obtained from rainfall-runoff simulation were used as input for the steady flow model, obtaining a flood map. For the NBS, the outgoing hydrographs from Bresso were obtained considering first the PP only (parking de-sealing) and, then the S6 scenario (PP, GR, BIO, RG, SW + detention pond, see Table 1) among the NBS combination scenarios. For the areas without NBS interventions the input hydrographs were modelled considering the parameters (areas and imperviousness) available from AdbPo. The default values for the unknown parameters were considered.

Two simulations, with temporal resolution of design-storms of 24-hours duration, 10 and 100-years RP, and Chicago storm with 0.3 time to peak (i.e. the time to reach the peak flow), were carried out. These storm events were chosen according to the Flood Management Plan, as these are considered critical for Seveso River by the Watershed Management Authority.

2.3.2. "Water quality regulation" ES assessment

2.3.2.1. Pollutant build-up/wash-off. For water quality regulation from stormwater NBS the service indicator pollutants load removal was obtained by modelling pollutant build-up/wash-off coupled with the rainfall-runoff routing using USEPA-SWMM. The evaluation was conducted solely for the community NBS combinations, as the limited spatial extent of municipal parking de-sealing with PP would have a minimal impact on load removal, given that the area covered by the PP is small relative to the entire watershed. The water quality model of USEPA-SWMM allows to simulate the build-up and the wash-off for each considered pollutant and to define categories of pollutants by evaluating their accumulation, removal, and propagation in the drainage network (Rossman, 2010). The exponential function on Equation (2) is used to represent the build-up of total suspended solids (TSS, Maglionico, 2007; Bolognesi and Maglionico, 2009).

$$M_a(t_s) = \frac{Accu}{Disp} \bullet (1 - e^{-Disp \bullet t_s}) \tag{2}$$

in which M_a is the mass accumulation in kg ha^{-1} d^{-1}, *Accu* is the accumulation coefficient rate in kg ha^{-1}, *Disp* is the coefficient of dispersion in d^{-1}, while t_s represents the days of dry time. For the wash-off phase Equation (3) is used:

$$\frac{dM_a}{dt} = -Arra \bullet P^{wash} \bullet M_a \tag{3}$$

in which *Arra* is the wash-off coefficient in mm^{-wash} $h^{(wash-1)}$, P is the net rainfall intensity in mm h^{-1}, *wash* is the dimensionless exponent and M_a is the mass accumulated when the rainfall starts in kg. The TSS (Total Suspended Solids) was the defined pollutant for the simulations as function of carrier for other pollutants as nutrients and heavy metals, especially the finer fractions (Sansalone et al., 1995; Sansalone and Buchberger, 1997; Sansalone and Cristina, 2004; Kim and Sansalone, 2008; Liu and Sansalone, 2022; Gnecco et al., 2019). Although most of the TSS are washed away in the first part of the precipitation (''first flush''), some studies suggest that to obtain good water chemistry it is necessary to treat the entire runoff and not just the one generated during the "first flush" (Sansalone et al., 1995; Sansalone and Buchberger 1997).

To determine the build-up *Accu* parameters for TSS, particulate matter sampling was carried out along the three main streets that delimit the community (Fig. 1d). Each sampling was carried out by sweeping the portion of the road adjoining the sidewalk for a width of about 0.3 m and a length of 10 m. Sampling was repeated two times for each street giving a total of 6 samples. The activity was carried out the day before the streets sweeping, which takes place once a week, and more than a month later from the last precipitation. The characteristics of the sampled roads are shown in Table 4. The samples were then weighed in the laboratory.

To calculate *Accu*, a value of 0.08 d^{-1} for Disp (Marchioni et al., 2021b), and a value of 33 days for ts were assumed, the latter corresponding to the number of preceding dry days. Considering a street sweeping efficiency equal to 80 % and by carrying out the weighted average based on the length of the roads sampled, an *Accu* value equal to 51.36 kg ha^{-1} d^{-1} was obtained through the Equation (2). The wash-off parameters were selected in agreement with studies and experiments conducted on areas considered similar and therefore set equal to 0.1 for *Arra* and 1 for *wash* (Bolognesi and Maglionico, 2009; Maglionico, 2007).

The temporal resolution was the same of the "water flow regulation" services for the continuous simulations, while for single storm-event, 1, 12, and 24-hours duration constant-rainfall-intensity storm, with 50 and 100-years RP were considered. The selection of single-storm events was intended to analyse both pollution build-up and wash-off effects for a relatively short event as well as two longer events. NBS such as rain gardens, are typically designed to manage the first flush rather than the entire volume of runoff. Therefore, evaluating a range of events with durations from 1 to 24 h allows for a comprehensive assessment of their effectiveness in managing the runoff.

2.3.2.2. Fluvial Functionality Index (FFI). The "river ecological quality improvement" indicator is assessed through the Fluvial Functionality Index (FFI; Ispra 2007), which is compliant with the requirements of the WFD. The FFI comprises 14 questions addressing key ecological characteristics of a watercourse (Table 10), each scored between a minimum of 1 and a maximum of 40, based on options provided in the FFI form (Section S5, Table S7). Higher scores reflect a more favorable functional state for the characteristic assessed. The overall FFI score, ranging from 14 to 300 and linked to a functionality rating (Section S5, Table S8), is calculated by summing the scores for each question. Details are reported in the SI (Section S5).

In this study, the FFI was evaluated by considering the proposed NBS for river restoration, which impact 14 parameters contributing to the score, and was compared to the current state.

3. Results

Service indicators are reported by service group and service type as described in Table 2. For the NBS for stormwater management, services are reported on municipal and community spatial scale.

3.1. Water flow regulation

3.1.1. Fluvial peak flow attenuation for river restoration NBS

The simulations carried out using hydrographs with a 10, 100, and 500-years RP, show that the areas involved in flooding in the conversion scenario are always smaller than the current ones (Table 5 and Fig. 2a and 2b).

A significant reduction in flooded areas was observed during recorded storm events, particularly in June-July 2018 and July-August 2016, which saw the greatest peak flow attenuation (RDP 59.4 %, as shown in Table 5). During the storm events of June–July 2014 (Fig. 2c) and November 2014, the positive impact of the storage areas was less evident, as flow rates approached those of 100-year RP events. NBS typically perform optimally during more frequent, moderate storm events, while less frequent, extreme events—such as a 100-year storm—demand larger storage structures to maintain effective performance.

Table 4
Characteristics of sampled roads.

Road name	Length [m]	Slope	Pavement type
Villoresi	615	2 %	Asphalt
Don Vercesi	458		
XX Settembre	485		

Table 5
Potentially flooded areas comparison and flooded area reduction indicator.

Temporal resolution	Flooded area time assessment	Flooded areas **Before conversion** [10^6 m^2]	**After conversion** [10^6 m^2]	**Relative Percentage Difference (RPD)** [%]
24-hours 10-years RP	5 h after the beginning	5.0	4.0	19.0
24-hours 100-years RP	5 h after the beginning	6.3	5.5	12.7
24-hours 500-years RP	5 h after the beginning	8.4	6.2	26.2
23rd June – 14th July 2014	8th July 2014, 05:30	6.3	5.4	14.3
3rd – 27th November 2014	15th November 2014, 20:30	8.5	8	5.9
31st July – 8th August 2016	7th August 2016, 00:00	3.2	1.3	59.4
19th June – 7th July 2018	5th July 2018, 08:00	2.4	1.1	54.2

In the conversion scenario, water levels in the flooded areas were reduced by 0.03–0.05 m, but only during the 2016 and 2018 storms. Furthermore, for these two events, the maximum flow velocity in the conversion scenario was about 50 % lower compared to the current scenario, and flooding onset was delayed by 30 min. The July-August 2016 and November 2014 events are interesting, as they show two close-range peaks. In 2016, the first peak (approximately 48 m^3 s^{-1}) appears to be fully managed by the system, while in 2014, the system proved insufficient due to the 100-year RP storm event, with flow rates consistently exceeding the culvert flow limit of 35 m^3 s^{-1} and peaks reaching 73 and 120 m^3 s^{-1} within three days.

3.1.2. Runoff peak flow attenuation for stormwater NBS

3.1.2.1. Municipal scale. Runoff peak flow attenuation for the NBS at municipal scale with the parking de-sealing with PP is reported in Table 6. NBS in the form of PP were applied to an area that constitutes 4 % of the total municipal area, resulting in peak flow attenuation between 5 % and 7 %, depending on the temporal resolution. Lag time delay was neglectable and thus not reported considering the small area effectively occupied by the PP. As expected, for design-storm events, attenuation decreases as RP slightly increases: with higher RP values, the intensity and volume of storm events increase, leading to a decline in NBS performance. Peak flow attenuation becomes less effective as the RP extends: with higher intensity, the NBS structures may struggle to cope with the full scale of the storm, which is reflected in both peak flow attenuation and the time to peak. Indeed, when looking to storm duration, there is a substantial difference between a 1-hour storm (5.6 % peak flow attenuation, 2-year RP) and 24-hour storm (8.0 % peak flow attenuation, 2-year RP), as the small storage available from PP have a more relevant impact in a longer storm. When considering continuous simulation, the maximum peak flow attenuation for a typical hydrological year (2015) was 6.5 %.

3.1.2.2. Community scale. Results on peak flow attenuation and lag time delay are presented in Table 6. The findings indicate that in the SB

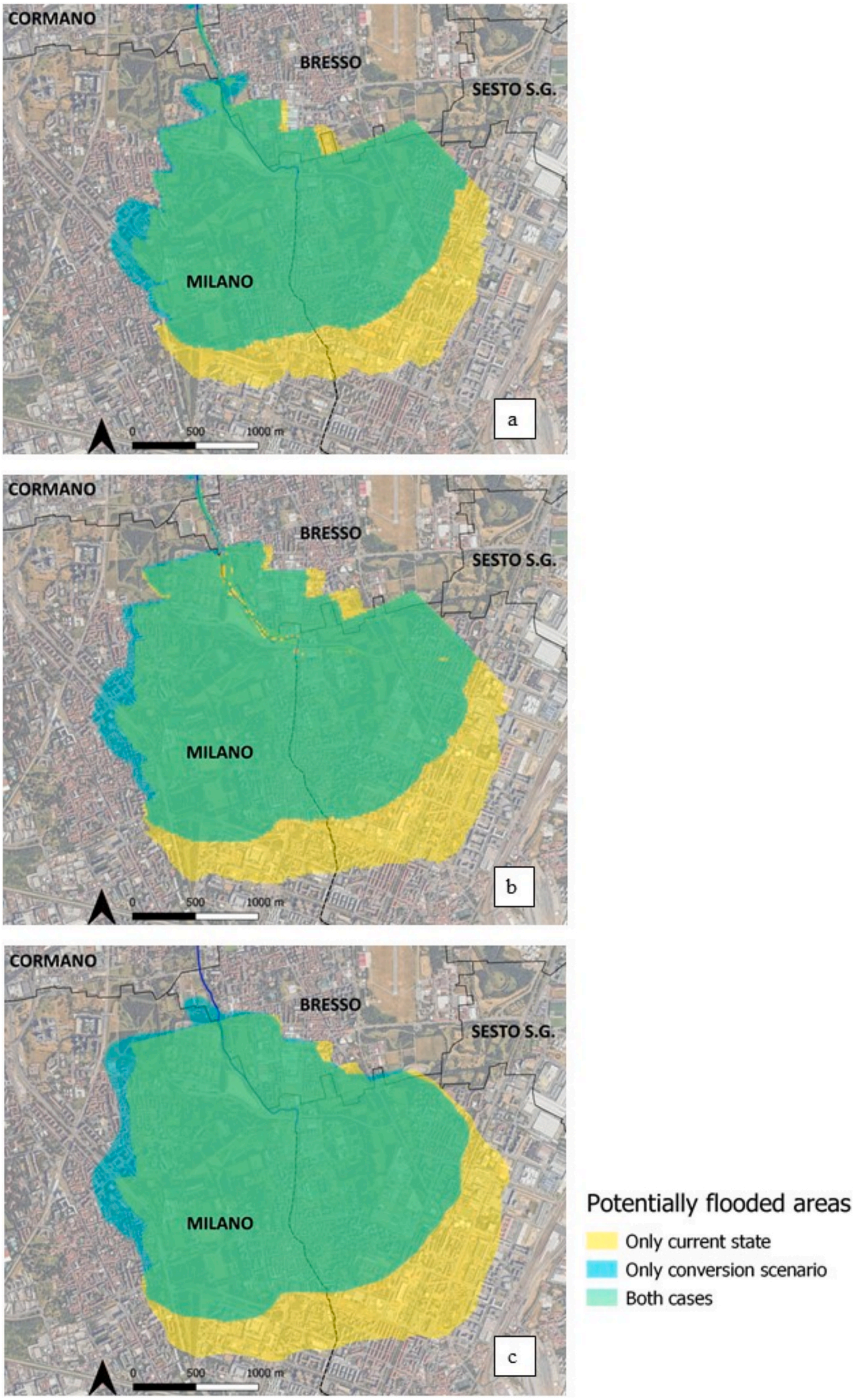


Fig. 2. Potentially flooded areas: for a 24-hours 10-years RP (Panel a), for a 24-hours 100-years RP (Panel b), for the period June-July 2014 (Panel c).

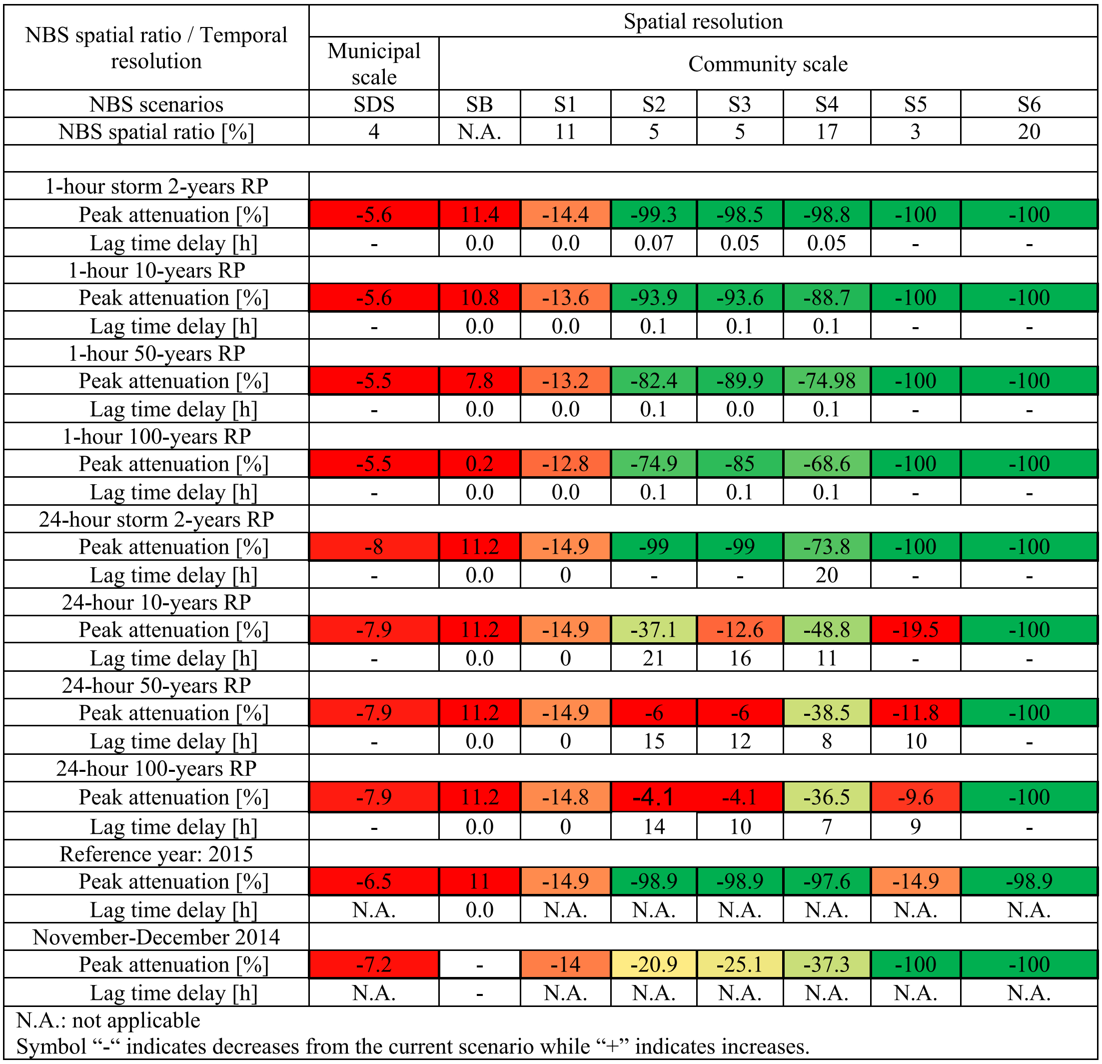
scenario, peak flow and volume increase by approximately 10 %. However, the introduction of NBS leads to significant reductions in both indicators. Notably, PP alone achieve reductions of around 15 %. These reductions are significantly enhanced when multiple NBS techniques are combined. For example, in S6, the simultaneous use of multiple NBS approaches, along with a detention pond designed to manage any excess runoff not addressed by upstream controls, can achieve the zero-discharge target.

Except for S1, all the scenarios promote lag time delay. The efficiency tends to decrease as the RP increases but remains significant. Details about the NBS performance parameters are reported in the SI (Section S4).

3.1.3. Water storage

Table 7 reports the volume reduction indicator and Fig. 3 shows the Stormwater Capture Index for both municipal and community scale interventions. Volume reduction is not reported for SB scenario, as volume would increase after the increase of impervious area.

Table 6
Runoff peak flow attenuation and lag time delay. The lag time delay is not reported for the continuous simulation as there are multiple storm events and therefore multiple lag times. '-' means no changes in lag time delay. The colors range from red (indicating minor reduction) to green (indicating greater reduction).



NBS spatial ratio / Temporal resolution	Spatial resolution							
	Municipal scale	Community scale						
NBS scenarios	SDS	SB	S1	S2	S3	S4	S5	S6
NBS spatial ratio [%]	4	N.A.	11	5	5	17	3	20
1-hour storm 2-years RP								
Peak attenuation [%]	-5.6	11.4	-14.4	-99.3	-98.5	-98.8	-100	-100
Lag time delay [h]	-	0.0	0.0	0.07	0.05	0.05	-	-
1-hour 10-years RP								
Peak attenuation [%]	-5.6	10.8	-13.6	-93.9	-93.6	-88.7	-100	-100
Lag time delay [h]	-	0.0	0.0	0.1	0.1	0.1	-	-
1-hour 50-years RP								
Peak attenuation [%]	-5.5	7.8	-13.2	-82.4	-89.9	-74.98	-100	-100
Lag time delay [h]	-	0.0	0.0	0.1	0.0	0.1	-	-
1-hour 100-years RP								
Peak attenuation [%]	-5.5	0.2	-12.8	-74.9	-85	-68.6	-100	-100
Lag time delay [h]	-	0.0	0.0	0.1	0.1	0.1	-	-
24-hour storm 2-years RP								
Peak attenuation [%]	-8	11.2	-14.9	-99	-99	-73.8	-100	-100
Lag time delay [h]	-	0.0	0	-	-	20	-	-
24-hour 10-years RP								
Peak attenuation [%]	-7.9	11.2	-14.9	-37.1	-12.6	-48.8	-19.5	-100
Lag time delay [h]	-	0.0	0	21	16	11	-	-
24-hour 50-years RP								
Peak attenuation [%]	-7.9	11.2	-14.9	-6	-6	-38.5	-11.8	-100
Lag time delay [h]	-	0.0	0	15	12	8	10	-
24-hour 100-years RP								
Peak attenuation [%]	-7.9	11.2	-14.8	-4.1	-4.1	-36.5	-9.6	-100
Lag time delay [h]	-	0.0	0	14	10	7	9	-
Reference year: 2015								
Peak attenuation [%]	-6.5	11	-14.9	-98.9	-98.9	-97.6	-14.9	-98.9
Lag time delay [h]	N.A.	0.0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
November-December 2014								
Peak attenuation [%]	-7.2	-	-14	-20.9	-25.1	-37.3	-100	-100
Lag time delay [h]	N.A.	-	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

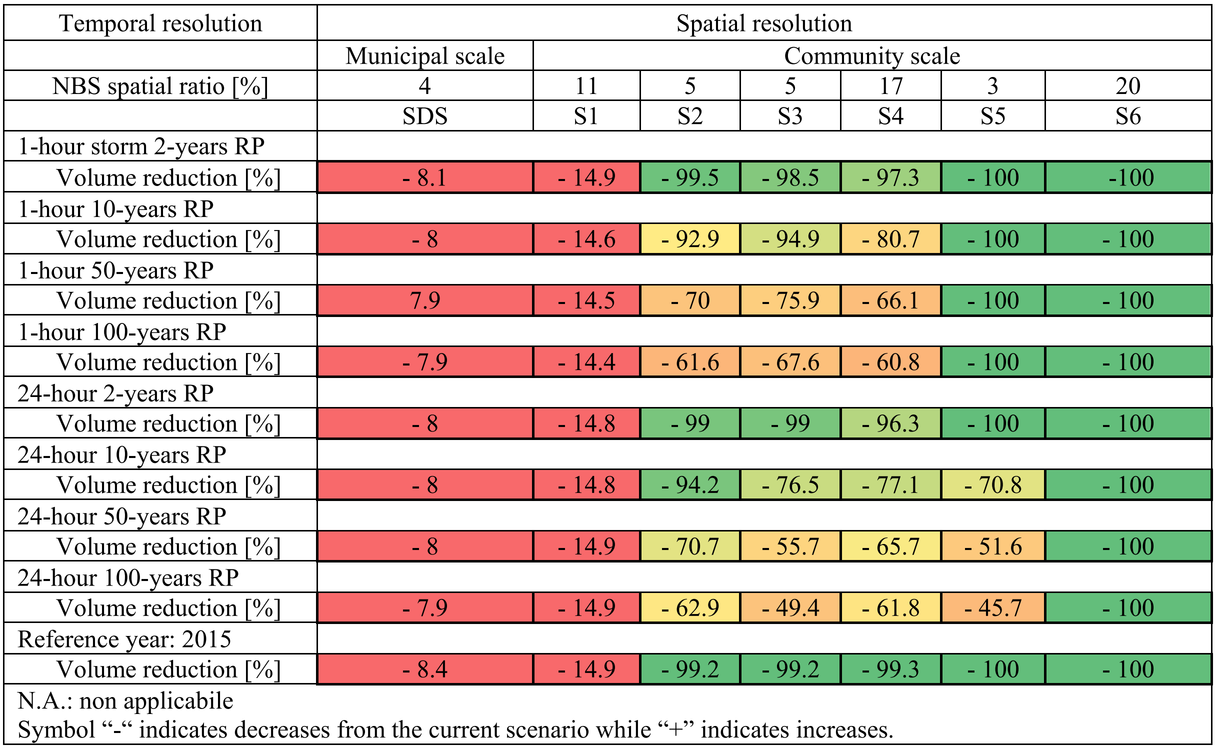
N.A.: not applicable
Symbol "-" indicates decreases from the current scenario while "+" indicates increases.

N.A.: not applicable.
Symbol "-" indicates decreases from the current scenario while "+" indicates increases.

3.1.3.1. Municipal scale. With a 4 % spatial ratio of NBS implementation, parking de-sealing with PP results in an 8 % volume reduction at the municipal level and an 8.4 % reduction on an annual basis (Table 7). The Stormwater Capture Index (Fig. 3) for the typical hydrological year 2015 reflects the expected scenario for a densely urbanized area with impervious surfaces, showing a capture index of 0.13 for the MSA, indicating that only 13 % of rainfall is captured. By implementing NBS for parking de-sealing with PP, the stormwater capture increases to 0.2. This is a positive step but emphasizes the need for further interventions to restore the area's water cycle. For scenarios S2-S5 (Table 7) the volume reductions are above 50 % for both design storm and continuous simulation. As expected, the NBS perform optimal for frequent storms (2-year storm) but still prove to be efficient for scenarios above 10-year storm.

3.1.3.2. Community scale. At community scale, where the NBS spatial ratio ranges from 3 % to 20 % the volume reduction service delivery ranges for the year-based simulation from 14.9 % to 100 %, with 100 % indicating that the entire rainfall of reference year was on-source managed.

Table 7
Volume reduction service for municipal and community scale interventions for design-storm simulations.



Temporal resolution	Spatial resolution						
	Municipal scale	Community scale					
NBS spatial ratio [%]	4	11	5	5	17	3	20
	SDS	S1	S2	S3	S4	S5	S6
1-hour storm 2-years RP							
Volume reduction [%]	- 8.1	- 14.9	- 99.5	- 98.5	- 97.3	- 100	-100
1-hour 10-years RP							
Volume reduction [%]	- 8	- 14.6	- 92.9	- 94.9	- 80.7	- 100	- 100
1-hour 50-years RP							
Volume reduction [%]	7.9	- 14.5	- 70	- 75.9	- 66.1	- 100	- 100
1-hour 100-years RP							
Volume reduction [%]	- 7.9	- 14.4	- 61.6	- 67.6	- 60.8	- 100	- 100
24-hour 2-years RP							
Volume reduction [%]	- 8	- 14.8	- 99	- 99	- 96.3	- 100	- 100
24-hour 10-years RP							
Volume reduction [%]	- 8	- 14.8	- 94.2	- 76.5	- 77.1	- 70.8	- 100
24-hour 50-years RP							
Volume reduction [%]	- 8	- 14.9	- 70.7	- 55.7	- 65.7	- 51.6	- 100
24-hour 100-years RP							
Volume reduction [%]	- 7.9	- 14.9	- 62.9	- 49.4	- 61.8	- 45.7	- 100
Reference year: 2015							
Volume reduction [%]	- 8.4	- 14.9	- 99.2	- 99.2	- 99.3	- 100	- 100

N.A.: non applicabile
Symbol "-" indicates decreases from the current scenario while "+" indicates increases.

N.A.: non applicabile.
Symbol "-" indicates decreases from the current scenario while "+" indicates increases.

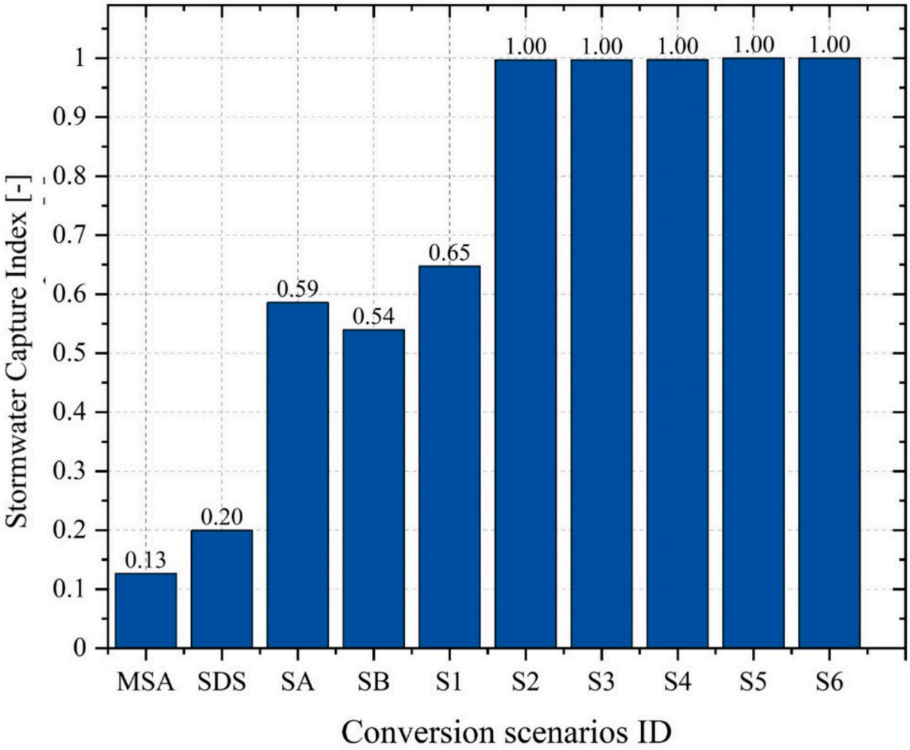


Fig. 3. Stormwater Capture Index for municipal and community scales for the reference year 2015.

3.1.4. Fluvial peak flow attenuation for coupled river restoration and stormwater controls

For a 10-year RP storm event (Table 8), parking de-sealing with PP at the municipal level results in an additional 0.6 % reduction in potentially flooded areas compared to the river restoration strategy. Community-scale NBS interventions achieve an additional reduction of approximately 1.1 %. Overall, applying NBS stormwater controls to less than 10 % of the municipality of Bresso leads to an extra 1.7 % reduction in flooded areas compared to the river restoration strategy alone. When both strategies are integrated, the reduction in potentially flooded areas reaches 21 % (see also Fig. S14 in the SI). For a 100-year RP storm event, the additional reduction from NBS implementation is significantly lower due to the small portion of watershed involved on the river restoration activities.

Table 8
Potentially flooded areas 4 h after flooding beginning (10-years RP – 24-hours) for different scenarios.

Scenario	Flooded area [10^6 m^2]	Relative Percentage Difference RPD [%]
Current scenario (downstream NDC)	4.97	–
River restoration	4.01	19.3
River restoration + parking de-sealing	3.98	19.9
River restoration + parking de-sealing + NBS combination scenarios	3.92	21.0

3.2. Water quality regulation

3.2.1. TSS load removal for stormwater

The “water quality regulation” service for stormwater was assessed through build-up and wash-off modelling for the TSS pollutants load. Fig. 4 shows the trend of the TSS load concentration in the wash-off stormwater for all scenarios for a 50-years RP 1-hour duration storm-event.

For the simulations with design-storm, the SB and S1 scenarios show the same trend as the SA scenario, with TSS load increasing for the expansion scenario (SB) and slightly decreasing for S1 (Table 9). For the S2, S3 and S4 scenarios, although not completely avoiding the pollutants load as for S5 and S6, the cumulative value is much lower than for S1, SA and SB. Similarly to runoff peak flow and volume, the best performance for quality control is also achieved through a combination of NBS. All the other scenarios, except for S5 and S6, for which zero-discharge is observed, show almost zero values initially, thus managing to capture the ‘‘first flush’’ which has the highest concentration of pollutants normally. As the storage capacity is completely unavailable, part of the storm overflows, but at this point the first flush was retained.

Table 9 reports the pollutants load wash-off as total cumulated TSS for the entire storm-event for the current scenario and the load removal performance rate for the conversion scenarios. The SB scenario results in an increase of TSS ranging from 7-11 % in comparison with the current state scenario (SA) as the impervious surfaces increase.

The introduction of PP alone (S1) reduces the pollutants load by

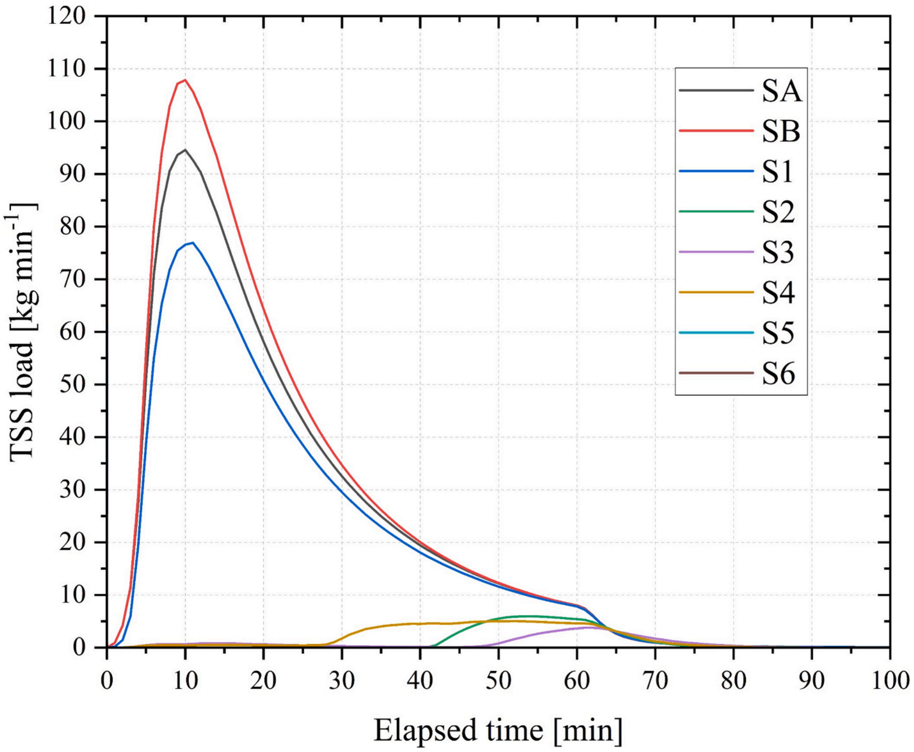
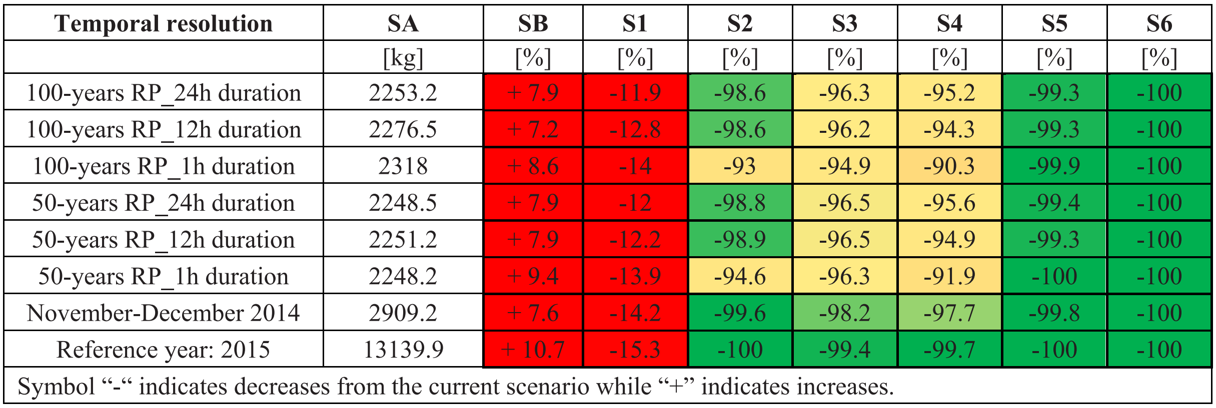


Fig. 4. TSS loads released from the watershed [kg min-^{1}] for 1-hour 50-years RP event.

Table 9
TSS cumulated wash-off for SA and RPD for load removal performance rate for current and conversion scenarios.



Temporal resolution	SA	SB	S1	S2	S3	S4	S5	S6
	[kg]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
100-years RP_24h duration	2253.2	+ 7.9	-11.9	-98.6	-96.3	-95.2	-99.3	-100
100-years RP_12h duration	2276.5	+ 7.2	-12.8	-98.6	-96.2	-94.3	-99.3	-100
100-years RP_1h duration	2318	+ 8.6	-14	-93	-94.9	-90.3	-99.9	-100
50-years RP_24h duration	2248.5	+ 7.9	-12	-98.8	-96.5	-95.6	-99.4	-100
50-years RP_12h duration	2251.2	+ 7.9	-12.2	-98.9	-96.5	-94.9	-99.3	-100
50-years RP_1h duration	2248.2	+ 9.4	-13.9	-94.6	-96.3	-91.9	-100	-100
November-December 2014	2909.2	+ 7.6	-14.2	-99.6	-98.2	-97.7	-99.8	-100
Reference year: 2015	13139.9	+ 10.7	-15.3	-100	-99.4	-99.7	-100	-100
Symbol "-" indicates decreases from the current scenario while "+" indicates increases.								

Symbol "-" indicates decreases from the current scenario while "+" indicates increases.

approximately 12–15 %. These percentages exceed 90 % in all other scenarios, especially S6, where pollutants are removed totally.

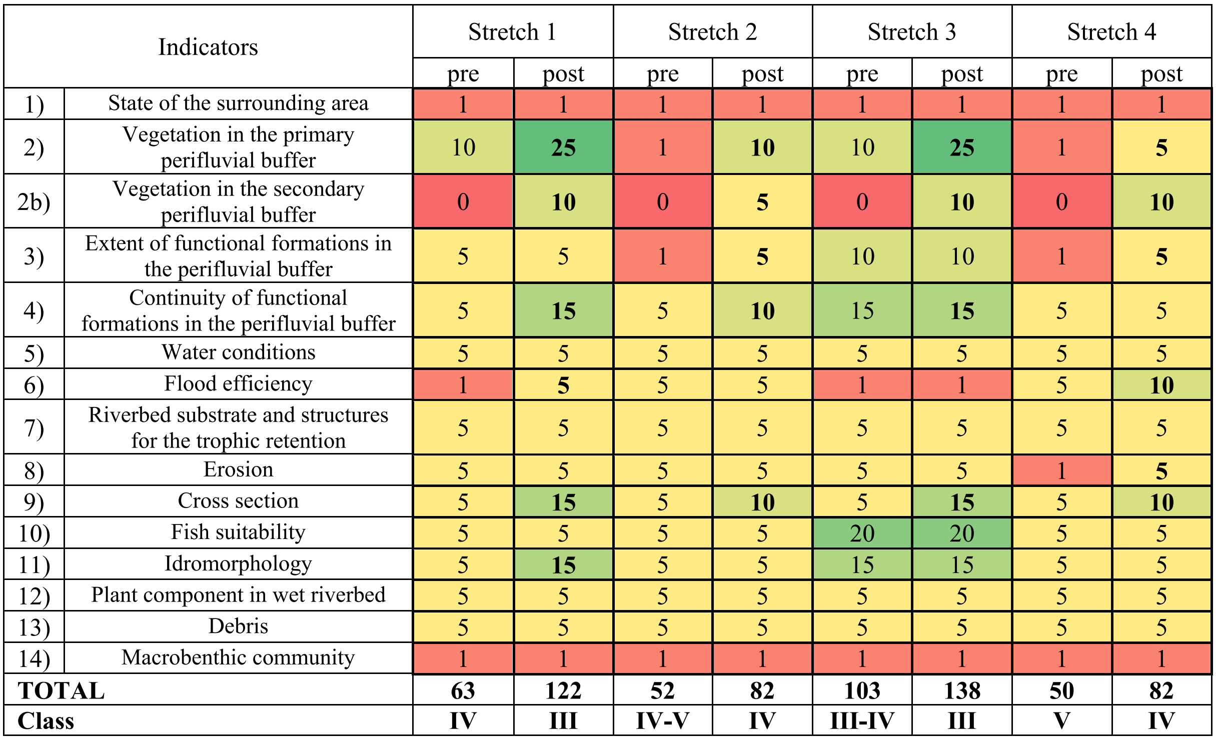
3.2.2. *River ecological quality improvement*

Despite the proposed river restoration interventions being on limited stretches with considerable space constraints, FFI results in an improvement of one class for all the stretches involved (Fig. 1b), enhancing specifically the environmental quality of vegetation and cross section (Table 10, Fig. 5).

4. Discussion

Considering the water-related ecosystem services according to the CICES classification (see SI Section S7), our results show that NBS

Table 10
Comparison of FFI indicators pre and post proposed interventions for each stretch involved.



	Indicators	Stretch 1		Stretch 2		Stretch 3		Stretch 4	
		pre	post	pre	post	pre	post	pre	post
1)	State of the surrounding area	1	1	1	1	1	1	1	1
2)	Vegetation in the primary perifluvial buffer	10	**25**	1	**10**	10	**25**	1	**5**
2b)	Vegetation in the secondary perifluvial buffer	0	**10**	0	**5**	0	**10**	0	**10**
3)	Extent of functional formations in the perifluvial buffer	5	5	1	**5**	10	10	1	**5**
4)	Continuity of functional formations in the perifluvial buffer	5	**15**	5	**10**	15	**15**	5	5
5)	Water conditions	5	5	5	5	5	5	5	5
6)	Flood efficiency	1	**5**	5	5	1	1	5	**10**
7)	Riverbed substrate and structures for the trophic retention	5	5	5	5	5	5	5	5
8)	Erosion	5	5	5	5	5	5	1	**5**
9)	Cross section	5	**15**	5	**10**	5	**15**	5	**10**
10)	Fish suitability	5	5	5	5	20	20	5	5
11)	Idromorphology	5	**15**	5	5	15	15	5	5
12)	Plant component in wet riverbed	5	5	5	5	5	5	5	5
13)	Debris	5	5	5	5	5	5	5	5
14)	Macrobenthic community	1	1	1	1	1	1	1	1
TOTAL		**63**	**122**	**52**	**82**	**103**	**138**	**50**	**82**
Class		**IV**	**III**	**IV-V**	**IV**	**III-IV**	**III**	**V**	**IV**

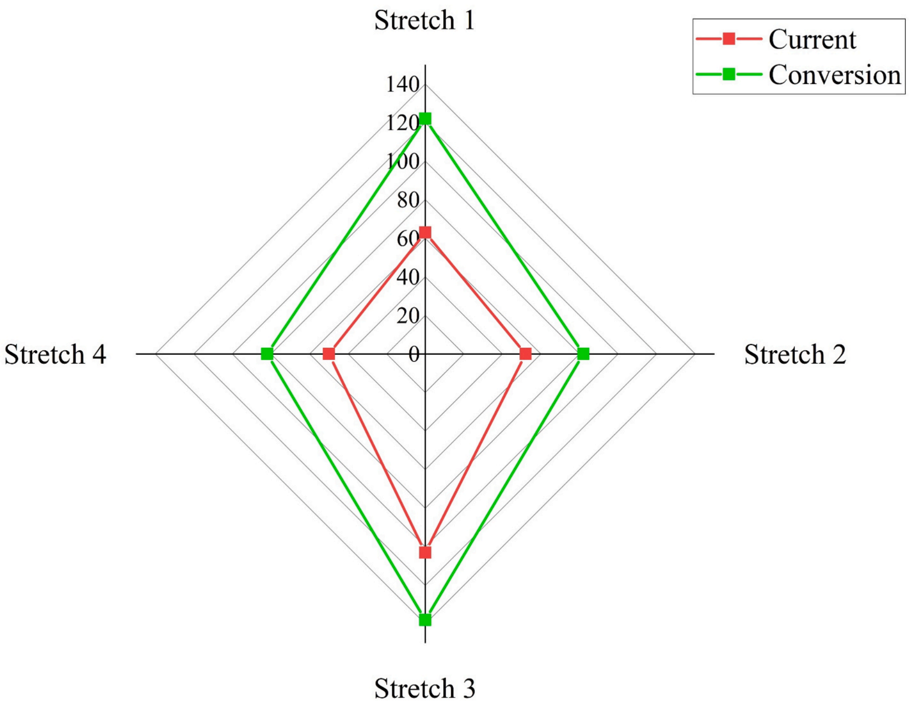


Fig. 5. Comparison of FFI value pre and post proposed interventions for each stretch involved.

implementation at different spatial scales effectively act on “water flow regulation” and “water quality regulation” and could support the development of policies and incentives for the transition towards these strategies (Goulden et al., 2018; Torres et al., 2023).

4.1. Water flow regulation

The proposed NBS for river restoration, which involve reconnecting floodplain areas, significantly reduce flooded areas during simulated storm events (up to 59 %), especially for frequent storms with a RP of 10 years or less (Table 5; Fig. 2). These interventions, although limited in scale (41,500 m^2 and 2,000 m of river stretch), effectively reduce water velocity and depth in flooded areas, delay flooding onset, and attenuate peak flow upstream of the culvert in a 617 km^2 watershed. The proposed NBS-based conversion scenarios for stormwater management significantly reduce peak flow, mitigating both the risk of pluvial flooding due to sewer system limitations and fluvial flooding from stormwater discharge into flood-prone watercourses (Schumann, 2011). Combined control strategies are more effective than single interventions. For the water storage service, the indicator water volume reduction was not directly dependent on the spatial ratio, as the available volume is more representative of this service. Specifically, scenarios S5 and S6 achieve 100 % service delivery by incorporating the relevant volume for stormwater storage when the detention pond is included (Table 7). Our research demonstrates that implementing NBS, even at the community scale in dense urban areas, is an effective strategy for stormwater retention. As the coverage of NBS increases, eventually covering nearly half of the total area, their efficiency improves, reducing peak flow to zero during the considered storm events. Notably, NBS do not require additional land, as they can be applied to rooftops through green infrastructure or integrated into existing land uses like permeable pavements (Table 6). Control structures with smaller infiltration areas and low-release capacities, like bioretention systems and rain gardens, are designed for frequent, low-intensity storm events. However, they become insufficient during extreme or successive events, as they may saturate or retain residual volumes, reducing their capacity. To effectively manage risks, these smaller controls should be combined with larger downstream systems, such as detention ponds. This approach is supported by Scenarios S5 and S6 (Table 9), where combining smaller structures with a larger system successfully managed extreme conditions without runoff. In all community-scale scenarios, the Stormwater Capture index exceeded 50 %, indicating a successful restoration of the natural water cycle.

In the municipal-scale parking de-sealing intervention with permeable pavements, which resulted in a 5 % reduction in peak flow during a 1-hour storm, NBS showed limited effectiveness in addressing water-related services during short-duration storm events, typically associated with flooding. The NBS footprint, covering just 4 % of a 160-hectare area, led to a modest improvement. This underscores the importance of combining multiple solutions, as relying solely on small interventions like permeable pavements in parking lots is unlikely to resolve significant flooding issues over large areas. Small-scale NBS contribute effectively to peak flow attenuation, with their impact increasing as the NBS spatial coverage expands. Although constraints like land use and costs may limit NBS expansion, their adoption remains beneficial for several reasons. First, NBS such as green roofs and permeable pavements can be implemented without altering land use. Second, smaller NBS like rain gardens offer design flexibility and are suitable for private properties, promoting community involvement in sustainable water management. Third, NBS provide a range of ecological and social co-benefits that traditional solutions often overlook (See Section 4.3).

4.2. Water quality regulation

The NBS actions for water quality regulation include stormwater management measures at both the municipal (SDS) and community scales (S1-S6), as well as river restoration techniques. Water quality improvements were evaluated based on pollutant load removal, with a particular focus on total suspended solids (TSS) from stormwater and the enhancement of river ecological quality. At the municipal scale, NBS implementation showed limited effectiveness due to their small spatial coverage within the watershed, resulting in minimal load control. However, at the community scale, different conversion scenarios demonstrated varying degrees of load reduction. Combined control strategies were more effective than single NBS solutions. Scenarios integrating multiple NBS approaches — such as managing runoff from rooftops, parking lots, and roads, along with a detention pond for final treatment — achieved full processing of stormwater generated by the community (Table 9). NBS solutions with storage layers and low-release mechanisms help attenuate peak flows and increase lag time, mitigating floods by reducing pressure on the sewer system and lowering combined sewer overflows (CSOs) activation frequency (Koiv-Vainik et al., 2022). From a water quality standpoint, these solutions could improve river water quality by reducing both the volume and discharge rates to the sewer system and, ultimately, to the Seveso River (Table 9). Although the final FFI score remains below the "good" rating (see SI Section S5), the proposed river restoration interventions improve the river environment. They enhance vegetation in both the primary and secondary perifluvial buffers across all four stretches (Indicators 2 and 2b in Table 10) and promote the continuity of functional formations in the perifluvial buffer in the first three stretches. Additionally, improvements are noted in the cross-sectional profile of all stretches, with enhanced flood efficiency in the first and fourth stretches, and improved hydromorphology in the first stretch. These interventions positively impact both river water quality and ecological functionality. Regarding riverbed morphology, it is important to note that the reduction in TSS resulting from NBS for stormwater retention in the Bresso municipality (see Section 3.2.1) does not significantly impact this parameter. This is due to the limited implementation of these NBS in only a small portion of the watershed, while the riverbed substrate and associated vegetation are influenced by the entire Seveso River watershed. Without a comprehensive study of solid transport, accurately assessing changes in riverbed morphology is challenging. Interventions like ecotonal buffers (SI Section S2) reduce pollutant loads and enhance self-cleaning, while riverbed diversification with scrapers, boulders, and brushes increases turbulence, lowers temperature, and improves oxygenation (Lepori et al., 2005). Boulders also retain coarse particulate organic matter (Lepori et al., 2005) and help direct flow during dry periods, preventing the formation of stagnant pools. This creates microhabitats (Groll, 2018) that restore macroinvertebrates, essential for the ecosystem (Wallace and Webster, 1996), potentially supporting the return of fish. Macrophytes enhance photosynthetic productivity (Jarvie et al., 2003), promote microbial communities that purify water, and aid sediment retention. Soil bioengineering and morphological interventions address riverbank instability and reduce tree fall risk. Ecotonal strips (SI Section S2) stabilize banks, providing refuge for birds and mammals, thus restoring the river's ecological corridor. While the FFI offers insights into ecological improvements and co-benefits, it provides only qualitative assessments, influenced by subjective judgments. More precise understanding requires further research using eco-hydrodynamic modeling.

4.3. Other considerations

NBS for stormwater management provide co-benefits like biodiversity, pollinator habitats, heat island mitigation, carbon sequestration, and groundwater recharge (Lee and Li, 2009; Engström et al., 2018; Remme et al., 2024). Even if covering less than 10 % of the Seveso River watershed, NBS significantly impact stormwater retention and other services, including social ones. Small-scale NBS, such as green roofs, may require community outreach and maintenance by local residents or volunteers, highlighting governance challenges (Remme et al., 2024). Broad stakeholder engagement is essential for addressing equity and justice (Langemeyer and Connolly, 2020). Our approach promotes NBS at the community scale to drive policy changes toward sustainability (Guerrero et al., 2018).

Additionally, NBS contribute to "Atmospheric Regulation" services (see Table S11 in the SI), helping reduce urban heat islands and greenhouse gas emissions, supporting climate change mitigation. Vegetation in NBS and river restoration also enhances habitat protection and lifecycle maintenance—services not provided by traditional grey infrastructure (Jo and McPherson, 1995; Yang et al., 2008; Veerkamp et al., 2021) (Table 2). Future assessments should consider temperature, climate change, and biodiversity impacts to provide a complete overview of ES for the Seveso River watershed.

5. Conclusions

This research highlights the crucial role of NBS in providing ES to address the urban challenge of stormwater management. Specifically, we focused on the use of NBS for integrated river restoration and stormwater management, with an emphasis on enhancing the "water flow regulation" and "water quality regulation" services, assessed using indexes derived from hydrological modelling. Our findings demonstrate that while NBS for river restoration and stormwater management can reduce flooding risks when applied separately, they are more effective when implemented in an integrated approach. Furthermore, the river restoration interventions enhance the river's ecological quality, while stormwater NBS demonstrate high pollutant removal efficiency by retaining urban runoff, improving the chemical quality of the discharged water, and, in turn, benefiting the Seveso River. In a conventional grey infrastructure system, these pollutants would otherwise be discharged directly into the river. The integrated approach provides a reliable and adaptable method for sustainable water management at the watershed level, enabling increased urban resilience to climate change and urbanization. This approach also supports the achievement of European Directive objectives concerning flood risk mitigation and water quality improvement.

The results comparing pre- and post-conversion performance showed limited improvements when NBS were implemented in small areas relative to the entire studied area (spatial ratio). The performance decreased as more extreme events (with higher RP) were considered. However, combining multiple NBS and increasing their spatial coverage led to significant performance improvements. In some cases, the entire storm event and TSS load could be managed on-site, highlighting the successful performance of NBS when covering a larger area, as evidenced by measurable indicators.

Our results, bringing quantitative indexes that provide a measurable evaluation, represent an important step that helps to justify the NBS inclusion into stormwater management planning, land-use regulations, green infrastructure planning and climate change adaptation and mitigation.

CRediT authorship contribution statement

Mariana Marchioni: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Franco Raimondi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gianfranco Becciu:** Writing – review & editing, Writing – original draft, Methodology. **Claudia Dresti:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2025.101718.

Data availability

Data will be made available on request.

References

Adams, C., Frantzeskaki, N., Moglia, M., 2023. Mainstreaming nature-based solutions in cities: A systematic literature review and a proposal for facilitating urban transitions. Land Use Policy 130, 106661. https://doi.org/10.1016/j.landusepol.2023.106661.

Adem Esmail, B., Suleiman, L., 2020. Analyzing Evidence of Sustainable Urban Water Management Systems: A Review through the Lenses of Sociotechnical Transitions. Sustainability 12, 4481. https://doi.org/10.3390/su12114481.

Albert, C., Brillinger, M., Guerrero, P., Gottwald, S., Henze, J., Schmidt, S., Ott, E., Schröter, B., 2021. Planning nature-based solutions: principles, steps, and insights. Ambio 50, 1446–1461. https://doi.org/10.1007/s13280-020-01365-1.

Arcement, G.J., Schneider, V.R., 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains, United States Geological Survey Water-supply. Paper 2339, 1989.

Babí Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., Geneletti, D., 2021. Nexus between nature-based solutions, ecosystem services and urban challenges. Land Use Policy 100, 104898. https://doi.org/10.1016/j.landusepol.2020.104898.

Babí Almenar, J., Rugani, B., Geneletti, D., Brewer, T., 2018. Integration of ecosystem services into a conceptual spatial planning framework based on a landscape ecology perspective. Landsc Ecol 8, 2047–2059. https://doi.org/10.1007/s10980-018-0727-8.

Ballard, B.W., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., Kellagher, R., 2015. The SUDS manual. CIRIA Publication, London, UK.

Barrow, C.J., 1998. River basin development planning and management: a critical review. World Dev. 26 (1), 171–186.

Becciu, G., Ghia, M., Mambretti, S., 2018. A century of works on River Seveso: from unregulated development to basin reclamation. Int. J. Environ. Impact. 1 (4), 461–472. https://doi.org/10.2495/EI-V1-N4-461-472.

Bouska, W.W., Keane, T., Paukert, C.P., 2010. The effects of road crossings on prairie stream habitat and function. J. Freshwater Ecol. 25 (4), 499–506. https://doi.org/10.1080/02705060.2010.9664398.

Braud, I., Breil, P., Thollet, F., Lagouy, M., Branger, F., Jacqueminet, C., Michel, K., 2013. Evidence of the impact of urbanization on the hydrological regime of a medium-sized periurban catchment in France. J. Hydrol. 485, 5–23. https://doi.org/10.1016/j.jhydrol.2012.04.049.

Bolognesi, A., Maglionico, M. Artina, S., 2009. Un supporto alla gestione delle caditoie stradali mediante simulazione numeriche di lungo periodo. Acqua e Città '09 - Convegno Nazionale di Idraulica Urbana. Milano.

Brown, R.R., 2003. Institutionalisation of integrated urban stormwater management: Multiple-case analysis of local management reform across metropolitan Sydney School of. In: Civil and Environmental Engineering. University of N.S.W.

Brunner, G. W., 1995. HEC-RAS River Analysis System. Hydraulic User's Manual . Hydrologic Engineering Center Davis CA . Version 1.0.

Carvalho, P.N., Finger, D.C., Masi, F., Cipolletta, G., Oral, H.V., Toth, A., Exposito, A., 2022. Nature-based solutions addressing the water-energy-food nexus: Review of theoretical concepts and urban case studies. J. Clean. Prod. 130652.

Castelli, G., Foderi, C., Guzman, B.H., Ossoli, L., Kempff, Y., Bresci, E., Salbitano, F., 2017. Planting waterscapes: green infrastructures, landscape and hydrological modeling for the future of Santa Cruz de la Sierra, Bolivia. Forests 8, 1–14. https://doi.org/10.3390/f8110437.

Ceppi, A., Gambini, E., Lombardi, G., Ravazzani, G., Mancini, M., 2022. Sol40: forty years of simulations under climate and land use change. Water (switzerland) 14 (6). https://doi.org/10.3390/w14060837.

Chow, V.T., 1959. Open Channel Hydraulics. McGraw-Hill, New York, pp. 101–125.

Costanza, R., 2020. Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. Ecosyst. Serv. 43, 101096. https://doi.org/10.1016/j.ecoser.2020.101096.

Costanza, R., d'Arge, R., Groot, R., Farber, S., Grasso, M., Hannon, B., Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630), 253–260.

Cowan, W.L., 1956. Estimating hydraulic roughness coefficients. Agricult. Eng. 37 (7), 473–475.

DDOE Stormwater Management Guidebook, 2013. District Department of the Environment Watershed Protection Division District of Columbia.

Ekka, A., Pande, S., Jiang, Y., der Zaag, 2020. Anthropogenic modifications and river ecosystem services: A landscape perspective. Water 12 (10), 2706. https://doi.org/10.3390/w12102706.

Engström, R., Howells, M., Mörtberg, U., Destouni, G., 2018. Multi-functionality of nature-based and other urban sustainability solutions: New York City study. Land Degrad. Dev. 29 (10), 3653–3662.

European Commission, 2000. Directive 2000/60/CE of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy.

European Commission, 2007. Directive 2007/60/CE of the European Parliament and of the Council on the assessment and management of flood risk.

European Commission, 2015. Towards an EU research and innovation policy agenda for nature-based solutions & Re-naturing cities. Final Report of the Horizon 2020 Expert Group on "Nature-based Solutions and Re-naturing cities".

Finewood, M.H., Matsler, A.M., Zivkovichm J., 2019. Green infrastructure and the hidden politics of urban stormwater governance in a Postindustrial City. Annals of the American Association of Geographers, 109 (3), 909 – 925. https://doi.org/10.1080/24694452.2018.1507813.

Fletcher, T.D., Andrieu, H., Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Adv. Water Resour., 51, 261 – 279. Doi: 10.1016/j.advwatres.2012.09.001.

Fogarty, J., van Bueren, M., Iftekhar, M.S., 2021. Making waves: Creating water sensitive cities in Australia. Water Res. 202, 117456.

Frantzeskaki, N., Kabisch, N., McPhearson, T., 2016. Advancing urban environmental governance: Understanding theories, practices and processes shaping urban sustainability and resilience. Environ Sci Policy 62, 1–6. https://doi.org/10.1016/j.envsci.2016.05.008.

Fu, G., et al., 2023. Are sponge cities the solution to China's growing urban flooding problems? Wiley Interdiscip. Rev. Water 10 (1), e1613.

Gambini, E., Ceppi, A., Ravazzani, G., Mancini, M., Valsecchi, I.Q., Cucchi, A., Negretti, A., Tolone, I., 2024. An empirical rainfall threshold approach for the civil protection flood warning system on the milan urban area. J. Hydrol. 628. https://doi.org/10.1016/j.jhydrol.2023.130513.

Geneletti, D., Cortinovis, C., Zardo, L., Adem Esmail, B. 2020. Introduction, in: Geneletti, D., Cortinovis, C., Zardo, L., Adem Esmail, B (Eds.), Planning for Ecosystem Services in Cities, SpringerBriefs in Environmental Science. Springer International Publishing, Cham, pp. 1-6. Doi: 10.1007/978-3-030-20024-4_1.

Gnecco, I., Palla, A., Sansalone, J.J., 2019. Partitioning of zinc, copper and lead in urban drainage from paved source area catchments. J. Hydrol. 578, 124128.

Goulden, S., Portman, M.E., Carmon, N., Alon-Mozes, T., 2018. From conventional drainage to sustainable stormwater management: Beyond the technical challenges. J. Environ. Manage. 219, 37–45.

Grabowski, R.C., Gurnell, A.M., 2016. Hydrogeomorphology—Ecology interactions in river systems. River Res. Appl. 32 (2), 139–141. https://doi.org/10.1002/rra.2974.

Grizzetti, B., Lanzanova, D., Liquete, C., Reynaud, A., Cardoso, A., 2016. Assessing water ecosystem services for water resource management. Environ. Sci. Policy 61, 194–203. https://doi.org/10.1016/j.envsci.2016.04.008.

Groll, M., 2018. Relations between the microscale riverbed morphology and the macrozoobenthos–implications for the ecological quality assessment and the definition of reference conditions. J. Environ. Impacts 1 (3), 375–389.

Haines-Young, R., & Potschin, M. (2012). Common international classification of ecosystem services (CICES, Version 4.1). Europ. Environ. Agency, 33, 107.

Guerrero, P., Haase, D., Albert, C., 2018. Locating spatial opportunities for nature-based solutions: A river landscape application. Water (Switzerland) 10, 1–15. https://doi.org/10.3390/w10121869.

Harrison, P.A., Dunford, R., Barton, D.N., et al., 2018. Selecting methods for ecosystem service assessment: a decision tree approach. Ecosyst. Serv. 29 (C), 481–498. https://doi.org/10.1016/j.ecoser.2017.09.016.

https://flanet.org/ (accessed 23 December 2017).

https://idro.arpalombardia.it (accessed 3 February 2020).

https://www.adbpo.gov.it/ (accessed 3 February 2020).

https://www.arpalombardia.it (accessed 3 February 2020).

https://www.geoportale.regione.lombardia.it/ (accessed 8 April 2023).

Jarvie, H.P., Love, A.J., Williams, R.J., Neal, C., 2003. Measuring in-stream productivity: the potential of continuous chlorophyll and dissolved oxygen monitoring for assessing the ecological status of surface waters. Water Sci. Technol. 48 (10), 191–198. https://doi.org/10.2166/wst.2003.0573.

Jo, H.K., McPherson, G.E., 1995. Carbon storage and flux in urban residential greenspace. J. Environ. Manage. 45 (2), 109–133.

Kabisch, N, Haase, D., 2014. Green justice of just green? Urban green space provision in the city of Berlin. Landscape and Urban Planning 139.

Kim, J.Y., Sansalone, J.J., 2008. Event-based size distributions of particulate matter transported during urban rainfall-runoff events. Water Res. 42 (10–11), 2756–2768.

Khoshkar, S., Hammer, M., Borgström, S., Balfors, B., 2020. Ways Forward for Advancing Ecosystem Services in Municipal Planning—Experiences from Stockholm County. Land 9, 296. https://doi.org/10.3390/land9090296.

Koiv-Vainik, M., Kill, K., Espenberg, M., Uuemaa, E., Teemusk, A., Maddison, M., Kasak, K., 2022. Urban stormwater retention capacity of nature-based solutions at different climatic conditions. Nature-Based Solut. 100038.

Lafortezza, R., Sanesi, G., 2019. Nature-based solutions: Settling the issue of sustainable urbanization. Environ. Res. 172, 394–398.

Langemeyer, J., Connolly, J.J.T., 2020. Weaving notions of justice into urban ecosystem services research and practice. Environ. Sci. Policy 109, 1–14. https://doi.org/10.1016/j.envsci.2020.03.021.

Lee, J.S., Li, M.H., 2009. The impact of detention basin design on residential property value: case studies using GIS in the hedonic price modeling. Landsc. Urban Plan. 89 (1–2), 7–16.

Lepori, F., Palm, D., Malmqvist, B., 2005. Effects of stream restoration on ecosystem functioning: detritus retentiveness and decomposition. J. Appl. Ecol. 42, 228–238. https://doi.org/10.1111/j.1365-2664.2004.00965.x.

Liu, Y., Sansalone, J.J., 2022. Gravimetric and Number Distributions of Urban PM Residuals from Urban Maintenance Practices. J. Environ. Eng. 148 (1), 04021075.

Loomis, J., Kent, P., Strange, L., Fausch, K., Covich, A., 2000. Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation survey. Ecol. Econ. 33 (1), 103–117. https://doi.org/10.1016/S0921-8009(99)00131-7.

MA, 2005. Assessment Millennium Ecosystem. Ecosystems and human well-being: wetlands and water. World Resources Institute.

Maglionico, M., 2007. Accumulo e dilavamento degli inquinanti dalle superfici urbane e misure di qualita' delle acque in rete e nei ricettori.

Marchioni, M., Andrés-Valeri, V.C., Giustozzi, F., Becciu, G., 2016. Laboratory study on the rainfall influence over the sediment transport dynamics on pervious pavements' discharge. Urban Water Systems and Floods 165, 165–176.

Marchioni, M., Becciu, G., 2015. Experimental results on permeable pavements in urban areas: a synthetic review, International. J. Sustain. Dev. Plann. 10 (6), 806–817. https://doi.org/10.2495/SDP-V10-N6-806-817.

Marchioni, M., Fedele, R., Raimondi, A., Sansalone, J., Becciu, G., 2022. Permeable asphalt hydraulic conductivity and particulate matter separation with XRT. Water Resour. Manag. 36 (6), 1879–1895.

Marchioni, M., Raimondi, A., Andrés-Valeri, V.C., Becciu, G., Sansalone, J., 2021a. Permeable pavement hydraulic conductivity indices for rainfall-runoff and particulate matter loadings. J. Environ. Eng. 147 (12), 04021064.

Marchioni, M., Raimondi, A., Sanfilippo, U., Sansalone, J., Mambretti, S., Becciu, G., 2021b. Modelling of particulate matter fate on urban highway stormwater control systems. Int. J. Computat. Method. Exp. Measure. 9 (1), 1–13.

McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrol. Sci. J. 61 (13), 2295–2311. https://doi.org/10.1080/02626667.2015.1128084.

McVittie, A., Hussain, S.S., 2013. The Economics of Ecosystems and Biodiversity - Valuation Database Manual.

Merril, M.A., Gregory, J., 2007. The Effects of Culverts and Bridges on Stream Geomorphology. In: Jay F. Levine et al., (Ed.) Technical Report (FHWA/NC/2006-15). Doi: 10.4314/ejesm.v6i6.14S.

Moosavi, S., 2017. Ecological coastal protection: pathways to living shorelines. Procedia Eng. 196, 930–938. https://doi.org/10.1016/j.proeng.2017.08.027.

Moosavi, S., Browne, G.R., Bush, J., 2021. Perceptions of nature-based solutions for Urban Water challenges: Insights from Australian researchers and practitioners. Urban for. Urban Green 57, 126937. https://doi.org/10.1016/j.ufug.2020.126937.

Ngan, G., 2012. Stormwater Source Control Design Guidelines 2012.

Poff, N.L., Olden, J.D., Merritt, D.M., Pepin, D.M., 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proc. Natl. Acad. Sci. 104, 5732–5737. https://doi.org/10.1073/pnas.0609812104.

Praskievicz, S., Chang, H., 2009. A review of hydrological modelling of basin-scale climate change and urban development impacts. Prog. Phys. Geogr. 33 (5), 650–671. https://doi.org/10.1177/0309133309348098.

Qiao, X.J., Liao, K.H., Randrup, T.B., 2020. Sustainable stormwater management: a qualitative case study of the Sponge Cities initiative in China. Sustain. Cities Soc. 53, 101963.

Rahel, F.J., 2007. Biogeographic barriers, connectivity and homogenization of freshwater faunas: it's a small world after all. Freshw. Biol. 52 (4), 696–710. https://doi.org/10.1111/j.1365-2427.2006.01708.x.

Raimondi, A., Di Chiano, M.G., Marchioni, M., Sanfilippo, U., Becciu, G., 2022a. Probabilistic modeling of sustainable urban drainage systems. Urban Ecosystems 1–10.

Raimondi, A., Marchioni, M., Sanfilippo, U., Stroppa, F.F., Becciu, G., 2022b. Probabilistic estimation of runoff from green roofs. Int. J. Computat. Method. Exp. Measure. 10 (1), 13–25.

Raimondi, A., Sanfilippo, U., Marchioni, M., Di Chiano, M.G., Becciu, G., 2023. Influence of climatic parameters on the probabilistic design of green roofs. Sci. Total Environ. 865, 161291.

Raymond, C.M., Pam, B., Breil, M., Nita, M.R., Kabisch, N., de Bel, M., Enzi, V., Frantzeskaki, N., Geneletti, D., Cardinaletti, M., Lovinger, L., Basnou, C., Monteiro, A., Robrecht, H., Sgrigna, G., Munari, L., Calfapietra, C., 2017. An Impact Evaluation Framework to Support Planning and Evaluation of Nature-based Solutions Projects. Report prepared by the EKLIPSE Expert Working Group on Nature-based Solutions to Promote Climate Resilience in Urban Areas, Horizon 2020. Doi: 10.13140/RG.2.2.18682.08643.

Remme, R.P., Meacham, M., Pellowe, K.E., Andersson, E., Guerry, A.D., Janke, B., Liu, L., Lonsdorf, E., Li, M., Mao, Y., Nootenboom, C., Wu, T., van Oudenhoven, A.P.E., 2024. Aligning nature-based solutions with ecosystem services in the urban century. Ecosyst. Serv. 66, 101610. https://doi.org/10.1016/j.ecoser.2024.101610.

Rossman, L.A., 2010. Storm Water Management Model User's Manual,Version 5.0. National Risk Management. Research Laboratory, Office of Research and Development, US Environmental Protection Agency:Cincinnati, p. 276.

Sansalone, J.J., Cristina, C.M., 2004. First flush concepts for suspended and dissolved solids in small impervious watersheds. J. Environ. Eng. 130 (11), 1301–1314.

Sansalone, J.J., Buchberger, S.G., 1997. Partitioning and first flush of metals in urban roadway storm water. J. Environ. Eng. 123 (2), 134–143. https://doi.org/10.1061/(ASCE)0733-9372(1997)123:2(134).

Sansalone, J.J., Buchberger, S.G., Koechling, M.T., 1995. Correlations between heavy metals and suspended solids in highway runoff: implications for control strategies. Transp. Res. Rec. 1483.

Schumann, A.H., 2011. Flood risk assessment and management: How to specify hydrological loads, their consequences and uncertainties. Springer Science & Business Media.

Suleiman, L., Olofsson, B., Saurí, D., Palau-Rof, L., 2020a. A breakthrough in urban rain-harvesting schemes through planning for urban greening: Case studies from Stockholm and Barcelona. Urban for Urban Green 51, 126678. https://doi.org/10.1016/j.ufug.2020.126678.

Suleiman, L., Olofsson, B., Saurí, D., Palau-Rof, L., García Soler, N., Papasozomenou, O., Moss, T., 2020b. Diverse pathways—common phenomena: comparing transitions of urban rainwater harvesting systems in Stockholm, Berlin and Barcelona. J. Environ. Plan. Manag. 63, 369–388. https://doi.org/10.1080/09640568.2019.1589432.

Thorp, J.H., Thoms, M.C., Delong, M.D., 2006. The riverine ecosystem synthesis: biocomplexity in river networks across space and time. River Res. Appl., 22, 123–147. https://doi.org/10.1002/rra.901.

Torres, P.H.C., de Souza, D.T.P., Momm, S., Travassos, L., Picarelli, S.B., Jacobi, P.R., da Silva Moreno, R., 2023. Just cities and nature-based solutions in the Global South: A diagnostic approach to move beyond panaceas in Brazil. Environ Sci Policy 143, 24–34.

Tsatsou, A., Frantzeskaki, N., Malamis, S., 2023. Nature-based solutions for circular urban water systems: A scoping literature review and a proposal for urban design and planning. J. Clean. Prod. 136325.

Tvedt, T., Coopey, R.G., 2006. A History of Water: Series II: Vol. II: Rivers and Society: from Early Civilizations to Modern times.

Urbonas, B., Stahre, P., 1993. Stormwater: Best management practices and detention for water quality, drainage. and CSO management.

Veerkamp, C.J., Schipper, A.M., Hedlund, K., Lazarova, T., Nordin, A., Hanson, H.I., 2021. A review of studies assessing ecosystem services provided by urban green and blue infrastructure. Ecosyst. Serv. 52, 101367. https://doi.org/10.1016/j.ecoser.2021.101367.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467 (7315), 555–561. https://doi.org/10.1038/nature09440.

Voulvoulis, N., Arpon, K.D., Giakoumis, T., 2017. The EU Water Framework Directive: From great expectations to problems with implementation. Sci. Total Environ. 575, 358–366. https://doi.org/10.1016/j.scitotenv.2016.09.228.

Wallace, J.B., Webster, J.R., 1996. The role of macroinvertebrates in stream ecosystem function. Annu. Rev. Entomol. 41, 115–139. https://doi.org/10.1146/annurev.en.41.010196.000555.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. J. N. Am. Benthol. Soc. 24 (3), 706–723. https://doi.org/10.1899/04-028.1.

Wild, T.C., Bernet, J.F., Westling, E.L., Lerner, D.N., 2011. Deculverting: reviewing the evidence on the 'daylighting'and restoration of culverted rivers. Water Environ. J. 25 (3), 412–421.

Wilkinson, C., Saarne, T., Peterson, G.D., Colding, J., 2013. Strategic Spatial Planning and the Ecosystem Services Concept - an Historical Exploration. Ecol. Soc. 18, art.37. https://doi.org/10.5751/ES-05368-180137.

Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Tarboton, D., 2005. River restoration. Water Resour. Res. 41 (10). https://doi.org/10.1029/2005WR003985.

Wohl, E., Merritts, D.J., 2007. What is a natural river? Geogr. Compass 1 (4), 871–900. https://doi.org/10.1111/j.1749-8198.2007.00049.x.

Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., Shaffer, P. (2007). The SUDS manual (Vol. 697). London: Ciria.

Yang, J., Yu, Q., Gong, P., 2008. Quantifying air pollution removal by green roofs in Chicago. Atmos. Environ. 42 (31), 7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003.

Yin, D., Chen, Y., Jia, H., Wang, Q., Chen, Z., Xu, C., Chen, A.S., 2021. Sponge city practice in China: A review of construction, assessment, operational and maintenance. J. Clean. Prod. 280, 124963.