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Accessing Synergies and Opportunities between Nature-Based Solutions and Urban Drainage Systems

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Abstract: Urban drainage systems face intrinsic constraints related to the deterioration of infrastructure, the interaction between systems, and increasing requirements and stresses that lower the quality of provided services. Furthermore, climate change and the need for the efficient use of resources are providing additional pressures that cannot be addressed solely with “Business-as-usual” solutions. In this paper, the consequences of such problems and limitations on the urban environment have been assessed through the identification of linked major impacts (e.g., urban flooding and pollution events) and societal externalities (e.g., economic losses, health and social issues, and environmental risks). Since Nature-based Solutions (NBS) consider human well-being, socio-economic development, and governance principles, they open new perspectives regarding urban sustainability, quality of life, and climate change adaptation. To highlight their added value to existing Urban Drainage Systems (UDS), the synergies that result from implementing NBS with traditional urban drainage systems were identified and assessed. Based on a comprehensive framework, for both wastewater and stormwater, the relevant opportunities for rethinking UDS and NBS were identified. Most relevant positive effects go beyond the mitigation of existing intrinsic constraints of traditional systems (e.g., dealing with the control of pollutants or stormwater management) since NBS also provide important economic, social, and environmental co-benefits by including water in urban planning and providing greener open spaces. This integrated and complementary solution not only represents a contribution to the sustainable management of urban water, but also enables an increase in the resilience of urban areas and, in particular, water services against climate change and for additional social co-benefits.

Keywords: urban pollution; urban environment; social co-benefits; urban runoff; diffuse pollution; floods

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1. Introduction and Motivation

Archaeological evidence reveals that the provision of drainage was highly considered in many ancient civilizations (e.g., Mesopotamians, Minoans, Greeks, and Romans). However, it was only after the strong deterioration of urban health, in the eighteenth and nineteenth centuries, that a sanitary awakening led to the generalized construction of foul drainage systems in cities that dramatically improved the health of urban populations [1].

Wastewater- and stormwater-related functions and services are an essential part of urban metabolism, but their desired performance levels are becoming harder to reach and ensure. This occurs due to internal constraints and external factors, such as urban growth, population concentration, loss of natural functions in urban centers, and climate dynamics.

Design practices over time have focused exclusively on networked systems, combined or separated, with a strong emphasis on the quantitative nature of flows and less on their quality. Today, this paradigm is part of the fabric of most urban areas, with known issues associated with the operation, maintenance, and rehabilitation of these systems. Delayed rehabilitation investments lead to infrastructure aging and, in some cases, obsolescence.

These intrinsic problems derive from their original design. The assets are mostly underground, without considering surface runoff as part of the solution, and face an aggressive internal environment, causing it to be difficult to detect pathologies and undertake correction works. Rapid urban development has been accelerating this process, resulting in significant environmental impacts and the deterioration of the quality of life. It is therefore of utmost importance to adopt measures to minimize the risks inherent to these systems.

Furthermore, knowledge uncertainties, management constraints, and the limitation in predicting meteorological conditions add additional complexity to the sustainable management of urban drainage systems. These conditions aggravate risks to urban activities (e.g., flooding and pollution load), instigating high economic losses and even risks to human life [2].

The sustainable management of the urban environment is one of the most important development challenges of the 21st century [3] since urban areas concentrate more than half of the world's population. However, the integrated management of different systems, services, and utilities has not been possible due to different management agendas and financing sources.

The integration of Nature-based Solutions (NBS), also known by several other terms [4], in the urban environment has been proposed and tested in numerous locations but has not generally been adopted on a large scale. The results suggest that they NBS can synergize with urban systems and promote multiple co-benefits.

This paper identifies the problems and limitations of traditional UDS. Based on these results, the opportunities and synergies that result from the adoption of NBS are identified for their contribution to addressing urban drainage challenges.

2. Methodology

A literature review will be the starting point of this research. Urban drainage design assumptions will be reviewed while identifying the intrinsic constraints and known limitations of these systems. This process will identify, analyze, and discuss future challenges and evaluate if these problems can be resolved within the water sector.

This analysis will constitute the substance to map the most relevant **intrinsic constraints** related to traditional urban drainage systems and the broad nature of **external pressures** that have been aggravating these problems and compromising their functions and desired performance levels. The most relevant **problems and limitations** associated with traditional urban drainage will be analyzed and categorized to assess the broad range of associated **consequences to the urban environment**, which are responsible for the direct impacts within the water sector, and the societal externalities, that are transferred to society.

Based on theory research and case studies, the possible opportunities and synergies between this traditional praxis and NBS will then be sought, aiming at how NBS can support and synergize traditional urban drainage systems while promoting associated co-benefits to the urban environment. This cross-linkage will estimate the **Intrinsic Improvements** to the urban water sector, which allow for the mitigating of the identified problems and limitations and the benefits to the urban environment; these improvements also represent important **External Benefits** that provide resilience to the consequences of broader phenomena such as those related to climate change. The obtained results will allow for the appraisal of the combination of traditional existing systems, with the strengths and potentialities of NBS, which can result in extended urban water ecosystems, with overall performance improvements.

The effective integration of NBS in the urban environment must consider the multiple relations between anthropogenic activities and the urban and natural environment, which are associated with complex processes and phenomena, that are characteristic of an open environment. This development depends on integrated planning and the inclusion of multiple stakeholders, which must be supported in an integrated framework. Since no specific framework was found to specifically identify synergies and opportunities between NSB and urban drainage systems, a multidimensional and comprehensive framework based on the performance assessment structure proposed by the ISO 24500 standards for water supply and wastewater system management will be tested to evaluate the opportunities and synergies between NBS and traditional drainage systems. One of the merits of this framework is its validation by a broad group of stakeholders (that included water utilities, municipal councils, and private organizations) from seven cities in Portugal, Spain, the United Kingdom, and Canada, which ensures its reliability and effectiveness in different conditions and for stakeholder validation.

The relevance of the different objectives and criteria that are relevant to wastewater and stormwater, including stakeholder awareness and involvement, public finance possibilities, resilience to extreme events, improvement of water treatment, and infrastructure improvements, will then be evaluated and tested. This process will allow to identify and graduate the possible synergies when using NBS in existing and new systems, to overcome the identified intrinsic constraints of traditional drainage solutions, and to mitigate the known direct impacts, external pressures, and societal externalities.

3. Results and Discussion

3.1. Urban Drainage Design Assumptions, Operation Constraints, and Future Challenges

Most of the challenges faced by wastewater and stormwater drainage solutions regard their outdated design criteria and maintenance and operation constraints that compromise their effectiveness. Additionally, the complex relationship between the conveyance of wastewater and stormwater [5], which have quite different natures and compositions (Table 1), confronts established design criteria and historical developments that have led to the implementation of combined or separate systems. The increasing use of these hybrid systems results in more problems for flood and pollution control.

Table 1. Pollutant concentrations for wastewater (mean and range) [6] and event mean concentrations for urban stormwater (mean and range) [7].

		Wastewater Mean Concentration (mg/L)	**Stormwater Event Mean Concentration (mg/L)**
Physical	Total suspended solids	300 (180–450)	21–2582 (90)
Chemical	Total BOD5	300 (200–400)	7–22 (9)
	Total COD	550(350–750)	20–365 (85)
	TOC	200 (100–300)	
	Total nitrogen	60 (30–85)	0.4–20 (3.2)
	Total phosphorus	15	0.02–4.30 (0.34)
	pH	7.2–7.8	
	Sulphates	100	
	FOG	100	
	Total lead		0.01–3.10 (0.14)
	Total zinc		0.01–3.68 (0.30)
	Hydrocarbons		0.04–25.9 (1.9)
	HPA		0.01
Microbiological	Total coliforms	10^7–10^8 MPN/100 mL	400–5 × 10^4 MPN/100 mL
	Faecal coliforms (*E. coli*)	10^6–10^7 MPN/100 mL	
	Viruses	10^2–10^3 infectious units/100 mL	

The identification of effective solutions, which contribute to improving the overall efficiency of these systems, operational imitations, and associated problems must be supported by theoretical concepts. They must also consider the phenomena and pressures that are beyond the studied ecosystem but can impact their performance.

The discussion of these aspects, based on relevant research, is presented in the following sections.

3.1.1. Design Assumptions

Since urban wastewater is mainly associated with water consumption patterns, flows are reasonably anticipated. However, unpredicted urban growth and unexpected migrations often differ from the original design scenarios, with consequences in the performance of drainage networks, pumping stations, and Wastewater Treatment Plants (WWTP). On the other hand, stormwater is dependent on precipitation patterns, having therefore an intermittent and capricious nature.

Additionally, surface runoff and infiltration inflows into foul sewers result in additional wastewater volume that dilutes the pollution load, providing negative impacts on network operations, sewer processes, and WWTP efficiencies [6,7]. While infiltration has a slow hydrodynamic response and does not represent an increased pollutant load, urban runoff includes contaminants that are rapidly washed from the urban surfaces. Due to the unpredictable nature of these flow patterns, typically not considered in the design of foul systems, they trigger potentially critical events. These include untreated discharges into receiving waters and flooding, which are commonly designated as Combined Sewer Overflows (CSO).

As wastewater travels through the sewer system, its main constituents undergo transformations in composition due to complex chemical, physical, and biological processes [8,9]. The relevance of biodegradation processes in gravity and pressurized sewer pipes has been demonstrated [10–12], revealing that the substrate is rarely limiting the growth of the microorganisms, given that fresh wastewater is normally added during the collection system. Due to the complexity of these processes and uncertainties on in situ environmental conditions, most of the time these phenomena are not taken into account [13].

The organic nature of wastewater has led to the implementation of WWTP with biological reactors, primarily designed to decrease their carbon and sometimes extended to decrease nitrogen and phosphorus load. The removal of other pollutants such as pharmaceutical and personal care products (PPCP), heavy metals, other chemicals, and illicit drugs is a relatively recent and growing concern.

Understanding the processes that occur during wastewater transport and the estimation of wastewater quality changes represents an opportunity. This is specifically relevant not only for enhancing wastewater treatment but also to control the release of undesired components, such as methane and hydrogen sulfide. These issues represent an operational problem in many systems.

Stormwater presents quite different characteristics and constituents since it results in the "wash-off" of substances that have accumulated on urban surfaces, constituting a pollution threat to surface waters and soils. The sources of these pollutants can be both stationary and mobile. While the first includes material leached from roofs, pavements, and streets [14], the second includes sub-products from fuel combustion and the wear of vehicle components (tire and brake wear), leaking of substances from vehicles (e.g., oil and fuel), deterioration of coatings, and airborne pollutants [15,16]. Road conservation operations, application of pesticides and fertilizers, and litter also contribute to this type of pollution [17,18].

3.1.2. Intrinsic Constraints and Known Limitations

The challenges for urban decision-makers and utility service managers are complex. A spatially dispersed infrastructure needs to be fully functional and able to address increasingly challenging operation conditions, but funds for investments and operation are limited. Additionally, the complex patterns of economic cycles, aging infrastructures, and vulnerability to climate change result in increased risks to urban areas.

This concern is not new. The authors of [19] explicitly stated that urban drainage solutions need to consider the trade-offs of risks and uncertainties, but, four decades after, we are still far from generalizing this practice into the application.

Urban water systems as a whole, and drainage systems in particular, need to address these challenges in consolidated and new urban areas.

The most visible impacts of urban drainage systems are floods that, according to [20], are costing USD 120 billion per year in urban property damage—about one-quarter of total global economic losses related to water insecurity. Additionally, according to [5], in 2050, approximately 1.3 billion people are estimated to live in flood-prone areas, of which the poorest and most vulnerable will suffer disproportionately.

The increasing imperviousness of urban areas over the last decades has caused important changes in precipitation-runoff processes. These led to higher peak flows and quicker build-up events, which create favorable conditions for urban flooding, increasing the risk to human lives and causing high economic losses. Flood control is intrinsically related to the urban environment and cannot be addressed only within the urban drainage sector. For such, it demands a holistic vision and an integrated approach, with engineers and planners, considering the urban metabolism and the drainage systems processes, and including the use of public space to promote innovative solutions that were not otherwise possible. Furthermore, and due to the short timeframe of flood occurrence, most of the time these spaces can be designed to serve other activities. This flexibility can generate positive externalities and allow citizens to understand the importance of urban drainage [21].

A closer look at wastewater processes corroborates that design conditions generally assume aerobic conditions, but anaerobic conditions also occur (e.g., in biofilm, sediment layers, and pressure pipes) and promote the microbial processes responsible for the formation of odor-causing substances, thus producing both inorganic gases and volatile organic compounds (VOC). Hydrogen sulfide (H_2S) and methane (CH_4) are two of the most harmful substances emitted from sewers [15,22] with direct environmental impacts, effects on infrastructures, and health risks [23].

The build-up of H_2S in the sewer atmosphere causes detrimental effects such as odor nuisance, health hazards, and corrosion of pipes [24,25] and, by a biological process, it can be converted to Sulphuric acid (H_2SO_4). Sulphuric acid promotes corrosion, which leads to the loss of concrete mass, the cracking of the sewer pipes, and, ultimately, structural collapses [23]. It has been estimated that the annual cost of asset depreciation due to sulfide-induced corrosion in Australia is AUD 100 million and that the annual cost of concrete corrosion within the water and wastewater infrastructure in the USA is about USD 36 billion [26]. Moreover, this cost is expected to increase with the aging of infrastructures.

Methane (CH_4) is a potent greenhouse gas with a lifespan of about 12 years and a global warming potential 21–23 times higher than that of carbon dioxide [27]. Significant amounts of methane have also been found to be formed and emitted from sewers. The uncontrolled release of CH_4 is also potentially unsafe since it forms an explosive mixture in the atmosphere at low concentrations (down to approximately 5%) and therefore poses occupational health and safety risks.

As with hydrogen sulfide, methane release also increases with the wastewater hydraulic residential time and with the area-to-volume ratios of sewer pipes [28].

3.1.3. External Pressures and Associated Challenges

Some of the most significant challenges faced by urban drainage systems are associated with pressures from external sources and cannot be addressed within this sector, requiring the involvement of a broad number of stakeholders that have complementary views and knowledge. The social perception of this reality is also increasingly pressing on the political agenda.

Anthropogenic activities throughout the 20th century have led to the release of emergent pollutants, which the study of depends on analytical methods that have only been developed during recent decades. The authors of [29] found that organic wastewater contaminants, including PPCPs, were present in 80% of 139 U.S. streams, while [30] focused on the magnitude of these compounds in wastewater, the efficiency of typical wastewater treatment plants to retain these compounds, and the resulting environmental load.

In response to these concerns, article 8b of Directive 2008/105/EC provides for the establishment of a watch list of substances that pose a threat to the aquatic environment. Furthermore, the documented presence of pharmaceutical compounds in the environment and the concerns about their potential adverse effect on humans and wildlife has led to the Directive 2010/84/EU and Regulation 1235/2010 on pharmacovigilance, which recommends the monitoring and environmental risk evaluation of medicinal related products [31]. The surface water Watch List, first published in 2015 and updated every 2 years, demonstrates the importance of regulating pharmaceutical and personal care products (PPCP) in water.

A wide discrepancy in removal efficiencies has been reported for individual compounds in separate studies as well as across therapeutic classes and treatment processes.

The removal of pharmaceuticals and personal care products from wastewater treatment systems are not limited to biological mechanisms but also include physical and chemical processes such as sorption, volatilization, and biotransformation. Different factors have been associated with the removal efficiencies observed in WWTP, namely the solids residence time (SRT), hydraulic residence time (HRT), and temperature. The authors of [31] evaluated the effect of in-sewer processes on pharmaceuticals while passing through a pressure sewer pipe and found that the concentration change was negligible for most of the analyzed compounds (up to 10%), while diltiazem, citalopram, clarithromycin, bezafibrate, and amlodipine had a 25–60% decrease and a negative removal was estimated for sulfamethoxazole (66 ± 15%) and irbesartan (58 ± 25%).

Stormwater constitutes more complex and less studied systems, whose pollution control represents a big challenge, especially when considering the existing restricted efforts.

The presence of non-biodegradable substances in stormwater that depend on site-specific characteristics has been proven to be associated with acute and chronic effects in the environment. These result from diffuse, intermittent, or cumulative pollution [32–35]. The most important groups of pollutants, due to their nature and environmental relevance are sediments, heavy metals, organic compounds, and nutrients. Heavy metals (Cu, Pb, Zn, and Cd and occasionally Ni and Cr), due to their environmental and health effects, have been one of the most studied groups [15], with their presence and speciation well documented.

Since this pollution is closely linked to the hydrological cycle, control techniques face unique challenges. Furthermore, since stormwater is often discharged without treatment, there is an urgent need to promote the control of this pollution load and to promote methodologies to reduce their source.

Filtration and sedimentation have been used for the retention of the fractionated part of heavy metals, but their effectiveness is constrained by particle size gradation and density, as well as specific site characteristics. Surface complexation and precipitation have been described as two main active processes of immobilization of metals in filtration systems [36]. The use of different natural substrates (e.g., iron-oxide-coated sand, natural zeolites, minerals, granular activated carbon, pine bark, etc) to immobilize dissolved heavy metals has been tested with success. Natural substrates represent a solution for "in situ" reactive filters that, through sorption, retain heavy metals and avoid their migration and the further contamination of surface or groundwater [34,36,37].

Therefore, an action that is beyond the managing of stormwater systems is required. This is one of the areas where non-traditional practices and a nature-based approach are necessary.

Finally, climate change's effects on the urban and natural environment are becoming more evident, resulting in changes to initial design criteria, with consequences that are not known. Associated hazardous events are estimated to result from a mix of flooding, pollution load, and operational problems that result in a decrease in water service performance and stronger public health, safety, and environmental and social-economic impacts.

Addressing climate change effects is therefore a worldwide priority that requires new practice, and the recognition of the acceptable level of risk, considering the combination of vulnerability and exposure of human and natural systems. An integrated response, involving different stakeholders, to create resilience is needed, with coordinated actions in isolated solutions and with synergetic combinations that can include co-benefits or trade-offs between different sectors [38].

3.2. Nature-Based Solutions: Context and Potential Benefits

3.2.1. Definition and Path to Recognition

According to [39], the term "nature-based solutions", firstly mentioned in the late 2000s [40,41] within the context of finding new solutions to mitigate and adapt to climate change effects while simultaneously protecting biodiversity and improving sustainable livelihoods, now has a recognized broader understanding. NBS go beyond the traditional biodiversity conservation and management principles by "re-focusing" the debate on humans and specifically integrating societal factors such as human well-being, socio-economic development, and governance principles. Therefore, they broaden the ecosystem (ES) framework, promoting and better relying on biological diversity, to increase the resistance and resilience of social-ecological systems to global changes and extreme or unexpected events.

The initial approaches aimed at controlling rain-induced flooding but also limiting the pollution carried to the environment [4,42,43]. However, significant changes were observed over recent decades, moving from an approach largely focused on flooding control and health protection to include explicitly environmental, social, and economic considerations [44].

A literature review identified the infrastructures that in multiple aspects considered a nature approach at least since the 1980s. In fact, [19,42,45], among others, already have been considering the benefits associated with NBS such as flooding control, recreation uses, environmental protection, and risk management (e.g., derived from flooding, water scarcity, or water pollution), but sometimes using different terms.

The term Low Impact Development (LID), which has references that go back to the late 1970s, builds on the idea of maintaining 'natural' hydrology conditions. This concept proposes smaller-scale stormwater treatment devices, such as bioretention systems, green roofs, and swales, located at or near the source of runoff, and has been most commonly used in North America and New Zealand, although similar approaches can also be found in New Zealand and France, where they are denoted as Alternative Techniques [46]. While the initial focus was primarily on human benefits, rather than ecosystem benefits, they slowly instigated that every urban design project began to include flow management (through detention, attenuation, infiltration, and source control retention) and the consideration of multi-function stormwater management corridors [42].

The Sustainable Urban Drainage Systems (SUDS) concept started in the UK in the late 1980s, as a change to established stormwater management practices and, based on the sustainable drainage triangle (quantity, quality, habitat/amenity), promoted a major set of new guidance documents with design manuals for the United Kingdom [47].

Initially, a Best Management Practice (BMP) was used in the United States and Canada to describe a type of practice or structured approach to prevent pollution, but the United States Environmental Agency went further by defining a BMP as a technique, process, activity, or structure that reduces the pollutant content of a stormwater discharge and can be implemented singly or in tandem to maximize effectiveness [48]. In this context of stormwater management, BMPs link non-structural methods (e.g., operational, procedural practices, social engagement) with structural deployments (e.g., Bioretention systems or Green Infrastructure) to achieve the overall goal of pollution prevention.

These concepts, which started as Source Control (SC) measures within the stormwater management concept, that guide near-source solutions (as opposed to larger downstream solutions), slowly stimulated more complex and diverse models. The concepts of Integrated Urban Water Management (IUWM) and Green Infrastructure (GI), which emerged in the USA in the 1990s, are closely linked with the term Water Sensitive Urban Design (WSUD) [49,50], which began to be used in the 1990s in Australia; they also start from urban water management but build on much broader concepts than those related to urban drainage management. These new systems desire to integrate and manage the water balance, enhance water quality, encourage water conservation, and maintain water-related environmental and recreational opportunities. This new philosophy has, over time, spread to the UK and to New Zealand, where new solutions are being studied. In China, since 2014, these concepts were incorporated in the Sponge City (SC) concept, which calls for the use of natural processes such as soil and vegetation as part of the urban runoff control strategy, considering similar LID solutions but aiming for integrated design and management in urban flood control, rainwater harvesting, water quality improvement, and ecological restoration and, therefore, broadening their scope as a GI or, due to the scale, an IUWM or WSUD approach.

Therefore, the recognition of the merits of these solutions and the need to act on a larger scale toward a nature-oriented approach has been gradually seen throughout the world. All these systems started to consider a systemic thinking mentality that, according to [51], is looking at the wholes and interactions rather than focusing on the properties of individual components.

The European Commission, which has included this theme in its agenda, defines NBS as "actions which are inspired by, supported by or copied from nature", that have been proven to be cost-effective and, simultaneously "provide environmental, social and economic benefits, and help build resilience" [52], helping societies to "address a variety of environmental, social and economic challenges in sustainable ways". Thus, the concept of NBS also combines ecosystem-based approaches, such as 'ecosystem services', 'green-blue infrastructure', 'ecological engineering', 'ecosystem-based management', and 'natural capital' [53] with assessments of the social and economic benefits of resource-efficient and systemic solutions that combine technical, business, finance, governance, regulatory, and social innovation [44].

NBS has already started to be included in the EU strategies [52] and in countries such as Australia, Canada, France, and the USA. The success of pioneer initiatives has led [54] to suggest that NBS should become part of the 'new normal' in infrastructure management.

3.2.2. Evaluating NBS Co-Benefits in the Urban Environment

A shared urban space has strong interactions and competition between different land uses and needs and requires the adequate coordination of actions, urban plans, and related policies. NBS can be designed to address various societal challenges, in a resource-efficient and adaptable manner, to simultaneously provide economic, social, and environmental co-benefits, and contribute to improving human wellbeing and quality of life [55].

According to [56], NBS can regulate four ecosystem services: water provision, water quality regulation, flood regulation, and soil protection. While some NBS improve the timing of water provision by promoting infiltration and storing water, flood regulation is achieved by promoting infiltration, soil water retention, vegetational obstructions, and wetlands that all reduce the velocity and converging of water during high-intensity rainfall events, while reducing suspended solids and retaining dissolved pollutants. As a soil-based solution, they also promote the reduction in the erodibility of the soil and the reduction in overland flow. Therefore, NBS also has a strong impact on flood control and urban pollution mitigation.

After analyzing the plans of 14 big European cities, [57] found that these measures are finding their way into climate adaptation plans, in response to a broad range of climate change challenges. Based on these findings, they recommend that methods to assess existing green/blue infrastructures and their potential to provide climate adaptation services should be mainstream in planning practice. These authors also suggest the adoption of a more formal analysis of co-benefit magnitudes in planning, since one of their strongest motivations is the environmental and socio-economic benefits that can be achieved, beyond climate adaptation.

The concept of NBS can also have a significant and positive impact on urban drainage systems, in retrofitting and adapting existing infrastructures and designing new engineered systems that account for the functions supplied by nature. This type of mindset and focus can also contribute to reducing the negative effects of unplanned urbanization, the adaptation to anticipated climate change (flooding and droughts), and the retention of relevant pollutants in the urban environment.

Based on an integrated valuation for water management, [51] have demonstrated these multi-purpose benefits in a peri-urban case study in northern Italy, concluding that NBS costs did not exceed those of traditional infrastructure while extending their multi-functionality and adding multiple benefits for a wider range of stakeholders.

The strong link of most of the Sustainable Development Goals to water and land management [56], also calls for the sustainable use of resources, ecosystem restoration, biodiversity, carbon sequestration, and sustainable catchment management, representing another motivation for the implementation of NBS. A call for this next generation of infrastructure—both green and traditional—echoes in the World Bank's Changing Wealth of Nations 2018 report, which showed that natural capital can be leveraged rather than liquidated through the development process. The World Bank Group is committed to elevating the role of natural infrastructure across its operations, demonstrating a commitment to leveraging its finance to catalyze actions for climate adaptation, and ensuring that the good performance of infrastructures is essential to face a changing climate [58].

Some of the nature-based engineered solutions already investigated in urban planning and water management (e.g., green roofs, bio-infiltration rain gardens, and vegetation in street canyons) have been demonstrated to be more efficient, cost-effective, adaptable, multi-purpose, and long-lasting than the traditional infrastructure alternatives (e.g., [48,51–63]). On the other hand, [64] suggest that a combination of green and traditional infrastructures into a "hybrid" solution may have a mutually beneficial effect and offer further potential in enhancing system resilience.

Therefore, the assessment of multifunctional solutions that progress far beyond their original mission and add considerable environmental, social, and economic value is of utmost importance.

NBS have also been successfully implemented to control diffuse pollution using source control measures (permeable surfaces, filter drains, strips, infiltration trenches, and grass swales), site controls (detention basins, filter drains, infiltration basins, and swales), or regional controls (treatment facilities that include retention ponds, stormwater wetlands, and enhanced extended detention basins). However, frequently, these measures are not integrated with existent systems [65], not considering the concept of dual system as proposed by [45].

The scope and co-benefits associated with NBS progress further than the drainage paradigm by requiring a multi-dimensional and complex framework. Therefore, the selection and assessment of NBS and related actions require the participation of a wide range of stakeholders, multi-disciplinary teams, and policy and decision-makers. The assessment of direct benefits and costs of actions relevant to NBS can be undertaken using a range of qualitative, quantitative, and mixed methods.

Guided by a review of over 1700 documents from science and practice, [63] proposed a seven-stage process for situating co-benefit assessment within policy and project implementation, based on a participatory process involving the most important stakeholders. The seven stages include: (1) identify the problem or opportunity; (2) select and assess NBS and related actions; (3) design NBS implementation processes; (4) implement NBS; (5) frequently engage stakeholders and communicate co-benefits; (6) transfer and upscale NBS; and (7) monitor and evaluate co-benefits across all stages.

While a global and holistic framework is not possible, due to the socio-cultural and socio-economic particularities and biodiversity, natural ecosystems, and the climate of each system, this study provides a framework that can be adapted for integrated NBS strategies in the urban environment.

The literature review demonstrates that there is clearly potential in the integration of NBS with traditional urban drainage solutions since they provide the control of smaller drainage areas, decrease runoff volume and the likelihood of cross-connection with foul drains, and promote the treatment of Combined Sewer Overflows, by creating engineered buffers that avoid the discharge of pollutants to receiving waters and soil. The retention of sediments and solids also contributes to improving the performance of the downstream network system in hybrid solutions.

3.3. Assessing Urban Drainage Problems, Consequences, and Potential Synergies

Based on the extensive research review, it is possible to map the most relevant intrinsic constraints and external pressures that traditional urban drainage systems are facing.

The major **intrinsic constraints** related to urban drainage systems can be categorized into two main categories: **interaction between systems (I1)** and infrastructure **management (I2)**. These problems have been aggravated by the broad nature of **external pressures** that have been compromising urban drainage functions and desired performance levels and can be categorized into three main categories: **changes to design criteria (E1)**, **urban planning and stakeholder awareness (E2)**, and **investment constraints (E3)**.

This complex interaction is depicted in Figure 1, where the problems and limitations of traditional drainage systems are associated with the consequences to the surrounding natural and urban environment and where NBS seems to attenuate some of these constraints and simultaneously increase the resilience of the urban environment.

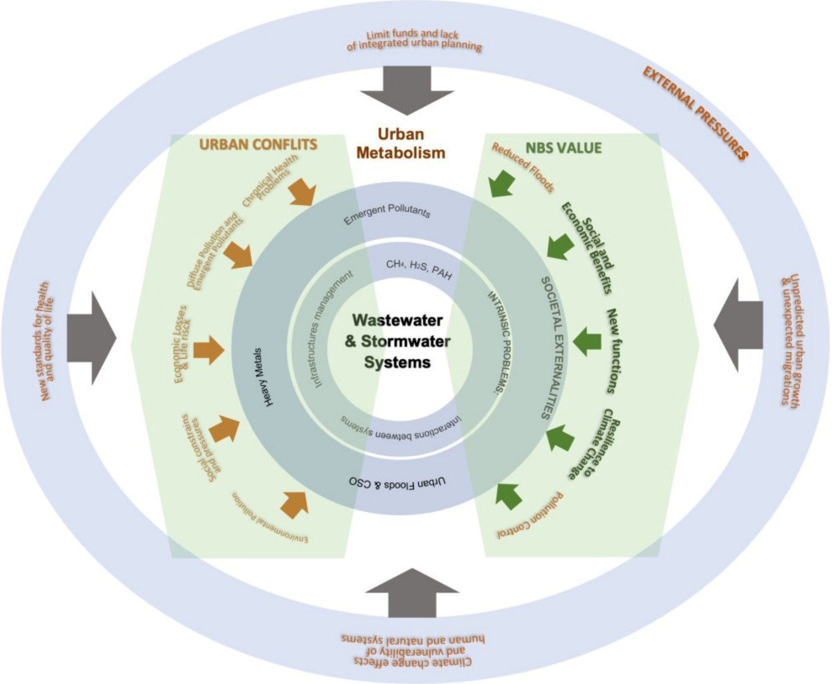

Figure 1. Urban drainage systems: intrinsic constraints and external pressures.

Table 2 resumes the identified problems and limitations associated with traditional urban drainage, and associated consequences, that are responsible for direct impacts and societal externalities and a broad range of consequences to the urban environment.

Table 2. Traditional urban drainage problems and limitations and associated consequences to the urban environment.

Tradition Urban Drainage Systems: *Identified Problems and Limitations*			**Consequences to the Urban Environment:** *Direct Impacts and Societal Externalities*				
			UFs	**PCs**	**ELs**	**HSOs**	**ERs**
A. Intrinsic constraints	Interactions between systems	Uncontrolled connections from stormwater systems or urban streams or groundwater infiltration into wastewater systems	-	–	–	-	–
		Uncontrolled wastewater connections into stormwater systems or urban streams	-	–	-	-	–
		Uncontrolled saline intrusion	0	0	-	0	-
		Uncollected point source discharges	0	-	0	–	–
	Infrastructure management	Outdated design criteria	-	–	–	–	–
		Buried and aging infrastructures	0	0	-	0	0
		Emission of VOC	0	0	–	-	0
		Reactive maintenance of existent systems	-	0	–	-	0
		Continuous pollution load emission	0	–	-	–	–
		Unknown fate of emergent pollutants	0	–	0	–	–

Table 2. *Cont.*

Tradition Urban Drainage Systems: *Identified Problems and Limitations*			**Consequences to the Urban Environment:** *Direct Impacts and Societal Externalities*				
			UFs	**PCs**	**ELs**	**HSOs**	**ERs**
B. External pressures	Changes to design criteria	Unexpected demographic growth	–	–	-	-	-
		Unpredicted migrations	–	-	-	-	-
		Changing and unforeseen precipitation patterns due to climate change	–	-	–	–	-
		Increased impervious areas	–	-	-	0	-
	Urban planning and stakeholder awareness	Increased impervious areas					
		Increased diffuse pollution emission	0	–	0	0	–
		Lack of integrated urban planning	–	–	–	-	–
		Fulfilment of new quality standards by society and legislation	–	–	–	–	–
	Investment constraints	Limited funds for infrastructure rehabilitation	–	0	–	–	-
		Limited funds for infrastructure upgrade due to obsolescence	–	0	–	-	0

Direct Impacts: "UFs"—Urban Floods and CSO; "PCs"—Pollution Consequences. Societal externalities: "ELs"—Economic Losses; "HSOs"—Health and Social Issues; "ERs"—Environmental Risks. Legend: "0"—No consequence; "–"—High negative consequence; "-"—Negative consequence.

A critical analysis of these direct impacts aggregates them into two main groups: (1) **Urban Floods and Combined Sewer Overflow (UFs)**, which are associated with the wastewater volume, and (2) **Pollution Load Consequences (PCs)**, which are associated with the acute and chronic effects of the associated pollutants. These direct impacts are also responsible for the broad nature of societal externalities that are related to **Economic Losses (ELs)**, **Health Problems and Social Issues (HSOs),** or **Environmental Risks (ERs)**.

Table 2 also evaluates the direct impact of the identified problems and limitations, allowing us to conclude that the known problems and limitations of traditional urban drainage systems, which are associated not only with their intrinsic constraints but also with relevant external pressures, have a significant and diffuse impact on the urban environment. While most direct impacts can be addressed within the water sector, the identified societal externalities are beyond the reach of this sector, transferring this responsibility to society.

Based on these conclusions, possible opportunities and synergies between this traditional praxis and NBS are depicted in Table 3, indicating how NBS can support and synergize traditional urban drainage systems and classify associated co-benefits to the urban environment.

Table 3. NBS contributes to urban drainage problems and limitations and has positive effects on the urban environment.

Nature-Based Solution Integration in the Urban Environment: *Synergies with Traditional Drainage Systems to Identified Problems and Limitations*			**Effects on the Urban Environment:** *Direct Impacts and Societal Externalities*				
			UF	**PC**	**EC**	**HSO**	**EN**
A. Intrinsic improvements	Interactions between systems	Decreased interactions between systems	++	++	++	++	++
		CSO off-line retention	++	++	+	+	++
		Cost-effective solution for non-biodegradable pollutants	0	++	+	++	++
		Facilitated small-decentralized treatment facilities	++	++	++	++	++
	Infrastructure management	Reduced buried sewer length	+	+	+	0	0
		Simpler retrofit operations and easier maintenance procedures	+	++	+	0	+
		Easier sediments and litter removal	+	++	+	0	+
		Visual alarms of unexpected situations	++	+	++	0	+
		Increased air-water transfer, reducing VOC	0	+	+	+	+

Table 3. *Cont.*

Nature-Based Solution Integration in the Urban Environment: *Synergies with Traditional Drainage Systems to Identified Problems and Limitations*			**Effects on the Urban Environment:** *Direct Impacts and Societal Externalities*				
			UF	**PC**	**EC**	**HSO**	**EN**
B. External pressures	Changes to design criteria	Positive hydrodynamic effect reducing runoff floods	++	+	++	0	+
		Flow equalization (by detention, retention, and infiltration)	++	++	++	0	++
		Urban space available for flood control	++	0	++	0	0
		Reduced drought risk and increased water provision	+	0	+	+	+
		Decreased urban vulnerability to floods	++	0	++	++	0
		Increased resilience to unexpected stresses	++	++	++	+	+
		Increased urban resilience to climate dynamics	++	++	++	++	++
	Urban planning and stakeholder awareness	Integrated urban/water planning	++	++	++	++	++
		Source-control of urban pollutants (by sorption, complexation, and filtration)	+	++	0	+	++
		Reduces diffuse pollution load	+	++	0	+	++
		Improved water quality by pollutants retention	+	++	0	+	++
		Contributes to the Sustainable Development Goals	++	++	++	++	++
		Urban space available for leisure	+	+	+	++	++
		Natural ecosystems in urban areas	+	+	++	++	++
		Improves air quality and temperature	0	0	0	+	+
		Improved livability and quality of life	+	+	+	+	+
	Investment opportunities	Increases real estate value	+	+	++	+	+
		Facilitated access to funding of sustainable urban solutions	++	++	++	++	++

Direct Impacts: "UFs"—Urban Floods and CSO; "PCs"—Pollution Consequences. Societal externalities: "ELs"—Economic Losses; "HSOs"—Health and Social Issues; "ERs"—Environmental Risks. Legend: "0"—No effect; "+" Positive effect; "++"—High positive effect.

The positive effects that are provided by NBS to the urban water sector are listed as **Intrinsic Improvements** in the two main groups: **Interaction Between Systems** and **Infrastructure Management**. However, these positive effects go beyond the water sector, providing **External Benefits**, which are categorized into three main groups: **Changes to design criteria, Urban Planning and Stakeholder Awareness,** and **Investment Opportunities**.

The effects of NBS on the urban environment are estimated for the two categories that aggregate the direct impacts: **Urban Floods and Combined Sewer Overflow (UFs)**, which are associated with the wastewater volume; and **Pollution Load Consequences (PCs)**, which are associated with the acute and chronic effects of the associated pollutants and the broad nature of societal externalities that are related to **Economic Losses (ECs)**, **Health Problems and Social Issues (SOs),** and **Environmental Risks (ENs)**.

The cross-linkage of the synergies between NBS and traditional urban water systems permits the estimation of the potential positive effects on the urban environment, including **Intrinsic Improvements** to the urban water sector that mitigate the identified problems and limitations and benefit the urban environment, which represents important **External Benefits** that address the constraints derived from the water sector and provide resilience to the consequences of broader phenomena as those related to climate change.

The combination of Tables 2 and 3 allows a manager to pinpoint, for operational constraints or societal impacts perceived in the system (identified in Table 2), how they can be addressed by NBS (in Table 3). The results prove that the combination of traditional existing systems, with the strengths and potentialities of NBS, can result in extended urban water ecosystems with overall performance improvements.

The complete interpretation of synergies and benefits that result from the inclusion of NBS in the urban environment indicates a way to address the problems and limitations of traditional praxis and provide a method to pave the way to sustainable and resilient cities, with integrated planning and the inclusion of multiple stakeholders.

3.4. Assessing Synergies between NBS and Urban Drainage

3.4.1. Establishing an Integrated Framework

The concept of combining traditional urban drainage systems with NBS has been developing, adopting system behavior thinking and including societal factors such as human well-being, socio-economic development, and governance principles. This hybrid concept represents an opportunity to enhance sustainability in the urban environment and foster adaptation to climate change.

Implementing NBS, which support and complement existing or new traditional drainage systems, is not the current praxis. An integrated framework is needed to assist designers and utility managers to identify the opportunities and synergies that derive from this joint solution.

However, the multiple relations between anthropogenic activities and the urban and natural environment are associated with complex processes and phenomena that are characteristic of an open environment. A holistic evaluation therefore requires an integrated framework that can represent this reality, include associated co-benefits (that are difficult to assess), and that can be understood and shared between different agencies and areas of knowledge.

The results from recent research (e.g., [63,66–70]) have been providing contributions to an integrated framework that can evaluate different co-benefits of NBS to the urban environment. Most of these frameworks are mostly focused on assessing NBS' effectiveness for climate resilience and specific urban challenges, such as green space management or air quality, while others have been proposed specifically to assess their resilience in cities. No specific framework was found to specifically identify synergies and opportunities between NSB and urban drainage systems.

The framework proposed by [69], based on the performance assessment structure proposed by the ISO 24500 standards for water supply and wastewater system management, includes (i) social, environmental, economic, and governance dimensions; (ii) spatial and land use planning at the city level; (iii) service and infrastructure management; (iv) potential capabilities to provide ecosystem services and to enhance natural capital and biodiversity; (v) impacts on the surrounding area; (vi) infrastructure implementation and design, including adequate monitoring and maintenance processes; (vii) infrastructure performance under normal and stressing conditions, considering acute shocks and continuous stresses; and (viii) infrastructure interdependencies with other urban services.

The proposed methodology is grounded on two dimensions: Dimension I, which accesses the integration of NBS in city governance and stakeholder involvement, economic sustainability and social involvement, and NBS' contributions to environmental resilience (including four associated objectives to evaluate the city's preparedness for governance, planning, and financial aspects); The operation and services of NBS constitute the core of Dimension II, which focuses on the adequacy of urban planning and both service and infrastructure management, NBS functioning regarding service management (e.g., service articulation between entities and the allocation of financial and technical resources), its consequences in the surrounding area (e.g., ecosystem services improvement, flooded area, and affected buildings), and the performance of the infrastructure.

The definitions of the objectives, criteria, and metrics are supported by three levels of complexity—based on the existing data in the city (data-based), based on a procedure defined for specific metrics (procedure-based), or based on results from a mathematical model (model-based).

One of the merits of this framework is related to the participation, contribution, and validation of a broad group of stakeholders (that include water utilities, municipal councils, and private organizations) from seven cities in Portugal, Spain, the United Kingdom, and Canada to ensure its reliability and effectiveness in different conditions and for stakeholder validation.

While this multidimensional and comprehensive framework was developed to assess NBS' contributions to urban resilience, it was used as a starting point to evaluate the opportunities and synergies between NBS and traditional drainage systems.

3.4.2. Testing a Resilience Framework to Assess Synergies and Opportunities

Table 4 presents the different objectives and criteria (for which the methodology was developed) and qualitatively evaluates the relevance of these criteria in identifying the benefit of including NBS coupled with traditional urban drainage system constraints, either to wastewater or stormwater systems.

Table 4. Testing a resilience framework to assess the NBS synergies and opportunities with traditional urban drainage systems.

			Wastewater Systems	**Storm Water Systems**
Dimension I—Integration of NBS in the City	Objective 1 Governance and stakeholders' involvement	Criterion 1.1—NBS planning at the city level	+	+
		Criterion 1.2—Stakeholders' awareness and involvement	+	++
	Objective 2 Economic sustainability	Criterion 2.1—Public finance	++	++
		Criterion 2.2—Economic opportunities	.	.
	Objective 3 Social involvement and co-benefits	Criterion 3.1—Citizens' engagement and accessibility to NBS	+	+
		Criterion 3.2—Social co-benefits	.	.
	Objective 4 Environmental resilience	Criterion 4.1—Fresh water provision	.	.
		Criterion 4.2—Local air quality regulation	.	.
		Criterion 4.3—Moderation of extreme events	+	++
		Criterion: 4.4—Water treatment	+	++
		Criterion 4.5—Erosion prevention and maintenance of soil fertility	.	.
		Criterion 4.6—Habitats for species promotion	.	.
Dimension II—Operation and Services of NBS NBS	Objective 5 Spatial planning	Criterion 5.1—Hazard and exposure mapping	+	+
		Criterion 5.2—Land use and NBS inclusion	+	+
	Objective 6 Service management	Criterion 6.1—Service management and planning	+	+
		Criterion 6.2—Resource availability and adequacy	+	+
	Objective 7 Resilience engaged to service	Criterion 7.1—Flexible service	.	+
		Criterion 7.2—Scenario relevance for disaster response	+	+
		Criterion 7.3—Reliable service	+	++
	Objective 8 Infrastructure safety and robustness	Criterion 8.1—Infrastructure asset criticality and protection	+	+
		Criterion 8.2—Infrastructure asset robustness	++	++
		Criterion 8.3—Infrastructure monitoring and maintenance	++	++
	Objective 9 Infrastructure preparedness	Criterion 9.1—Infrastructure preparedness for recovery and buildback	++	++
	Objective 10 Infrastructure dependence and autonomy	Criterion 10.1—Infrastructure dependence	+	+
		Criterion 10.2—Infrastructure autonomy	+	+

Legend: "."—Not relevant; "+"—Moderately relevant; "++"—Highly Relevant.

From a total of 24 criteria, only 6 criteria were found to not be relevant for both wastewater and stormwater systems, while 18 and 19 demonstrated to be moderately relevant or highly relevant for both, respectively, covering all Objective categories. Furthermore, five of the considered criteria demonstrated a higher relevance for stormwater systems than wastewater systems. Additionally, the criteria associated with stakeholder awareness and involvement, public finance possibilities, resilience to extreme events, improvement of water treatment, and infrastructure improvements were demonstrated to benefit most from the integration of NBS.

These results indicate that, in wastewater systems, synergies with NBS are mostly associated with decentralized treatment facilities (avoiding long transport distances and decreasing operational problems) and providing a feasible solution for the control of inorganic pollutants by reactive filtration systems that consider the use of natural substrates.

On the other hand, the benefits of NBS in stormwater management and associated pollution control are noticeable. They promote a decrease in impervious urban areas, enhancing higher infiltration rates and, consequently, reducing associated flood flows. These solutions are effective wet-weather source control solutions that support the livability of urban spaces and contribute to better temperature control in dry-weather conditions. NBS can also promote the retention of urban pollutants since several studies have shown their effectiveness for the retention of particulate and dissolved substances present in stormwater.

The criteria that were demonstrated to be highly relevant (identified with ++ in Table 4) were then assessed to identify possible synergies by NBS, to existing and new systems, namely, to overcome identified intrinsic constraints of traditional drainage solutions and to mitigate known direct impacts, external pressures, or societal externalities. Table 5 presents the result of this process, identifying the synergies related to wastewater, stormwater, or both systems with vertical stripes, horizontal stripes, and a grid layout, respectively.

Table 5. Assessing synergies that result from NBS integration.

Criteria	**Intrinsic Constraints**		**Direct Impacts**		**External Pressures**			**Societal Externalities**		
	IS	**IM**	**UFs**	**PCs**	**DC**	**UP&SA**	**ICs**	**ELs**	**HSOs**	**ERs**
1.2—Stakeholders' awareness and involvement		🟦				🟦			🟦	
2.1—Public finance		🟩				🟩	🟩			
4.3—Moderation of extreme events	🟦		🟦	🟦	🟦					🟦
4.4—Water treatment				🟦					🟦	🟦
7.3—Reliable service	🟦		🟦	🟦	🟦			🟦	🟦	🟦
8.2—Infrastructure assets robustness	🟩	🟩	🟩	🟩	🟩					
8.3—Infrastructure monitoring and maintenance	🟩	🟩	🟩	🟩					🟩	🟩
9.1—Infrastructure preparedness for recovery and buildback	🟩	🟩	🟩	🟩					🟩	🟩

Legend: Blue—stormwater, Green—Wastewater and Stormwater. IS—Interactions between Systems; IM—Infrastructures' Management; UFs—Urban Floods and CSOs; PCs—Pollution Consequences; DC—changes in Design Criteria; UP&SA—Urban Planning and Stakeholders' Awareness; ICs—Investment Constraints; ELs—Economic losses; HSOs—health and Social Issues; ERs—Environmental Risks.

The combined analysis of the presented methodology and associated results confirms that NBS conveys clear benefits when combined with traditional urban systems. This provides multiple positive effects (Table 3), that may overcome the existing constraints (Table 2). Furthermore, the tested criteria (Table 4) have diagnosed benefits for traditional urban systems, given the prospective synergies and the contributions to mitigate identified external pressures (Table 5). It should be noted that, in Table 5, each column may be further assessed by other criteria that are characteristic of each case study and whose assessment and quantification may be further scrutinized by additional metrics included in each criterion.

4. Conclusions

Although urban drainage systems are essential for urban metabolism, they are facing intrinsic problems related to aging infrastructures and interactions between systems that compromise their performance and objectives. Furthermore, to embrace new challenges, such as those related to climate change, a "business-as-usual" solution must be replaced by integrated urban planning.

This paper starts by identifying the existing urban drainage constraints and external pressures, their effect on the provided services and functions, and the associated consequences to the urban environment. Beyond the more known direct impacts, important social externalities were found, thus demonstrating the increasing importance of external pressures that cannot be addressed within the urban water sector.

An integrated framework that was initially proposed for the evaluation of urban resilience was the starting point to test a methodology that can access the multiple and complex relations between anthropogenic activities and the urban and natural environment. This instrument has proven to be an effective tool to assist designers and utility managers to identify the opportunities and synergies that derive from this joint solution and evaluate the synergies and opportunities between NBS and traditional urban systems, including the associated co-benefits.

Based on the proposed methodology and presented results, the synergies that result from the integration of NBS in the urban environment, as interventions that contribute to the sustainable management of water in the urban environment, were assessed. These results have also demonstrated that this praxis, besides providing intrinsic improvements to urban drainage systems, promotes relevant external benefits that emerge as direct impacts and relevant social externalities. These revealed synergies have also surfaced and represent important adaptation measures that increase resilience to climate change while providing additional important economic, social, and environmental co-benefits.

The completion of all NBS synergies and opportunities depend, however, on integrated design and management, involving different agencies and areas of knowledge. The success of this co-implementation relies therefore on the ability of urban planners, managers, and water utilities to communicate and align their organization objectives and plans.

A new paradigm for urban water management is imposing itself, demonstrating the urgency of an integrated vision of the urban environment, with demonstrated opportunities and synergies. Based on the presented results, it can be concluded that NBS represents an effective opportunity to address existent urban drainage problems and limitations while introducing new green spaces, increasing the livability of cities, and contributing to a better life in the urban environment and, therefore, enhancing urban sustainability and providing additional social co-benefits.

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References

1. Galea, S.; Vlahov, D. URBAN HEALTH: Evidence, Challenges, and Directions. *Annu. Rev. Public Health* **2005**, *26*, 341–365. [CrossRef] [PubMed]
2. Jha, A.K.; Bloch, R.; Lamond, J. *Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century*; World Bank: Washington, DC, USA, 2012.
3. United Nations Department of Economic Social Affairs (UN DESA). *World Urbanization Prospects*; UN DESA: New York, NY, USA, 2014.
4. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.-L.; et al. SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **2015**, *12*, 525–542. [CrossRef]
5. Butler, D.; Davies, J. *Urban Drainage*, 3rd ed; CRC Press: Boca Raton, FL, USA, 2011; ISBN 9781315272535.
6. Ainger, C.M.; Armstrong, R.A.; Butler, D. Dry Weather Flow in Sewers. In *CIRIA Report R 177*; CIRIA: London, UK, 1998.
7. Ellis, B.; Bertrand-Krajewski, J. *Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems*; IWA Publishing: London, UK, 2010.

8. Malik, M. In-Sewer Treatment of Domestic Wastewater. Ph.D. Thesis, University of Newcastle upon Tyne, Newcastle upon Tyne, UK, 1996.
9. Malik, M. Substrate Removal by In-Sewer Oxygenation. *Water Environ. J.* **1998**, *12*, 6–8. [CrossRef]
10. Hvitved-Jacobsen, T.; Vollertsen, J.; Nielsen, P.H. A process and model concept for microbial wastewater transformations in gravity sewers. *Water Sci. Technol.* **1998**, *37*, 233–241. [CrossRef]
11. Almeida, M.C.; Vieira, P.; Smeets, P. Extending the water safety plan concept to the urban water cycle. *Water Policy* **2014**, *16*, 298–322. [CrossRef]
12. Özer, A.; Kasirga, E. Substrate removal in long sewer lines. *Water Sci. Technol.* **1995**, *31*, 213–218. [CrossRef]
13. Warith, M.; Kennedy, K.; Reitsma, R. Use of sanitary sewers as wastewater pre-treatment systems. *Waste Manag.* **1998**, *18*, 235–247. [CrossRef]
14. Van Dam, C.H.; Scholten, M.; van de Ven, F. Urban Water Quality in Lelystad: Rainfall and Runoff from Selected Surfaces. In Proceedings of the 2ème Conférence de Wageningen, Urban Storm Water Quality and Ecological Effects upon Receiving, The Hague, The Netherlands, October 1986; pp. 25–37.
15. Hvitved-Jacobsen, T.; Vollertsen, J.; Nielsen, A.H. *Sewer Processes: Microbial and Chemical Process Engineering of Sewer Networks*; CRC Press: Boca Raton, FL, USA, 2013.
16. Ramísio, P.; Vieira, J. Characterization of Road Runoff: A Case Study on the A3 Portuguese Highway. Alliance for Global Sustainability Bookseries: Science and Technology: Tools for Sustainable Development. In *Urban Environment*; Morrison, R., Ed.; Springer: Dodrecht, The Netherlands, 2012; Volume 19, pp. 285–295. ISSN 1571-4780.
17. Sansalone, J.J.; Buchberger, S.G. Partitioning and First Flush of Metals in Urban Roadway Storm Water. *J. Environ. Eng.* **1997**, *123*, 134–143. [CrossRef]
18. Ellis, J.B.; Mitchell, G. Urban diffuse pollution: Key data information approaches for the Water Framework Directive. *Water Environ. J.* **2006**, *20*, 19–26. [CrossRef]
19. Yevjevich, V. Pressing Urban Water Problems in the United States. In Proceedings of the 2nd International Conference on Urban Storm Drainage, Urbana, IL, USA, 15–19 June 1981; pp. 469–474.
20. PBL (Netherlands Environmental Assessment Agency); Ligtvoet, W.; Hilderink, H. *Towards a World of Cities in 2050: An Outlook on Water-Related Challenges*; PBL: The Hague, The Netherlands, 2014; Available online: http://www.pbl.nl/sites/default/files/cms/publicaties/PBL_2014_To-wards%20a%20world%20of%20cities%20in%202050_1325_0.pdf (accessed on 1 June 2022).
21. Kabisch, N.; Frantzeskaki, N.; Pauleit, S.; Naumann, S.; Davis, M.; Artmann, M.; Haase, D.; Knapp, S.; Korn, H.; Stadler, J.; et al. Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecol. Soc.* **2016**, *21*, 39. [CrossRef]
22. Foley, J.; Yuan, Z.; Lant, P. Dissolved methane in rising main sewer systems: Field measurements and simple model development for estimating greenhouse gas emissions. *Water Sci. Technol.* **2009**, *60*, 2963–2971. [CrossRef] [PubMed]
23. Risch, E.; Gutierrez, O.; Roux, P.; Boutin, C.; Corominas, L. Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems. *Water Res.* **2015**, *77*, 35–48. [CrossRef] [PubMed]
24. Nielsen, A.H.; Vollertsen, J.; Jensen, H.S.; Wium-Andersen, T.; Hvitved-Jacobsen, T. Influence of pipe materi-al and surfaces on sulfide related odor and corrosion in sewers. *Water Res.* **2008**, *42*, 4206–4214. [CrossRef] [PubMed]
25. Vollertsen, J.; Nielsen, A.H.; Jensen, H.S.; Wium-Andersen, T.; Hvitved-Jacobsen, T. Corrosion of concrete sewers—The kinetics of hydrogen sulfide oxidation. *Sci. Total Environ.* **2008**, *394*, 162–170. [CrossRef]
26. Sudarjanto, G.; Gutierrez, O.; Ren, G.; Yuan, Z. Laboratory assessment of bioproducts for sulphide and methane control in sewer systems. *Sci. Total Environ.* **2013**, *443*, 429–437. [CrossRef]
27. IPCC; Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme*; IGES: Kanagawa, Japan, 2006.
28. Guisasola, A.; de Haas, D.; Keller, J.; Yuan, Z. Methane formation in sewer systems. *Water Res.* **2008**, *42*, 1421–1430. [CrossRef]
29. Kolpin, D.W.; Furlong, E.; Meyer, M.; Thurman, E.M.; Zaugg, S.D.; Barber, L.B.; Buxton, H.T. Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999−2000: A National Reconnaissance. *Environ. Sci. Technol.* **2002**, *36*, 1202–1211. [CrossRef]
30. Jelic, A.; Gros, M.; Ginebreda, A.; Cespedes-Sanchez, R.; Ventura, F.; Petrovic, M.; Barcelo, D. Occurrence, parti-tion and removal of pharmaceuticals in sewage water and sludge during wastewater treatment. *Water Res.* **2011**, *45*, 1165–1176. [CrossRef]
31. Jelic, A.; Rodriguez-Mozaz, S.; Barceló, D.; Gutierrez, O. Impact of in-sewer transformation on 43 pharmaceuticals in a pressurized sewer under anaerobic conditions. *Water Res.* **2015**, *68*, 98–108. [CrossRef]
32. Luker, M.; Montague, K. *Control of Pollution from Highway Drainage Discharges*; CIRIA Report 142; CIRIA: London, UK, 1994; ISBN 086017-415-8.
33. Kayhanian, M.; Suverkropp, C.; Ruby, A.; Tsay, K. Characterization and prediction of highway runoff constituent event mean concentration. *J. Environ. Manag.* **2007**, *85*, 279–295. [CrossRef]
34. Ramísio, P.; Vieira, J. Heavy Metal Removal Efficiency in a Kaolinite–Sand Media Filtration Pilot-Scale Installation. In *Highway and Urban Environment*; Morrison, G.M., Rauch, S., Eds.; Alliance for Global Sustainability Bookseries; Springer: Dordrecht, The Netherlands, 2007; Volume 12.
35. Opher, T.; Friedler, E. Factors affecting highway runoff quality. *Urban Water J.* **2010**, *7*, 155–172. [CrossRef]

36. Farm, C. Metal sorption to natural filter substrates for storm water treatment—Column studies. *Sci. Total Environ.* **2002**, *298*, 17–24. [CrossRef] [PubMed]
37. Ramísio, P.; Vieira, J. Evaluation of Zn, Cu and Pb Sorption-Desorption Phenomena in Kaolinite-Sand Media Filtration Pilot Scale Installation. In *Highway and Urban Environment. Alliance for Global Sustainability Bookseries (Science and Technology: Tools for Sustainable Development)*; Rauch, S., Morrison, G., Monzón, A., Eds.; Springer: Dordrecht, The Netherlands, 2009; Volume 17.
38. Reckien, D.; Salvia, M.; Heidrich, O.; Church, J.M.; Pietrapertosa, F.; De Gregorio-Hurtado, S.; D'Alonzo, V.; Foley, A.; Simoes, S.G.; Lorencová, E.K.; et al. How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *J. Clean. Prod.* **2018**, *191*, 207–219. [CrossRef]
39. Eggermont, H.; Balian, E.; Azevedo, J.; Beumer, V.; Brodin, T.; Claudet, J.; Fady, B.; Grube, M.; Keune, H.; Lamarque, P.; et al. *Nature-Based Solutions: New Influence for Environmental Management and Research in Europe*; GAIA—Ecological Perspectives for Science and Society: Munich, Germany, 2015; Volume 24, pp. 243–248.
40. MacKinnon, K.; Sobrevila, C.; Hickey, V. *Biodiversity, Climate Change and Adaptation: Nature-Based Solutions from the Word Bank Portfolio*; World Bank: Washington, DC, USA, 2008.
41. Mittermeier, R.A.; Totten, M.; Ledwith Pennypacker, L.; Boltz, F.; Prickett, G.; Mittermeier, C.G.; Cardoso, D.S. *A Climate for Life: Meeting the Global Challenge*; International League of Conservation Photographers: Arlington, VA, USA, 2008.
42. Azzout, Y.; Cres, F.N.; Barraud, S. *Techniques Alternatives en Assainissement Pluvial. Choix, Conception, Eéalisation et Entretien*; Collection Tec & Doc Lavoisier: Paris, France, 1994.
43. Selection aid of alternative techniques in urban storm drainage—proposition of an expert system. *Water Sci. Technol.* **1999**, *39*, 241–248. [CrossRef]
44. European Commission. *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: Brussels, Belgium, 2015.
45. Wisner, P.E.; Kassem, A.M.; Cheung, P.W. Parks Against Storm. In Proceedings of the Second International Conference on Urban Drainage, Urbana, IL, USA, 14–19 June 1981; pp. 322–330.
46. Chen, J.; Hill, A.A.; Urbano, L.D. A GIS-based model for urban flood inundation. *J. Hydrol.* **1981**, *373*, 184–192. [CrossRef]
47. Department of Environmental Resources. *Low-Impact Development: An Integrated Design Approach*; Department of Environmental Resources: Prince George's County, MA, USA, 1999.
48. Wong, T.H.F. Water sensitive urban design—The journey thus far. *Australas. J. Water Resour.* **2007**, *10*, 213–222. [CrossRef]
49. CIRIA. *Sustainable Urban Drainage Systems—Design Manual for Scotland and Northern Ireland*; CIRIA Report No. C521; CIRIA: Dundee, UK, 2000.
50. Whelans, C.; Maunsell, H.G.; Thompson, P. *Planning and Management Guidelines for Water Sensitive Urban (Residential) Design*; Department of Planning and Urban Development of Western Australia: Perth, WA, Australia, 1994.
51. Schueler, T.R. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs*; Washington Metropolitan Water Resources Planning Board: Washington, DC, USA, 1987.
52. Liquete, C.; Udias, A.; Conte, G.; Grizzetti, B.; Masi, F. Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. *Ecosyst. Serv.* **2016**, *22*, 392–401. [CrossRef]
53. European Commission. Topics: Nature-Based Solutions. 2016. Available online: https://ec.europa.eu/research/environment/index.cfm?pg=nbs (accessed on 1 July 2022).
54. Nesshöver, C.; Assmuth, T.; Irvine, K.N.; Rusch, G.M.; Waylen, K.A.; Delbaere, B.; Haase, D.; Jones-Walters, L.; Keune, H.; Kovacs, E.; et al. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Sci. Total Environ.* **2016**, *579*, 1215–1227. [CrossRef]
55. Davies, C.; Lafortezza, R. Transitional path to the adoption of nature-based solutions. *Land Use Policy* **2018**, *80*, 406–409. [CrossRef]
56. Escobedo, F.J.; Giannico, V.; Jim, C.Y.; Sanesi, G.; Lafortezza, R. Urban forests, ecosystem services, green infra-structure and nature-based solutions: Nexus or evolving metaphors? *Urban For. Urban Green* **2018**, *31*, 130–141. [CrossRef]
57. Keesstra, S.; Nunes, J.; Novara, A.; Finger, D.; Avelar, D.; Kalantari, Z.; Cerdà, A. The superior effect of nature based solutions in land management for enhancing ecosystem services. *Sci. Total Environ.* **2018**, *610–611*, 997–1009. [CrossRef]
58. Geneletti, D.; Zardo, L. Ecosystem-based adaptation in cities: An analysis of European urban climate adaptation plans. *Land Use Policy* **2016**, *50*, 38–47. [CrossRef]
59. Browder, G.; Ozment, S.; Rehberger Bescos, I.; Gartner, T.; Lange, G.-M. *Integrating Green and Gray: Creating Next Generation Infrastructure*; World Bank and World Resources Institute: Washington, DC, USA, 2019; Available online: https://openknowledge.worldbank.org/handle/10986/31430 (accessed on 25 February 2020).
60. Gill, S.E.; Handley, J.F.; Ennos, A.R.; Pauleit, S. Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built Environ.* **1998**, *33*, 115–133. [CrossRef]
61. Pugh, T.A.M.; MacKenzie, A.R.; Whyatt, J.D.; Hewitt, C.N. Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environ. Sci. Technol.* **2012**, *46*, 7692–7699. [CrossRef]
62. Martin, C.; Ruperd, Y.; Legret, M. Urban stormwater drainage management: The development of a multicriteria decision aid approach for best man-agement practices. *Eur. J. Oper. Res.* **2007**, *181*, 338–349. [CrossRef]
63. Flynn, K.M.; Traver, R.G. Green infrastructure life cycle assessment: A bio-infiltration case study. *Ecol. Eng.* **2013**, *55*, 9–22. [CrossRef]

64. Raje, S.; Kertesz, R.; Maccarone, K.; Seltzer, K.; Siminari, M.; Simms, P.; Wood, B.; Sansalone, J. Green infrastruc-ture design for pavement systems subject to rainfall-runoff loadings. *Transp. Res. Rec.* **2013**, *2358*, 79–87. [CrossRef]
65. Raymond, C.M.; Frantzeskaki, N.; Kabisch, N.; Berry, P.; Breil, M.; Nita, M.R.; Geneletti, D.; Calfapietra, C. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ. Sci. Policy* **2017**, *77*, 15–24. [CrossRef]
66. Dong, X.; Guo, H.; Zeng, S. Enhancing future resilience in urban drainage system: Green versus grey infrastructure. *Water Res.* **2017**, *124*, 280–289. [CrossRef]
67. Zhou, Q.A. Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts. *Water* **2014**, *6*, 976–992. [CrossRef]
68. Alemaw, B.F.; Chaoka, T.R.; Tafesse, N.T. Modelling of Nature-Based Solutions (NBS) for Urban Water Management—Investment and Outscaling Implications at Basin and Regional Levels. *J. Water Resour. Prot.* **2020**, *12*, 853–883. [CrossRef]
69. Beceiro, P.; Brito, R.S.; Galvão, A. The Contribution of NBS to Urban Resilience in Stormwater Management and Control: A Framework with Stakeholder Validation. *Sustainability* **2020**, *12*, 2537. [CrossRef]
70. Shkaruba, A.; Skryhan, H.; Likhacheva, O.; Katona, A.; Maryskevych, O.; Kireyeu, V.; Shpakivska, I. Development of sustainable urban drainage systems in Eastern Europe: An analytical overview of the constraints and enabling conditions. *J. Environ. Plan. Manag.* **2021**, *64*, 2435–2458. [CrossRef]