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A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature

Hasan Volkan Oral[a], Pedro Carvalho[b], Magdalena Gajewska[c], Nadia Ursino[d], Fabio Masi[e], Eric D. van Hullebusch[f], Jan K. Kazak[g], Alfonso Exposito[h], Giulia Cipolletta[i], Theis Raaschou Andersen[j], David Christian Finger[k], Lena Simperler[l], Martin Regelsberger[m], Vit Rous[n], Matej Radinja[o], Gianluigi Buttiglieri[p,q], Pawel Krzeminski[r], Anacleto Rizzo[e], Kaveh Dehghanian[s], Mariyana Nikolova[t] and Martin Zimmermann[u]

[a] Energy Politics and Market Research Center (EPPAM) and Civil Engineering Department, Istanbul Aydin University, Istanbul, Turkey E-mail: volkanoral@aydin.edu.tr

[b] Department of Environmental Science, Aarhus University, Frederiksborgsvej 399, Roskilde, 4000, Denmark

[c] Faculty of Civil and Environmental Engineering, Gdansk University, 11/12 Gabriela Narutowicza Street, 80-233 Gdańsk, Poland

[d] Dept. ICEA, University of Padova, via Loredan 20, 35131 Padova, Italy

[e] IRIDRA Srl, Via Alfonso La Marmora, 51, 50121, Florence, Italy

[f] Université de Paris, Institut de Physique du Globe de Paris, CNRS, F-75005 Paris, France

[g] Department of Spatial Economy, Wrocław University of Environmental and Life Sciences, ul. Grunwaldzka 55, 50-357 Wrocław, Poland

[h] Department of Economic Analysis, University of Seville, Ramón y Cajal 1, 41018, Seville, Spain

[i] Department of Materials, Environmental Sciences and Urban Planning-SIMAU, Polytechnic University of Marche (UNIVPM) – INSTM Research Unit, Via Brecce Bianche 12, 60121 Ancona, Italy

[j] Research Center for Built Environment, Energy, Water and Climate, VIA University College, 8700 Horsens, Denmark

[k] The Sustainability Institute and Forum (SIF), School of Science and Engineering, University Reykjavik, Menntavegur 1, 101 Reykjavik, Iceland

[l] University of Natural Resources and Life Sciences, Institute for Sanitary Engineering and Water Pollution Control, Vienna (BOKU), Muthgasse 18, A-1190 Vienna, Austria

[m] Technisches Büro für Kulturtechnik, Marburger Gasse 11 8200 Gleisdorf, Austria

[n] Faculty of Environmental Sciences, Czech University of Life Sciences, Kamycka 129 165 21 Prague 6 – Suchdol, Czech Republic

[o] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, 1000 Ljubljana, Slovenia

[p] Catalan Institute for Water Research (ICRA), C. Emili Grahit 101, 17003 Girona, Spain

[q] Universitat de Girona, Girona, Spain

[r] Section of Systems Engineering and Technology, Norwegian Institute for Water Research (NIVA), Gaustadalléen 21, N-0349 Oslo, Norway

[s] Civil Engineering Department, Istanbul Aydin University, Istanbul, Turkey

[t] Geodesy and Geography, National Institute of Geophysics, Sofia, Bulgaria

[u] ISOE – Institute for Social-Ecological Research, Frankfurt am Main, Germany

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Abstract

Nature-based solutions (NBS) can protect, manage and restore natural or modified ecosystems. They are a multidisciplinary, integrated approach to address societal challenges and some natural hazards effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. NBS applications can be easily noticed in circular cities, establishing an urban system that is regenerative and accessible. This paper aims to offer a review on NBS for urban water management from the literature and some relevant projects running within the COST Action 'Implementing nature-based solutions for creating a resourceful circular city'. The method used in the study is based on a detailed tracking of specific keywords in the literature using Google Scholar, ResearchGate, Academia.edu, ScienceDirect and Scopus. Based on this review, three main applications were identified: (i) flood and drought protection; (ii) the water-food-energy nexus; and (iii) water purification. The paper shows that NBS provide additional benefits, such as improving water quality, increasing biodiversity, obtaining social co-benefits, improving urban microclimate, and the reduction of energy consumption by improving indoor climate. The paper concludes that a systemic change to NBS should be given a higher priority and be preferred over conventional water infrastructure.

Key words: climate change resilience, nature-based solutions, stormwater, urban water, wastewater treatment

INTRODUCTION

According to the 2018 Intergovernmental Panel on Climate Change (IPCC) report, global climate change will cause irreversible harm to humans, the built environment and the biosphere (IPCC 2015). In particular, the depletion and degradation of pristine water resources is expected to affect significantly human and environmental health. In addition, the rapid increase of urban areas, resulting in a higher demand for water resources as well as disruption of the natural water cycle, accentuates the importance of sustainable and resilience-based water management. Hence, it is essential for urban water management (UWM) to be an integral part of urban planning. Moreover, land use decisions affect water supply and wastewater system designs and operation, as well as measures needed for managing stormwater runoff. Furthermore, an urban infrastructure system requires energy, which in turn, typically requires water (Loucks & Van Beek 2017). Consequently, water is one of the key elements of the United Nations Sustainable Development Goals (SDGs), alone or interlinked with different aspects. For instance, several of the 17 objectives are strongly connected to urban farming and call for an economical utilisation of assets, environment rebuilding, biodiversity, carbon sequestration, feasible catchment management and soil management (Keesstra *et al.* 2016).

Urban water refers to all water that is present in urban environments which includes natural surface water, groundwater, drinking water, sewage, stormwater, flood overflow water and recycled water (a third pipe, stormwater harvesting, sewer mining, managed aquifer recharge, etc.). Furthermore, a wide range of techniques can solve urban water-related problems, for example, improving water use efficiency and water demand reduction techniques, water sensitive urban design (WSUD) techniques, living streams, environmental water and protection of natural wetlands, waterways and estuaries in urban landscapes (water.gov.au, 2017). Larsen & Gujer (1997) defined UWM as a combination of water supply, urban drainage, wastewater treatment and water-related sludge handling. Accordingly, UWM includes the plan, design and operation of infrastructure to secure drinking water and sanitation, the control of infiltration and stormwater runoff, recreational parks and the maintenance of urban ecosystems.

Sustainable urban development includes a holistic management approach consisting of the water-energy-food nexus, land use and the diversification of water sources for reliable supplies (Kalantari *et al.* 2018). Further, integrated urban water management (IUWM) provides a framework and objective for planning, designing, and managing urban water systems. Moreover, IUWM is a flexible process that responds to change and enables stakeholders to participate in, and predict the impacts of development decisions. Consequently, adequate IUWM includes the environmental, economic, social, technical and political aspects of UWM. It enables better land use planning and the management of its impacts on freshwater supplies, treatment and distribution; wastewater collection, treatment, reuse and disposal; stormwater collection, use and disposal; and solid waste collection, recycling and disposal systems. Accordingly, it makes urban development part of integrated basin management, which is oriented toward a more economically, socially and environmentally sustainable mixed urban-rural landscape (Loucks & Van Beek 2017; Kalantari *et al.* 2018; Arabameri *et al.* 2019). IUWM also aims to help cities progress towards a circular economy, thus closing the loop of water resource circulation, and helps to limit the discharge of liquid waste and the constantly growing need for additional water resources (High level Panel on Water 2018).

As a result of increasing urban areas, the interaction of many factors such as demographic, economic, political, environmental, cultural and social factors creates challenges related to the use and management of water resources. Several of these issues can be addressed with nature-based solutions (NBS). NBS aim to protect, sustainably manage, and restore natural or modified ecosystems. NBS address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN 2018). NBS also have the potential to underpin a sustainable water management strategy (FAO 2018).

This study is conducted under the European Cooperation in Science and Technology (COST), which funds the research Action 'CA17133 – Implementing NBS for creating a resourceful circular city'. The circular city model recognises the importance of organising the city's systems in an analogy to the organisation of natural systems and it incorporates the principles of the circular economy, establishing an urban system that is regenerative and accessible (Girard & Nocca 2019). This study aims to offer a brief review on NBS for UWM, together with a description of some relevant projects running within the action. In this COST Action, the definition of a common language and understanding across disciplines is seen as a crucial success factor, while circular economy (CE) concepts are seen as a key approach and NBS or green infrastructure (GI) solutions are seen as core elements of the toolbox (Langergraber *et al.* 2019). Our working group has focused on the implementation of a safe and functional water cycle within the urban biosphere, where wastewater needs to be streamlined as a source of nutrients, hazardous pollutants that should be controlled (e.g., heavy metals or emerging organic contaminants), heavy metals being phytomined, the treated water looped back for irrigation, and recreational purposes should be considered side by side with sanitation, water supply or stormwater management. Furthermore, we critically appraise the established centralised water flow, defining available resources within the water flow and risk assessment on urban water, NBS for stormwater management and wastewater treatment.

The main research question addressed in this paper is 'How can NBS be integrated with the sustainable UWM?' To answer this question we followed two parallel approaches: (i) a traditional literature review targeting a set of different subtopics, coupled with (ii) an overview of case studies from projects running within the framework of the COST Action. By combining both, we wish to provide not only the most complete overview of the current existing knowledge but also to discuss and challenge the current existing frameworks for NBS implementation. Therefore, the aim of this paper is to define the challenges, present benefits and future trends, provide an overview of the usage of NBS for UWM and to offer implementation recommendations for urban water utilisation towards circular cities.

The paper is organised as follows. The 'methodology' section presents both the framework for the literature review and the selection criteria of relevant case studies. The next section describes the review through existing NBS tools for sustainable water management, subdivided into the sections 'stormwater management', 'flood protection and risk management', 'implementation of blue-green infrastructures', 'urban water in the field of food, water, and energy ecosystem', and 'urban water pollution control: constructed wetlands'. Following on, a section describes some case studies, linking them with the existing literature. The final section offers a brief discussion, and some concluding remarks are provided to point the way forward for an increased implementation of NBS for UWM.

METHODOLOGY

Owing to the broad scope of the topic, different levels of implementation of NBS and availability of international peer-reviewed literature for certain subtopics, we propose a combined approach where both existing literature and case studies were reviewed using different criteria. This section is divided into two subsections. In the first subsection, we present the details of the literature survey to collect data of relevant international peer-reviewed journals, while in the second we describe the criteria for selecting relevant case studies important for the current review.

Literature review approach

The literature survey was performed independently by different sub-groups of authors involved in this work. Therefore, the details of the literature search are described in the next paragraphs per each subsection.

For the stormwater management section, the literature was searched in Google Scholar, ResearchGate, Academia.edu, ScienceDirect and Scopus by using the key words 'stormwater management' AND 'nature based solutions', 'stormwater management' AND 'historical development', 'climate change' AND 'resilience'. A total of 40 manuscripts (i.e., 10 Google Scholar, 2 ResearchGate, 2 Academia.edu, 15 ScienceDirect, 4 Scopus and 7 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 19 papers were disregarded and 11 were read and are presently discussed in this paper.

For the flood protection and risk management section, the literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'flood' 'risk management' AND 'nature based solutions'. A total of 34 manuscripts (i.e., 12 Google Scholar, 3 ResearchGate, 10 Science Direct, 3 Scopus and 6 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 23 papers were disregarded and 11 were read and are presently discussed in this paper.

For implementation of blue-green infrastructures section for flood protection and risk management section, the literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'flood', 'risk management', AND 'nature based solutions'. A total of 45 manuscripts (i.e., 10 Google Scholar, 12 ResearchGate, 8 ScienceDirect, 10 Scopus and 5 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 26 papers were disregarded and 19 were read and are presently discussed in this paper.

For the urban water pollution control section, a total of 60 manuscripts (i.e., 20 Google Scholar, 10 ResearchGate, 15 ScienceDirect, 10 Scopus and 5 other publications) were retrieved by Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'nature based solutions' AND 'urban water pollution control'. Among them, 10 papers were disregarded and 50 were read and discussed.

For the water-energy-food nexus section, the literature was searched in Google Scholar, ResearchGate, ScienceDirect and Scopus by using the key words 'nature based solutions' 'water' AND 'energy' AND 'food nexus'. A total of 36 manuscripts (i.e., 4 Google Scholar, 1 ResearchGate, 12 Science Direct, 2 Scopus and 17 other publications were retrieved by cross-checking references from the initial retrievals from the databases) were retrieved and revised. After the first screening of the abstracts, 13 papers were disregarded and 23 were read and are presently discussed in this paper. This section also generated two supplementary tables: Table S1 overviews the existing NBS and their link with the water-food-energy nexus and Table S2 compares groundwater-based natural infrastructure solutions with grey infrastructure.

Case studies selection criteria

International projects in which the CA1733 action members are directly involved dealing with NBS and sustainable water management were selected as case studies for this article. The data related to these case studies were obtained from the researchers involved in both the projects and COST Action. Figure 1 shows the geographical location of the case studies, further detailed in the section 'Case studies'.

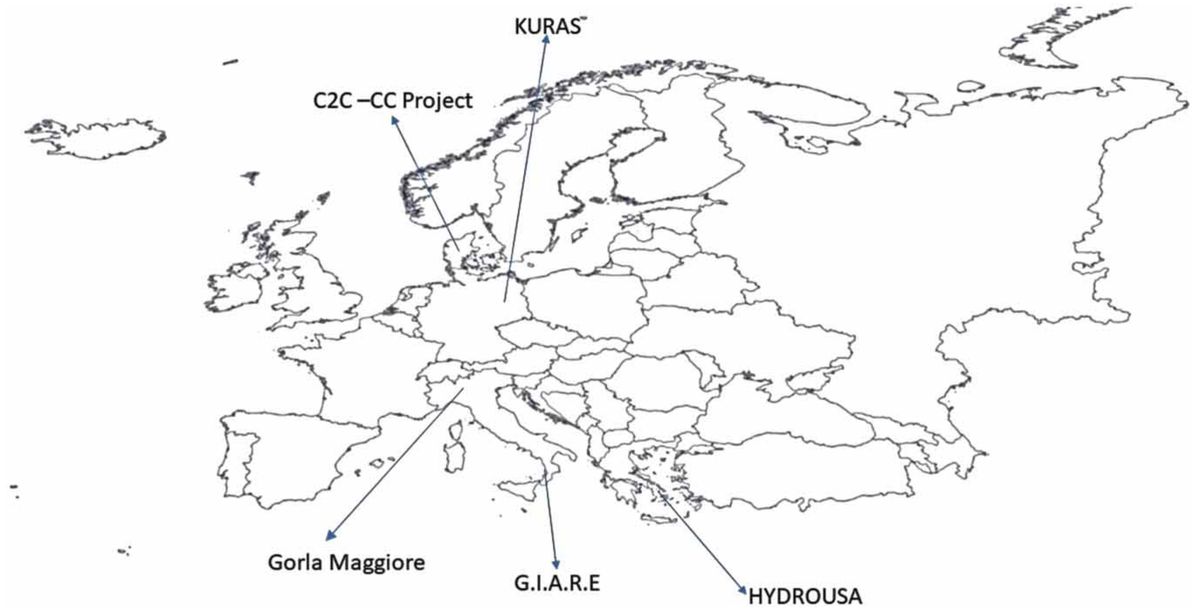

Figure 1 | Location of reviewed case studies within the COST Action.

REVIEW OF THE EXISTING NBS TOOLS FOR SUSTAINABLE WATER MANAGEMENT

In this time of anthropogenic climate change, urban regions around the world face natural disasters such as heat islands, droughts and floods, as well as urban pressures, for instance, air and water pollution along with resource management inefficiency. Consequently, the sustainable development of urban areas has resulted in decision-makers being caught in challenging situations, while simultaneously having to solve the problem of the excess of one resource and the lack of others. Therefore, based on individual cases, it seems rational to consider the possibility of implementing the concept of the circular economy in addition to connecting two problems – instead of defining them and seeing one aspect as the solution for other elements of a healthy urban socio-environmental system.

In this section, we group the sustainable water management under five categories as: (i) stormwater management, (ii) flood protection and risk management, (iii) implementation of blue-green infrastructures, (iv) urban water in the field of food, water and energy ecosystem and (v) urban water pollution control: constructed wetlands.

Stormwater management

In recent years, stormwater management has become an increasingly multidimensional and multidisciplinary issue. Moreover, stormwater presents very distinct qualitative and quantitative characteristics from domestic sewage. It is recognised as the most important source of heavy metals, whereas wastewater constitutes the main source of organic and nitrogenous pollution (Bavor *et al.* 2001; Eriksson *et al.* 2007; Barbosa *et al.* 2012).

In many countries, separate sewer network systems are predominant, and most rainwater networks discharge rainwater directly to receiving waters, without any purification, which is a serious threat to the quality of such water. This is particularly dangerous for small watercourses flowing through cities for which rapid discharge from rainwater drainage systems exceeds the hydraulic capacities, and the introduced pollution load is a serious threat. Further, until the 1990s, it was believed that the best solution to the rainwater problem in cities should be drainage, i.e., efficiently collecting and discharging stormwater to receiving waters (Figure 2).

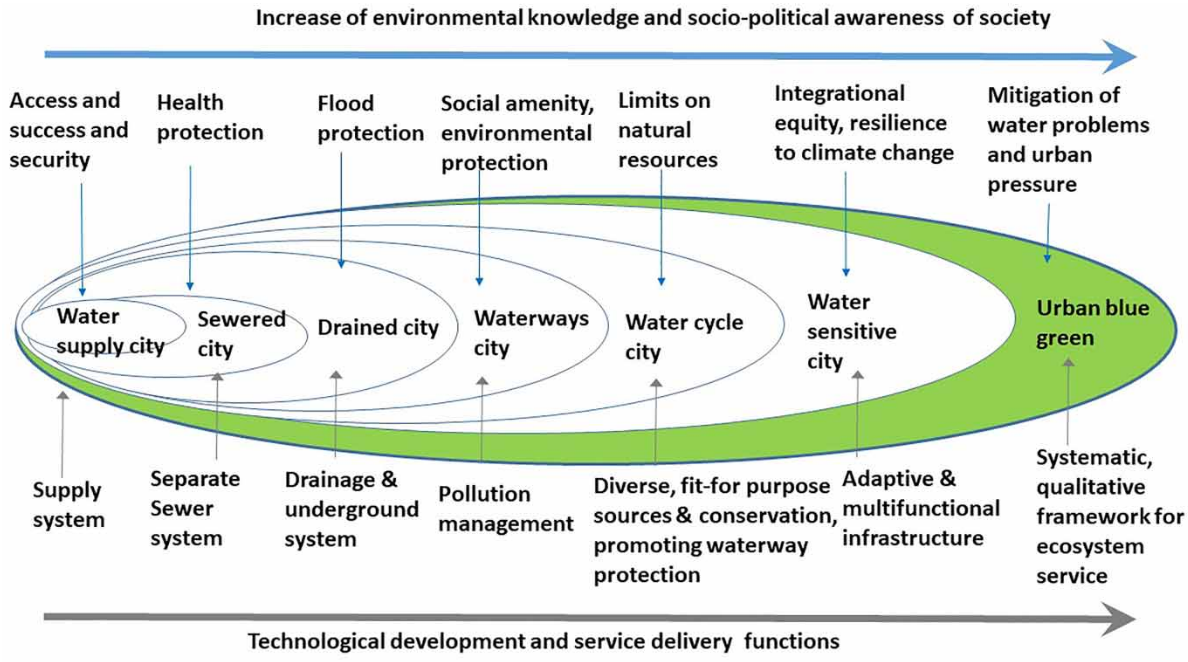

Figure 2 | Historical development of water supply and management (modified from Brown *et al.* (2009) and Blue Green Solution (2017)).

However, progressing urbanisation is inevitably connected to replacing the natural land cover with impermeable surfaces, which leads to increased surface runoff. Additionally, climate change is leading to more volatile rainfall patterns with an increasing number of extreme events, thereby causing frequent overloading of the drainage systems. As a result, floods are occurring, especially in central city districts with a high level of impervious surfaces. Such events, referred to as pluvial flash floods, are followed by long dry spells. For example, over the last 18 years in Gdańsk, Poland, more than four rainfall events with a 100-year return period (i.e., over 100 mm/day) have occurred. On 14/15 July 2016, 160 mm of rain fell within 14 hours, exceeding the total rainfall of two months. On the other hand, as mentioned above, long periods without precipitation are also causing functional problems for cities. Thus, the lack of stored rainwater increases the need for watering urban green areas with irrigation systems. Such approaches require both natural resources and financial support, thereby leading to their unsustainability (Wojciechowska *et al.* 2015).

Despite the risks that water can pose in urban spaces, it is an integral part of the city and a vital resource for the residents. From the human health perspective, it is necessary to integrate water in the urban layout. Therefore, a modern approach to the urban planning of the so-called WSUD assumes the use of the most natural technological solutions, the so-called eco-engineering. We count green roofs, bioretention systems, 'rainforests' and hydrophyte systems that combine the function of purification and retention and provide many ecosystem services (ES), including biodiversity and returning rainwater to the local water cycle by evapotranspiration. The natural ground cover would only have 10% runoff with 40% via evapotranspiration and 50% through infiltration while the impervious cover would have 55% runoff with 30% evapotranspiration and 15% infiltration (US EPA 2003).

As presented above, existing water management systems are not sufficient in many cases, and the need to solve the problem of quantity and quality of water exists in order to implement the concept of an urban circular economy. The synergy of constantly growing urban areas with impervious surfaces and pollution associated with human activities, and climate change with an increasing number of meteorological extremes, requires a new approach for cities to become more resilient to socio-environmental pressures (Figure 3).

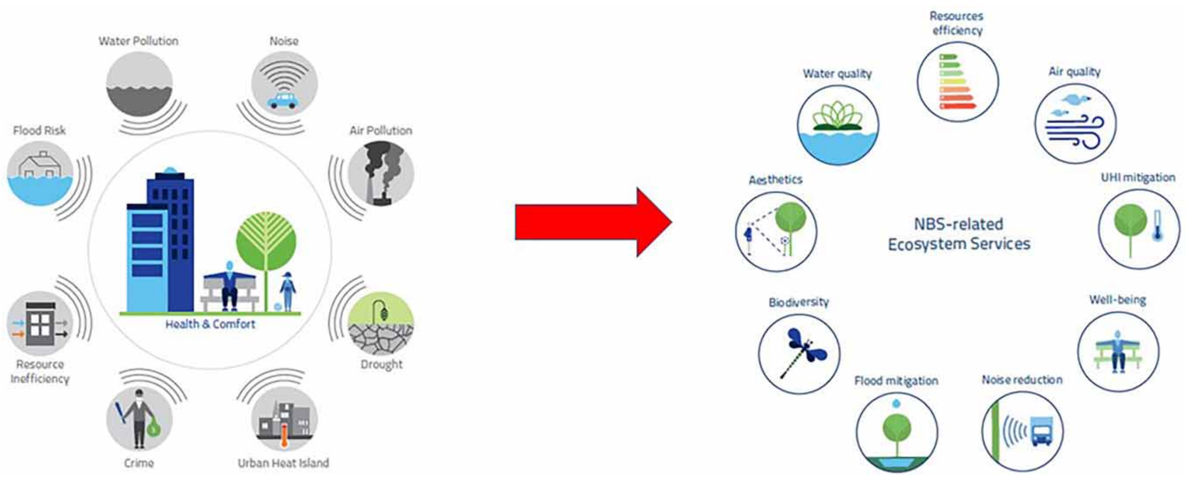

Figure 3 | Identified water problems and urban pressures and mitigation options by the application of NBS (Blue Green Solution 2017).

Therefore, based on the identified challenges, there is an urgent need to support the implementation of NBS in cities in order to contribute to climate change adaptation by reducing their vulnerability to environmental threats. NBS allow mimicking pre-development hydrologic regime and detaining runoff close to its source following the principle of low-impact development (Coffmann 1999; Bavor *et al.* 2001; Wong & Brown 2009; Hoyer *et al.* 2011) and use plants to later return the water to the local water cycle through evapotranspiration, thus supporting the plants in dry periods. Therefore, NBS become an essential feature of urban resilience managing stormwater, contributing to urban cooling through evapotranspiration and alleviating urban heat island effects while supporting urban green with local water resources.

Flood protection and risk management

Ecosystems, depending on their management, can either contribute to the problem or provide effective NBS for flood risk reduction or climate change mitigation and adaptation (Cohen-Shacham *et al.*

2016). At the same time, the implementation of NBS depends on the state and capacity of ecosystems to provide particular regulating services (flood, erosion, climate). Their spatial dimensions provide a basis for land use management and urban planning decisions in accordance with an ecosystem-based approach for flood risk management and other aspects of urban environmental management (Szopińska *et al.* 2019). On the other hand, there are other, potentially very cost-effective ways of achieving flood protection by tapping into nature's own capacity to absorb excess waters. Consequently, NBS implementation aims at preventing natural disasters to make urban areas safe and resilient, which can be achieved in combination with technological and engineering solutions if necessary.

Planning infrastructures to manage flood risk is related to connectivity (Parson *et al.* 2015), circularity (Kirchherr *et al.* 2017; Comino *et al.* 2018; Keesstra *et al.* 2018) and finding a balance between natural and urban elements (Gaines 2016). Moreover, in a fast developing city, the loss of circularity is often associated with the altered hydrological cycle, implying that water is not a natural, valuable resource, but rather a threat to the urban environment, when it flows at rates different from those of natural paths, from/toward locations that are functional to the development of human activity rather than to the environmental dynamics, through man-managed (often fast) connections, with quality standards far from those provided by natural water bodies (EPA 2005).

Consequently, the loss of circularity in the altered natural water cycle is derived from the reduction of soil infiltration capacity and resulting in fast surface runoff. The fact that the natural water cycle is replaced by the urban water cycle threatens soil, channelised urban drainage systems, receiving water bodies and downstream cities. Furthermore, the wash-off of pollutants from anthropogenic catchments poses a threat to the receiving water bodies and their biomes. The loss of infiltration and uncontrolled leakage from sewage threaten groundwater and connected surface water bodies. Subsequently, the resources, politics and awareness affect the socio-environmental dynamics and determine whether the socio-hydrological system will undergo irreversible decline or be self-sustainable (Ursino 2019).

NBS, in this context, is meant to partially recover the pre-development water fluxes and water quality, thus reducing the flood risk (WWAP 2018). Therefore, the use of NBS in this context is strongly related to the well-known concept of sustainable urban drainage, known in the literature with different key words, such as sustainable drainage systems (SuDS), WSUD or low impact development (LID), as reviewed by Fletcher *et al.* (2015). All these concepts aim to restore the water cycle within an urban catchment, from post-development back to the pre-development state (Fletcher *et al.* 2013). Thus, based on site-specific characteristics and the aim of implementation (to recover original functionality of the urban catchment or address specific issues linked to water management and risk control), NBS alone may not be able to re-establish complete circularity of the natural water cycle but rather provide multiple services to the community (e.g., mitigate flood and drought risk, affect local climate conditions, increase amenity and biodiversity). Further, based on the scale at which NBS are integrated into the so-called GI, different benefits can arise (Golden & Hoghooghi 2018). For instance, Zhang *et al.* (2019) investigated how NBS across facility, catchment and continental scales differently impact the hydrological, water quality and bioecological benefits.

Implementation of blue-green infrastructures

One of the most common ways to implement NBS is by the so-called blue-GI. Blue-green infrastructures are key elements in the holistic planning of (future) urban regions (Winker *et al.* 2019). Accordingly, blue-green infrastructures create strategically planned networks of (artificial) natural spaces in cities (Bundesamt für Naturschutz 2017). Therefore, the use of NBS seeks to minimise the effects of climate change on urban areas and create various ecosystem services with benefits for the society, environment and economy. NBS can help create natural circumstances in urban areas for 'alleviating urban pressures and achieve resilience to climate change' (Maksimovic *et al.* 2017).

Blue-green infrastructures establish multifunctional structures as diverse green spaces in combination with elements of WSUD (Winker *et al.* 2019) to strengthen urban sustainable development. Accordingly, 'green' infrastructural elements take essential roles in creating a healthy microclimate in cities. For instance, trees reduce flood risks and the effect of urban heat islands and expand shading while pocket parks (and streams) aesthetically attract citizens and provide space relieving mental aspects of urban pressure (Maksimovic *et al.* 2017). 'Greening' transforms cities by unsealing surfaces and is applied on building structures to lower buildings' energy level by natural cooling, which saves costs and works in aesthetical ways. Further, green rooftops have a multifunctional use within blue-green infrastructures from urban gardening to collecting spaces for rainwater. As precipitation is a scarce resource and floods and droughts will accumulate due to climate change, cities can adapt WSUD strategies which focus on managing all water streams within the city. In addition, a water supply from rainwater, stormwater and treated wastewater from a sustainable blue infrastructure for cities can relieve or replace grey infrastructure (Depietri & McPhearson 2017). For example, natural or close to natural ways of flood risk prevention such as sponge cities are more sustainable than flood walls. In combination, blue-green infrastructures provide health benefits for society and relieve the pressure on the environment and urban space. Furthermore, blue-green infrastructures are more cost-effective than the current predominant urban infrastructures. As such, a long-term sustainability approach can be pursued with regard to the design of cities of the future.

The urban blue-green infrastructures provide various valuable regulating ecosystem services in respect to global climate regulation by reduction of greenhouse gas concentrations through carbon storage and sequestration (Kazak *et al.* 2016), water flow maintenance and flood protection (Szewrański *et al.* 2018), micro and regional climate regulation (Kołecka *et al.* 2018; Ziemiańska & Kalbarczyk 2018) and improvement of air and water quality (Lakatos *et al.* 2012; Dąbrowska *et al.* 2017; Bawiec 2019). Consequently, creating well-designed built environments rich in ecosystem services provides various options for mitigation and adaptation of urban areas for the impact of climate change. Most of the adaptation measures in cities depend mainly on particular urban planning solutions and public regulations. Therefore, based on the technological solutions, local authorities can improve urban development processes by decision support systems, which effectively suggest suitable solutions in the case of many domains of environmental management (Kazak & van Hoof 2018). Identification and consideration of the dependency of the local population on the particular ecosystem services in the living areas make the valuation of the ecosystem services an important factor in sustainable landscape planning and territorial integration policymaking (Borisova 2013; Świąder *et al.* 2018).

As mentioned above, the implementation of blue-green infrastructures does not only solve the problem of water management in cities, but it supplies much more influential ecosystem services on increasing urban resilience to socio-environmental challenges. These ecosystem services can be assessed and mapped for better understanding of the environmental carrying capacity in the land management system to cope with flood hazard at all levels – region, basin and settlement (Boyanova *et al.* 2014; Świąder 2018). In some cases, the ecological boundaries, in terms of the area providing ecosystem services to the cities, exceed their administrative boundaries up to 1,000 times (Folke *et al.* 1997). At the same time, cities rely heavily on the capacity of the ecosystems in the urban environment provided by the green and blue areas. Thus, the interaction between biophysical and geophysical processes determines the potential capacity of natural capital to provide regulating ecosystem services. The water flow can be influenced by several natural processes and functions of the ecosystems, which contribute to the absorption of water and therefore reduce surface runoff or vice versa. The main factors of the capacity for water retention are the vegetation cover, the soil structure and texture, the presence of bare land or water bodies, the slopes and the land cover

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in the territory. In the study by Nikolova & Nedkov (2018), the flood regulation supply capacity was assessed by an Index of Capacity for Water Retention of urban ecosystems (as defined by Zhiyanski *et al.* 2017). The assessment of flood regulation services is carried out in four main steps according to the methodological framework for ecosystem services assessment developed by Burkhard *et al.* (2012):

1. identification of the urban ecosystems with potential to provide flood regulation;
2. selection of indicators for ecosystem services assessment;
3. quantification of the ecosystem services indicators;
4. assessment and mapping of flood regulating urban ecosystem services.

The results of such assessment show that the water retention capacity of residential, industrial and public areas is lower, while urban green areas have higher potential. Thus, detailed assessment gives decision-makers the exact information about the impact of future actions on biocapacity and the ecological footprint of human activity.

Urban water in the field of food, water and energy ecosystem

Liquete *et al.* (2016) as well as Leigh & Lee (2019) indicated that the future of urban water systems is shifting towards resource oriented, integrated, sustainable, distributed and NBS. Accordingly, wastewater treatment will be replaced by the production of goods. Further, one optimised system will allow multiple targets to be reached, instead of having a separate infrastructure for every purpose. This should give treated wastewater access to everybody. Multiple targets besides water treatment can be the production of fertilisers, provision of urban green, enhancing biodiversity and cooling, to name just one possible set. These targets must be defined during the concept phase in a case by case approach and their fulfilment must be measurable. According to present knowledge, this is the way forward to eliminate present untreated wastewater releases, a target set in SDG 6: clean water and sanitation (UN 2015).

NBS can help face these challenges by providing the means for cities to successfully achieve long-term sustainability in the use of resources (e.g., energy, water, land) and increase urban resilience to climate change (Maes & Jacobs 2017). Nevertheless, water-energy-food nexus relationships are complex and poorly understood, especially in urban environments, thus leading to significant potential risks. However, there are benefits if society is able to manage them adequately (Bennett *et al.* 2016). Further, Bennett *et al.* (2016) address the water-energy-food nexus and natural infrastructure investment on the entire watershed scale, taking large-scale infrastructure investment programmes into account, thus going beyond the city boundaries. Consequently, the implementation of NBS in urban areas can benefit from the water-energy-food nexus at local scales to efficiently manage natural resources for the optimal ecosystem services' delivery. Nevertheless, to the best of our knowledge, there are no literature reviews focused on the water-energy-food nexus in urban areas and how multifunctional NBS may help manage this nexus to improve the usage efficiency of these resources, thus helping to achieve long-term sustainability of cities. Some recent studies, such as those of Hansen *et al.* (2015), Lafortezza *et al.* (2018), Krauze & Wagner (2019) and Keesstra *et al.* (2018), describe NBS with multifunctional targets and affecting the water-energy-food nexus in urban areas. At the European scale, besides the main reports from the EC (2013, 2015), recent studies have analysed NBS applications in urban environments: Faivre *et al.* (2017) focus on NBS to address social, economic and environmental challenges in EU areas; Kabisch *et al.* (2016) review NBS for climate change adaptation in urban areas; Nikolaidis *et al.* (2017) study new approaches to improve regulatory instruments and demonstrate the long-term value of NBS; Raymond *et al.* (2017a) develop a framework for assessing and implementing the co-benefits of NBS in urban areas; Russo *et al.* (2017) review NBS based on edible GI for better management of the water-energy-food nexus; and the reports from the Naturvation project (Bockarjova & Botzen 2017; da Rocha *et al.* 2017; Hanson *et al.* 2017), which review the different dimensions of NBS implemented in urban areas, including those related to a more efficient use of natural resources and the nexus between water, energy and food in NBS.

Most frequently, NBS are designed for: (1) urban water regeneration; (2) watershed management; (3) ecosystem restoration; (4) increasing the sustainable use of matter; (5) generation of renewable energy; and (6) increasing carbon sequestration. Likewise, European authorities (EC 2013, 2015) have highlighted the multifunctional benefits of NBS to improve resource efficiency in urban areas. Among these solutions, we find: (1) urban agriculture for local food production; (2) water regeneration; (3) green roofs for climate adaptation; (4) higher energy and water efficient use; (5) regeneration of abandoned land by afforestation; (6) food production; (7) rain gardens for stormwater regulation; and (8) the use of permeable surfaces and vegetation for run-off control. Tables S1 and S2, given as the Supplementary material, present the examples of relevant NBS related to the water-energy-nexus. Finally, one of the main challenges in the topic is the assessment of the performance and impacts of NBS in addressing the objectives of higher resource efficiency and resilience in urban areas. The assessment schemes have been developed to measure performance and impacts through different indicators: Mapping and Assessment of Ecosystems and their Services (MAES) (Maes *et al.* 2013), Knowledge and Learning Mechanism on Biodiversity and Ecosystem Services (EKLIPSE) (Raymond *et al.* 2017b) and the Smart City Performance Measurement Framework (CITYkeys) (Bosch *et al.* 2017). In addition to the examples of relevant NBS related to the food-energy-nexus, the application of groundwater-based natural infrastructure solutions and comparison with the grey infrastructure also exist. Table S2 explains the function, goal and solution, which are the outcomes of the comparison.

Urban water pollution control: constructed wetlands

Urban water pollution control nowadays is predominantly carried out as an ‘end of the pipe’ solution with highly intensified wastewater treatment systems in order to protect downstream freshwaters from contamination and eutrophication (Finger *et al.* 2013). Yet, in addition to the benefits related to management of stormwater, flood protection and efficient use of resources in a water-energy-food nexus discussed in the previous sections, NBS offers an untapped potential for urban water pollution control. The treatment potential of NBS depends, among other factors, on the type of NBS used (infiltration basin, constructed wetland, raingarden, etc.), quantity and quality of water to be treated, and local conditions (climate, precipitation patterns, etc.).

In the concepts of GI, LID and sustainable drainage systems, water pollution controls are provided by the so-called planted/unplanted biofiltration systems. According to the definition of Fonder & Headley (2013), planted (surface) systems are a type of constructed wetlands (CWs). Among the various types of NBS, CWs are the most common and accepted NBS for pollution control nowadays, and they can be used in cities, especially for Masi *et al.* (2018):

- rainwater treatment;
- combined sewer overflow treatment;
- polishing of the outflow from existing wastewater treatment plants, including for the treatment of contaminants of emerging concern (CEC);
- greywater treatment.

In respect to water quantity and quality, stormwater presents different qualitative and quantitative characteristics compared to domestic sewage. It is recognised as the most important source of heavy metals, whereas wastewater constitutes the main source of organic and nitrogenous pollution (Barbosa *et al.* 2012). On the other hand, the quality of stormwater can vary greatly in time and between locations, especially in urban areas where over 650 substances were identified in stormwater

(Eriksson *et al.* 2007). Table 1 displays the classification of five main groups of pollutants that can be encountered in stormwater.

Table 1 | List of main stormwater pollutant types (adapted from Eriksson *et al.* 2007)

Pollutant types	**Indicator parameters**
Basic parameters	Organic matter (BOD_5, COD), suspended solids, nitrogen, phosphorus, pH
Heavy metals	Zinc, cadmium, chromium (VI), nickel, lead, platinum
Polycyclic aromatic hydrocarbons	Benzopyrene, naphthalene, pyrene
Herbicides	Terbuthylazine, pendimethalin, phenmedipham, glyphosate
Organic compounds	Nonylphenol ethoxylates and degradation products, e.g., nonyl phenol, pentachlorophenol, di-2-ethylhexyl phthalate, 2,4,4′-trichlorobiphenyl (polychlorinated biphenyl 28), methyl-tert-butyl ether
Bacterial indicators	Faecal coliforms (*E. coli*), pathogens (*Pseudomonas aeruginosa*)

Typically, NBS are employed to reduce the levels of traditional pollutants such as total suspended solids (TSS), organic matter, nutrients and also heavy metals. TSS belong to the group of basic pollutants but, at the same time, are classified as being the most dangerous due to their impact, both on the aquatic environment and humans (Makepeace *et al.* 1995; Paschke 2003; Eriksson *et al.* 2007; Madrid & Zayas 2007; Ingvertsen *et al.* 2011; Gasperi *et al.* 2012; Zgheib *et al.* 2012). The concentration of TSS could vary significantly depending on the place of origin (e.g., for streets: TSS ranges from 61 to 320 mg/L; for parking: TSS ranges from 42 to 240 mg/L; and for motorways: TSS is around 200 mg/L (Boogaard 2015). It must also be considered that very often TSS are constituted or covered by organic matter which works as a binding material for the sorption of the above-mentioned emergent pollutants, allowing, therefore, their transport even for a long distance. Therefore, retention of suspended solids has been a primary function of many of the NBS. Typically, CWs can remove up to 88% of TSS, 92% of BOD_5, 83% of COD even after 20+ years of operation (Vymazal 2019). For the nutrients, the removals vary greatly between the systems and are in the range of 46–90% for total phosphorus and 16–84% for total nitrogen (Malaviya & Singh 2012).

In addition to the removal of traditional pollutants such as suspended solids, organic matter and nutrients (Zhang *et al.* 2014a, 2014b; Machado *et al.* 2017; Arden & Ma 2018), CWs are capable of removing organic and inorganic pollutants (Verlicchi & Zambello 2014; Krzeminski *et al.* 2019). Among these, the removal of pesticides (Barceló & Petrovic 2008), heavy metals (Wang *et al.* 2017), pharmaceuticals (Li *et al.* 2014; Zhang *et al.* 2014a, 2014b; Ilyas & van Hullebusch 2019; Zraunig *et al.* 2019) and various other contaminants of emerging concern (CEC) (Imfeld *et al.* 2009; Matamoros *et al.* 2010; Gorito *et al.* 2017; Talib & Randhir 2017) have been explored in the last decade. The observed removal of heavy metals was between 23 and 97% depending on the heavy metal, CWs' type, type of water matrix and others (Malaviya & Singh 2012).

Regarding the CEC, plant-associated NBS have been reported to be crucial for the removal of different CEC (Carvalho *et al.* 2014; Zhang *et al.* 2016; Ilyas & van Hullebusch 2019), which can favour the solution of creating more 'green' in the cities. Therefore, the key removal pathways are the uptake by plants (e.g., carbamazepine), microbial degradation (e.g., ibuprofen, salicylic acid, galaxolide), adsorption and subsequent sedimentation (e.g., triclosan, tetracycline) and photodegradation (e.g., ketoprofen, naproxen, triclosan, diclofenac) (Bi *et al.* 2019).

Although treatment wetlands can achieve high removal of up to 100% of different organic and inorganic chemicals, the removal effectiveness varies significantly and the removal effectiveness of particular compounds may vary depending on the CW design, its operation mode and seasonal conditions (Verlicchi & Zambello 2014; Zhang *et al.* 2016; Ilyas & van Hullebusch 2019; Krzeminski *et al.* 2019; Zraunig *et al.* 2019). This indicates that for efficient removal, CWs need to be designed and/or adjusted for targeted pollutants. While CWs can be very effective, they are not able to completely remove CEC from the (waste) water. Moreover, hybrid systems combining different types of CWs, or other treatment techniques, might offer increased removal due to the synergistic effects against specific types of pollutants (Garcia-Rodríguez *et al.* 2014; Verlicchi & Zambello 2014; Zhang *et al.* 2014a, 2014b; Ilyas & Masih 2017; Zhang *et al.* 2019). Furthermore, treated water from CWs may be suitable for some reuse applications if they are well designed and maintained (Ilyas & Masih 2017; Arden & Ma 2018; Krzeminski *et al.* 2019). Nevertheless, current knowledge gaps restrict holistic evaluation of CWs' applicability and the estimation of CWs' potential for the removal of CEC.

Regarding the climatic conditions, CWs have been demonstrated to work efficiently in different climatic conditions, but tropical conditions tend to favour treatment performance due to continuous plant growth, extended sunlight exposure and increased microbial activity, these being of particular importance for more recalcitrant pollutants (Zhang *et al.* 2014a, 2014b; Machado *et al.* 2017). However, good comparable removal rates of suspended solids, organic matter and phosphorus are reported for temperate conditions, with only nitrogen removal being affected in a cold climate (Wang *et al.* 2017).

For urban water pollution control, other NBS (and GI elements) can be very effectively used in combination with CWs for purposes such as wastewater source control and separation, water reuse and other means of sustainable sanitation framework (Masi *et al.* 2018). Accordingly, one of the key concepts could be a combination of composting and vermicomposting toilets (Hill & Baldwin 2012; Anand & Apul 2014) and greywater treatment with wetlands or green walls providing the treated water for further reuse. Furthermore, as the space in cities becomes a highly valuable commodity, multipurpose NBS offering other benefits beyond the water treatment and pollution control become a viable alternative (Raymond *et al.* 2017a; Frantzeskaki 2019). Multifunctionality is a key factor, as the water pollution control does not have to be the major role of NBS but can be integrated into stormwater management and biodiversity enhancement.

PROJECTS/CASE STUDIES APPROACH

In spite of the different potential for implementing NBS for UWM, the showcased projects from the COST Action members are only dealing with stormwater management. The applications range from rainwater harvesting in water-scarce areas (e.g., HYDROUSA project in Greece) to the reforestation of watersheds (e.g., Rangárvellir project in Iceland (Keesstra *et al.* 2018)). While both aforementioned cases aim at re-establishing the natural water cycle and increasing natural water retention, the means and purposes differ. Moreover, the Natural Water Retention Measures project, directed by the EU Directorate-General for Environment from 2013 to 2014, aimed to improve the water status on hydromorphology and diffuse pollution, by offering a catalogue of case studies showcasing a broad range of concepts and case studies (nwrm.eu, 2015). However, for effective selection of NBS for stormwater management planning, instruments are still needed. Within the project Concepts for urban rainwater management, drainage and sewage systems (KURAS) in Germany, an integrated planning approach for stormwater management measures was developed considering the other aspects of NBS besides water retention (Matzinger *et al.* 2017). The potential multi-functionality of NBS is an important feature, especially regarding the implementation in circular cities. The Gorla Maggiore water park project in the northern territories of Italy, which includes the use of a water park for NBS applications, and the integrated and sustainable management service for water–energy cycle in urban drainage systems (G.I.A.R.E.) project in southern Italy based on water–energy interaction in Milan, Italy are also summarised in this section. In addition to these two Italian projects, the C2C-CC project, which is carried out in Denmark and includes flood control, water treatment, base-flow and sustainable heat energy applications, is summarised in the section. The main purpose of explaining these five projects in this section is to emphasise the representative of multipurpose NBS implementations for stormwater management.

Project 1: The Gorla Maggiore water park

The Gorla Maggiore water park project, located in Gorla Maggiore, northern Italy, is an urban wetland development focusing on NBS and ecosystem services (The Gorla Maggiore Project 2019). The park aims to protect the city against flooding, improving water quality, increasing biodiversity and obtaining social co-benefits (Rizzo *et al.* 2018). The park, with a total area of approximately 3 ha, comprises sections with different functionalities: (1) stormwater detention for flood prevention (1 ha); (2) domestic water treatment (0.4 ha); and (3) recreational areas (1.3 ha). Furthermore, the combined sewer overflow and excess runoff may be diverted into the park in the case of extreme rainfall events, with an expected reduction of peak flow by 86% and downstream discharge of 8,900 m^3 for events with a ten-year return period. Moreover, it reduces the downstream dissolved organic carbon load by 11.7 t/yr and nitrogen load by 0.4 t/yr, along with social and ecological benefits (Masi *et al.* 2017). In addition, the project demonstrates that the performance and costs of the park are similar or even better than the grey infrastructure for water purification and flood protection (Masi *et al.* 2017).

Project 2: coast to coast climate challenge (C2C-CC project)

The C2C-CC project is a Danish cross-municipality climate adaptation project with 31 partners and 19 supportive partners working to create a climate resilient central region in Denmark (C2-CCC 2018). The sub-project 'Infiltration of surface water through permeable coating' has the primary aim of re-establishing the natural pre-development water cycle and preventing flooding. This is done by harvesting rainwater in the roadbed as the road is made of permeable asphalt. The roadbed is constructed using a gravel mix ensuring a porosity of 30% which can detain the volume of water generated by a 100-year flood. Moreover, the gravel mix removes TSS and heavy metals from the water. Subsequently, the detained water transmits its heat to a geothermal tube, with a length of 800 m, connected to a nearby day-care centre for heating, which is then infiltrated into the soil. Thus, this NBS provides flood control, water treatment, base-flow and sustainable heat energy.

Project 3: HYDROUSA

HYDROUSA aims to revolutionise the water supply chain in Mediterranean regions by demonstrating innovative solutions for water/wastewater treatment and management, which will close the water loops and will also boost their agricultural and energy profile. Relevant to NBS applications, HYDROUSA demonstrates that circular NBS technologies work for wastewater treatment and nutrient recovery, while creating further environmental and societal benefits. The project offers a solution for the problem of rare water reserves in Mediterranean regions in the summer during the high tourism season. The project will not only develop and demonstrate innovative water services, but will also revolutionise the water value chains in Mediterranean areas from water abstraction and use up to sewage treatment and reuse (www.hydrousa.org, 2019). There are five water categories in the HYDROUSA project: rainwater, groundwater, wastewater, water vapour and sea water and the systems defined between these categories are harvesting, recharge and restore, wetlands, vapour condensation and tropical greenhouse. Moreover, biomimicry design concepts and fertigation are being applied to increase the efficiency of the selected NBS. Some of the recovered products of these systems are water for domestic use, irrigation water, biogas, drinking water and salt (Figure 4).

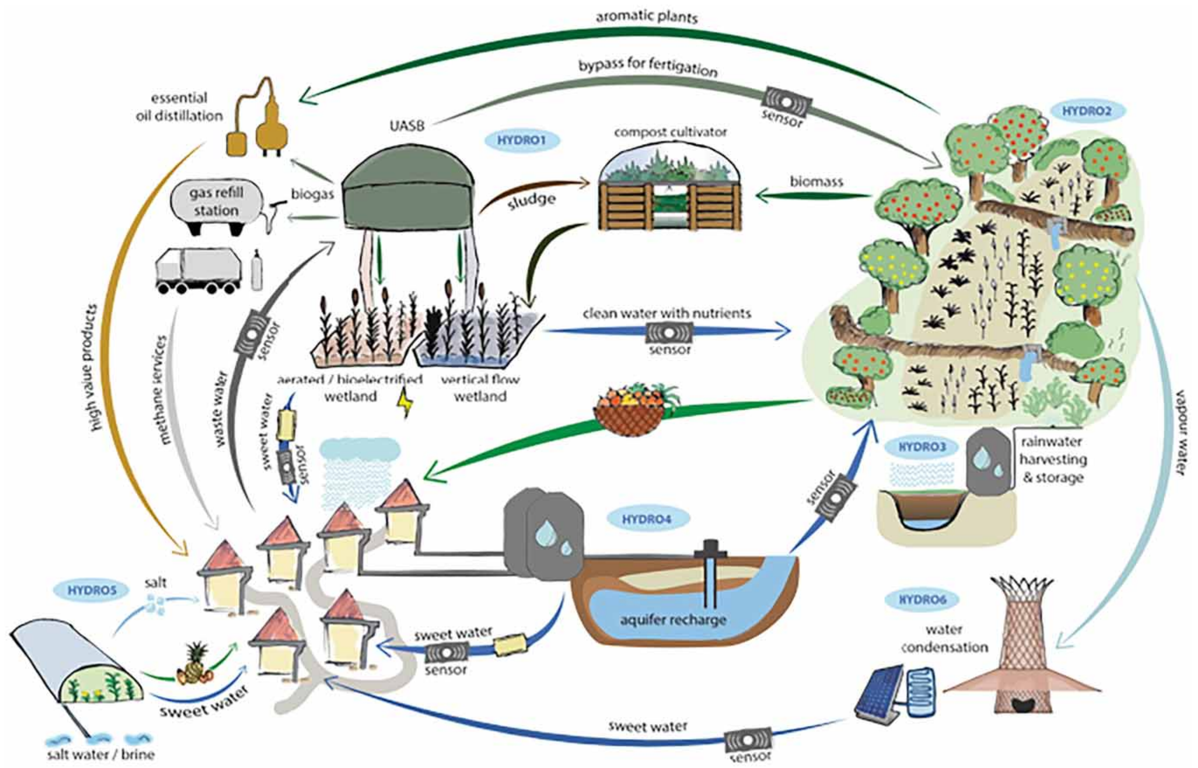

Figure 4 | The HYDROUSA project working principles and the processes (from www.hydrousa.org, 2019).

Project 4: concepts for urban rainwater management, drainage and sewage systems (KURAS)

The aim of this project is to give the answer to the question 'How can the future wastewater discharge, water quality, urban climate and quality of life in the city be improved through intelligently coupled storm water and waste water management?' The project consists of a network of partners from research and industry as well as the city of Berlin decision-makers. KURAS is the elaboration and exemplary demonstration of integrated concepts for a sustainable handling of wastewater and rainwater for urban locations. As mentioned in the Introduction section, NBS aim to protect, sustainably manage and restore natural or modified ecosystems. The KURAS project aims to decrease water consumption after heavy rainfall in the city and enables the sustainable management. Some of the following sub-goals, which are defined, to reach this achievement are as follows (www.watershare.eu, 2019):

- For wastewater disposal companies and operators of municipal sewer networks, which, like Berlin, have a slight gap, options for the adaptation of wastewater infrastructure to climate change and its consequences are being developed.
- Prognosis models are intended to investigate the effects of measures – e.g., to avoid deposits in the sewer system after long periods of dry weather or of mixed water overflows in waters during heavy rainfall – for real Berlin model areas.

Project 5: integrated and sustainable management service for water-energy cycle in urban drainage systems (G.I.A.R.E.)

The main objective of the project, relevant to the aim of NBS, was to develop an integrated approach for sustainable water-energy cycle management in the urban context. In this perspective, a technological platform was implemented in order to both optimise the use of water resources that rely on the urban drainage network such as meteoric waters deriving from the roof of buildings (40% of total urban area) and paved areas, i.e., roads, yards, etc. (35%) and to allow energy saving (Figure 5). For these purposes, experimental activities were conducted on:

- control of inflows to the drainage network;
- control of the polluting load generated;
- thermo-energy benefits;
- potential of rainwater for reuse.

Specific objectives of the project (Figure 5) are listed as follows:

- OR1: Realisation of a compact storm drain prototype device for the treatment of run-off rainwater.
- OR2: Module for management and optimisation of water–energy performance of green roof systems in Mediterranean climate.
- OR3: Urban drainage planning and design service through sustainable technologies to reduce inflows and pollutants.
- OR4: Development of a technological platform for decision-making support for the integrated and sustainable management of the water-energy cycle in the urban drainage system.

An 'Urban Hydraulic Park' was constructed as a demo site at the Vermicelli catchment (University of Calabria) where a green roof with a rainwater harvesting system, permeable pavement, a stormwater filter and a traditional sedimentation tank were connected to a treatment unit. Further, a monitoring and acquisition system was used to analyse the environmental benefits and the hydraulic and thermal efficiency of each unit.

The results of the project showed good hydraulic performance of the green roof concerning stormwater retention in Mediterranean weather conditions (Palermo *et al.* 2019; Piro *et al.* 2018). The hydraulic behaviour of the green roof, permeable pavement and stormwater filter were also analysed by means of a modelist approach (Brunetti *et al.* 2016, 2017; Garofalo *et al.* 2016; Piro *et al.* 2019).

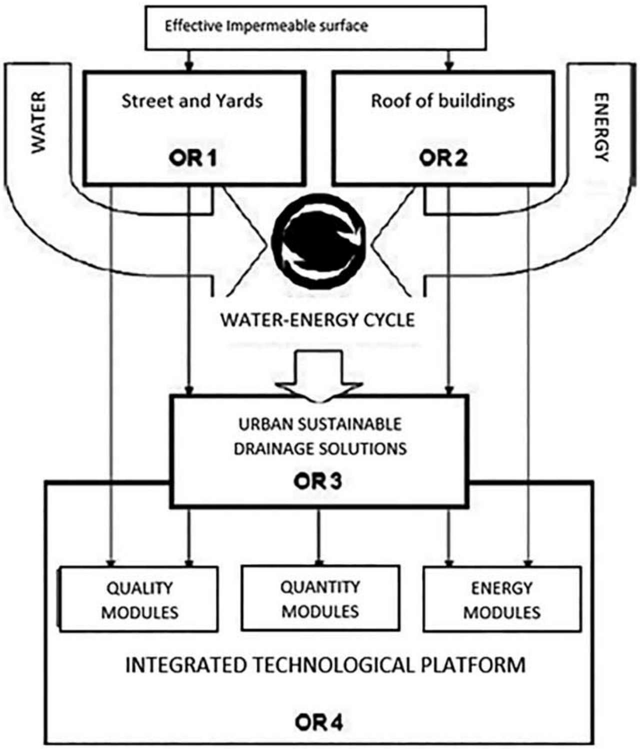

Figure 5 | The working principle of the G.I.A.R.E project (from www.giare.eu, 2019).

Moreover, life cycle assessment (LCA) analysis of the green roof and permeable pavement highlighted the sustainability of these low-impact infrastructures (Maiolo *et al.* 2017).

DISCUSSION AND CONCLUDING REMARKS

Based on the presented literature review and case studies, three main focuses of NBS implementation could be identified: (i) stormwater management, (ii) water-food-energy nexus using water for food and energy production and (iii) water pollution control. The presented overview demonstrates that NBS are not only effective and efficient, but are also largely accepted by people neighbouring such facilities. The present review differentiates from previous studies by combining a literature review with the analysis of case studies involving different NBS applications in European cities. Table 2 presents the review of these case studies that highlight the links between the NBS approach, main services and references. For instance, stormwater management can be implemented by establishing water parks with extended retention basins that withhold rainwater during heavy precipitation events as

Table 2 | Review summary of the case studies

Case studies and implementation years	Description of the NBS	Type of water	Main services	References
The Gorla Maggiore water park, 2013–2015	Constructed wetlands for water pollution control and hydraulic risk management	Combined sewer overflow	Water pollution control; Flood mitigation; Biodiversity increase; Aesthetic/Social benefits	Liquete *et al.* (2016), Masi *et al.* (2017) and Rizzo *et al.* (2018)
HYDROUSA, 2018–present	Constructed wetlands in the food-water-energy nexus; Constructed wetlands for greywater treatment and reuse; Rainwater harvesting systems; Agroforestry	Wastewater; Greywater; Rainwater; Seawater	Reuse of nutrient (N,P) rich treated wastewater; Reuse of treated greywater; Reuse of harvested rainwater; Recreation of high-biodiversity and productive agroforestry site; Removal of emerging organic micropollutants from the water phase and plant uptake in edible plants	The project is still running – www.hydrousa.org (2018–2022)
KURAS, 2016–present	Rainwater harvesting; Decreasing water consumption	Rainwater, Water sewer overflow	Avoiding deposits in the sewer system; Reuse of harvested rainwater	The project is still running – www.kuras-projekt.de
G.I.A.R.E., 2011–2014	Compact storm drain prototype device for run-off rainwater treatment; Green roof systems for support in the management of urban drainage system; Urban drainage planning and design service to inflows and pollutant reduction; Development of a technological platform	Rainwater; Stormwater	Removal of pollutants at storm drain inlet; Management and optimisation of water–energy performance; Hydraulic defence of urban area and control on discharge quality into water bodies; Decision-making support for sustainable management of water–energy cycle in urban drainage system	Brunetti *et al.* (2016), Garofalo *et al.* (2016), Brunetti *et al.* (2017), Maiolo *et al.* (2017), Palermo *et al.* (2019) and Piro *et al.* (2018, 2019)
C2C-CC, 2016–present	Providing flood control; Running water treatment; Waste-flow; Launching sustainable heat energy	Rainwater; Groundwater; Lakes; Rivers; Seawater	Water pollution control; Flood mitigation; Management and optimisation of water–energy performance	Project is still running – https://www.c2ccc.eu/

illustrated in the example of Gorla Maggiore in northern Italy. Such water parks offer protection from floods but also create ecosystems within the cities. Moreover, permeable coating of streets and paths are another way of reducing flood risk in cities. These systems can also produce energy for district heating by simply using the heated surface of paved streets and paths. The Danish project, C2C-CC, is an illustrative example of such a system. The HYDROUSA project investigates options for NBS to manage water resources on Greek islands which experience increased water demand during the tourist season. The KURAS project in Berlin, Germany, focuses on NBS for stormwater and wastewater management in large urbanised areas. Water parks, permeable coating of streets and green roofs function as water retention reservoirs, slowing down the runoff during heavy precipitation events. In some cases, the water stored in these NBS can become available at later points during dry periods, thereby reducing the drought effects. The G.I.A.R.E. in Italy focuses on integrated and sustainable management service for water–energy cycle applications.

Figure 6 illustrates the suggested scheme of sustainable water management in an urban settlement with the case studies HYDROUSA and GORLA MAGGIORE and Figure 7 shows the case studies C2C-CC, KURAS and G.I.A.R.E.

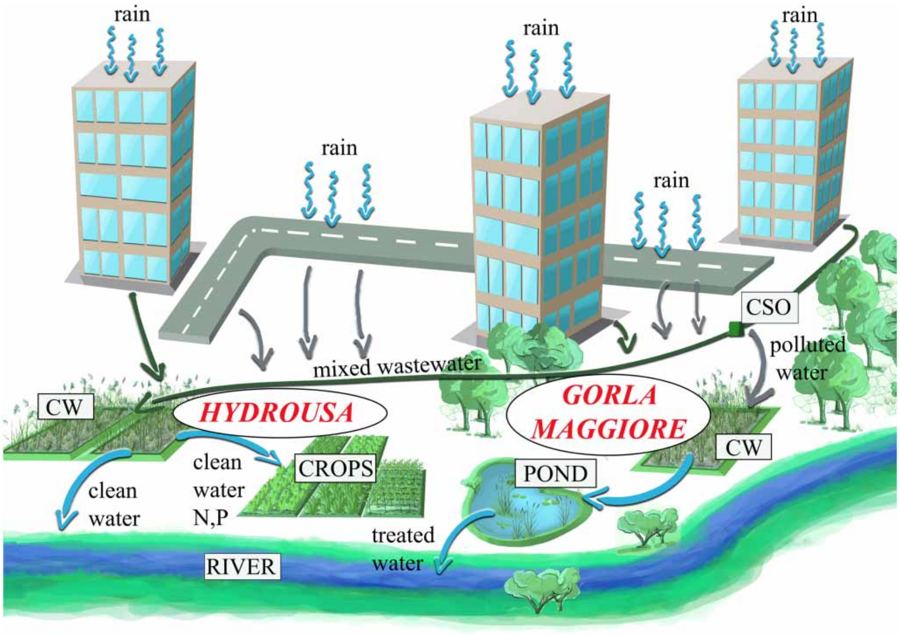

Figure 6 | Transition scheme towards a decentralised and integrated, sustainable water management in an urban settlement with the contributions of the case studies HYDROUSA and GORLA MAGGIORE highlighted (SUDS: sustainable drainage systems, CW: constructed wetlands) (adapted from Masi *et al.* 2018).

The presented review and selected case studies relevant to NBS demonstrate the advantages of NBS both in social and economic terms, i.e., creation of new jobs and saving of energy and resources. Closed-loop recycling of greywater can decrease the amount of potable water used and wastewater by up to 50–60%, reducing water production and sewage treatment costs at centralised WWTPs. Other projects have focused on NBS and the water-food-energy nexus, as summarised in the Supplementary material tables. Hence, NBS include constructed wetlands, restored wetlands, coastal Mediterranean wetlands, green walls and green roofs. NBS, moreover, act as groundwater storage, water retention, water purification and improvement of environmental value.

The most frequent NBS are constructed wetlands, which can remove nutrients and organic components, including organic micropollutants and other emerging compounds. They can be designed for water sources with very different characteristics. In addition to treating water for a particular

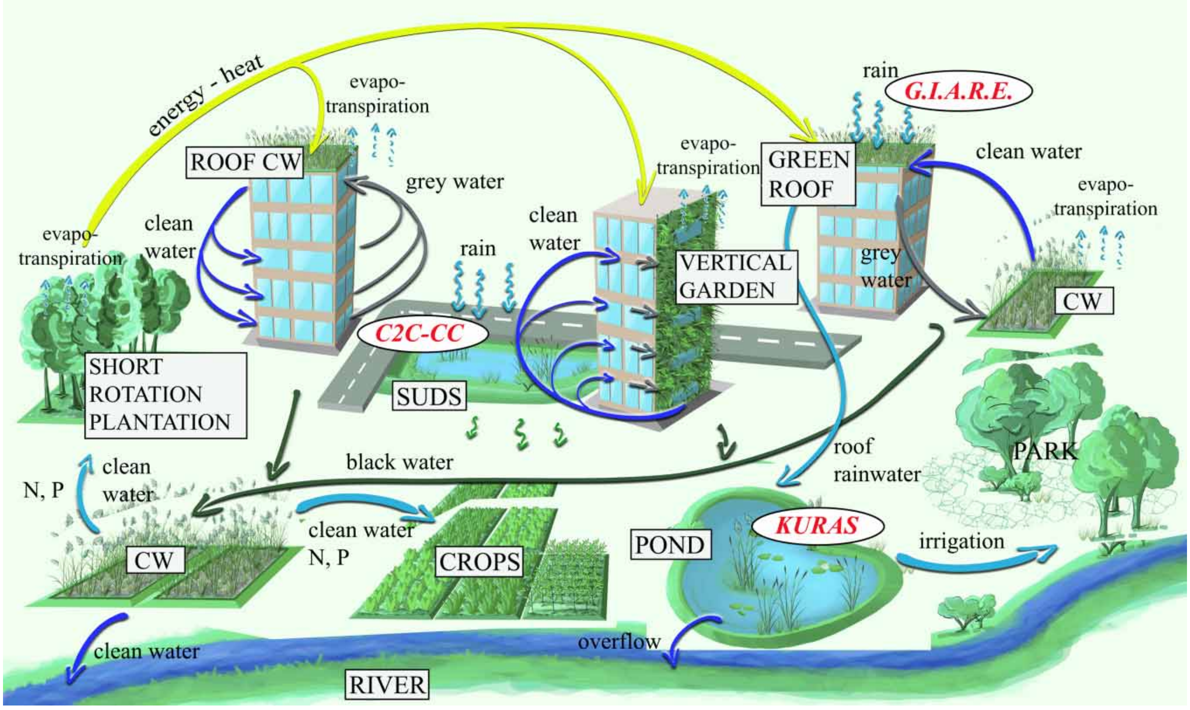

Figure 7 | Advisable scheme of decentralised and integrated, sustainable water management in an urban settlement with the contributions of the case studies C2C-CC, KURAS and G.I.A.R.E. highlighted (SUDS: sustainable drainage systems, CW: constructed wetlands) (adapted from Masi *et al.* 2018).

purpose, wetlands can be designed for water storage, infiltration and evapotranspiration, important functions of the urban water cycle. They also provide a series of additional benefits that grey infrastructure cannot, such as providing ecological niches within urban areas, or preferred recreation and educational areas. However, most of the research and technical development of treatment wetlands historically relates to decentralised treatment, normally away from urban areas. Thus, we still have only a small number of examples and limited data on the implementation of treatment wetlands in the urban environment. In spite of the potential of other NBS implemented in the urban area, such as green walls or SUDS, to purify water, the majority of the existing examples and publications deal only with the attenuation of the heat island effect or stormwater management, respectively. It is thus clear that in order to increase the implementation of NBS in the urban environment, further research and demonstration should more effectively combine different disciplines and needs in aligning with the holistic perspectives required by the water-food-energy nexus and taking into consideration the ecosystem services provided.

The implementation of NBS applications in urban areas is, at the same time, limited by some challenges. For instance, especially in densely built urban areas or protected historical city centres, the limited space available is a major drawback. Nevertheless, while this represents a present challenge, in the future, architecture and urban planning can be adapted to more easily accommodate NBS, which provide the widest possible range of benefits. In fact, NBS present a multifunctional capacity for resource recovery and pollution control, delivering multiple benefits in this issue, although it is worth noting that NBS for UWM clearly address other challenges, such as biodiversity enhancement and a more efficient management of the water-food-energy nexus, among others.

In the future, the reliance on NBS in sustainable water use is expected to increase. Given the still-increasing effects of climate change, it is necessary that in the future, planning for city infrastructure will be based on climate change mitigation, adaptation and resilience. The most common applications for NBS will be in parallel with integrated river management practices and re-establishment of wetlands. The developments towards more holistic concepts of resources flow management imply integrated, cross-sectoral systems and approaches. In the context of UWM, pollution control is shifting towards resource recovery. The traditional separation between water supply, wastewater and stormwater is challenged towards reusing properly treated wastewater and stormwater for purposes where potable water quality is not necessarily needed. NBS implementation can support this paradigm shift.

Based on the presented literature review, the NBS case studies and the discussion above, we conclude the following:

1. NBS help mitigate flood and drought impacts simultaneously supporting stormwater and water supply management.
2. NBS are essential to maintain the natural hydrologic regime despite development and partial sealing of surfaces, not least to keep the natural water cycle of evapotranspiration and rainfall, but also to mitigate urban heat island effects and allow the growth of urban green with local water resources.
3. NBS can efficiently purify very different water sources, greywater, rain water, sewer overflow or wastewater, for various purposes of further use, while generating numerous side benefits. Besides treating water, NBS can also retain stormwater, produce or irrigate for food production and save energy.
4. NBS create very promising new opportunities to use water more effectively and efficiently, enable urban farming or mitigate energy consumption. However, the urban water-food-energy nexus is still in a very early stage of development.
5. Ultimately, a wide application of NBS needs a systemic change from wanting to do things separately with various technologies towards learning to let nature take care of them in an integrated way that restores a close to natural local water balance and further important nature functions.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available at https://dx.doi.org/10.2166/bgs.2020.932.

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