

Green infrastructure

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Green infrastructure: the future of urban flood risk management?

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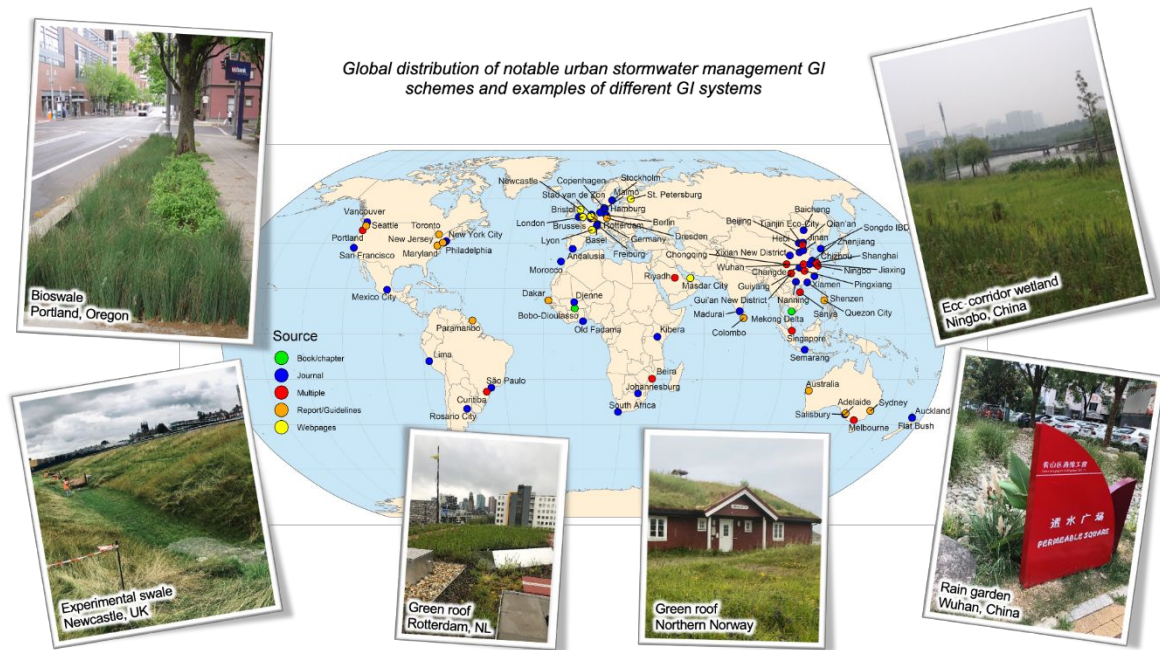
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One-line social media abstract: Urban flooding is a key global challenge which is expected to become exacerbated by climate change. How does green infrastructure contribute towards a suitable, integrated solution?

WIREs Water article type: *Overview*



30 **Visual abstract:** *Global distribution of notable urban stormwater management GI schemes and examples of different GI systems.*

Abstract:

Urban flooding is a key global challenge which is expected to become exacerbated under global change due to more intense rainfall and flashier runoff regimes over increasingly urban landscapes. Consequently, many cities are rethinking their approach to flood risk management by using Green Infrastructure (GI) solutions to reverse the legacy of hard engineering flood management approaches. The aim of GI is to attenuate, restore and recreate a more natural flood response, bringing hydrological responses closer to pre-urbanised conditions. However, GI effectiveness is often difficult to determine, and depends on both the magnitude of storm events and the spatial scale of GI infrastructure. Monitoring of the successes and failures of GI schemes is not routinely conducted. Thus, it can be difficult to determine whether GI provides a sustainable solution to manage urban flooding. This paper provides an international perspective on the current use of GI for urban flood mitigation and the solutions it offers in light of current and future challenges. An increasing body of literature further suggests that GI can be optimised alongside grey infrastructure to

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3 provide a holistic solution that delivers multiple co-benefits to the environment and
4 society, while increasing flood resilience. GI will have to work synergistically with
5 existing and upgraded grey infrastructure if urban flood risk is to be managed in a
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8 50 futureproof manner. Here, we discuss a series of priorities and challenges that must
9 be overcome to enable integration of GI into existing stormwater management
10 frameworks that effectively manage flood risk.
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15 **Keywords:** Green Infrastructure, SuDS, urban flooding, sustainable drainage, water sensitive urban
16 55 design, resilience.
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19 1. Introduction

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21 Urban flooding is a key global challenge that is projected to be exacerbated by future
22 intensification of climate extremes, changes in land-use (e.g. widespread urbanisation
23 and subsequent reduction in permeable green spaces), as well as ageing and
24 deteriorating critical infrastructure. Consequently, many global cities are rethinking
25 and adapting their approach to flood risk management (Soz *et al.*, 2016). This involves
26 60 a transition from *flood defence* (where cities are protected from rivers and rising sea
27 levels through engineering structures, and surface water is transported and removed
28 rapidly via subsurface systems), to *flood resilience* (where urban spaces are designed
29 to make space for water and adapt to the increasing threat of urban flooding whilst
30 providing wider improvements to the environment and society (Lennon *et al.*, 2014;
31 O'Donnell *et al.*, 2020). This is achieved through a shift from grey infrastructure
32 solutions towards increasingly decentralised facilities that utilise Green Infrastructure
33 (GI) to retain, attenuate, store and reuse surface water on site (Lennon *et al.*, 2014;
34 70 Golden and Hoghooghi, 2018). Enhancing urban flood resilience is a key driver in the
35 transition from '*Drained Cities*', where service delivery focuses on drainage and
36 channelisation, to '*Water Sensitive Cities*', where adaptive, multifunctional
37 infrastructure and assets provide ecosystem services and facilitates to promote water
38 sensitive behaviours (Wong and Brown, 2009; Radhakrishnan *et al.*, 2018). As such,
39 flexibility in engineering design (De Neufville and Scholtes, 2011) is required to ensure
40 that water management systems are designed to be 'antifragile' (Taleb, 2012; Babovic
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3 *et al.*, 2018), a term used to reflect a system's enhanced resilience and adaptability
4 through exposure to disorder, shocks and chaos.
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9 80 Definitions of GI vary considerably (Bartesaghi Koc *et al.*, 2017), but GI generally
10 refers to the use of natural processes to protect, restore and emulate the natural
11 functioning of floodplains, rivers and the coasts to effectively manage flood risk. GI fits
12 within the wider umbrella term of nature-based solutions (NBS) and is used to recreate
13 a more natural water cycle in urban areas to help conserve natural ecosystem value
14 whilst reducing the risk of surface water (pluvial) flooding. The European Commission
15 highlighted the potential multiple benefits of GI, defined as '*a strategically planned*
16 *network of high quality natural and semi-natural areas with other environmental*
17 *features, which are designed and managed to deliver a wide range of ecosystem*
18 *services and protect biodiversity in both rural and urban settings'* (European
19 Commission, 2013). Whilst urban GI are often presented as multifunctional assets, in
20 practice, most schemes focus on a single benefit, such as stormwater management
21 (Kabisch *et al.*, 2016; Meerow, 2019). As such, GI is a key component of the surface
22 water management strategies of many progressive global cities at risk of urban
23 flooding (see Figure 1). However, there are several bio-physical and socio-political
24 barriers to innovation in urban flood and water management that hamper the move
25 towards more holistic, integrated systems that utilise both grey and green
26 infrastructure (Lennon *et al.*, 2014; O'Donnell *et al.*, 2017; Thorne *et al.*, 2018).
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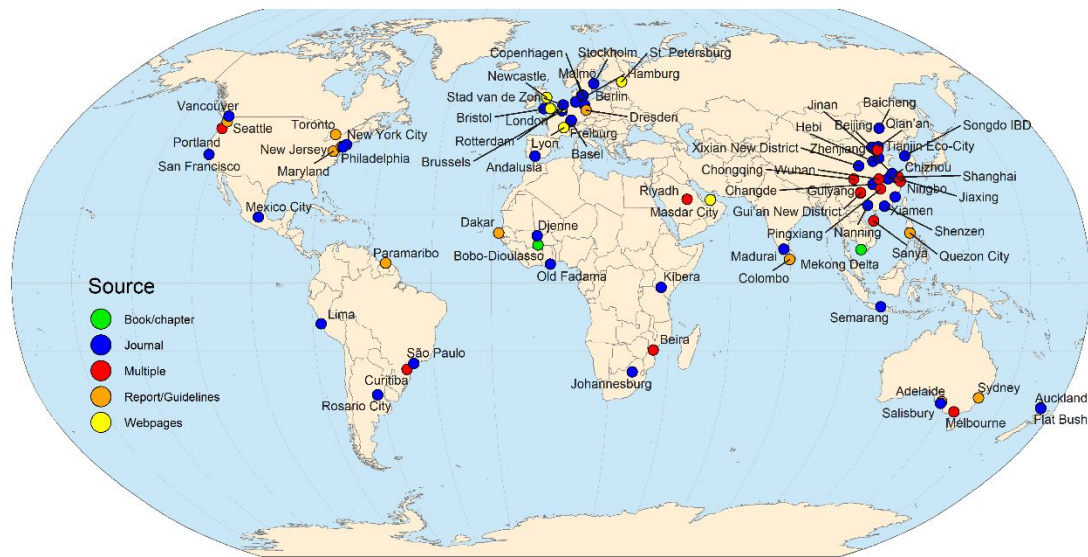
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43 100 Studies on the efficacy of GI schemes have been underway for almost a decade but
44 there are very few monitoring results quantifying the hydrological success of such
45 schemes. The implementation and effectiveness of urban drainage infrastructure and
46 GI are both highly dependent on physical site conditions (*e.g.* topography, land-use,
47 climate, maintenance measures, availability of space and soil physical characteristics)
48 which vary on a site-by-site basis. As such, it is imperative to tailor GI systems to fit
49 site-specific needs (Golden and Hoghooghi, 2018) and prioritise additional co-benefits
50 alongside flood risk reduction. Socio-political factors and governance of the urban
51 environment will also vary by city, region and country, and significantly influence the
52 availability of funding, policies and legislation and the existence of cross-organisational
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3 collaborations to champion and deliver successful GI solutions (Li *et al.*, 2020; te
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5 110 Wierik *et al.*, 2020). Overarching challenges associated with the implementation of GI,
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7 and any urban drainage infrastructure, also differ significantly between new build
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9 developments and urban retrofits (Stangl *et al.* 2019).

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12 Integrated systems of grey and green infrastructure build urban flood resilience by
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14 115 being 'designed for exceedance' (Digman *et al.*, 2014), accepting that it is not possible
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16 to prevent future urban flooding entirely due to a number of limiting factors during the
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18 design and maintenance processes, such as high capital costs, competing land uses,
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20 spatial constraints and maximum drainage capacities, especially under saturated
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22 antecedent moisture conditions and uncertainties in future levels of flood protection
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24 120 required under climate change. Thus, the use of GI within urban stormwater design
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26 should be used to the 'maximum extent feasible' (Tackett, 2008), recognising that GI
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28 implementation will be constrained by the physical limitations of the site, practical
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30 considerations of engineering design and reasonable consideration of financial costs
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32 and infiltration of flood water up to their spatially- or economically-limited capacity, after
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34 125 which they continue to reduce flood-damage and disruption when that capacity is
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36 exceeded by, for example, routing excess runoff to avoid critical infrastructure. GI is a
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38 crucial component of such sustainable drainage and urban stormwater management
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40 130 systems yet there are challenges which must be addressed to facilitate the design and
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42 widespread implementation of GI solutions. This paper provides a perspective on how
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44 GI contributes towards a sustainable and integrated urban flood risk management
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46 solution, discussing the challenges, priorities and opportunities to evaluate the place
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48 135 GI has in wider flood management frameworks. Literature from a series of illustrative
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50 global case studies of varying scale and functional, structural (morphological) and
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52 configurational (spatial) characteristics are drawn upon throughout. After briefly
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54 introducing urban flooding and GI, this paper addresses four key challenges:

1. Whilst recognising that GI must be part of an integrated approach to build resilience toward hydrological extremes, how do spatial scale and storm magnitude impact the effectiveness and suitability of GI approaches?

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3 140 2. What role does GI play in providing a sustainable, flexible and realistic
4 approach to tackle future (uncertain) hydroclimatic conditions?
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7 3. How can blue, green and grey infrastructure be integrated into urban design to
8 optimise the delivery of flood attenuation and multiple co-benefits, and;
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11 4. What metrics and/or monitoring have been used to determine the success of
12 145 GI?



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Figure 1: Distribution of notable urban GI schemes which consider stormwater management at a variety of scales. References from a range of sources (books, journals, reports or guidelines, webpages or multiple sources) are provided in Supplementary Table 1 for each city/location. Please note, case studies are not exhaustive and those presented are aggregated over a variety of scales and functional typologies. Sprakman et al. (2020) note that GI research is predominantly focused in Global North countries and literature is largely absent from locations with water stresses in the Global South. There is a strong focus on GI research in temperate regions (where flood hazards are increasing the most at the global scale; Slater et al., 2021), especially the United States Eastern Seaboard and Australia, emerging in places with strong policy and research cluster interest, such as China (relating to the Sponge City Program) and Europe.

160 2. Urban flood risk

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6 The occurrence of urban surface water flooding relates to short, intense precipitation
7 events where excess rainfall cannot infiltrate into the sub-surface or drain via natural
8 or artificial drainage systems (Riel, 2011), or where rainfall intensity exceeds the
9 localised drainage capacity (Evans *et al.*, 2004). Many severe urban floods are caused
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13 165 by coincident flooding, where an area is exposed to multiple flood risks alongside
14 surface water flooding, such as fluvial flooding, groundwater flooding, sewer flooding,
15 and coastal inundation caused by storm surge events (Evans *et al.*, 2004). This is the
16 case in many coastal megacities, such as New York, London, Mexico City, Mumbai,
17 Shanghai, Tokyo and Bangkok (Nicholls *et al.*, 2008; Syvitski *et al.*, 2009).
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23 Urban flooding is a substantial international issue and is projected to become more
24 frequent and severe due to changes in precipitation intensity, phase and variability
25 (Wilby and Keenan, 2012; Zhou *et al.*, 2012), population growth in urban areas putting
26 larger numbers of people at risk (United Nations, 2018) and widespread replacement
27 of vegetated surfaces in favour of impermeable surfaces (e.g. roads, concrete
28 surfaces and buildings) resulting in more flashy runoff regimes in cities. Furthermore,
29 existing drainage systems in many cities are unsuitable for current and future climate
30 175 of vegetated surfaces in favour of impermeable surfaces (e.g. roads, concrete
31 surfaces and buildings) resulting in more flashy runoff regimes in cities. Furthermore,
32 existing drainage systems in many cities are unsuitable for current and future climate
33 conditions and deterioration of existing assets are a key driver of future urban flood
34 risk (O'Donnell and Thorne, 2020a). Many UK cities are still relying on Victorian-aged
35 drainage infrastructure, parts of which do not fully conform to contemporary design
36 specifications (e.g. being constructed to deal with a 1 in 30-year rainfall event; Jones
37 and Macdonald, 2007), while other urban conurbations such as Shanghai and many
38 urban areas within the Netherlands, have drainage systems with one- and two-year
39 180 return period design standards, respectively (Riel, 2011; Yin *et al.*, 2016), putting these
40 cities at significant risk of urban flooding. Additionally, the effective drainage capacity
41 of a sewer system may be significantly reduced over time if maintenance and
42 rehabilitation of assets fail to keep pace with deterioration, causing issues such as
43 misconnections, sedimentation and blockages (Tait *et al.*, 2008; Coulthard and
44 Frostick, 2010). Thus, urban areas may be unable to manage future high intensity
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3 190 precipitation events and the impacts of urban flooding may become increasingly
4 severe and widespread.
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9 The occurrence of urban flooding may lead to large and long-lasting economic losses
10 associated with damage to property and infrastructure (Bosher, 2014), disruption to
11 travel, emergency service provision and human activities (Dawson *et al.*, 2011; Green
12 195 *et al.*, 2017), spread of water-borne diseases (Tunstall *et al.*, 2006) and loss of life.
13 Thus, cities should be investing significant time, capital and resource to prepare for,
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15 reduce and mitigate the impacts of urban flooding.
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20 200 Traditional strategies to managing flooding in urban areas are typically focused on
21 hard-engineering approaches (e.g. culverts, sewer systems and large capacity
22 compound river, stream and urban drainage channels) to contain and convey water
23 through an urban system as rapidly as possible, treating water as an 'unruly substance'
24 (Jones and Macdonald, 2007). However, flood management schemes that work with
25 natural processes, deliver ecosystem services and 'make space for water' (Burgess-
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27 205 Gamble *et al.*, 2017) have seen significant developments in recent years.
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34 **3. Green infrastructure for stormwater management**

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37 The terms 'Nature-Based Solutions', 'Soft Engineering', 'Blue-Green Infrastructure'
38 210 and 'Working with Natural Processes' are used somewhat interchangeably with the
39 term 'Green Infrastructure' but have subtle differences which are beyond the scope of
40 this paper (see Fletcher *et al.*, 2015, Bartesaghi Koc *et al.*, 2017 and Debele *et al.*,
41 2019). GI is a key component of UK Sustainable Drainage Systems (SuDS), termed
42 Low Impact Developments (LIDs) or Best Management Practices (BMPs) in North
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44 215 America, which incorporate GI in order to attenuate, drain, infiltrate and store surface
45 and sub-surface water (Loperfido *et al.*, 2014; Woods-Ballard *et al.*, 2015;
46 Vijayaraghavan *et al.*, 2021). GI is a key element of Water Sensitive Urban Design
47 (WSUD) and nature-based solutions that integrates water cycle management within
48 the built environment (Sharma *et al.*, 2016), and other more holistic concepts, such as
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55 220 'Blue-Green Cities', where naturally oriented water cycles are recreated in urban
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3 environments by bringing together water management and GI (Hoyer *et al.*, 2011;
4 O'Donnell and Thorne, 2020b), and '*Sponge Cities*', describing Chinese conurbations
5 designed to increase infiltration capacity, reduce surface runoff and recharge
6 groundwater resources (Chan *et al.*, 2018; Li *et al.*, 2020).
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11 In this paper, GI approaches which focus specifically on stormwater management in
12 predominantly urban areas are considered. These tend to be relatively small scale due
13 to the competing demands of urban development and land-use changes and are often
14 purpose-built to offset or reduce elevated surface runoff induced by new and existing
15 developments (Golden and Hoghooghi, 2018). The primary flood mitigation purpose
16 of such schemes is to slow the flow of water through urban areas and to store excess
17 water in storage and detention areas, reducing peak runoff rates by mimicking or
18 replicating a more natural hydrological response following a storm event. Bartesaghi
19 Koc *et al.* (2017) suggested that GI schemes can be divided into four categories (tree
20 canopy, green open spaces, green roofs and vertical greenery systems) based on
21 their functional, structural (morphological) and configurational (spatial arrangements)
22 characteristics. Typical GI assets with functional roles of managing urban floods
23 include features such as rain gardens/bioretention cells (Vijayaraghavan *et al.*, 2013),
24 bioswales, green roofs, wetlands, detention basins, de-culverted rivers, tree pit
25 planters, green streets, rainwater harvesting systems and permeable pavements (see
26 Figure 2). These features may vary from site to site, but typically have structural and
27 configurational characteristics which are designed to increase their efficacy in
28 managing flood risk; their key functional component.
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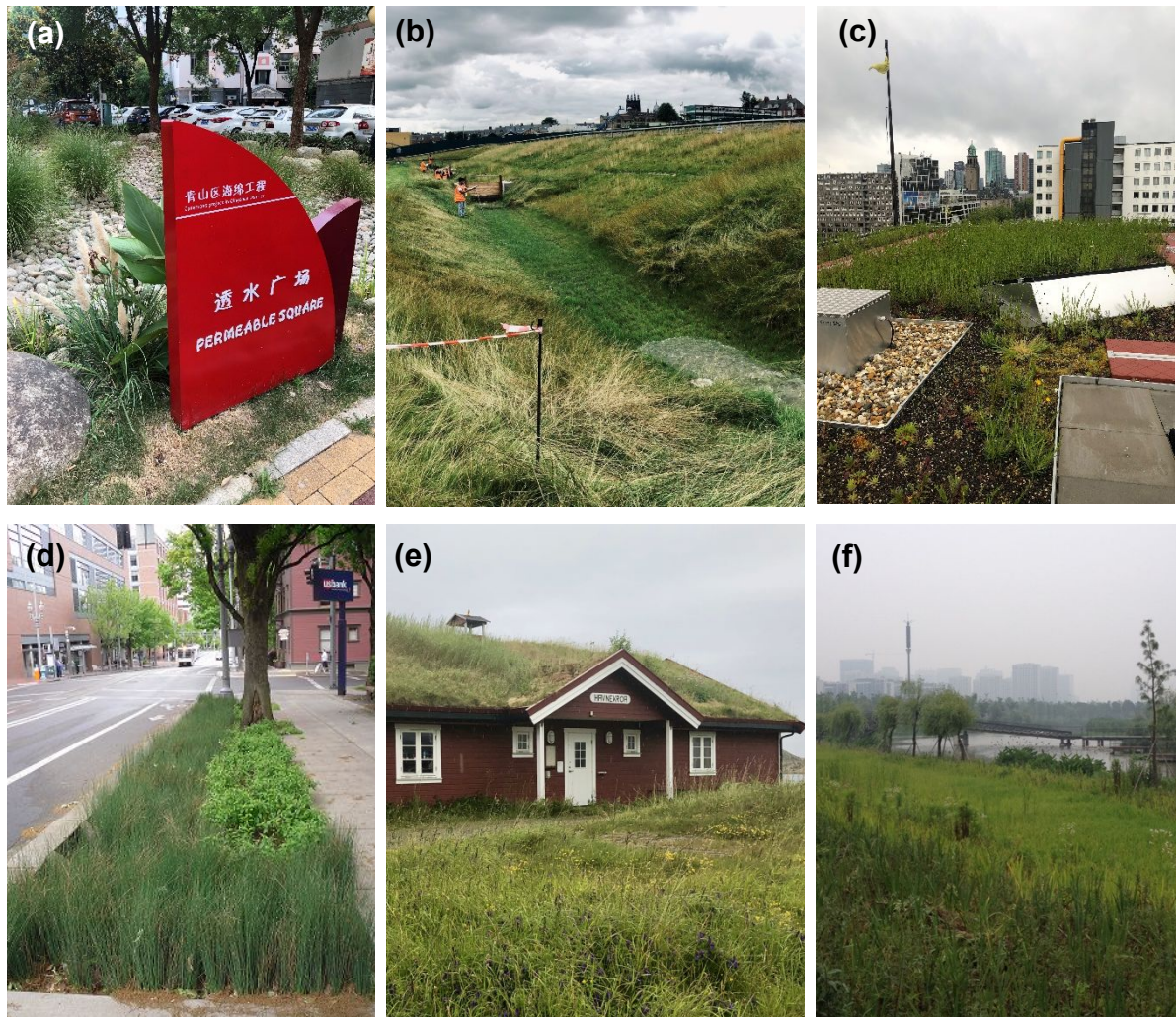


Figure 2: Examples of urban green infrastructure solutions of varying scale and function from across the world: **(a)** Sponge City rain garden in Wuhan, China; **(b)** extreme event swale in National Green Infrastructure Facility, Newcastle-upon-Tyne, UK; **(c)** retrofitted green roof and urban farm in Rotterdam, Netherlands; **(d)** bioswale along street pavement as part of the Grey to Green programme in Portland, Oregon USA; **(e)** green roof and green open areas in peri-urban region in Northern Norway; **(f)** Ningbo (China) eco-corridor wetland, running through the heart of Ningbo Eastern New Town.

Using GI as a complementary method of urban flood risk management, alongside traditional grey infrastructure, is becoming increasingly recognised in many international cities (Lennon *et al.*, 2014; O'Donnell *et al.*, 2021). This is partly due to

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3 GI delivering multiple social, environmental and economic benefits and services in
4 conjunction with their primary purpose of flood risk reduction, such as improving water
5 and air quality, creating attractive and aesthetically pleasing social spaces with
6 recognised health benefits, and enhancing species diversity (Fenner, 2017; Hoang *et al.*
7 *et al.*, 2018; Kattel *et al.*, 2021). A growing number of studies further evaluate, value and
8 monetise the multiple benefits of GI (e.g. Ashley *et al.*, 2018; Alves *et al.*, 2019;
9 Ghofrani *et al.*, 2020). Nonetheless, multiple benefit valuation is not typically included
10 when making the business case for GI implementation. The development of B&ST
11 (Benefits Estimation Toolkit; CIRIA, 2019) has enabled the multiple benefits of Blue-
12 Green infrastructure (BGI) to be assessed without the need for full scale economic
13 inputs. Despite this, uptake is limited and outputs are often case study specific
14 (Susdrain, no date).
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26 Assessment of the hydrological and/or sedimentological performance of such
27 schemes are not routinely conducted and relatively few studies exist (e.g. Fu *et al.*,
28 2021). Examples from UK SuDS schemes (Woods-Ballard *et al.*, 2015); stormwater
29 ponds (Ahilan *et al.*, 2019; Krivtsov *et al.*, 2020); green roofs (Stovin *et al.*, 2013),
30 swales (Allen *et al.*, 2015), bioretention and integrated stormwater control systems
31 (Traver and Ebrahimian, 2017; Ebrahimian *et al.*, 2019) and a decade of monitoring
32 by the Bureau of Environmental Services (BES) in Portland, Oregon USA (BES, 2010;
33 2013a) are available. However, few schemes, to date, have had sufficient long-term
34 monitoring to provide an evidence base of the effectiveness of GI during a range of
35 flood events and weather conditions. Given the increasing interest and investment in
36 the use of GI within urban areas, it is necessary to quantify and assess the
37 effectiveness of GI in reducing flood risk and to identify a series of transferable best
38 management practices to enhance and maximise the hydrological benefits of such
39 schemes through time.
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51 **4. Challenges and Recommendations**

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54 Increased understanding of the effectiveness of GI to enhance resilience to urban
55 flooding is required to support widespread and holistic adoption of GI in urban
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3 environments. Given the relative lack of assessment or measurement of GI success
4 in reducing flood risk, we believe that four key questions must be considered, which
5 are discussed individually below.
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4.1. Spatial scale and storm magnitude impacting effectiveness and suitability of GI approaches

14 Whilst recognising that GI must be part of an integrated approach to build evolutionary
15 resilience toward hydrological extremes (Tackett, 2008; Lennon *et al.*, 2014), the issue
16 of scale is an important consideration when assessing the effectiveness of GI. Barker
17 *et al.* (2019) highlight that, although GI has emerged as a dominant component of the
18 built environment, one core challenge is to understand how the benefits of GI vary at
19 different scales. Golden and Hoghooghi (2018) present a detailed review of scaling
20 within GI systems, examining localised interventions, as well as upscaling the
21 influence of multiple localised interventions to quantify broader, cumulative catchment-
22 level influences of multiple GI practices. Collentine and Futter (2016) note that natural
23 water retention measures have the potential to reduce flood peaks and maintain base
24 flows at a range of scales, from small urban measures, to catchment-wide approaches,
25 including systematic catchment afforestation.
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37 Urban GI can be considered and understood at three different spatial scales: *(i)* the
38 micro-scale, an individual site or development and its immediate surroundings; *(ii)* the
39 meso-scale, typically spanning multiple micro locations, such as a neighbourhood or
40 small settlement, and; *(iii)* the macro-scale, consisting of macro locations and spatially
41 covering a larger urban area, region or combined authority area (*i.e.* council or
42 municipality level; UK Green Building Council, 2020). In the case of rural natural flood
43 management, increasing the connectivity with floodplains generally provides
44 additional upstream storage capacity, which is likely to result in decreased peak flows
45 downstream (Dadson *et al.*, 2017). However, for urban areas where space is limited,
46 the strategic spatial placement of GI as a patchwork or mosaic of natural vegetation is
47 crucial and tends to focus on source level control. Vercruyssen *et al.*, (2019b) introduce
48 the concept of 'interoperability' to actively manage connections between local and city-
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3 scale infrastructure systems to facilitate the transition from local multifunctionality of
4 blue, green and grey infrastructure to city-scale multisystem flood risk management.
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8 Numerous urban drainage models, such as the Storm Water Management Model
9 (SWMM), InfoWorks ICM, MIKE URBAN and Model for Urban Stormwater
10 Improvement Conceptualisation (MUSIC) all provide functional packages to help
11 understand the influences of GI on urban stormwater reduction (EPA, 2020) and allow
12 a low-cost option to test and optimise GI measures in a simulated environment without
13 the construction of such features, providing adequate catchment and hydrological data
14 is available. For example, Schubert *et al.* (2017) provide a numerical modelling
15 assessment of GI performance in the Little Stringybark Creek watershed, Melbourne,
16 Australia, using MUSIC. Hydrological modelling suggests that current retrofitted GI
17 features in the catchment, including rainwater tanks and infiltration trenches, account
18 for a reduction of 29% of downstream flooded area. Full implementation of retrofit GI
19 could reduce the downstream flooded area by up to 91% and could lower flow
20 intensities by 83% on average for smaller magnitude events with flood durations of up
21 to 3 hours and annual exceedance probabilities of <1%.
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33 The SWMM5 engine, which is seen as one of the most accurate tools for GI
34 representation in a review of 20 simulation modelling tools by Jayasooriya *et al.* (2014),
35 allows the simulation of a number of GI systems, including bioretention cells,
36 permeable pavements and swales (EPA, 2020). Such models are useful in examining
37 GI response to design storm events of high magnitude in the absence of experimental
38 monitoring data. Numerical modelling has been used to understand the influence of
39 GI on urban hydrology, with Lee and Nietch (2017) providing a practical guide for
40 representing and modelling GI and LID controls within SWMM. McCutcheon and Wride
41 (2013) applied SWMM to simulate the hydrological responses of turf grass and prairie-
42 vegetated rain gardens in clay and sandy soils during a single storm event and
43 compared this to experimental field data. Results from the modelling in SWMM yielded
44 good agreement with measured in-field data, within an acceptable range of error
45 associated with field measurement techniques. However, McCutcheon and Wride
46 (2013) suggest that long term monitoring of GI is required to provide robust validation
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3 360 data to ensure that GI processes are accurately represented in modelling
4 environments and that changes in performance are captured within numerical
5 representations of such systems. Additionally, Macro *et al.* (2018) provide a framework
6 for simulating GI features within a coupled model applying the SWMM engine with
7 Optimisation Software Toolkit for Research Involving Computational Heuristics;
8 (OSTRICH) to investigate the influence of GI types, sizing and placement. SWMM-
9 OSTRICH was utilised to provide a decision-making tool to investigate rain barrel
10 (water butt) placement within Buffalo, New York and to examine trade-offs between
11 the cost of rain barrel placement and the resulting reduction in combined sewer
12 overflows. However, the OSTRICH-SWMM methodology is currently only applicable
13 for rainwater harvesting systems and support for other GI features, such as permeable
14 pavement, vegetated swales and green roofs, is ongoing. Nevertheless, this study
15 highlights the flexible, open-source nature of the SWMM engine to be adapted to suit
16 specific case studies and research questions. The SWMM engine has also been
17 implemented within the open-source programming language *R* under the package
18 *swmmr* (Leutnant *et al.*, 2020), opening up future opportunities to standardise or
19 harmonise GI modelling practices and allow more clear comparisons between studies
20 (Slater *et al.*, 2019).
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36 Using a GIS-based analysis, Pennino *et al.* (2016) found that when GI controls cover
37 over 5% of a catchment drainage area, flashy urban hydrology is reduced. Although
38 the magnitude of influence was minimal at low levels of GI adoption, this was shown
39 to increase with an increase in GI coverage. This was also observed within the
40 numerical rainfall-runoff modelling conducted by Liu *et al.* (2014), which suggested
41 that implementing a single GI feature within an urban neighbourhood of Beijing, China,
42 had limited influence on reducing peak flows, whereas integrated and systematic
43 urban GI configurations (e.g. increasing the area and storage capacity in existing
44 green spaces by creating detention basin features consisting of concave green spaces
45 to temporarily pond water) acted to effectively reduce all storm events considered.
46 Thus, if a large number of relatively small (meso-scale) GI installations are
47 interconnected (ideally through green corridors, or by grey infrastructure buried
48 underground), optimised (through the use of gradient to create surface detention) and
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3 designed to operate synergistically as a stormwater treatment train, their effect can
4 match or exceed that of a single large GI asset covering the macro-scale (Bastien *et*
5 *al.*, 2010), linking back to the concept of 'interoperability' (Vercruyssen *et al.*, 2019b).
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10 Certainly, there is a role for larger GI features, such as reconnected and restored
11 floodplains (BES, 2013b; Hoang *et al.*, 2018; Leicester City Council, 2018) or
12 expansive areas of open green space with high potential for water storage. However,
13 the overall performance and efficacy of localised interconnected GI may be greater
14 than using larger, individual source control or end of pipe SuDS features with a larger
15 footprint due to optimising the benefits through effective placement and design
16 (Bastien *et al.*, 2010). Consequently, the placement of decentralised urban GI
17 400 elements is important to ensure that schemes are optimised in their performance and
18 provide appropriate source-level treatment of surface water flows at locations where
19 runoff control is most required. As such, there is not a direct relationship between the
20 size of GI schemes and effectiveness, which will vary significantly between different
21 case studies, methods of evaluation, and spatial characteristics. Figure 3
22 conceptualises the linkages between scale and effectiveness of key GI features with
23 the fundamental purpose of stormwater management (Bartesaghi Koc *et al.*, 2017),
24 405 but this is likely to vary significantly between case study locations depending on
25 specific site conditions and whether the GI scheme is new or retrofitted.
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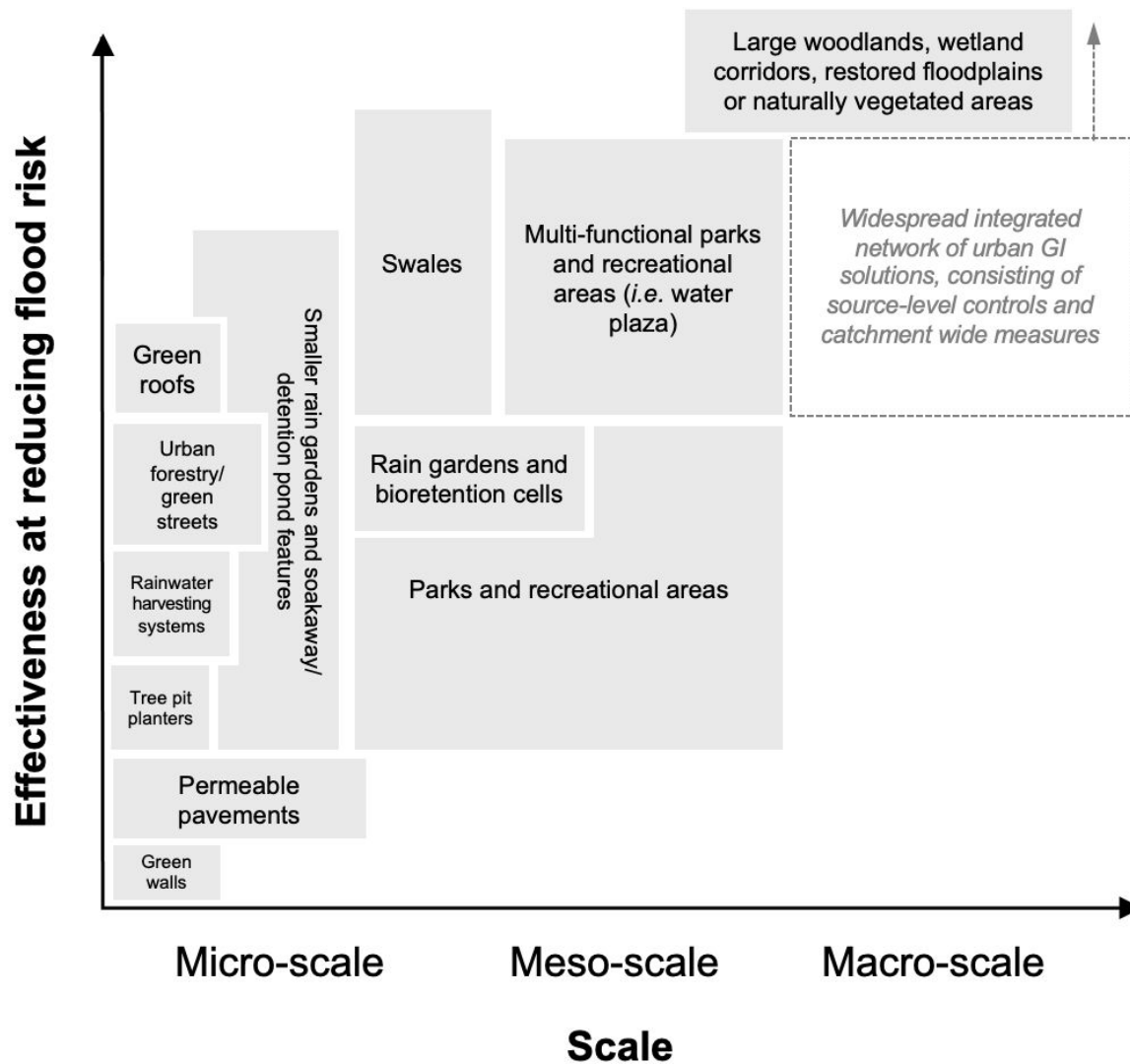


Figure 3: Conceptual diagram showing the scale and effectiveness of different GI features. The scale and cost of such features are highly variable and may vary significantly between sites, design specifications and whether the system is new or retrofitted. N.B. Some features may be better at dealing with single, high intensity events, but may be fully saturated after one event, whereas others may have greater capacity to deal with multiple flood events.

A key question is whether GI schemes are able to provide hydrological benefits during larger magnitude storm events (Schubert *et al.*, 2017). Limited research has been undertaken to compare intervention effectiveness during moderate to extreme intensity rainfall events which are typically responsible for surface water flooding (Webber *et al.* (2019). A study by Sørensen and Emilsson (2019) shows how retrofit stormwater control measures help alleviate the impacts of an extreme precipitation event in Malmö, Sweden (50 – 200 years return period), demonstrating that retrofitted

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3 stormwater systems performed better than transitional conventional sewer systems.
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5 Despite this, Webber *et al.* (2019) suggest that although catchment-wide decentralised
6
7 430 rainwater capture appears to be the most effective mechanism for managing moderate
8
9 rainfall events, there is much uncertainty on whether this is a viable solution for larger
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11 events and such measures are dependent on space availability within the local
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13 catchment.
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15 435 It is disputed whether GI provides a unified solution to protect urban areas from
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17 extreme rainfall events, especially if prolonged rainfall results in the saturation of
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19 storage capacity (Schubert *et al.*, 2017). Moreover, using a widespread remote
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21 sensing analysis of GI at regional and local scales, Calderón-Contreras and Rosas
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23 (2017) found that a vast proportion of GI systems within Mexico City were of low quality,
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25 440 hindering the provision of such systems to provide any notable urban ecological
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27 services, including the reduction of flood risk. This suggests that, although GI is
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29 essential in securing long-term resilience of urban systems, the quality, quantity and
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31 diversity of such systems should be evaluated to ensure that systems are designed
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33 445 appropriately and are fit for purpose. As such, GI certainly has a place in wider,
34
35 integrated and sustainable flood risk strategies in urban areas if it is correctly designed
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37 and implemented. Experimental monitoring and scenario-based modelling studies
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39 (see Section 4.4) will help to provide an evidence-base of the effectiveness of GI
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41 450 during high magnitude events, but it is often difficult to isolate the individual influence
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43 of GI features when they form part of an integrated catchment drainage approach in
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45 conjunction with grey infrastructure. Further, such integrated systems build flood
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47 resilience through the principles of 'designing for exceedance' (Digman *et al.*, 2014),
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49 accepting that an area should have an acceptable level of flood protection but should
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51 455 be designed to safely fail when this capacity is surpassed. Using this framework, GI
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53 failures are often less catastrophic when compared to grey infrastructure failures, and
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55 some levels of protection are still offered even when the design level of flood protection
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57 is exceeded, which is often not the case for grey infrastructure as this is seldom
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59 designed to be 'safe-to-fail' (Dong *et al.*, 2017).
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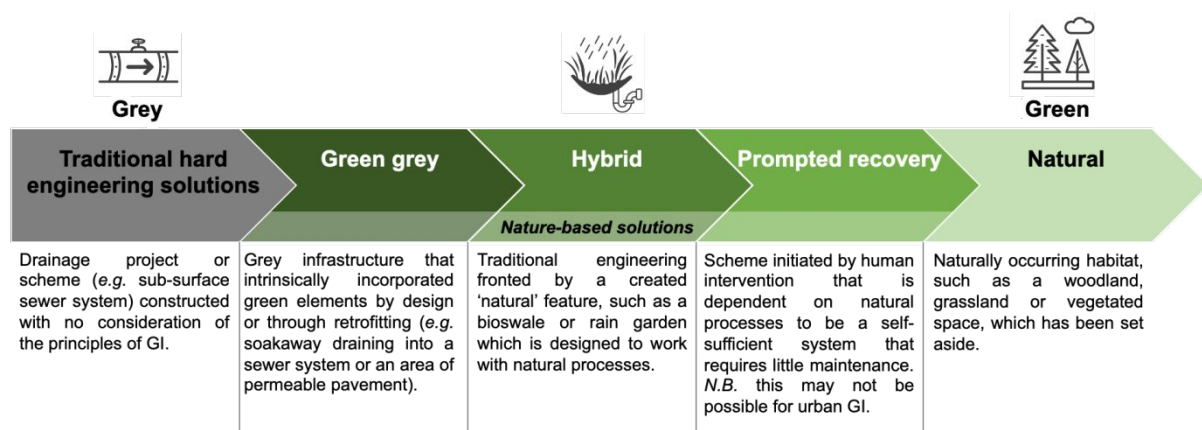
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5 460 As Spraakman *et al.* (2020) and Zuniga-Teran *et al.* (2020) note, there is a need for
6 standardisation within the design process of GI schemes to ensure alignment with
7 regulatory frameworks, with challenges in design standards reflecting the significant
8 uncertainty around how best to plan, design, implement and maintain GI (Baptiste *et*
9 *al.*, 2015; Sinnett *et al.*, 2018). Nevertheless, this may be challenging because the
10 performance of GI is largely site specific and their additional ability to deliver multiple
11 co-benefits under the ‘four pillars of SuDS development’ – i.e. (1) flood risk
12 management; (2) improvement to water quality; (3) the provision of public amenity and
13 465 aesthetic, and; (4) benefits to biodiversity (Woods-Ballard *et al.*, 2015) – must also be
14 considered alongside their ability to mitigate high intensity storm events. GI research
15 has proliferated in recent years, but studies often have disparate aims, intents and
16 metrics used to assess performance (Spraakman *et al.*, 2020). Thus, GI alone cannot
17 address all scales of urban flood risk management but should be considered as part
18 of a wider system which integrates across spatial scales encompassing landscapes,
19 watersheds and river valleys down to individual streets and buildings (Carter *et al.*,
20 2018) to help manage higher magnitude flood events.
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32 **4.2. The role of GI in providing sustainable, flexible and realistic approaches to** 33 **tackle future (uncertain) flood conditions** 34 35 36

37 One of the key benefits of GI is that systems are designed to operate using natural
38 processes rather than trying to unnaturally control rainfall-runoff processes, thus
39 representing a sustainable flood risk management option that is more resilient to future
40 480 climate change than hard engineering approaches (*e.g.* Graham *et al.*, 2012; Kapetas
41 and Fenner, 2020). However, GI schemes operate along a continuum of working with
42 nature (see Figure 4). Although a bioretention system appears to be a self-regulating,
43 natural system on the surface, there may be many engineered and artificial elements
44 to the system, designed to ensure that the system works under certain design
45 485 considerations, such as reducing peak flow rates and detaining surface water.
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For example, ‘hidden’ engineered elements within a rain garden or bioretention system
may include: (i) a single concrete drainage orifice connected to slotted drainage piping

490 to ensure adequate drainage into stormwater drainage systems; (ii) a geotextile membrane to prevent blockages resulting from the migration of fine sediment to the outflow piping and; (iii) an engineered soil profile designed to sustain plant life, permit adequate drainage whilst having sufficient water storage capacity to enable hydrological benefits, and graded to prevent any blockages or sedimentation. Thus, 495 despite appearing fully 'natural', urban GI schemes often mimic natural processes and functioning and sit somewhere along the grey-to-green continuum (see Figure 4) to ensure they are optimised and regulated for their specific function. This allows GI schemes to be adapted to suit a variety of locations, conditions and functional requirements, and also adds the potential for adaption to suit future conditions, which 500 may be more difficult in hidden, underground drainage systems (Zimmermann *et al.*, 2016). As such, the need for standardisation within GI features as Zuniga-Teran *et al.* (2020) suggest may not be possible or necessary. Despite this, clearer understanding of best management practices within GI scheme design is needed to ensure long term functioning and to mitigate against failure. Tools for evaluating GI success and 505 providing an evidence base for GI implementation are beginning to be compiled for GI schemes (e.g. Meerow, 2019; Kapetas and Fenner, 2020), but GI should be designed to be resilient to future changes, implying that GI should possess adaptive capacity and, ideally, the ability to naturally respond to changes in the surrounding areas (Johnson *et al.*, 2019), much like a natural system.



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Figure 4: Green-grey continuum of urban GI. **Source:** adapted from framework within Roca *et al.*, 2017.

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3 The longevity and sustainability of GI may also be highly variable, not least because
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5 515 of a lack of routine measurements and monitoring data on performance. This has led
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7 to GI sometimes being viewed as a solution that once built, can be left alone and will
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9 continue to be effective against managing flood risk indefinitely with minimal further
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11 input. This is often not the case and such schemes should have an associated
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13 maintenance plan to ensure their function and performance is maintained over time
14 520 (Woods-Ballard *et al.*, 2015). Maintenance plans will vary significantly between
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16 schemes but should be tailored to include regular maintenance tasks (*e.g.* litter
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18 picking, vegetation cutback and inlet/outlet inspection), less frequent undertakings
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20 (*e.g.* siltation inspection and excavation) and remedial work as required, such as fixing
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22 any damages or replacing failed functional elements. GI needs maintenance like any
23 525 other drainage infrastructure and, in some cases that maintenance will need to be
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25 more regular, intensive and destructive (Woods-Ballard *et al.*, 2015). Research has
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27 shown that accessibility to SuDS facilities is one of the biggest challenges to ensuring
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29 systems are properly maintained (*e.g.* Barrett, 2003; Blecken *et al.*, 2015), with
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31 Hirschman and Woodworth (2010) highlighting that 14% of SuDS systems
32 530 investigated within Virginia, USA, lacked adequate access for maintenance. However,
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34 these challenges are likely to be comparable or more difficult within hard engineered
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36 systems which involve buried and interconnected drainage elements.

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38 Further, the need for maintenance and remediation may only be acknowledged when
39 535 failures within one or more of the four pillars of SuDS development are apparent (*e.g.*
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41 insufficient drainage and waterlogging, dieback of vegetation, *etc.*), which may link
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43 back to poor design specifications. There is also the issue of misdiagnosing or not
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45 noticing issues with GI performance until a significant loss in performance or
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47 aesthetics are observed. Again, this is often the case for comparable hard engineered
48 540 solutions. However, there is substantial potential for monitoring and maintenance to
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50 be more community driven, *i.e.* using the public to report incidents or issues, or actively
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52 maintain the GI through stewardship opportunities, *e.g.* Portland's Green Street
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54 Steward Programme (BES, 2020). The public may feel a greater sense of ownership
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56 or responsibility to maintain their 'local GI' due to the recognition of benefits that are
57 545 important to them, *e.g.* improved aesthetics, recreational opportunities and health and

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3 wellbeing benefits (Roy *et al.*, 2008; Visitacion *et al.*, 2009; Ando *et al.*, 2020; Kattel *et*
4 *al.*, 2021), which is not the case for traditional engineered solutions. As a result, lower
5 maintenance costs and a reduced frequency for on-site inspections due to out-sourced
6 public monitoring and reporting of issues may be possible, but this should not replace
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10 550 the need for professional, recorded inspections (Blecken *et al.*, 2015).

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13 Ensuring suitable GI design and implementation along the grey-green continuum is
14 also crucial to prevent future failure. Certain GI features may trap sediment in surface
15 runoff (e.g. Deletic, 2005; Merriman and Hunt, 2014) which is beneficial from a water
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18 555 quality perspective (Allen *et al.* 2017) and can prevent sedimentation of terrestrial
19 water bodies and any subsequent reduction in detention and flood mitigation capacity.
20 However, sediment trapping may reduce the capacity of GI features over time, leading
21 to a reduction in conveyance during subsequent events. For instance, if the aggregate
22 used to construct GI soakaway features (such as rain gardens) are not appropriately
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27 560 washed and treated before installation to remove dust elements, this may lead to self-
28 sedimentation, blocking or reduced capacity of the slotted drainage piping which these
29 features rely on to drain. Thus, poor design leads to high maintenance and failures
30 can occur within the planning, construction or post-construction phases of
31 implementation, which is true of any urban drainage system. It is also essential that
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36 565 well designed GI features are adequately maintained over their lifetime to ensure
37 continued functionality.
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41 **4.3. Optimising the delivery of flood attenuation and multiple co-benefits** 42 **through integrated blue, green and grey infrastructure** 43 44

45 570 GI is only part of the solution for managing urban flood risk (as explored in Section
46 4.1). To achieve urban flood resilience, integrated systems of blue-green-grey
47 infrastructure, specifically selected to constitute effective stormwater treatment trains,
48 are needed. Such integrated systems will facilitate management of current and future
49 flood events, whilst delivering environmental, social and economic benefits that
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54 575 address the specific strategic priorities of the city; ultimately aiming to achieve the best
55 cost:benefit ratio. Integrated flood management is essential in urban planning and an
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3 urban catchment should be considered holistically in terms of its hydrological linkages
4 between flood source and impact areas to provide targeted and appropriate GI
5 measures (Vercruysse *et al.* 2019a).
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10 Blue infrastructure includes the watercourses, ponds, wetlands and wet detention
11 basins that exist within drainage networks. BGI interconnects blue assets with
12 networks of natural and designed green landscape components that are designed to
13 turn 'blue' during rainfall events to fulfil their flood risk management function (O'Donnell
14 and Thorne, 2020b). BGI are assets that fulfil both blue (flood risk and water
15 management) and green (urban green space) functions; they may be green most of
16 the time and blue some of the time (*e.g.* detention ponds), or they may have some
17 permanent blue features (*e.g.* retention basins), which expand during heavy runoff
18 events. However, while the limited space in highly urbanised catchments restricts the
19 opportunities for retrofitting some types of BGI, experience shows that opportunities
20 do exist for other types of BGI, especially as part of urban renewal. It may not be
21 possible to restore and deculvert river channels in urban centres due to existing built
22 infrastructure on the floodplain (Wild *et al.*, 2011), and the potential for creation of
23 swales along public highways must compete with other demands, such as pedestrian
24 and cycle access. Whilst pedestrians and cyclists can usually be accommodated, it is
25 usually on-street car parking that prevents wider implementation of BGI and SuDS.
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In new developments, economic pressures to maximise development opportunities
may be to the detriment of expansive BGI systems. Instead, combinations of blue-
green-grey infrastructure may be employed to manage surface runoff above and below
the ground and deliver environmental benefits (*e.g.* improving water and air quality,
mitigating urban heat island effects, enhancing biodiversity) and societal
improvements (*e.g.* amenity and recreation, health and wellbeing improvements and
the creation of attractive, aesthetically pleasing places) when the system is not
inundated and operating at full capacity, which accounts for the great majority of the
time. When considering SuDS retrofit in managing environmental risks to urban
infrastructure at a catchment level through an economic appraisal of all benefits (*i.e.*
flood reduction and wider benefits), Ossa-Moreno *et al.* (2016) found that the

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3 economic feasibility of urban SuDS systems within London, UK, improved significantly,
4 suggesting that uptake of SuDS systems should be more widely adopted. The benefits
5 610 of widespread GI adoption are likely to vary between locations, but Ossa-Moreno *et*
6 *al.* (2016) provide key recommendations regarding incentives and policies to enhance
7 the uptake of urban GI to ensure that the economic appraisal is considered within
8 urban planning. GI has the additional benefit of flexibility in engineering design (De
9 Neufville and Scholtes, 2011), allowing such systems to embrace adaptability within
10 the context of uncertainties associated with climate change and urbanisation.
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19 Connected SuDS systems often include grey elements located below the ground, such
20 as proprietary treatment products (e.g. silt traps, oil interceptors, gully and pipe
21 systems) or flood attenuation storage tanks (e.g. geocellular storage, concrete tanks
22 620 or oversized pipes). However, the concept of SuDS places greatest emphasis on
23 above-ground blue-green components (that may be connected by 'hidden' grey
24 assets), to deliver the 'four pillars of SuDS development' (Woods-Ballard *et al.*, 2015).
25 By managing surface water above-ground, BGI can also help extend the lifetime of
26 ageing grey infrastructure assets, reduce the number of combined sewer overflows,
27 limit the quantity of rainwater that travels through combined sewers and wastewater
28 treatment plants (thus saving energy and carbon), and create capacity in the
29 subsurface piped drainage network to accommodate foul flows from new development.
30 The above ground, soft and living elements of GI also allow for continual adaptation,
31 625 whereby features can be easily altered in response to local climatic extremes or to
32 protect against future events (Babovic *et al.*, 2018). This flexibility and adaptability
33 feeds into a robust, antifragile and integrated flood management strategy which can
34 perform well under changing and uncertain future conditions. However, despite the
35 potential benefits of multifunctional blue-green-grey infrastructure, in practice,
36 optimisation of more than one benefit is particularly challenging, and trade-offs will
37 need to be made between, for example, objectives to minimise risks from urban heat
38 or urban flooding (Caparros-Midwood *et al.*, 2019), or stormwater management and
39 630 water reuse/harvesting (Schmitter *et al.*, 2016).
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3 640 Integrated blue-green-grey infrastructure has been used to address international
4 urban water challenges, demonstrating its potential as multifunctional infrastructure
5 (O'Donnell et al., 2021). For example, flood risk management strategies have been
6 shown to improve water quality in Philadelphia (USA), reduce water footprints in Berlin
7 and Singapore, save potable water for consumption in Melbourne (Liu and Jensen,
8 2018) and provide a food resource to urban populations (the concept of edible GI and
9 urban agriculture; Russo *et al.*, 2017).
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17 Integrated blue-green-grey systems that offer flexible/adaptive design are
18 recommended to enable the delivery of flood risk management solutions despite the
19 current uncertainty surrounding future climate, extreme events and level of
20 650 urbanisation. Assessing a range of flexible adaptation pathways comprising different
21 combinations of blue-green-grey infrastructure will highlight where incremental
22 investment in infrastructure can effectively meet performance requirements and
23 remain cost-effective (Kapetas and Fenner, 2020). The use of GI can be a sustainable
24 and cost-effective solution for urban flood management, with Duffy *et al.* (2008)
25 655 emphasising that the annual maintenance costs of SuDS systems are 17 – 20%
26 cheaper than grey infrastructure. However, maintenance within GI schemes can be
27 more complex and more difficult to remediate (DelGrosso *et al.*, 2019; see Section
28 4.2).
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39 Alongside the development of blue-green-grey flood risk management strategies,
40 urban flood resilience is further dependent on investment in mitigation, preparation,
41 response, flood modelling, prediction and forecasting, flood warnings and emergency
42 response, community preparedness and property level protection (Surminski and
43 Thielen, 2017). Resilient retrofitting of buildings and prioritising flood protection by
44 665 creating 'floodable' spaces are options for dense urban areas with little space for
45 extensive GI. The Water Square Benthemplein in Rotterdam, Netherlands, is an
46 exemplar of blue-green-grey multifunctional space, combining water storage capacity
47 with recreational opportunities during 'non-flood' conditions (De Urbanisten, 2013).
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3 Ultimately, a whole mosaic of GI, BGI and integrated systems of blue-green-grey
4 infrastructure, both proactive and reactive, exist; with different options available
5 depending on the objective. It is generally recognised that a portfolio of measures
6 including source control, infiltration, conveyance, and storage is required to achieve
7 urban flood resilience sustainably. Such systems must be delivered using a treatment
8 train approach developed along optimum adaptation pathways to achieve the best
9 performance, maximise cost-benefit ratios and to work within design/physical site
10 675 constraints.

18 680 **4.4. Routine monitoring and reporting to evaluate success of GI**

21 Reporting on the successes, and indeed failures, of GI flood risk management
22 schemes is imperative to provide an evidence base for urban GI and to learn from
23 limitations and shortcomings of existing schemes/studies. Although we can represent
24 GI systems using numerical modelling environments (see Section 4.1) which are
25 useful to examine responses outside of the instrumented record, experimental
26 685 monitoring using field-based systems is required to enhance our understanding of
27 model representation of the physical processes of GI (Green, 2014). Further, this helps
28 to understand any spatio-temporal changes in performance and failure and provides
29 insight into best-management practices to enhance and optimise such features. Thus,
30 as better monitoring data is collected, better models can be developed.
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40 Schemes and research facilities like the UKCRIC National Green Infrastructure Facility
41 (NGIF), based in Newcastle, UK, are pioneering integrated solutions for GI, providing
42 specialised 'living laboratories' to explore how GI can help to relieve pressure on grey
43 infrastructure (Green *et al.*, 2021). Novel, purpose-built GI features of varying scale
44 695 (e.g. an experimental full-scale swale shown in Figure 2b, heavily instrumented
45 lysimeter bioretention cells, a length of rain-garden 'ensembles' and a monitored green
46 roof) which are equipped with dense sensor networks allow the measurement of key
47 hydrological and biophysical variables (e.g. precipitation, soil moisture, water depth,
48 runoff and outflow rates) to be conducted unobtrusively and in-situ. This allows the
49 collection of quantitative experimental data to support the application of urban GI and
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3 to provide quantitative indications on the hydrological performance of such systems.
4 Currently, very few monitored schemes exist. Notable examples include extensively
5 monitored green roofs at the University of Sheffield (e.g. Stovin *et al.*, 2013) and over
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8 705 20 monitored stormwater capture and infiltration/evapotranspiration systems across
9 the Villanova University campus (e.g. Traver and Ebrahimian, 2017; Ebrahimian *et al.*,
10 2019), including a detention pond, a series of bioretention systems and vegetated
11 swales which monitor runoff within a functioning urban system and provide insights
12 into the maintenance requirements to allow such systems to continue to fulfil their
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17 710 function.

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21 Long-term monitoring campaigns which capture trends in GI response to events of
22 varying magnitude and temporal sequencing over a longer timeframe (*i.e.* more than
23 a decade) are crucial to inform design guidance, urban policy and to ultimately
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25 715 evaluate the success of GI to manage flood risk within urban environments. Such
26 schemes would provide longer-term records on GI response to extreme events and
27 would also provide a basis for assessing how GI may respond to localised changes
28 in climate. Babovic *et al.* (2018) highlight that routine monitoring and collection of
29 data from urban water infrastructure systems links GI into ‘Smart City’ paradigms
30 and can be extremely beneficial in informing local decision-makers. Such increased
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34 720 empirical data collected from GI systems develops ‘antifragility’ (Taleb, 2012) and
35 allows for the identification of urban water system performance and any required
36 adjustments to management procedures or design protocols (Babovic *et al.*, 2018).

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43 725 Despite the benefits of such monitoring schemes, instrumenting GI in public and
44 private space is rarely conducted as it is often time consuming, expensive and requires
45 specific knowledge to set-up experimental plots, maintain sensor equipment and
46 analyse data outputs. City-wide monitoring of GI schemes may be more accessible
47 with advances in low-cost, hidden mobile technologies (Bulot *et al.* 2019) and may
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51 730 promote public engagement and participation in such schemes (Roy *et al.*, 2008;
52 Visitacion *et al.*, 2009). Stakeholders and decision makers are often reluctant to
53 monitor and instrument schemes due to potential upfront cost implications and
54 additional maintenance and data processing requirements. However, Bastien *et al.*

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3 (2010) highlight that, on average, SuDS are about 70% cheaper in construction costs
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5 735 and over 50% cheaper in lifetime costs; attenuation storage within existing retention
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7 areas is considered to be the most cost-effective solution compared to conventional
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9 underground storage. This highlights the case for a much-needed evidence base to
10
11 support widespread adoption of alternative, integrated and antifragile drainage
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13 systems using GI over traditional hard engineered stormwater management systems.
14 740 Such experimental data obtained from monitored schemes will also help in the
15
16 development of pre-development conceptual models and 'hybrid/composite models'
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18 which are imperative for calibrating and validating schemes (Green, 2014).
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20 Experimental data will also ensure that results can be upscaled or transferred to
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22 ensure robust new developments based on previously successful schemes.

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5. Conclusion

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27 Urban GI cannot tackle the problem of urban flooding alone and must form part of an
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29 integrated approach to flood risk management. A holistic approach is likely to include
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31 traditional grey engineering approaches, catchment-wide natural flood management,
32 750 urban GI and property flood resilience, representing a multitude of scales and
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34 operating within a variety of stakeholder groups, including the government, private
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36 sector and the public. The interaction between blue-green and grey infrastructure is
37
38 understudied, but critically significant to understanding flood resilience particularly in
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40 response to future uncertain change in climate and land use. For example, GI can
41 755 reduce pressure on ageing grey infrastructure and/or be combined with existing or
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43 upgraded, grey infrastructure to generate a sustainable solution to urban flood risk.
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45 Conversely, GI can have hidden grey, engineered elements, such as GI features that
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47 eventually drain through a pipe or outlet; however, such engineered features may limit
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49 adaptive capacity and self-regulating properties that can be beneficial in GI, with
50 760 implications for future resilience. Such limitations are inevitable and comparable to
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52 engineered alternatives but should be considered in assessments of GI effectiveness.

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54 As the hydrological cycle intensifies under climate change, urban infrastructure will
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56 need to be resilient to a range of possible scenarios. The self-regulating properties

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3 765 associated with GI and “working with nature” approaches are therefore desirable,
4 promoting adaptation to changes in flood magnitudes, timing and frequencies. Whilst
5 the adaptive properties of GI should be promoted, opportunities will be limited in many
6 scenarios given space and logistical constraints. Monitoring and maintenance will be
7 required to maintain key functions related to flood protection, such as managing the
8 effects of sedimentation, excess plant growth, and anthropogenic impacts such as the
9 presence of litter. Therefore, understanding how regular maintenance relates to the
10 ongoing effectiveness of GI is important in assessing longer-term efficacy of such
11 schemes.
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20 775 There is clear potential for GI to reduce regular, chronic flood events of low to medium
21 magnitude, and large-scale GI such as restored floodplains may help mitigate against
22 more extreme flood events if there is space for these interventions in the catchment,
23 which is unlikely in many urban areas. The significance of the placement of urban GI
24 to the success of its function means there is not a direct relationship between GI
25 scheme size and effectiveness. Instead, resilience is built through creation of an
26 integrated network of urban resilience solutions, including building resilience against
27 hydrological extremes and attenuating urban flood risk.
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37 785 Monitoring of GI schemes is lacking, which has implications for designing successful
38 infrastructure, informing physically-based modelling work and determining best
39 management practices. Long-term monitoring from laboratory-, field- and numerical
40 modelling-based studies are required to strengthen the evidence base to promote
41 appropriate and successful adoption of urban GI. One major barrier for widespread GI
42 implementation is the need for standardisation within the design process of GI
43 schemes to ensure alignment with regulatory frameworks and for GI systems to be
44 recognised with the same level of flood protection and recurrence intervals as piped
45 drainage systems. Nevertheless, this is difficult due to the living elements of such
46 drainage systems, which are prone to degradation, loss of functionality and changes
47 in performance, both spatially and over time. Ultimately the success of GI schemes
48 should either be determined by comparison to design purpose (*e.g.* flooding) or using
49 a holistic set of criteria which values the mutual benefits of GI schemes. For the
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3 management of low-level flood events, it is the additional co-benefits delivered by GI
4 that place them apart from their grey infrastructure counterparts.
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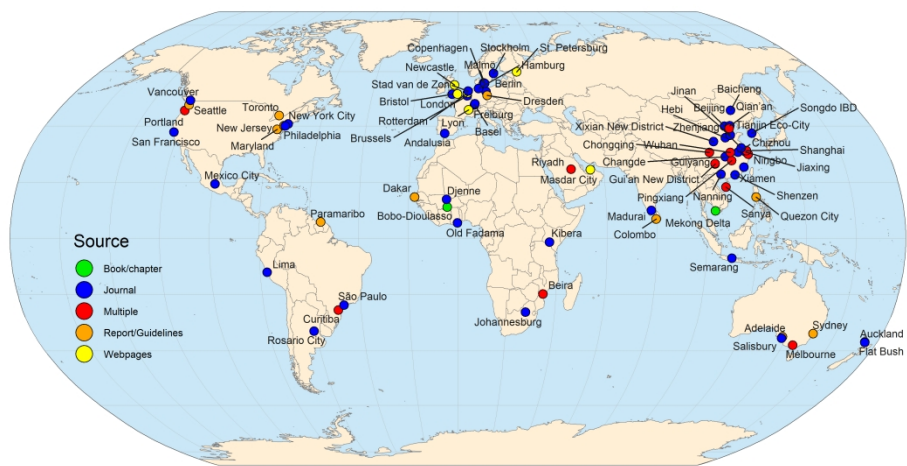


Figure 1: Distribution of notable urban GI schemes which consider stormwater management at a variety of scales. References from a range of sources (books, journals, reports or guidelines, webpages or multiple sources) are provided in Supplementary Table 1 for each city/location. Please note, case studies are not exhaustive and those presented are aggregated over a variety of scales and functional typologies. Spraakman et al. (2020) note that GI research is predominantly focused in Global North countries and literature is largely absent from locations with water stresses in the Global South. There is a strong focus on GI research in temperate regions (where flood hazards are increasing the most at the global scale; Slater et al., 2021), especially the United States Eastern Seaboard and Australia, emerging in places with strong policy and research cluster interest, such as China (relating to the Sponge City Program) and Europe.

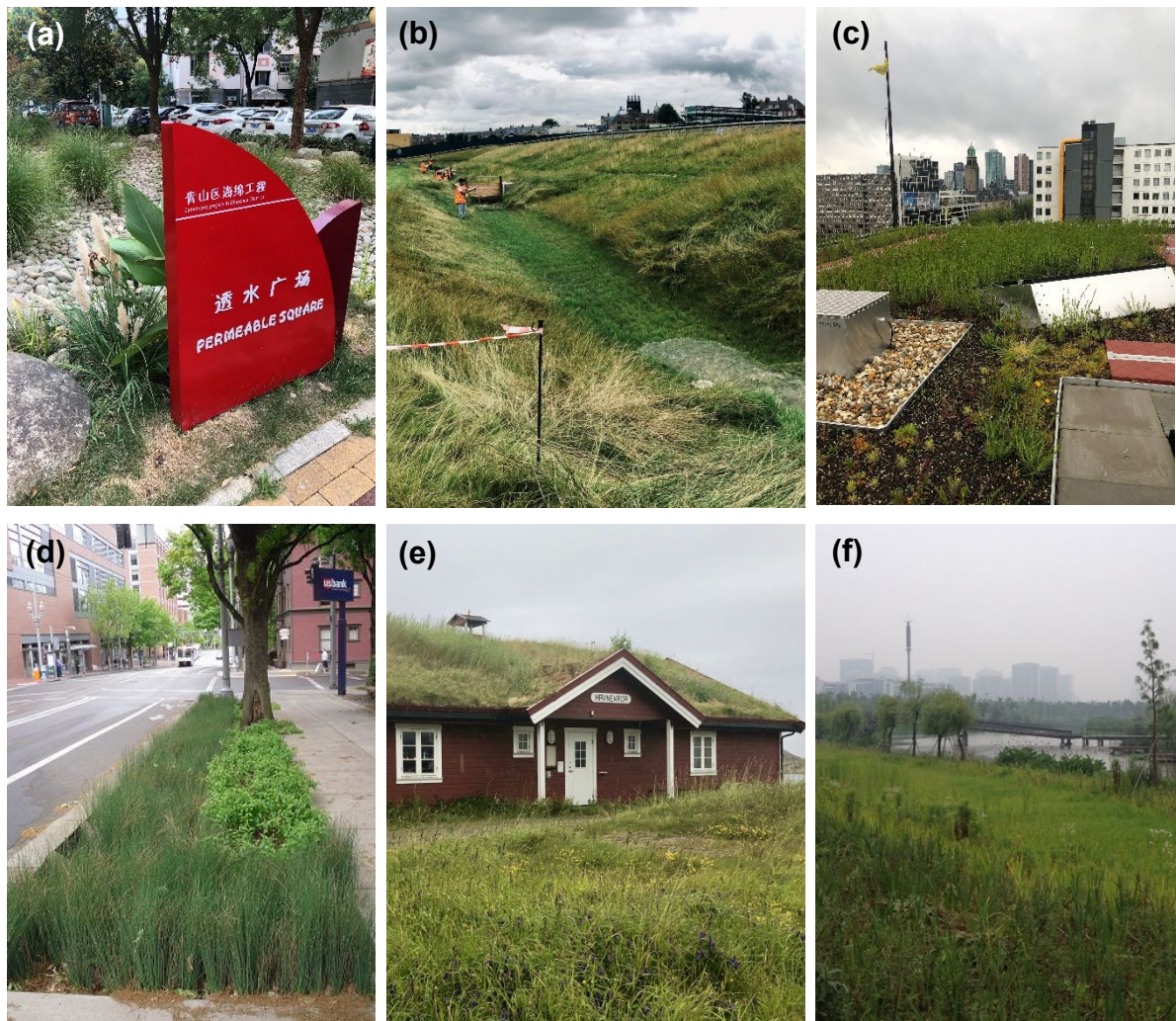


Figure 2: Examples of urban green infrastructure solutions of varying scale and function from across the world: **(a)** Sponge City rain garden in Wuhan, China; **(b)** extreme event swale in National Green Infrastructure Facility, Newcastle-upon-Tyne, UK; **(c)** retrofitted green roof and urban farm in Rotterdam, Netherlands; **(d)** bioswale along street pavement as part of the Grey to Green programme in Portland, Oregon USA; **(e)** green roof and green open areas in peri-urban region in Northern Norway; **(f)** Ningbo (China) eco-corridor wetland, running through the heart of Ningbo Eastern New Town.

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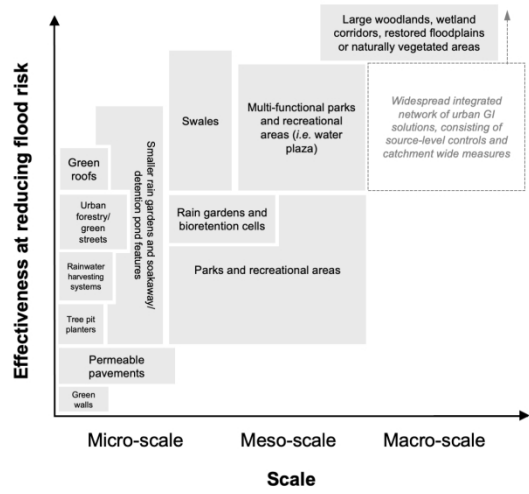


Figure 3: Conceptual diagram showing the scale and effectiveness of different GI features. The scale and cost of such features are highly variable and may vary significantly between sites, design specifications and whether the system is new or retrofitted. N.B. Some features may be better at dealing with single, high intensity events, but may be fully saturated after one event, whereas others may have greater capacity to deal with multiple flood events.

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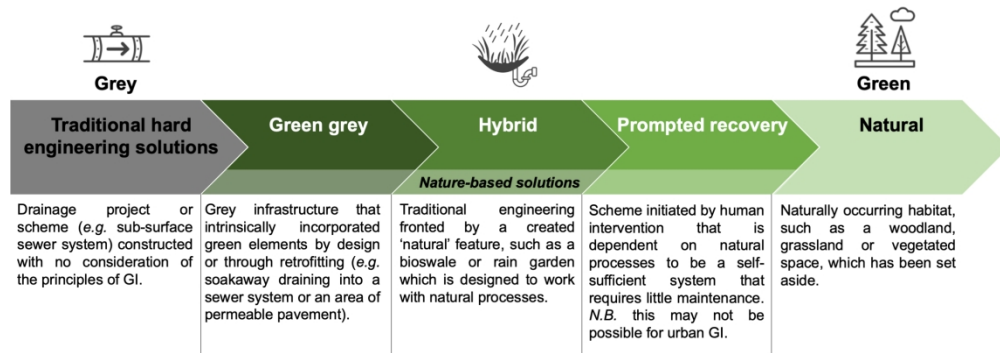
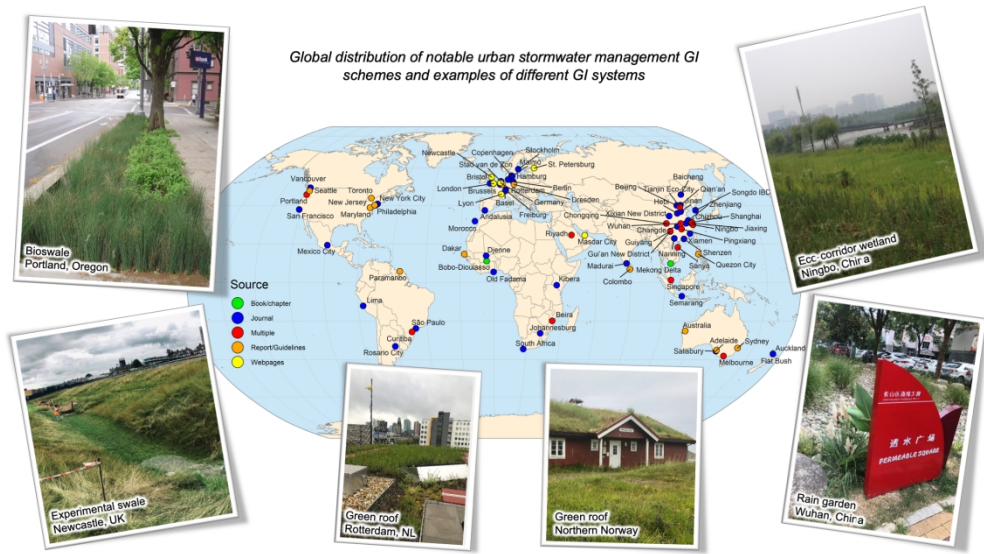


Figure 4: Green-grey continuum of urban GI. Source: adapted from framework within Roca et al., 2017.

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