Green infrastructure: the future of urban flood risk management?

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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?

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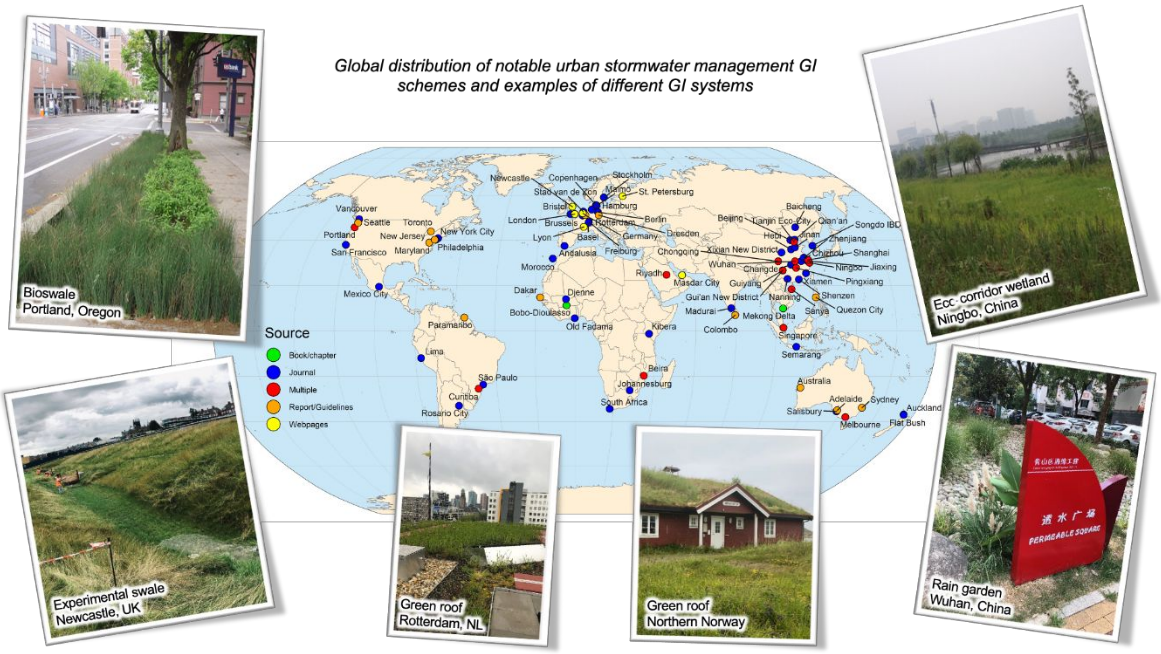

Visual abstract: *Global distribution of notable urban stormwater management GI schemes and examples of different GI systems.*

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

provide a holistic solution that delivers multiple co-benefits to the environment and society, while increasing flood resilience. GI will have to work synergistically with existing and upgraded grey infrastructure if urban flood risk is to be managed in a futureproof manner. Here, we discuss a series of priorities and challenges that must be overcome to enable integration of GI into existing stormwater management frameworks that effectively manage flood risk.

Keywords: Green Infrastructure, SuDS, urban flooding, sustainable drainage, water sensitive urban design, resilience.

1. Introduction

Urban flooding is a key global challenge that is projected to be exacerbated by future intensification of climate extremes, changes in land-use (*e.g.* widespread urbanisation and subsequent reduction in permeable green spaces), as well as ageing and deteriorating critical infrastructure. Consequently, many global cities are rethinking and adapting their approach to flood risk management (Soz *et al.,* 2016). This involves a transition from *flood defence* (where cities are protected from rivers and rising sea levels through engineering structures, and surface water is transported and removed rapidly via subsurface systems), to *flood resilience* (where urban spaces are designed to make space for water and adapt to the increasing threat of urban flooding whilst providing wider improvements to the environment and society (Lennon *et al.,* 2014; O'Donnell *et al*., 2020). This is achieved through a shift from grey infrastructure solutions towards increasingly decentralised facilities that utilise Green Infrastructure (GI) to retain, attenuate, store and reuse surface water on site (Lennon *et al.,* 2014; Golden and Hoghooghi, 2018). Enhancing urban flood resilience is a key driver in the transition from *'Drained Cities'*, where service delivery focuses on drainage and channelisation, to *'Water Sensitive Cities'*, where adaptive, multifunctional infrastructure and assets provide ecosystem services and facilitates to promote water sensitive behaviours (Wong and Brown, 2009; Radhakrishnan et al., 2018). As such, flexibility in engineering design (De Neufville and Scholtes, 2011) is required to ensure that water management systems are designed to be 'antifragile' (Taleb, 2012; Babovic *et al.,* 2018), a term used to reflect a system's enhanced resilience and adaptability through exposure to disorder, shocks and chaos.

Definitions of GI vary considerably (Bartesaghi Koc *et al*., 2017), but GI generally refers to the use of natural processes to protect, restore and emulate the natural functioning of floodplains, rivers and the coasts to effectively manage flood risk. GI fits within the wider umbrella term of nature-based solutions (NBS) and is used to recreate a more natural water cycle in urban areas to help conserve natural ecosystem value whilst reducing the risk of surface water (pluvial) flooding. The European Commission highlighted the potential multiple benefits of GI, defined as '*a strategically planned network of high quality natural and semi-natural areas with other environmental features, which are designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings'* (European Commission, 2013). Whilst urban GI are often presented as multifunctional assets, in practice, most schemes focus on a single benefit, such as stormwater management (Kabisch *et al*., 2016; Meerow, 2019). As such, GI is a key component of the surface water management strategies of many progressive global cities at risk of urban flooding (see Figure 1). However, there are several bio-physical and socio-political barriers to innovation in urban flood and water management that hamper the move towards more holistic, integrated systems that utilise both grey and green infrastructure (Lennon *et al.,* 2014; O'Donnell *et al.,* 2017; Thorne et al., 2018).

Studies on the efficacy of GI schemes have been underway for almost a decade but there are very few monitoring results quantifying the hydrological success of such schemes. The implementation and effectiveness of urban drainage infrastructure and GI are both highly dependent on physical site conditions (*e.g.* topography, land-use, climate, maintenance measures, availability of space and soil physical characteristics) which vary on a site-by-site basis. As such, it is imperative to tailor GI systems to fit site-specific needs (Golden and Hoghooghi, 2018) and prioritise additional co-benefits alongside flood risk reduction. Socio-political factors and governance of the urban environment will also vary by city, region and country, and significantly influence the availability of funding, policies and legislation and the existence of cross-organisational collaborations to champion and deliver successful GI solutions (Li *et al.*, 2020; te Wierik *et al.,* 2020). Overarching challenges associated with the implementation of GI, and any urban drainage infrastructure, also differ significantly between new build developments and urban retrofits (Stangl *et al.* 2019).

Integrated systems of grey and green infrastructure build urban flood resilience by being ‘designed for exceedance’ (Digman *et al*., 2014), accepting that it is not possible to prevent future urban flooding entirely due to a number of limiting factors during the design and maintenance processes, such as high capital costs, competing land uses, spatial constraints and maximum drainage capacities, especially under saturated antecedent moisture conditions and uncertainties in future levels of flood protection required under climate change. Thus, the use of GI within urban stormwater design should be used to the ‘maximum extent feasible’ (Tackett, 2008), recognising that GI implementation will be constrained by the physical limitations of the site, practical considerations of engineering design and reasonable consideration of financial costs and environmental impacts. Flood resilient cities will enable the conveyance, storage and infiltration of flood water up to their spatially- or economically-limited capacity, after which they continue to reduce flood-damage and disruption when that capacity is exceeded by, for example, routing excess runoff to avoid critical infrastructure. GI is a crucial component of such sustainable drainage and urban stormwater management systems yet there are challenges which must be addressed to facilitate the design and widespread implementation of GI solutions. This paper provides a perspective on how GI contributes towards a sustainable and integrated urban flood risk management solution, discussing the challenges, priorities and opportunities to evaluate the place GI has in wider flood management frameworks. Literature from a series of illustrative global case studies of varying scale and functional, structural (morphological) and configurational (spatial) characteristics are drawn upon throughout. After briefly 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?

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

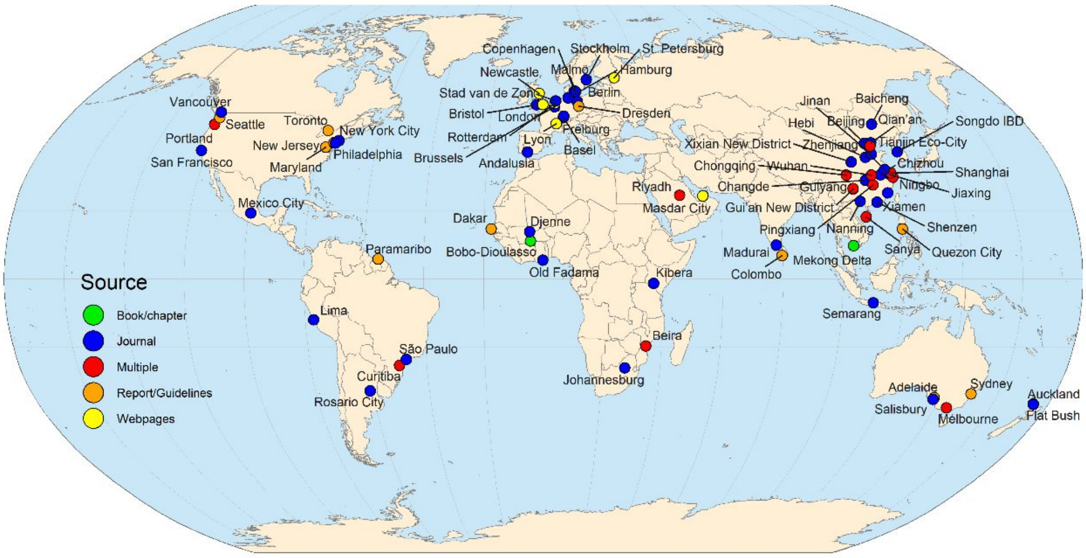

Figure 1: *Distribution of notable urban GI schemes which consider stormwater management at a variety of scales. References from a range of sources (books, journals, reports or guidelines, webpages or multiple sources) are provided in Supplementary Table 1 for each city/location. Please note, case studies 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.*

2. Urban flood risk

The occurrence of urban surface water flooding relates to short, intense precipitation events where excess rainfall cannot infiltrate into the sub-surface or drain via natural or artificial drainage systems (Riel, 2011), or where rainfall intensity exceeds the localised drainage capacity (Evans *et al*., 2004). Many severe urban floods are caused by coincident flooding, where an area is exposed to multiple flood risks alongside surface water flooding, such as fluvial flooding, groundwater flooding, sewer flooding, and coastal inundation caused by storm surge events (Evans *et al.,* 2004). This is the case in many coastal megacities, such as New York, London, Mexico City, Mumbai, Shanghai, Tokyo and Bangkok (Nicholls *et al.,* 2008; Syvitski *et al.,* 2009).

Urban flooding is a substantial international issue and is projected to become more frequent and severe due to changes in precipitation intensity, phase and variability (Wilby and Keenan, 2012; Zhou *et al.,* 2012), population growth in urban areas putting larger numbers of people at risk (United Nations, 2018) and widespread replacement of vegetated surfaces in favour of impermeable surfaces (*e.g.* roads, concrete surfaces and buildings) resulting in more flashy runoff regimes in cities. Furthermore, existing drainage systems in many cities are unsuitable for current and future climate conditions and deterioration of existing assets are a key driver of future urban flood risk (O'Donnell and Thorne, 2020a). Many UK cities are still relying on Victorian-aged drainage infrastructure, parts of which do not fully conform to contemporary design specifications (*e.g.* being constructed to deal with a 1 in 30-year rainfall event; Jones and Macdonald, 2007), while other urban conurbations such as Shanghai and many urban areas within the Netherlands, have drainage systems with one- and two-year return period design standards, respectively (Riel, 2011; Yin *et al.,* 2016), putting these cities at significant risk of urban flooding. Additionally, the effective drainage capacity of a sewer system may be significantly reduced over time if maintenance and rehabilitation of assets fail to keep pace with deterioration, causing issues such as misconnections, sedimentation and blockages (Tait *et al.,* 2008; Coulthard and Frostick, 2010). Thus, urban areas may be unable to manage future high intensity precipitation events and the impacts of urban flooding may become increasingly severe and widespread.

The occurrence of urban flooding may lead to large and long-lasting economic losses associated with damage to property and infrastructure (Bosher, 2014), disruption to travel, emergency service provision and human activities (Dawson *et al.,* 2011; Green *et al.,* 2017), spread of water-borne diseases (Tunstall *et al.,* 2006) and loss of life. Thus, cities should be investing significant time, capital and resource to prepare for, reduce and mitigate the impacts of urban flooding.

Traditional strategies to managing flooding in urban areas are typically focused on hard-engineering approaches (*e.g.* culverts, sewer systems and large capacity compound river, stream and urban drainage channels) to contain and convey water through an urban system as rapidly as possible, treating water as an 'unruly substance' (Jones and Macdonald, 2007). However, flood management schemes that work with natural processes, deliver ecosystem services and 'make space for water' (Burgess-Gamble *et al.,* 2017) have seen significant developments in recent years.

3. Green infrastructure for stormwater management

The terms 'Nature-Based Solutions', 'Soft Engineering', 'Blue-Green Infrastructure' and 'Working with Natural Processes' are used somewhat interchangeably with the term 'Green Infrastructure' but have subtle differences which are beyond the scope of this paper (see Fletcher *et al*., 2015, Bartesaghi Koc *et al.,* 2017 and Debele *et al.,* 2019). GI is a key component of UK Sustainable Drainage Systems (SuDS), termed Low Impact Developments (LIDs) or Best Management Practices (BMPs) in North America, which incorporate GI in order to attenuate, drain, infiltrate and store surface and sub-surface water (Loperfido *et al*., 2014; Woods-Ballard *et al*., 2015; Vijayaraghavan *et al.,* 2021). GI is a key element of Water Sensitive Urban Design (WSUD) and nature-based solutions that integrates water cycle management within the built environment (Sharma *et al*., 2016), and other more holistic concepts, such as '*Blue-Green Cities'*, where naturally oriented water cycles are recreated in urban environments by bringing together water management and GI (Hoyer *et al*., 2011: O'Donnell and Thorne, 2020b), and '*Sponge Cities'*, describing Chinese conurbations designed to increase infiltration capacity, reduce surface runoff and recharge groundwater resources (Chan *et al*., 2018; Li *et al*., 2020).

In this paper, GI approaches which focus specifically on stormwater management in predominantly urban areas are considered. These tend to be relatively small scale due to the competing demands of urban development and land-use changes and are often purpose-built to offset or reduce elevated surface runoff induced by new and existing developments (Golden and Hoghooghi, 2018). The primary flood mitigation purpose of such schemes is to slow the flow of water through urban areas and to store excess water in storage and detention areas, reducing peak runoff rates by mimicking or replicating a more natural hydrological response following a storm event. Bartesaghi Koc *et al.* (2017) suggested that GI schemes can be divided into four categories (tree canopy, green open spaces, green roofs and vertical greenery systems) based on their functional, structural (morphological) and configurational (spatial arrangements) characteristics. Typical GI assets with functional roles of managing urban floods include features such as rain gardens/bioretention cells (Vijayaraghavan *et al.,* 2013), bioswales, green roofs, wetlands, detention basins, de-culverted rivers, tree pit planters, green streets, rainwater harvesting systems and permeable pavements (see Figure 2). These features may vary from site to site, but typically have structural and configurational characteristics which are designed to increase their efficacy in managing flood risk; their key functional component.

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

GI delivering multiple social, environmental and economic benefits and services in conjunction with their primary purpose of flood risk reduction, such as improving water and air quality, creating attractive and aesthetically pleasing social spaces with recognised health benefits, and enhancing species diversity (Fenner, 2017; Hoang *et al.*, 2018; Kattel *et al.,* 2021). A growing number of studies further evaluate, value and monetise the multiple benefits of GI (*e.g.* Ashley *et al.,* 2018; Alves *et al.,* 2019; Ghofrani *et al.,* 2020). Nonetheless, multiple benefit valuation is not typically included when making the business case for GI implementation. The development of B£ST (Benefits Estimation Toolkit; CIRIA, 2019) has enabled the multiple benefits of Blue-Green infrastructure (BGI) to be assessed without the need for full scale economic inputs. Despite this, uptake is limited and outputs are often case study specific (Susdrain, no date).

Assessment of the hydrological and/or sedimentological performance of such schemes are not routinely conducted and relatively few studies exist (*e.g.* Fu *et al.,* 2021). Examples from UK SuDS schemes (Woods-Ballard *et al.,* 2015); stormwater ponds (Ahilan *et al.,* 2019; Krivtsov *et al.,* 2020); green roofs (Stovin *et al.,* 2013), swales (Allen *et al*., 2015), bioretention and integrated stormwater control systems (Traver and Ebrahimian, 2017; Ebrahimian *et al.,* 2019) and a decade of monitoring by the Bureau of Environmental Services (BES) in Portland, Oregon USA (BES, 2010; 2013a) are available. However, few schemes, to date, have had sufficient long-term monitoring to provide an evidence base of the effectiveness of GI during a range of flood events and weather conditions. Given the increasing interest and investment in the use of GI within urban areas, it is necessary to quantify and assess the effectiveness of GI in reducing flood risk and to identify a series of transferable best management practices to enhance and maximise the hydrological benefits of such schemes through time.

4. Challenges and Recommendations

Increased understanding of the effectiveness of GI to enhance resilience to urban flooding is required to support widespread and holistic adoption of GI in urban environments. Given the relative lack of assessment or measurement of GI success in reducing flood risk, we believe that four key questions must be considered, which are discussed individually below.

4.1. Spatial scale and storm magnitude impacting effectiveness and suitability of GI approaches

Whilst recognising that GI must be part of an integrated approach to build evolutionary resilience toward hydrological extremes (Tackett, 2008; Lennon *et al.,* 2014), the issue of scale is an important consideration when assessing the effectiveness of GI. Barker *et al.* (2019) highlight that, although GI has emerged as a dominant component of the built environment, one core challenge is to understand how the benefits of GI vary at different scales. Golden and Hoghooghi (2018) present a detailed review of scaling within GI systems, examining localised interventions, as well as upscaling the influence of multiple localised interventions to quantify broader, cumulative catchment-level influences of multiple GI practices. Collentine and Futter (2016) note that natural water retention measures have the potential to reduce flood peaks and maintain base flows at a range of scales, from small urban measures, to catchment-wide approaches, including systematic catchment afforestation.

Urban GI can be considered and understood at three different spatial scales: *(i)* the micro-scale, an individual site or development and its immediate surroundings; *(ii)* the meso-scale, typically spanning multiple micro locations, such as a neighbourhood or small settlement, and; *(iii)* the macro-scale, consisting of macro locations and spatially covering a larger urban area, region or combined authority area (*i.e.* council or municipality level; UK Green Building Council, 2020). In the case of rural natural flood management, increasing the connectivity with floodplains generally provides additional upstream storage capacity, which is likely to result in decreased peak flows downstream (Dadson *et al.,* 2017). However, for urban areas where space is limited, the strategic spatial placement of GI as a patchwork or mosaic of natural vegetation is crucial and tends to focus on source level control. Vercruysse *et al.*, (2019b) introduce the concept of 'interoperability' to actively manage connections between local and city-scale infrastructure systems to facilitate the transition from local multifunctionality of blue, green and grey infrastructure to city-scale multisystem flood risk management.

Numerous urban drainage models, such as the Storm Water Management Model (SWMM), InfoWorks ICM, MIKE URBAN and Model for Urban Stormwater Improvement Conceptualisation (MUSIC) all provide functional packages to help understand the influences of GI on urban stormwater reduction (EPA, 2020) and allow a low-cost option to test and optimise GI measures in a simulated environment without the construction of such features, providing adequate catchment and hydrological data is available. For example, Schubert *et al.* (2017) provide a numerical modelling assessment of GI performance in the Little Stringybark Creek watershed, Melbourne, Australia, using MUSIC. Hydrological modelling suggests that current retrofitted GI features in the catchment, including rainwater tanks and infiltration trenches, account for a reduction of 29% of downstream flooded area. Full implementation of retrofit GI could reduce the downstream flooded area by up to 91% and could lower flow intensities by 83% on average for smaller magnitude events with flood durations of up to 3 hours and annual exceedance probabilities of <1%.

The SWMM5 engine, which is seen as one of the most accurate tools for GI representation in a review of 20 simulation modelling tools by Jayasooriya *et al.* (2014), allows the simulation of a number of GI systems, including bioretention cells, permeable pavements and swales (EPA, 2020). Such models are useful in examining GI response to design storm events of high magnitude in the absence of experimental monitoring data. Numerical modelling has been used to understand the influence of GI on urban hydrology, with Lee and Nietch (2017) providing a practical guide for representing and modelling GI and LID controls within SWMM. McCutheon and Wride (2013) applied SWMM to simulate the hydrological responses of turf grass and prairie-vegetated rain gardens in clay and sandy soils during a single storm event and compared this to experimental field data. Results from the modelling in SWMM yielded good agreement with measured in-field data, within an acceptable range of error associated with field measurement techniques. However, McCutcheon and Wride (2013) suggest that long term monitoring of GI is required to provide robust validation data to ensure that GI processes are accurately represented in modelling environments and that changes in performance are captured within numerical representations of such systems. Additionally, Macro *et al.* (2018) provide a framework for simulating GI features within a coupled model applying the SWMM engine with Optimisation Software Toolkit for Research Involving Computational Heuristics; OSTRICH) to investigate the influence of GI types, sizing and placement. SWMM-OSTRICH was utilised to provide a decision-making tool to investigate rain barrel (water butt) placement within Buffalo, New York and to examine trade-offs between the cost of rain barrel placement and the resulting reduction in combined sewer overflows. However, the OSTRICH-SWMM methodology is currently only applicable for rainwater harvesting systems and support for other GI features, such as permeable pavement, vegetated swales and green roofs, is ongoing. Nevertheless, this study highlights the flexible, open-source nature of the SWMM engine to be adapted to suit specific case studies and research questions. The SWMM engine has also been implemented within the open-source programming language *R* under the package ***swmmr*** (Leutnant *et al.,* 2020), opening up future opportunities to standardise or harmonise GI modelling practices and allow more clear comparisons between studies (Slater *et al.,* 2019).

Using a GIS-based analysis, Pennino *et al.* (2016) found that when GI controls cover over 5% of a catchment drainage area, flashy urban hydrology is reduced. Although the magnitude of influence was minimal at low levels of GI adoption, this was shown to increase with an increase in GI coverage. This was also observed within the numerical rainfall-runoff modelling conducted by Liu *et al.* (2014), which suggested that implementing a single GI feature within an urban neighbourhood of Beijing, China, had limited influence on reducing peak flows, whereas integrated and systematic urban GI configurations (e.g. increasing the area and storage capacity in existing green spaces by creating detention basin features consisting of concave green spaces to temporarily pond water) acted to effectively reduce all storm events considered. Thus, if a large number of relatively small (meso-scale) GI installations are interconnected (ideally through green corridors, or by grey infrastructure buried underground), optimised (through the use of gradient to create surface detention) and designed to operate synergistically as a stormwater treatment train, their effect can match or exceed that of a single large GI asset covering the macro-scale (Bastien *et al.,* 2010), linking back to the concept of 'interoperabilty' (Vercruysse *et al.*, 2019b).

Certainly, there is a role for larger GI features, such as reconnected and restored floodplains (BES, 2013b; Hoang *et al*., 2018; Leicester City Council, 2018) or expansive areas of open green space with high potential for water storage. However, the overall performance and efficacy of localised interconnected GI may be greater than using larger, individual source control or end of pipe SuDS features with a larger footprint due to optimising the benefits through effective placement and design (Bastien *et al.,* 2010). Consequently, the placement of decentralised urban GI elements is important to ensure that schemes are optimised in their performance and provide appropriate source-level treatment of surface water flows at locations where runoff control is most required. As such, there is not a direct relationship between the size of GI schemes and effectiveness, which will vary significantly between different case studies, methods of evaluation, and spatial characteristics. Figure 3 conceptualises the linkages between scale and effectiveness of key GI features with the fundamental purpose of stormwater management (Bartesaghi Koc *et al.,* 2017), but this is likely to vary significantly between case study locations depending on specific site conditions and whether the GI scheme is new or retrofitted.

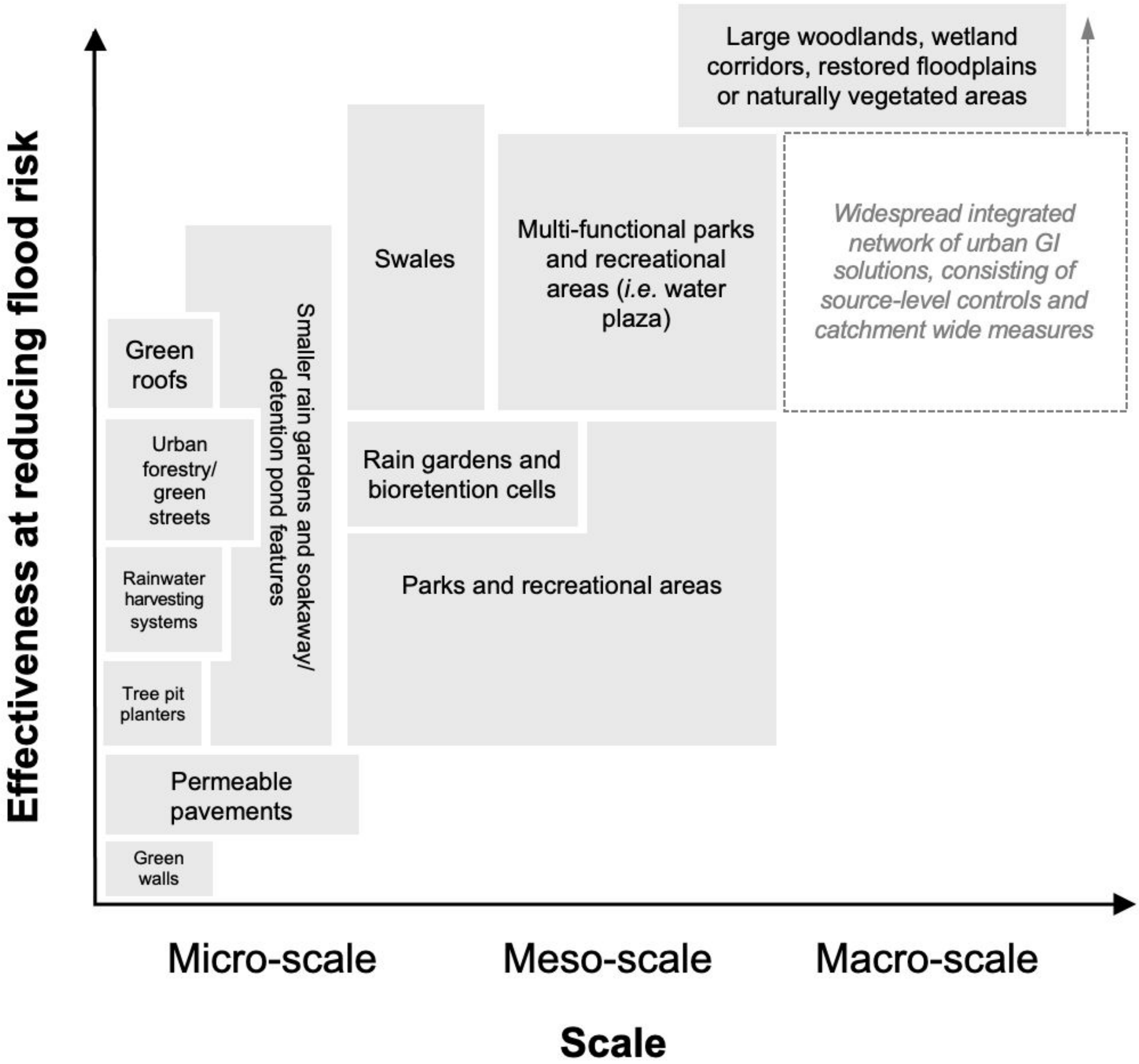

Figure 3: *Conceptual diagram showing the scale and effectiveness of different GI features. The scale and cost of such features are highly variable and may vary significantly between sites, design specifications and whether the system is new or retrofitted. N.B. Some features may be better at dealing 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 Sörensen 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 stormwater systems performed better than transitional conventional sewer systems. Despite this, Webber *et al.* (2019) suggest that although catchment-wide decentralised rainwater capture appears to be the most effective mechanism for managing moderate rainfall events, there is much uncertainty on whether this is a viable solution for larger events and such measures are dependent on space availability within the local catchment.

It is disputed whether GI provides a unified solution to protect urban areas from extreme rainfall events, especially if prolonged rainfall results in the saturation of storage capacity (Schubert *et al.,* 2017). Moreover, using a widespread remote sensing analysis of GI at regional and local scales, Calderón-Contreras and Rosas (2017) found that a vast proportion of GI systems within Mexico City were of low quality, hindering the provision of such systems to provide any notable urban ecological services, including the reduction of flood risk. This suggests that, although GI is essential in securing long-term resilience of urban systems, the quality, quantity and diversity of such systems should be evaluated to ensure that systems are designed appropriately and are fit for purpose. As such, GI certainly has a place in wider, integrated and sustainable flood risk strategies in urban areas if it is correctly designed and implemented. Experimental monitoring and scenario-based modelling studies (see Section 4.4) will help to provide an evidence-base of the effectiveness of GI during high magnitude events, but it is often difficult to isolate the individual influence of GI features when they form part of an integrated catchment drainage approach in conjunction with grey infrastructure. Further, such integrated systems build flood resilience through the principles of 'designing for exceedance' (Digman *et al*., 2014), accepting that an area should have an acceptable level of flood protection but should be designed to safely fail when this capacity is surpassed. Using this framework, GI failures are often less catastrophic when compared to grey infrastructure failures, and some levels of protection are still offered even when the design level of flood protection is exceeded, which is often not the case for grey infrastructure as this is seldom designed to be 'safe-to-fail' (Dong *et al.,* 2017).

As Spraakman *et al.* (2020) and Zuniga-Teran *et al.* (2020) note, there is a need for standardisation within the design process of GI schemes to ensure alignment with regulatory frameworks, with challenges in design standards reflecting the significant uncertainty around how best to plan, design, implement and maintain GI (Baptiste *et al.,* 2015; Sinnett *et al.,* 2018). Nevertheless, this may be challenging because the performance of GI is largely site specific and their additional ability to deliver multiple co-benefits under the 'four pillars of SuDS development' – i.e. *(1)* flood risk management; *(2)* improvement to water quality; *(3)* the provision of public amenity and aesthetic, and; *(4)* benefits to biodiversity (Woods-Ballard *et al.,* 2015) – must also be considered alongside their ability to mitigate high intensity storm events. GI research has proliferated in recent years, but studies often have disparate aims, intents and metrics used to assess performance (Spraakman *et al.,* 2020). Thus, GI alone cannot address all scales of urban flood risk management but should be considered as part of a wider system which integrates across spatial scales encompassing landscapes, watersheds and river valleys down to individual streets and buildings (Carter *et al.,* 2018) to help manage higher magnitude flood events.

4.2. The role of GI in providing sustainable, flexible and realistic approaches to tackle future (uncertain) flood conditions

One of the key benefits of GI is that systems are designed to operate using natural processes rather than trying to unnaturally control rainfall-runoff processes, thus representing a sustainable flood risk management option that is more resilient to future climate change than hard engineering approaches (*e.g.* Graham *et al.,* 2012; Kapetas and Fenner, 2020). However, GI schemes operate along a continuum of working with nature (see Figure 4). Although a bioretention system appears to be a self-regulating, natural system on the surface, there may be many engineered and artificial elements to the system, designed to ensure that the system works under certain design considerations, such as reducing peak flow rates and detaining surface water.

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 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, 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 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 providing an evidence base for GI implementation are beginning to be complied 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.

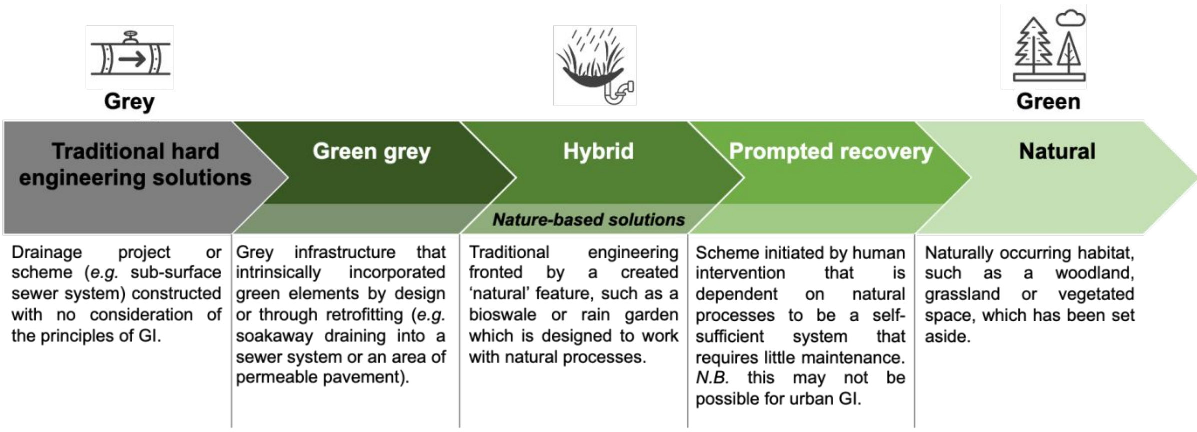

Figure 4:** Green-grey continuum of urban GI.* ***Source: *adapted from framework within Roca et al., 2017.*

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

Further, the need for maintenance and remediation may only be acknowledged when failures within one or more of the four pillars of SuDS development are apparent (*e.g.* insufficient drainage and waterlogging, dieback of vegetation, *etc.*), which may link back to poor design specifications. There is also the issue of misdiagnosing or not noticing issues with GI performance until a significant loss in performance or aesthetics are observed. Again, this is often the case for comparable hard engineered solutions. However, there is substantial potential for monitoring and maintenance to be more community driven, *i.e.* using the public to report incidents or issues, or actively maintain the GI though stewardship opportunities, *e.g.* Portland's Green Street Steward Programme (BES, 2020). The public may feel a greater sense of ownership or responsibility to maintain their 'local GI' due to the recognition of benefits that are important to them, *e.g.* improved aesthetics, recreational opportunities and health and wellbeing benefits (Roy *et al.,* 2008; Visitacion *et al.,* 2009; Ando *et al*., 2020; Kattel *et al.,* 2021), which is not the case for traditional engineered solutions. As a result, lower maintenance costs and a reduced frequency for on-site inspections due to out-sourced public monitoring and reporting of issues may be possible, but this should not replace the need for professional, recorded inspections (Blecken *et al.,* 2015).

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

4.3. Optimising the delivery of flood attenuation and multiple co-benefits through integrated blue, green and grey infrastructure

GI is only part of the solution for managing urban flood risk (as explored in Section 4.1). To achieve urban flood resilience, integrated systems of blue-green-grey infrastructure, specifically selected to constitute effective stormwater treatment trains, are needed. Such integrated systems will facilitate management of current and future flood events, whilst delivering environmental, social and economic benefits that address the specific strategic priorities of the city; ultimately aiming to achieve the best cost:benefit ratio. Integrated flood management is essential in urban planning and an urban catchment should be considered holistically in terms of its hydrological linkages between flood source and impact areas to provide targeted and appropriate GI measures (Vercruysse *et al.* 2019a).

Blue infrastructure includes the watercourses, ponds, wetlands and wet detention basins that exist within drainage networks. BGI interconnects blue assets with networks of natural and designed green landscape components that are designed to turn 'blue' during rainfall events to fulfil their flood risk management function (O'Donnell and Thorne, 2020b). BGI are assets that fulfil both blue (flood risk and water management) and green (urban green space) functions; they may be green most of the time and blue some of the time (*e.g.* detention ponds), or they may have some permanent blue features (*e.g.* retention basins), which expand during heavy runoff events. However, while the limited space in highly urbanised catchments restricts the opportunities for retrofitting some types of BGI, experience shows that opportunities do exist for other types of BGI, especially as part of urban renewal. It may not be possible to restore and deculvert river channels in urban centres due to existing built infrastructure on the floodplain (Wild *et al.,* 2011), and the potential for creation of swales along public highways must compete with other demands, such as pedestrian and cycle access. Whilst pedestrians and cyclists can usually be accommodated, it is usually on-street car parking that prevents wider implementation of BGI and SuDS.

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 economic feasibility of urban SuDS systems within London, UK, improved significantly, suggesting that uptake of SuDS systems should be more widely adopted. The benefits of widespread GI adoption are likely to vary between locations, but Ossa-Moreno *et al.* (2016) provide key recommendations regarding incentives and policies to enhance the uptake of urban GI to ensure that the economic appraisal is considered within urban planning. GI has the additional benefit of flexibility in engineering design (De Neufville and Scholtes, 2011), allowing such systems to embrace adaptability within the context of uncertainties associated with climate change and urbanisation.

Connected SuDS systems often include grey elements located below the ground, such as proprietary treatment products (*e.g.* silt traps, oil interceptors, gully and pipe systems) or flood attenuation storage tanks (*e.g.* geocellular storage, concrete tanks or oversized pipes). However, the concept of SuDS places greatest emphasis on above-ground blue-green components (that may be connected by 'hidden' grey assets), to deliver the 'four pillars of SuDS development' (Woods-Ballard *et al.,* 2015). By managing surface water above-ground, BGI can also help extend the lifetime of ageing grey infrastructure assets, reduce the number of combined sewer overflows, limit the quantity of rainwater that travels through combined sewers and wastewater treatment plants (thus saving energy and carbon), and create capacity in the subsurface piped drainage network to accommodate foul flows from new development. The above ground, soft and living elements of GI also allow for continual adaptation, whereby features can be easily altered in response to local climatic extremes or to protect against future events (Babovic *et al.,* 2018). This flexibility and adaptability feeds into a robust, antifragile and integrated flood management strategy which can perform well under changing and uncertain future conditions. However, despite the potential benefits of multifunctional blue-green-grey infrastructure, in practice, optimisation of more than one benefit is particularly challenging, and trade-offs will need to be made between, for example, objectives to minimise risks from urban heat or urban flooding (Caparros-Midwood *et al.,* 2019), or stormwater management and water reuse/harvesting (Schmitter *et al.,* 2016).

Integrated blue-green-grey infrastructure has been used to address international urban water challenges, demonstrating its potential as multifunctional infrastructure (O'Donnell et al., 2021). For example, flood risk management strategies have been shown to improve water quality in Philadelphia (USA), reduce water footprints in Berlin and Singapore, save potable water for consumption in Melbourne (Liu and Jensen, 2018) and provide a food resource to urban populations (the concept of edible GI and urban agriculture; Russo *et al.,* 2017).

Integrated blue-green-grey systems that offer flexible/adaptive design are recommended to enable the delivery of flood risk management solutions despite the current uncertainty surrounding future climate, extreme events and level of urbanisation. Assessing a range of flexible adaptation pathways comprising different combinations of blue-green-grey infrastructure will highlight where incremental investment in infrastructure can effectively meet performance requirements and remain cost-effective (Kapetas and Fenner, 2020). The use of GI can be a sustainable and cost-effective solution for urban flood management, with Duffy *et al.* (2008) emphasising that the annual maintenance costs of SuDS systems are 17 – 20% cheaper than grey infrastructure. However, maintenance within GI schemes can be more complex and more difficult to remediate (DelGrosso *et al.,* 2019; see Section 4.2).

Alongside the development of blue-green-grey flood risk management strategies, urban flood resilience is further dependent on investment in mitigation, preparation, response, flood modelling, prediction and forecasting, flood warnings and emergency response, community preparedness and property level protection (Surminski and Thieken, 2017). Resilient retrofitting of buildings and prioritising flood protection by creating 'floodable' spaces are options for dense urban areas with little space for extensive GI. The Water Square Benthemplein in Rotterdam, Netherlands, is an exemplar of blue-green-grey multifunctional space, combining water storage capacity with recreational opportunities during 'non-flood' conditions (De Urbanisten, 2013).

Ultimately, a whole mosaic of GI, BGI and integrated systems of blue-green-grey infrastructure, both proactive and reactive, exist; with different options available depending on the objective. It is generally recognised that a portfolio of measures including source control, infiltration, conveyance, and storage is required to achieve urban flood resilience sustainably. Such systems must be delivered using a treatment train approach developed along optimum adaptation pathways to achieve the best performance, maximise cost-benefit ratios and to work within design/physical site constraints.

4.4. Routine monitoring and reporting to evaluate success of GI

Reporting on the successes, and indeed failures, of GI flood risk management schemes is imperative to provide an evidence base for urban GI and to learn from limitations and shortcomings of existing schemes/studies. Although we can represent GI systems using numerical modelling environments (see Section 4.1) which are useful to examine responses outside of the instrumented record, experimental monitoring using field-based systems is required to enhance our understanding of model representation of the physical processes of GI (Green, 2014). Further, this helps to understand any spatio-temporal changes in performance and failure and provides insight into best-management practices to enhance and optimise such features. Thus, as better monitoring data is collected, better models can be developed.

Schemes and research facilities like the UKCRIC National Green Infrastructure Facility (NGIF), based in Newcastle, UK, are pioneering integrated solutions for GI, providing specialised 'living laboratories' to explore how GI can help to relieve pressure on grey infrastructure (Green *et al.,* 2021). Novel, purpose-built GI features of varying scale (*e.g.* an experimental full-scale swale shown in Figure 2b, heavily instrumented lysimeter bioretention cells, a length of rain-garden 'ensembles' and a monitored green roof) which are equipped with dense sensor networks allow the measurement of key hydrological and biophysical variables (*e.g.* precipitation, soil moisture, water depth, runoff and outflow rates) to be conducted unobtrusively and in-situ. This allows the collection of quantitative experimental data to support the application of urban GI and to provide quantitative indications on the hydrological performance of such systems. Currently, very few monitored schemes exist. Notable examples include extensively monitored green roofs at the University of Sheffield (*e.g.* Stovin *et al.,* 2013) and over 20 monitored stormwater capture and infiltration/evapotranspiration systems across the Villanova University campus (*e.g.* Traver and Ebrahimian, 2017; Ebrahimian *et al.,* 2019), including a detention pond, a series of bioretention systems and vegetated swales which monitor runoff within a functioning urban system and provide insights into the maintenance requirements to allow such systems to continue to fulfil their function.

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

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

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

5. Conclusion

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

As the hydrological cycle intensifies under climate change, urban infrastructure will need to be resilient to a range of possible scenarios. The self-regulating properties associated with GI and "working with nature" approaches are therefore desirable, promoting adaptation to changes in flood magnitudes, timing and frequencies. Whilst the adaptive properties of GI should be promoted, opportunities will be limited in many scenarios given space and logistical constraints. Monitoring and maintenance will be required to maintain key functions related to flood protection, such as managing the effects of sedimentation, excess plant growth, and anthropogenic impacts such as the presence of litter. Therefore, understanding how regular maintenance relates to the ongoing effectiveness of GI is important in assessing longer-term efficacy of such schemes.

There is clear potential for GI to reduce regular, chronic flood events of low to medium magnitude, and large-scale GI such as restored floodplains may help mitigate against more extreme flood events if there is space for these interventions in the catchment, which is unlikely in many urban areas. The significance of the placement of urban GI to the success of its function means there is not a direct relationship between GI scheme size and effectiveness. Instead, resilience is built through creation of an integrated network of urban resilience solutions, including building resilience against hydrological extremes and attenuating urban flood risk.

Monitoring of GI schemes is lacking, which has implications for designing successful infrastructure, informing physically-based modelling work and determining best management practices. Long-term monitoring from laboratory-, field- and numerical modelling-based studies are required to strengthen the evidence base to promote appropriate and successful adoption of urban GI. One major barrier for widespread GI implementation is the need for standardisation within the design process of GI schemes to ensure alignment with regulatory frameworks and for GI systems to be recognised with the same level of flood protection and recurrence intervals as piped drainage systems. Nevertheless, this is difficult due to the living elements of such drainage systems, which are prone to degradation, loss of functionality and changes in performance, both spatially and over time. Ultimately the success of GI schemes should either be determined by comparison to design purpose (*e.g.* flooding) or using a holistic set of criteria which values the mutual benefits of GI schemes. For the management of low-level flood events, it is the additional co-benefits delivered by GI that place them apart from their grey infrastructure counterparts.

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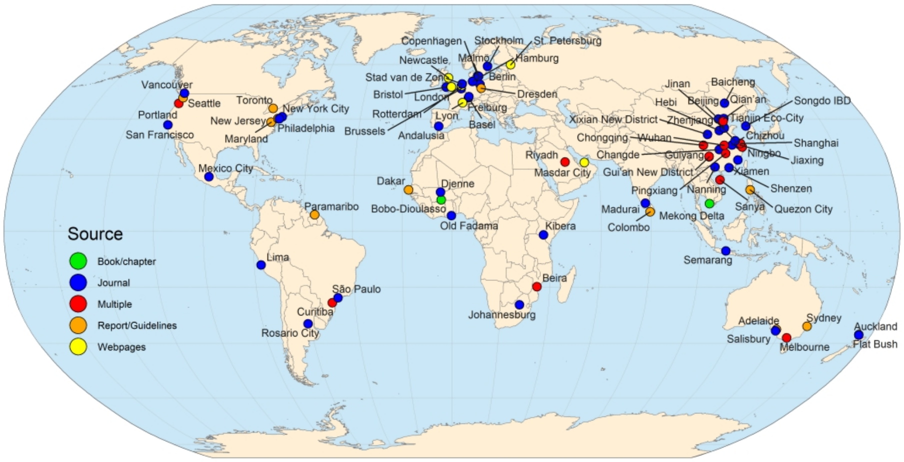

Figure 1: Distribution of notable urban GI schemes which consider stormwater management at a variety of scales. References from a range of sources (books, journals, reports or guidelines, webpages or multiple sources) are provided in Supplementary Table 1 for each city/location. Please note, case studies 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.*

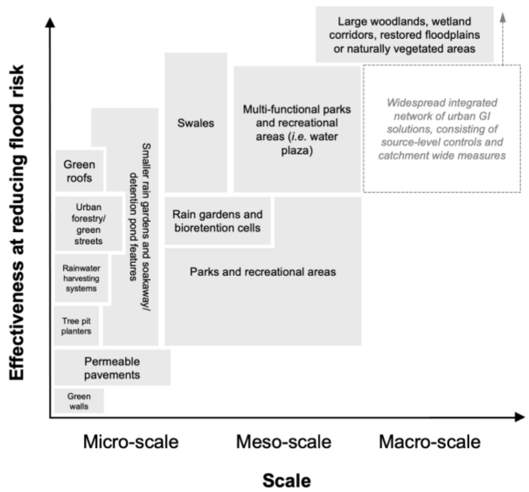

Figure 3: Conceptual diagram showing the scale and effectiveness of different GI features. The scale and cost of such features are highly variable and may vary significantly between sites, design specifications and whether the system is new or retrofitted. N.B. Some features may be better at dealing 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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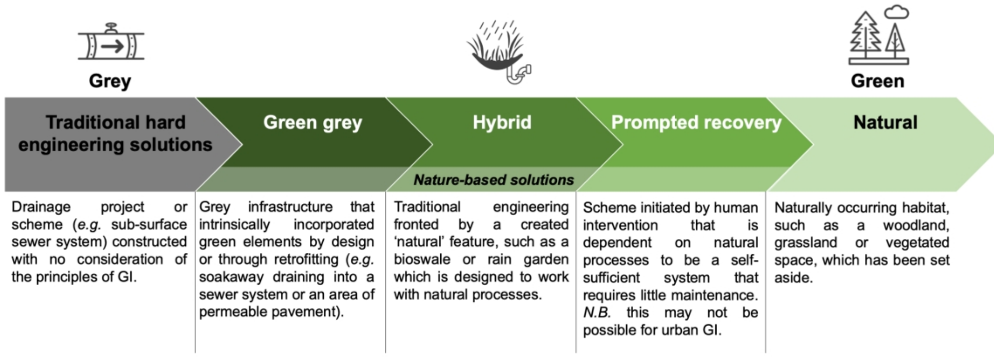

Figure 4: Green-grey continuum of urban GI. Source: adapted from framework within Roca et al., 2017.

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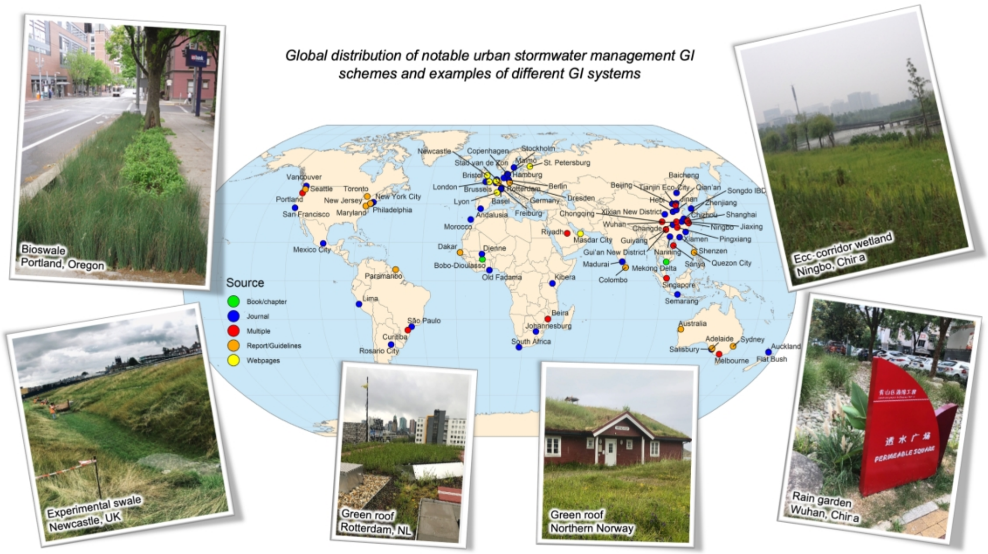

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