The Blue-Green Path to Urban Flood Resilience

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Abstract

Achieving urban flood resilience at local, regional and national levels requires a transformative change in planning, design and implementation of urban water systems. Flood risk, wastewater and stormwater management should be re-envisaged and transformed to: ensure satisfactory service delivery under flood, normal and drought conditions, and enhance and extend the useful lives of ageing grey assets by supplementing them with multi-functional Blue-Green infrastructure. The aim of the multidisciplinary Urban Flood Resilience (UFR) research project, which launched in 2016 and comprises academics from nine UK institutions, is to investigate how transformative change may be possible through a whole systems approach. UFR research outputs to date are summarised under three themes. Theme 1 investigates how Blue-Green and Grey (BG+G) systems can be co-optimised to offer maximum flood risk reduction, continuous service delivery and multiple co-benefits. Theme 2 investigates the resource capacity of urban stormwater and evaluates the potential for interoperability. Theme 3 focuses on the interfaces between planners, developers, engineers and beneficiary communities and investigates citizens' interactions with BG+G infrastructure. Focussing on retrofit and new build case studies, UFR research demonstrates how urban flood resilience may be achieved through changes in planning, practice and policy to enable widespread uptake of BG+G infrastructure.

Keywords: Blue-Green Cities, Blue-Green infrastructure, flood risk management, interoperability, sustainable drainage systems, urban flood resilience

Introduction

There is a recognised need for a transformative change in how urban environments manage water in response to more frequent and extreme storm events, drier summers and increasing urbanisation that reduces permeable greenspace and moves cities further away from natural water cycle processes. More than 50% of the world's population currently reside in cities, which is expected to rise to 68% by 2050 (UN, 2018), resulting in stress on already overburdened drainage infrastructure and elevated flood risk to people, property and critical infrastructure systems, e.g. transport, communications and energy. In the UK, annual expected damages due to flooding exceed £1 billion (Environment Agency, 2014). The economic losses of flooding go far beyond direct damages; frequently the consequential business disruption, supply chain shocks and welfare effects (e.g. health and wellbeing impacts) equal or exceed direct damages (Hallegatte, 2008), in addition to costs associated with degradation of ecosystem services.

In response to these trends and predictions, global cities are rethinking their approaches to flood risk management. Alongside continuing investment in traditional grey infrastructure (e.g. flood walls, barriers, lined drainage channels, underground pipes and detention tanks), many cities are transitioning from solely flood defence to greater water resilience by implementing approaches centred on, for example, water sensitive urban design (Sharma et al., 2016), sustainable drainage systems (SuDS) (Lashford et al., 2019), green infrastructure (Trogrlić et al., 2018) and 'Sponge Cities' (Zevenbergen et al., 2018). These approaches are subtly different but all embody the concept of a 'Blue-Green City', where integrated water management and green infrastructure work in concert to recreate a naturally-oriented water cycle to help manage flood risk while delivering multiple benefits to the environment, society and economy (Lawson et al., 2014).

In 2015 the UK House of Commons Commission of Inquiry into flood resilience highlighted a change in mindset from protection towards resilience, proposing '*living with and making space for water and the opportunity to get "more from less" by seeing all forms of water as providing multiple benefits'* (House of Commons, 2015). The intense, prolonged rainfall and catastrophic flooding in December 2015, which followed the winter 2013-14 floods, provided an unwelcome but powerful endorsement of the need for greater urban flood resilience.

We define 'urban flood resilience' as a city's capacity to maintain future flood risk at tolerable levels by preventing deaths and injuries, minimising damages and disruption during floods, and recovering quickly afterwards, while managing water quality and ecosystems, and ensuring social equity, and economic, environmental and cultural vitality. The multidisciplinary Urban Flood Resilience (UFR) research project was launched in October 2016 to conduct the research necessary to understand how UK urban flood resilience may be achieved at local, regional and national levels. The UFR project, scheduled to finish in May 2020, investigates how such transformative change may be possible using a BG+G whole systems approach to urban flood and water management. The project is funded by the Engineering and Physical Sciences Research Council (EPSRC) and comprises academics from nine UK institutions with expertise in hydrology, hydraulics, water engineering, urban drainage, planning and governance, flood risk management, ecology, sediment transport, stakeholder and community engagement, citizen behaviours, infrastructure resilience and interoperability. Research builds on the earlier Blue-Green Cities research project (2013-2016) that developed new strategies for managing urban flood risk as part of wider, integrated urban planning intended to achieve environmental enhancement and urban renewal in which the multiple benefits of Blue-Green Cities are rigorously evaluated and understood (Fenner, 2017).

With a focus predominantly on pluvial flooding, the objectives of the UFR Consortium are to re-envisage and transform flood risk and stormwater management to develop strategies that ensure satisfactory service delivery under flood, normal and drought conditions, and; enhance and extend the useful lives of ageing grey assets by supplementing them with multi-functional Blue-Green infrastructure (BGI). This includes swales, rain gardens, green roofs, wetlands, restored urban streams, and other SuDS that actively use BGI to attenuate, store and infiltrate surface water. This paper introduces UFR research under three themes: 1) engineering design to enhance service delivery, 2) optimum resource use across the flood-drought spectrum, and 3) flood risk management at the heart of urban planning and delivery. Research is presented under five sub-themes that cover resilience under change, stormwater as a resource, interoperability, citizens' interactions with BGI and achieving urban flood resilience in practice (Figure 1). The key research findings (to date) are summarised and future deliverables from current research are outlined. We reference several publications that have resulted from the UFR project (Costa et al., 2019; Fenner et al., 2019; Krivtsov et al., 2019; Vercruysse et al., 2019) where more detailed methodology and in-depth discussion are presented. We begin by outlining the overarching methods and scope.

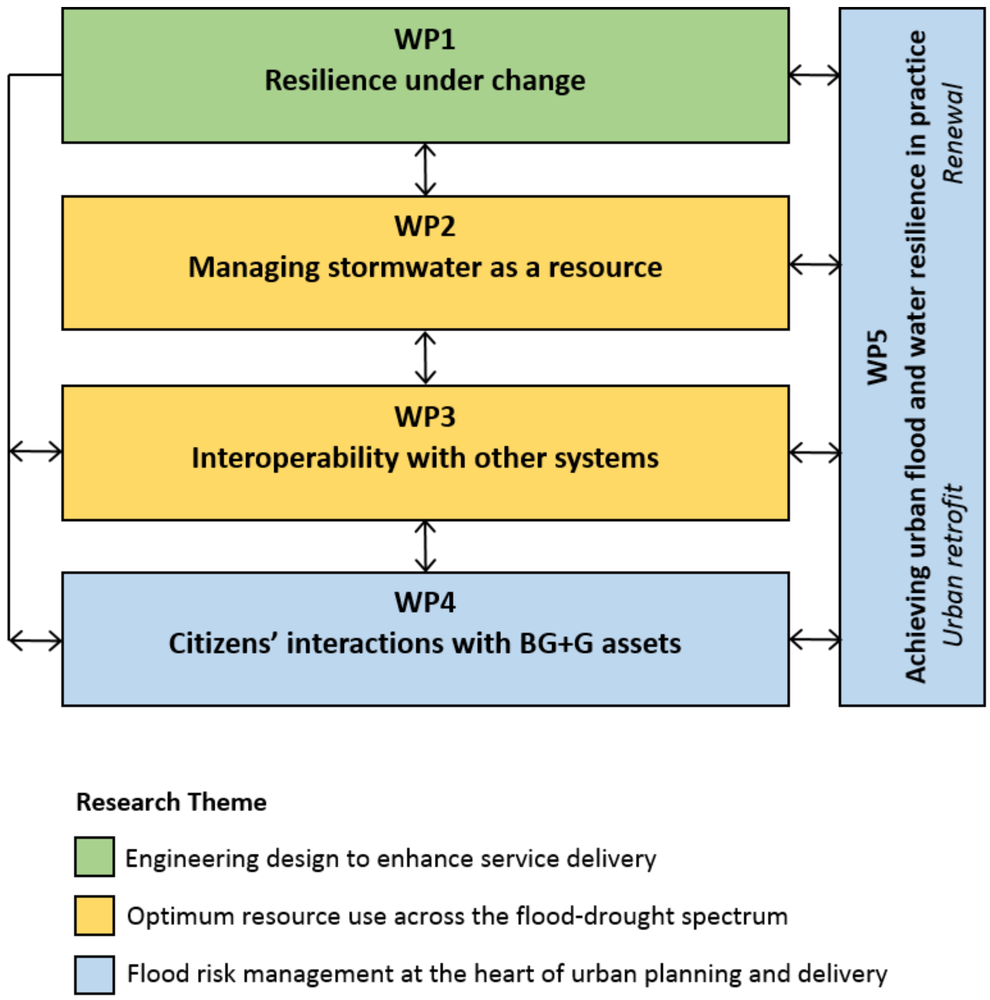


Figure 1 Urban Flood Resilience research project structure. The Work Packages (WP) are shaded according to research theme. BG+G = Blue-Green and Grey.

Methods and scope

Locally-defined methods and models are tested in several UK case studies (including Newcastle, Ebbsfleet, Edinburgh and Carshalton, London) and spatially linked through the 'stormwater' cascade (Figure 2), enabling transferability and up-scaling to regional and national levels. The engineering core of the project couples an array of physics-based models to support investigations of how stormwater travels through a city's drainage system, accounting for the dynamics of water, sediment, debris and contaminants carried by urban runoff. Simulations of water flow and storage are used to investigate how the performance of grey systems can be improved by adding BGI to create integrated treatment trains designed to manage both the quantity and quality of urban runoff. Models and design solutions are being developed and tested in the contexts of retro-fit (e.g. as part of urban renewal and uplift in Newcastle) and new build (e.g. as part of the creation of a 'Garden City' in Ebbsfleet, Kent), to demonstrate how resilience to floods and droughts can be achieved using integrated systems of BG+G assets, under a range of future climates, to assure continuous, long-term service delivery. Adopting a whole systems perspective is necessary to recognise interdependencies between the urban water system and other systems, including transport and energy. This highlights potential opportunities for managing stormwater as a resource, including non-potable uses in homes or commercial buildings via rainwater harvesting (RWH), irrigating green infrastructure, groundwater recharge and micro-hydropower.

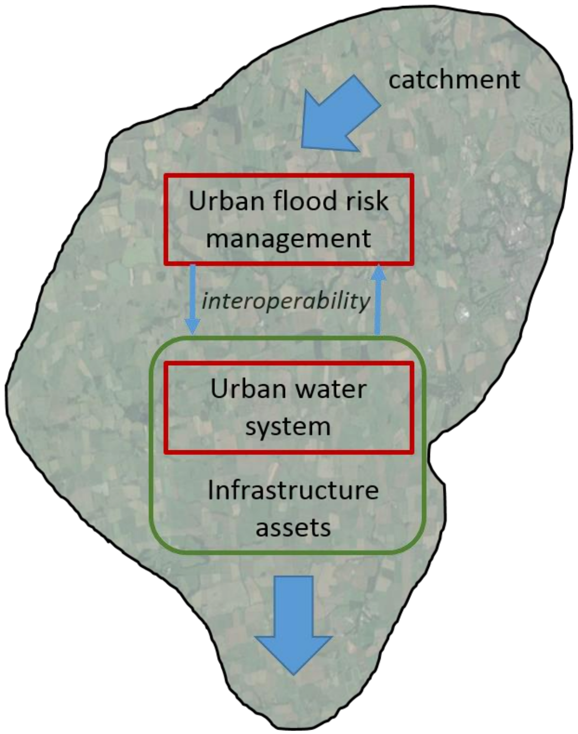
The path to urban flood resilience is also dependent on understanding citizen and community preferences with respect to managing flood risk, and incorporating these into future system designs and upgrades. Participatory Action Research and Social Practice Theory are used to examine the attitudes and responses of citizens, communities and practitioners to innovation in flood and water management. The engineering core of this project is thus underpinned by research into planning, urban development, and the collaborative governance of urban flood risk management, to identify mechanisms whereby the engineering solutions identified above may be incorporated into practice and policy to enable transformative change in urban flood risk management applicable to many countries and regions. Engagement with planners, developers, land-owners, and engineers (local government, private sector and NGOs) through Learning and Action Alliances in Newcastle and Ebbsfleet explore responses to the innovative changes needed to achieve urban flood resilience and helps ensure that research outputs meet the need of local practitioners (O'Donnell et al., 2018).

Stakeholder actions and evaluation:

Participatory Action Research and **Social Practice Theory** are used to examine relationships between researchers, urban flood risk management practitioners and communities, based on **Learning and Action Alliances** and **Community Engagement** in case study cities (Newcastle, Ebbsfleet, Bristol). *This explores tacit knowledge, behaviours and citizen's attitudes with respect to diverse flood mitigation measures and links the desirability of specific asset interventions with wider urban planning.*

Real Options analysis and **Adaptation Pathway** development investigates the most synergistic mix of Blue-Green and grey assets, with new objective functions for option isolation based around maximising multiple benefits and service delivery. *This leverages protocols for evaluating the benefits of SuDS-GI from the earlier Blue-Green Cities project (www.bluegreencities.ac.uk). The optimisation includes Totex (including maintenance liabilities) and monetised benefits using the B£ST Evaluation tool (CIRIA, 2018).*

GIS visualisation of the flood mitigation performance of potential Blue-Green and grey assets and their wider multifunctional benefits. *This consolidates the model outputs for use locally to aid development and upscaled regionally/ nationally to inform policy and practice.*



Physical models:

CityCAT models urban flooding to assess pluvial and fluvial flood risk and flood alleviation measures with simulations driven by rainfall, flow and/or water depth time series (Glenis et al., 2018). Maps of water depths and velocities at different times are combined to animate the flood propagation. *This central tool examines how stormwater cascades through an urban system and where capture and re-use is possible and how subsequent resource potential is constrained.*

WaterMet^2 is an urban water system performance model providing flows/fluxes in four subsystems: water supply, sub-catchment, wastewater and water resource recovery. *This is coupled with CityCAT to explore the interconnections between all forms of urban water.*

SHETRAN handles multi-fraction sediment transport and multiple, reactive solute transport within a river basin model, fully coupled to water flow. *This couples the natural hydrology with the urban responses provided by CityCAT and WaterMet^2.*

Stormwater resource potential

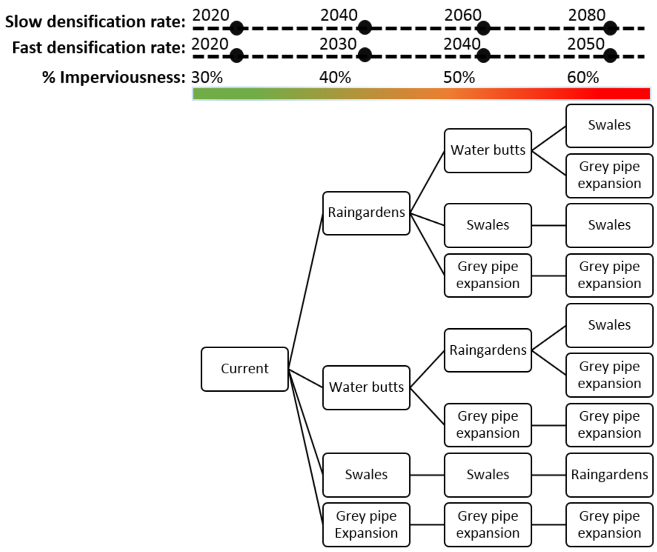
Non-potable use, irrigation of Blue-Green infrastructure, groundwater and soil moisture recharge, micro hydropower, maintaining urban green spaces and ecosystem services

Figure 2 The Urban Flood Resilience research project scope, covering the entire 'stormwater cascade' from when water enters to when it leaves the urban area, employing a suite of linked research methods and models to simulate physical processes, and cross-tabulating with water governance, planning, and stakeholder attitudes, preferences and actions.

Theme 1. Engineering design to enhance service delivery (WP1)

Theme 1 investigates how integrated BG+G treatment trains may be engineered to support resilient management of water quantity and quality. Evaluating how multifunctional BG+G systems can be co-optimised to offer maximum flood risk reduction, while delivering multiple co-benefits, under a range of future scenarios that account for climate and socio-economic change, is a key objective.

Urban drainage infrastructure has previously been developed to meet expected levels of service performance criteria assuming stable conditions. In many cases the buried pipework is reaching the limits of its capacity and systems must be retrofitted to respond to new pressures including extreme storm events that are exacerbated by climate change and rapid urban densification. The uncertainty associated with these drivers results in potentially costly solutions that are overdesigned or inadequate system extensions that fail to provide the necessary additional capacity. This highlights a need for flexible/adaptive designs that allow incremental investment in infrastructure to meet performance requirements while maintaining cost-effectiveness (Buurman and Babovic, 2016). WP1 have developed methodology and guidance on assessing a range of flexible adaptation pathways as part of long-term planning and infrastructure design, to address the question: *what is the most effective mix of BG+G systems in any given location at any time?* The method has been tested in Carshalton (London Borough of Sutton), exploring and prioritising a series of potential pathways and developing a roadmap for adaptation over the next 40 years (Figure 3). This combines hydrodynamic modelling to identify when service thresholds are exceeded and trigger further intervention, and evaluation (monetised and spatial incorporating a real options approach) of the multiple benefits of different BG+G pathways (Gersonius et al., 2015; Manocha and Babovic, 2017; Fenner et al., 2019). Additional criteria beyond a standard cost benefit analysis (CBA) form part of the decision making process. For instance, although grey pipe expansion scores ‘medium’ in the CBA it offers no adaptiveness as it is a one-off large scale intervention, nor does it offer any environmental or social benefits (Figure 3). The adaptive pathways approach provides a pragmatic response to managing the uncertainties inherent in climate change and urbanisation over a variable planning horizon and can be used to identify the most suitable mix of drainage infrastructure assets.



Pathways	Current Criteria	Additional Criteria		
	Standard CBA	Adaptiveness	Ease of Implementation	Multiple Benefits
1	Medium	High	High	High
2	Medium	Medium	Medium	High
3	High	High	Medium	Medium
4	Medium	Medium	High	Low
5	Medium	Medium	Medium	High
6	Medium	High	Medium	Medium
7	Medium	Low	Medium	Low
8	High	Medium	Medium	High
9	Medium	Low	Medium	None

Figure 3 Adaptation pathways tree and multi-criteria pathway assessment as a response to different rates of urbanisation. Tipping points are identified when the (future) system reaches a capacity threshold due to urban densification pressure, as expressed by an increasing % imperviousness of the urban catchment. A fast or slower rate of densification suggest that the next step should be taken sooner or later, respectively. CBA = cost benefit analysis.

Hydrodynamic modelling of BG+G systems has also been advanced through the development of a new comprehensive model that bridges the interfaces between urban/rural and engineered/natural hydrosystems by simulating water flow on the surface, in sub-surface pipe networks, and in the soil and groundwater systems. Several previous studies have coupled hydraulic and hydrologic models, e.g. semi-lumped hydrologic models providing the lateral and tributary flows to a hydraulic model of the main channel reach (Lian et al., 2007, Nguyen et al., 2016). The impacts of urbanisation on groundwater recharge using physically based hydrologic models coupled to urban stormwater models have also been examined (Locatelli et al., 2017). Our focus is on runoff generation within urban conurbations, which comprise a mosaic of impervious and green spaces. Hydrodynamic models typically simulate runoff dynamics in urban areas over the duration of a storm event, neglecting the long-term hydrological processes in green spaces and the specification of antecedent conditions. To overcome this limitation, the physically based SHETRAN hydrological model (Ewen et al., 2000) has been coupled with the CityCAT hydrodynamic model (Glenis et al., 2018). SHETRAN simulates a continuous representation of runoff, evapotranspiration, soil moisture and groundwater storage to provide the antecedent conditions for CityCAT. This allows improved representation of the impacts of land use and management on urban flood hydrology.

The physical basis and high spatial resolution of the coupled hydrosystems model provides a basis for simulating the effects of land-use change, SuDS and BGI implementation, and climate change on runoff and water storage, demonstrating a pivotal advancement in hydrosystems modelling. Interpretation of model simulations has led to the following three key recommendations for future hydrosystems modelling:

1) It is necessary to differentiate between combined and separate sewer systems to accurately model flows in urbanised water courses. This is illustrated by the increase in peak flow and reduction in lag time when the Kingston Park surface water sewer discharges runoff into the Ouseburn, evident by the rapid increase in discharge at the Three Mile depth gauge (Figure 4);
2) Accurate representations of effective impermeable and green areas (including gardens) requires high resolution data; vector data is often preferable as detailed attribute information can be assigned to individual features, with the OS Mastermap (UK Ordnance Survey) dataset used here, and;
3) The problem of specifying the initial antecedent conditions in green spaces in an event based hydraulic model can be overcome through the coupling with a hydrologic model that explicitly accounts for the role of seasonal variations in evaporation.

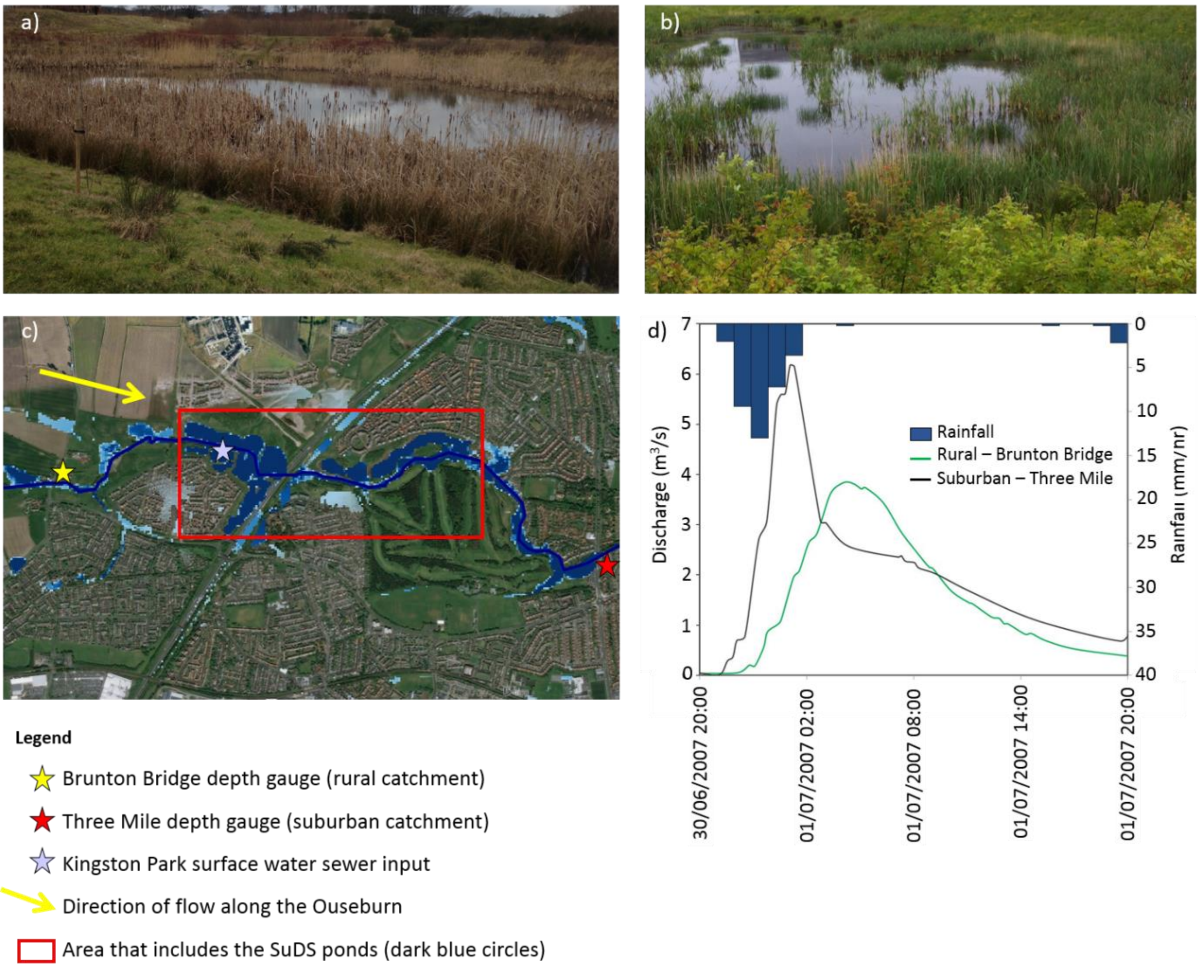


Figure 4. a, b) Photographs of two SuDS ponds along a section of the Ouseburn, Newcastle, modelled in the CityCAT simulation (source: Emily O'Donnell, June 2013 and February 2015, respectively). c) CityCAT simulation showing water depth and inundated SuDS features along the Ouseburn. The SuDS ponds are represented by the dark blue circles within the red box. d) Discharge hydrographs illustrating how the separate sewers from Kingston Park increase peak flow and decrease lag time, illustrated by the rapid increase in discharge at the Three Mile (suburban) depth gauge.

Achieving satisfactory levels of service in urban water systems is subject to a range of challenges including increasing urban water demands due to population growth, increased flood risk due to urbanisation and climate change, expectations of good water quality, ageing infrastructure and issues associated with potential grey infrastructure retrofit, including negative environmental and social impacts, and high energy demands. Evaluating new interventions in urban water systems requires an integrated framework to measure system performance and interactive pathways, and assess the sustainability of proposed schemes. WaterMet[2], a conceptual simulation-type, mass-balance-based model which quantifies metabolism related performance of integrated urban water systems (Behzadian and Kapelan, 2015) is being used to evaluate the sustainability performance and quantify resource flows in the Ebbsfleet Garden City for three major urban water subsystems (water supply, stormwater and wastewater). Outputs from the CityCAT hydrodynamic model (surface and subsurface flows) feed into the stormwater and wastewater modules in the WaterMet^2 model, along with the water supply system characteristics, to evaluate overall urban water systems performance. A sustainability assessment of the existing urban water system is being undertaken (as business as usual) and different strategic future interventions are assessed over a long-term planning horizon that aligns with priorities of the Ebbsfleet Development Corporation and local water companies. Sustainable urban water management options, e.g. RWH, greywater reuse and wastewater reuse, are incorporated into the model, and different wastewater treatment options are evaluated, including centralised and decentralised strategies. Performance of the urban water system is assessed through social, environmental, economic and asset key performance indicators over the planning horizon. Metabolism-based modelling is an advancement of current approaches as issues commonly encountered by independent modelling of urban water system components are overcome by considering the interconnection and interdependencies of the urban water sub-systems.

Theme 2. Optimum resource use across the flood-drought spectrum (WP2 and WP3)

Stormwater is often considered a hazard with a focus on extreme events, yet the need to retain and utilise stormwater as a vital resource is paramount as we enter a more uncertain climate. Theme 2 investigates how engineered stormwater management systems can be better aligned with natural processes and other physical infrastructure to 1) realise the resource potential of urban water, with opportunities for storage, recovery and reuse identified at every stage of the urban water cycle (WP2); and 2) improve integration of urban flood risk management and water, energy and transport infrastructure through interoperability of urban systems-of-systems (WP3).

Managing stormwater as a resource

A range of stormwater reuse options are listed in Figure 5. We briefly discuss three options, focussing first on the potential for micro-hydropower generation from the controlled release of water from SuDS ponds. A novel screening tool to assess the feasibility of such energy recovery based on physical site, climate and economic parameters has been developed (see Costa et al., 2019). This approach focuses on how a retention pond may decouple the problem of intermittent rainfall and continuous energy generation, and provides key insight into preferred characteristics for viable sites, e.g. significant head being favoured over a large flow as this permits smaller pipes and turbines which reduce overall costs. The application of the tool to two case studies (Herefordshire, UK and Oregon City, USA) highlights several critical dependent factors that influence the potential energy recovery from stormwater discharge, notably abundant rainfall with a relatively even annual distribution, a large contributing catchment and steep slopes. However, the requirements for optimal energy recovery and to create effective SuDS schemes are likely to differ; SuDS on sloping ground with a large difference in head are rare. This suggests that micro-hydropower recovery from SuDS that generates enough revenue to justify the investment is highly dependent on unique site characteristics and there may be limited opportunities in the UK.

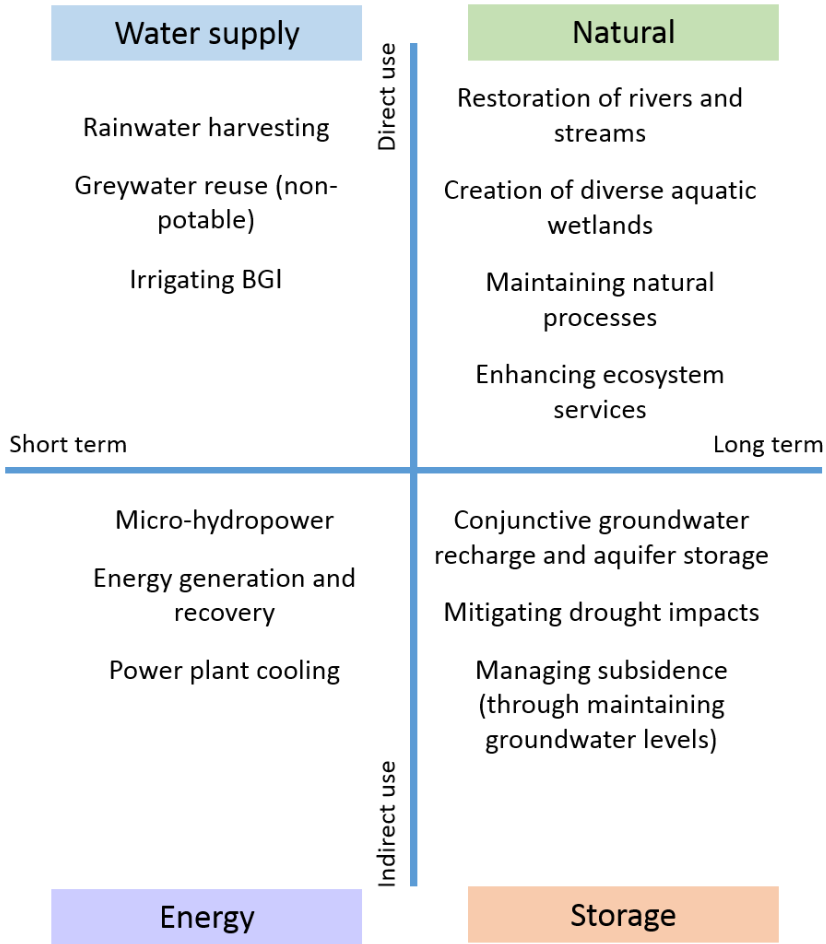


Figure 5 Options for direct and indirect stormwater reuse over the short and long term. BGI = Blue-Green Infrastructure.

The potential benefits of RWH on water supply augmentation and urban flood risk management highlights an alternative approach with regards to stormwater as a resource. Nonetheless, the global implementation of convention RWH systems varies greatly and systems often do not maximise the potential benefits (Campisano et al., 2017). The UFR Consortium are evaluating the evolution of RWH to Rainwater Management Systems (RMS), which represents a step-change whereby multifunctional systems can increase urban water resilience and sustainability by concurrently reducing water demand, stormwater discharge and energy usage (embodied and operational). The performance of a residential RMS in Newcastle based on a 3-bedroom house with an 80 m^2 roof area was evaluated using 2012 rainfall data and the Rainwet model (Fewkes and Butler, 2000) that calculates a daily supply-demand balance of rainfall, water demand and overflow discharges based on ‘yield after spillage’. A control simulation without RMS (Figure 6a) was compared to a passive RMS (Figure 6b) and an active RMS (Figure 6c), based on a 3000 L storage tank. Active RMS, where storage tanks are designed to be operated actively (i.e. with the user determining the level of discharge based on the current weather and forecast), are found to optimise water supply demand and stormwater discharge reduction of the maximum daily event. In Newcastle, the low supply (rainfall) relative to a higher non-potable household water demand (i.e. toilet flushing) yields a low water supply efficiency from RMS as tanks are likely to be emptied more frequently. However, frequent emptying of tanks increases the potential for stormwater control as the tanks will have greater capacity to collect water during future storm events.

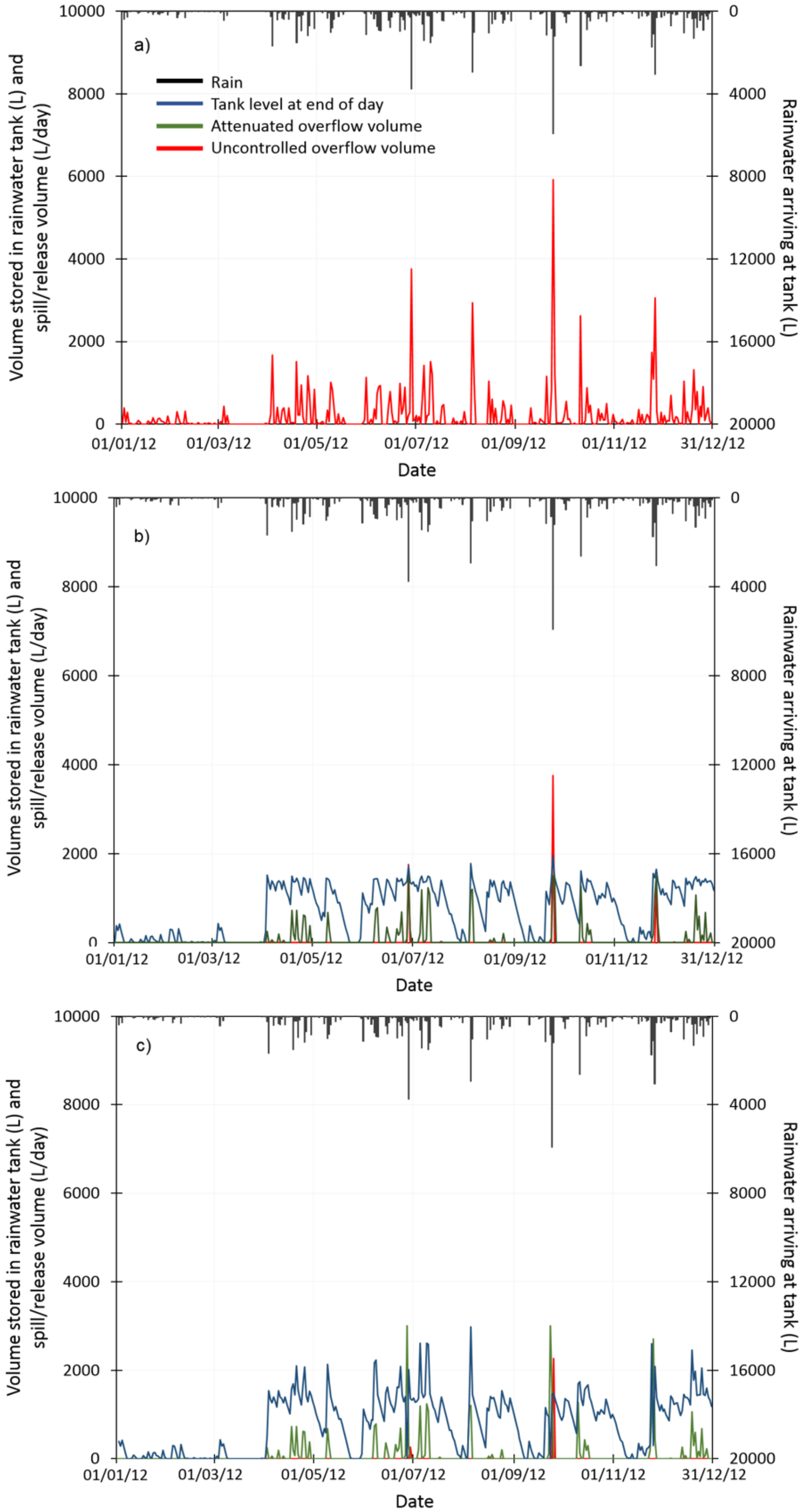


Figure 6 Household stormwater management based on a 3-bedroom house in Newcastle with an 80 m^2 roof area, using Newcastle rainfall data from 2012. a) Without RMS (Rainwater Management System), b) passive RMS and c) active RMS.

UFR research also investigates the natural resources generated by BGI through a study of the ecosystem functioning and benefits provided by SuDS ponds, comparing them with semi-natural and ornamental ponds that are also part of BGI networks. The characteristics of suspended particulate matter and water quality significantly impact pond ecology, as well as pollutant transport and biogeochemical cycling. Nine ponds in Scotland are being regularly sampled (Krivtsov et al., 2019) to investigate the seasonality of suspended particulate matter, the impact of outside inputs (i.e. rainfall events) and internal changes within the pond systems. A number of ecological surveys are being carried out including vegetation, fungi, vertebrates and aquatic invertebrates. Results find that SuDS ponds have reasonably high species richness, providing an important contribution to ecosystem services (Figure 7). The number of reliably identified vascular plants at the sites ranged from 16 (Juniper Green) to 92 (RBGE, Royal Botanic Gardens, Edinburgh). The relationship between pond size and species richness is not clear; the smallest site (Juniper Green) has the lowest number of species and large ponds such as Inverleith and Blackford have high species richness, yet species richness is the highest in RBGE, which is a relatively small ornamental pond. Plant biodiversity at BGI ponds, therefore, is influenced by several factors including area, pond age, planting regimes and pond maintenance.

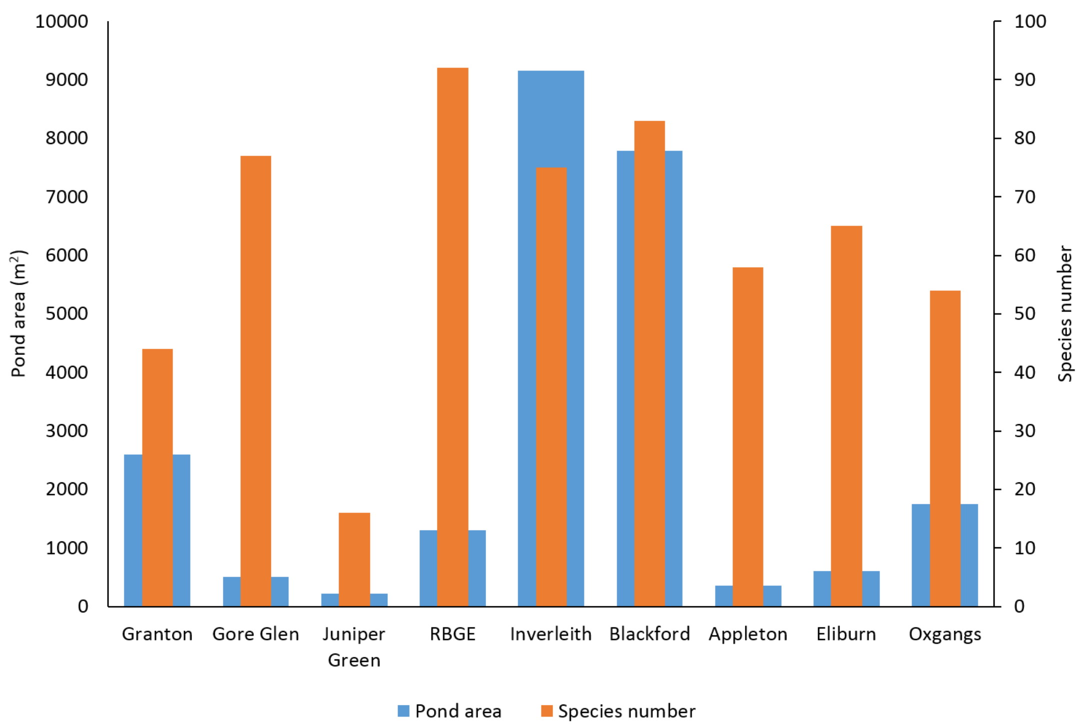


Figure 7 Species richness of vascular plants at nine ponds of varying size in Scotland. RBGE = Royal Botanic Gardens, Edinburgh.

Interoperability with other systems

Resource use across the flood-drought spectrum, and in particular during exceedance events, can be enhanced by actively managing connections between a range of infrastructure systems to increase the functionality of the whole system (i.e. the city) to deal with floods. This introduces the concept of *interoperability*: the ability of any water management system to redirect water and make use of other system(s) to maintain or enhance its performance function during exceedance events (Vercruysse et al., 2019). Interoperability can progress the adaptive design process from a system with single multi-functional assets towards an interoperable 'system-of-systems' to enhance flood resilience, bridging the gap between multi-functional and multi-system urban flood management. To promote and facilitate interoperability in practice, a spatial analysis framework has been developed to systematically identify flood impact and flood source areas along with opportunity areas for integration of different infrastructure systems to manage surface water (Figure 8). Linking flood hazard to flood source areas provides insights into the hydrological processes and interactions within the urban catchment, and can help prioritize locations for flood management intervention. Furthermore, identification of different types of flood source areas (e.g. wide superficial flooding, local deep flooding), combined with information on infrastructure systems, can guide the selection of appropriate flood management solutions from a catchment perspective. The analysis framework aims to bring together stakeholders from diverse organisations, facilitating collaborative projects and aligning investment in flood management and other infrastructure development projects.

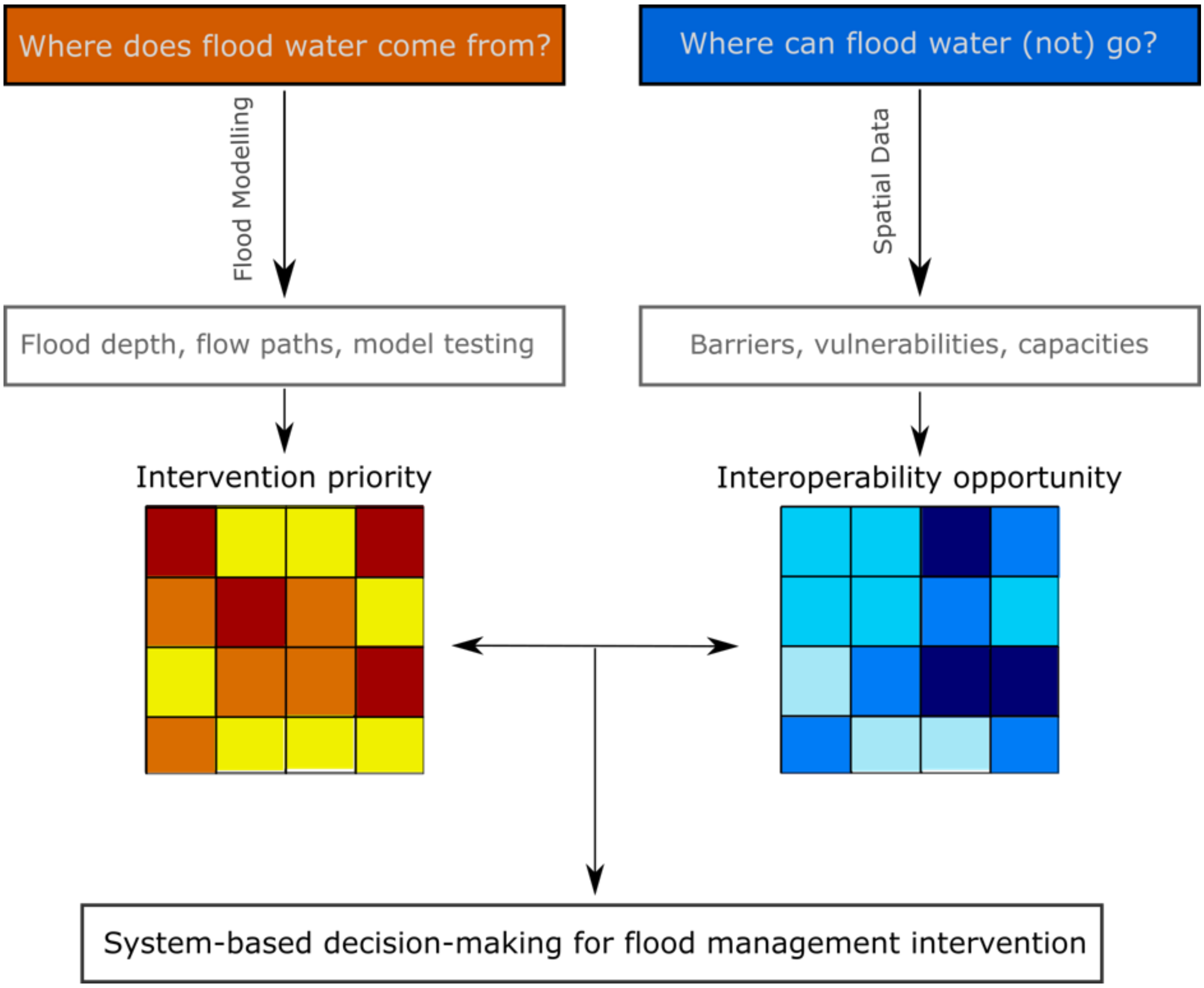


Figure 8 Conceptual architecture of a spatial mapping tool for system-based flood management aiming to combine two main aspects: (i) where does flood water come from and how can intervention priority areas be identified, and (ii) where can flood water (not) go based on the existing infrastructure systems that create opportunities and barriers for interoperability (Vercruysse et al., 2019).

Theme 3. Flood risk management at the heart of urban planning and delivery (WP4 and WP5)

In addition to the engineering advances detailed above, the path to urban flood resilience is characterised by two types of transformative social change. First, planners, developers, design engineers and system operators must demonstrate increased awareness of, and responsiveness to, citizens' physical, social and environmental needs and preferences. Second, citizens' attitudes and behaviours to flood and water infrastructure must change to better understand and appreciate the multiple benefits of BG+G innovation.

Understanding public perceptions of BG+G is a critical step to addressing barriers to their implementation, gaining support and improving awareness (O'Donnell et al., 2017). Nonetheless, little work has been done to unpick conflicting attitudes (installations seen as attractive and yet unsafe) or to understand the gulf between expressed positive attitudes to natural spaces and behaviours around them. For instance, examples of liking the concept of BGI ("everyone likes a bit of nature"), but not engaging with proposals for specific spaces or being prepared to fund them suggests contrasting beliefs and values (Everett and Lamond, 2019). Therefore, to enhance understanding of attitudes, and preferences that may affect behaviours around BG+G, it is necessary to explore the deepening of traditional stated preference approaches (explicit measures) together with novel tests that reveal more subconscious attitudes (implicit preferences). Perceptions are typically evaluated by explicit, or self-report, measures such as questionnaires and Likert scale tests (e.g. Bastien et al., (2012)). However, these approaches assume that respondents know and can articulate their beliefs and have an internal concept of BG+G and SuDS that they consciously base their attitudes on. The limited public awareness of the functionality of SuDS, and frequently encountered issues with respondents giving more 'socially acceptable' responses of 'liking' all types of blue-green space, suggests added value of social psychology techniques, such as Implicit Association Tests (IAT). IATs measure hidden perceptions and negate issues of social desirability bias, self-enhancement bias, and self-ignorance bias common with explicit tests. The IAT reveals implicit attitudes by measuring the strengths of associations between stimuli (e.g. images of blue and green space) and evaluative attributes (e.g. good and bad words) based on reaction times. IATs have been used in environmental research evaluating, for example, implicit connectedness with nature (Liu et al., 2019), and are being trialled by the UFR Consortium to help identify some of the underlying implicit attitudes towards the use of blue, green and grey space, such as perceptions of attractiveness, tidiness and safety, that may exert a significant influence on public preferences (Fenner et al., 2019).

The effectiveness of contemporary models of community engagement have also been evaluated. The specific challenges inherent in engagement around BGI suggest that engagement frameworks need to draw on elements of good practice from urban planning and flood risk management to enhance understanding of the long-term need for BGI across diverse communities, and to maximise the multiple benefits that may be delivered. It was observed that such a framework for BGI was lacking. Drawing on fundamental principles that BGI engagement needs go beyond tokenism in order to achieve the required goals (Arnstein, 1969), a typology of BGI-community engagement based on different levels of acceptance and influence was developed and applied to case studies of existing practice (Everett and Lamond, 2018). Five fundamental principles to guide more effective BGI engagement and encourage a greater sense of ownership, appreciation and care around BGI, has been developed. This focuses on both outcomes and processes, to ensure the enablement of longer-term engagement with functional and amenity aspects of the proposed measures:

- People: necessitating two-way engagement building capacity and awareness, but also highlighting the importance of practitioners' knowledge of communities' perceptions, interests and needs;
- Design: preference for BGI that fit into the local context, provide multiple benefits (that are valued by the community) and are low maintenance;
- Power: community engagement should not reinforce existing social inequalities but should improve community integration where possible and recognise existing power relationships;
- Procedure: BGI establishment should be collaborative, efficient and sustainable, considering all community perspectives (where given) to deliver co-designed BGI, and;
- Engagement: local understanding and participation should be developed, to ensure that different communities' perspectives are heard and encourage democratic outcomes.

These concepts are being further developed to understand the inherent multiplicity of 'communities'; not simply communities of *place* and of *practice*, but also of *circumstance*, *interest* and *action* (Meikle and Jones, 2013) that will require consideration and appropriate modes of engagement. The use of Social Practice Theory reveals that such thinking can help identify communities with specific capacities or interests, and improve understanding of their motivations and perceptions towards BGI.

The governance and political issues around flood and water management and planning are also being investigated, focussing on the implementation of SuDS through England's strengthened planning system. We are investigating barriers to innovation within the planning process and how planners may play the crucial collaborative role and achieve consensus in strategic land-use decisions on BG+G infrastructure. The Government announcement in 2014 that SuDS would be implemented though a strengthened planning system, instead of via enactment of Schedule 3 of the 2010 Flood and Water Management Act (FWMA, 2010), can be characterised as a more flexible and adaptive form of governance, supported by light regulation and using existing arrangements and wide stakeholder engagement. However, much of the evidence to date suggests that SuDS implementation has been complex, resulting in suboptimal uptake (LI & CIC, 2019), and ambiguous and noncommittal legislation. Local authorities typically lack the legislative backing and resources to provide valuable incentives to developers to implement SuDS and issues over ongoing maintenance arrangements remain firm barriers. Monitoring progress with the introduction of Schedule 3 in Wales (January 2019), located on the other side of the governance spectrum to strengthened planning policy, presents an opportunity for comparative research to examine these two approaches to governance and implications for SuDS and BGI, in addition to wider environmental and societal gains.

Learning and Action Alliances (LAA) to align research outputs with practitioner needs

The final objective of the UFR Consortium is to embed research in the primary case study cities (Newcastle and Ebbsfleet) through Participatory Action Research and co-produce strategies to overcome the myriad socio-political, governance and biophysical barriers to BG+G innovation. The Learning and Action Alliance (LAA) framework has been developed to meet this objective. Local stakeholders in Ebbsfleet and Newcastle regularly meet to discuss innovative BG+G solutions to flood and water management challenges that align with a range of stakeholder objectives. The intention is for these co-produced solutions to be subsequently incorporated into practice and policy (Table 1). LAAs are a response to increasingly louder calls for integrated solutions to 'wicked problems'; communal problems that cannot be solved by science or traditional top-down governance alone, and are beyond the remit of individual stakeholders or organisations. LAAs typically have an atmosphere of mutual ownership that permits open discussion, rational criticism and co-production of knowledge to create a join understanding of a problem and its possible solutions (Ashley et al., 2012). The Newcastle LAA has focussed on enhancing the evidence base, and sharing best practice of, BG+G flood and water management projects in the NE region, suggesting alternatives to traditional schemes when opportunities arise and helping move the City forward in its ambition to become a 'Blue-Green City'. This is exemplified in the 'Newcastle Declaration on Blue and Green Infrastructure' that commits signatory organisations to greater implementation of BGI, collaborative working and a move towards partnership funding strategies. The Declaration was relaunched in 2019 with ten signatory organisations from a range of disciplines, including flood and water management, planning, ecology, estate management and water resources (UFR, 2019). In Ebbsfleet, the LAA has developed a system dynamics model to investigate water use options for the Garden City. The primary objective is to reduce residential potable water use, enabling greater resilience to the risk of future water scarcity and drought. Outputs from model scenarios under a range of future climate and socio-economic conditions will provide options for alternative stormwater management, including RWH and greywater reuse, more water efficient behaviour, and enhance the capacity of local stakeholders to influence policy in a more sustainable direction. The system dynamics model is also a catalyst for bringing stakeholders to the table, helping align their agendas around a common issue to create a sustainable vision for Ebbsfleet.

	Newcastle LAA	Ebbsfleet LAA
Location	Newcastle upon Tyne	Ebbsfleet Garden City, Kent
Established	2014	2017
Key issue	Innovative flood risk management solutions	Sustainable water use in the Garden City
Core stakeholders	Newcastle City Council, Northumbrian Water, Environment Agency, Newcastle University, consultancies (e.g. Arup, Royal HaskoningDHV, Stantec), major landowners	Ebbsfleet Development Corporation, Southern and Thames Water, Local Authorities, Kent County Council, Environmental NGOs
Current focus	Promoting Blue-Green infrastructure in Newcastle flood and water management practice and policy, opportunistic intervention, dissemination of best practice BG+G	Development of a system dynamics model that investigates current and future water use in Ebbsfleet
Impact	Incorporation of Blue-Green infrastructure in policy, e.g. Newcastle Local Flood Risk Management Plan (Newcastle City Council, 2016), Newcastle City Strategic Surface Water Management Plan, Newcastle Blue and Green Declaration (UFR, 2019)	The model will be used to generate future water use scenarios and provide a policy basis for future local policy making. It will also provide input to the Ebbsfleet Water Strategy, developed with Ebbsfleet Development Corporation.

Table 1 Characteristics of the Newcastle and Ebbsfleet Learning and Action Alliances (LAA). Note the different dates of establishment and longer operating period of the Newcastle LAA, and hence, potential for greater impact and outputs to date.

Discussion and concluding remarks

Transformative change in practice, policy and governance of flood and water management is necessary if global cities are to progress along the blue-green path to achieving urban flood resilience. Planning, design and implementation of urban water systems must be reconfigured towards greater water sensitive urban design and multifunctional BG+G infrastructure to effectively manage urban water under future climates characterised by more extreme weather events, and under future development scenarios whereby increased urbanisation stresses drainage infrastructure and reduces permeable greenspace in cities. UFR research contributes to the growing evidence base to support the case for multifunctional BG+G infrastructure that delivers multiple environmental, societal and economic benefits, and enhances urban flood resilience by bringing water management and green infrastructure together to create *Blue-Green Cities*. The main outputs (to date) and planned deliverables from ongoing research are now discussed in relation to their potential impact on current practice and policy.

Key to creating future flood resilient cities is the development of BG+G systems that may be co-optimised to maximum flood risk reduction, while delivering multiple co-benefits, under a range of future scenarios that account for climate and socio-economic change. The adaptation pathways approach that we present provides the rational basis on which to plan (long-term) and deliver urban water resilience in an uncertain future. The methodology and guidance on assessing a range of flexible adaptation pathways that has been developed by the UFR project allows the most effective mix of BG+G systems in any given location at any time to be determined according to site specific characteristics and requirements. The innovation for practice and policy lies in the evaluation of pathways rather than options in separation, and the co-valuation of multiple benefits. The approach (termed 'adaptive pathways') is promoted in the Draft National Flood and Coastal Erosion Risk Management Strategy for England as a mechanism to help places plan and adapt to flooding and coastal change across a range of climate futures (Environment Agency, 2019), suggesting that there is already interest from policy-makers and practitioners in this approach to delivering flood resilience. Developing urban flood and water management systems with the adaptive capacity essential to keep flood risk at acceptable levels however climate changes are further dependent on accurate modelling of urban hydrosystems that bridge the interfaces between urban/rural and engineered/natural hydrosystems. The CityCAT/SHETRAN combination presented in this paper advances current hydrosystems modelling by providing a physical basis for simulating the effects of land-use change, BG+G implementation, and climate change on runoff and water storage. The inclusion of antecedent conditions are crucial to understanding how a range of wet and dry soil conditions impact the runoff fraction and how, and when, a rainstorm may turn into an urban flood. The creation of impact maps from such modelling may provide a rapid assessment tool for flood risk practitioners, and identify appropriate location-specific BG+G infrastructure combinations based on how they impact local hydrosystems.

The importance of integration between urban water and other infrastructure systems is a concurrent theme in UFR research. The creation of interoperable BG+G infrastructure systems that aim to increase the functionality of the whole system (i.e. the city), and increase urban flood resilience while meeting the objectives of stakeholders working within other urban systems, e.g. transport and energy, is an exciting area of research within the UFR project. The spatial analysis framework that we present (described in greater detail in Vercruysse et al., (2019)) combines several components of UFR research. CityCAT is used to identify the source-to-impact pathways and help highlight locations for flood management intervention that will have the most impact on reducing flood hazard (and damages). Expert local knowledge from Newcastle LAA members further helped identify specific interoperability challenges in Newcastle. This also demonstrates how UFR research has become embedded in the Newcastle case study and how the LAA has facilitated social learning amongst academics and practitioners. By combining flood risk management with spatial information on urban infrastructure and social, political and environmental characteristics, the interoperability analysis framework will allow planners to identify opportunities for investment in resilient solutions for sustainable city development, and is currently being explored with Local Authority input.

UFR research has further investigated the potential for integrating urban water and energy systems, through the development of a screening tool to assess the feasibility of micro-hydropower generation from the controlled release of water from SuDS ponds (Costa et al., 2019). Nonetheless, the limited potential for micro-hydropower in the UK suggests that there are alternative, more effective, ways to utilise stormwater as a resource, such as RWH, which may provide both flood risk reduction and drought mitigation benefits at the property scale, with opportunities to upscale those benefits across urban areas. For RWH to reach its potential, planners and developers must move away from *ad hoc* and localised RWH schemes towards integrated catchment-wide strategies that utilise RMS to concurrently reduce water demand, stormwater discharge and energy usage. Active RMS have greater potential to optimise water supply demand and reduce stormwater discharge, as demonstrated by the Newcastle residential example presented here. The success of such systems in practice would be dependent on the levels of engagement, understanding and commitment by users to managing the system, which represents an interesting avenue of further research. There is typically a trade-off between supply efficiency and potential for stormwater control in RMS, influenced primarily by the frequency and severity of rainfall events, suggesting that local conditions would be essential in designing RMS that were fit for purpose in different parts of the UK. Conjunctive SuDS-Managed Aquifer Recharge systems may also be a viable option for addressing both stormwater management and drought mitigation, depending on hydrogeology and urban context, and is currently being investigated by the UFR Consortium.

Shifting the research focus to the interfaces between planners, developers, engineers and beneficiary communities, the final UFR research theme addresses the need for greater awareness of, and responsiveness to, citizens' physical, social and environmental preferences, and investigates how interactions between responsible authorities and stakeholders must evolve to enable cities to achieve flood resilience in ways that are sustainable and enduring. Novel measures that determine implicit preferences for BGI and SuDS have been developed that reveal insight into subconscious attitudes towards BG+G that may be used to improve public acceptability of features via better design (Fenner et al., 2019). IATs have the potential to help planners and policy-makers understand conflicting attitudes towards BGI that may not be captured by explicit measures, such as questionnaire and interviews, which are commonly used to survey public perceptions. For example, positive attitudes towards attractiveness of BGI may be offset by concerns over safety or perceived tidiness (which is highly subjective and based on how one values different types of nature i.e. manicured vs. wild). Understanding what influences implicit perceptions can guide planners and designers to solutions that are more highly valued and accepted. Greater sense of ownership, appreciation and care around BGI may also be encouraged by more effective BGI community engagement, which may be achieved by following the five fundamental principles outlined herein. Longer term engagement with potential beneficiary communities regarding the functional and amenity aspects of BGI are essential to build both capacity and awareness of communities and develop BGI designs that fit into the local context (environmental and socio-economic) and provide multiple benefits that are acknowledged and valued. BGI community engagement in flood resilient cities would be founded on collaboration and co-design between practitioners' and communities', improved community integration, inclusion of a range of community perspectives (including, where possible, the voices of groups that are typically perceived as disengaged), and a reduction in social inequalities through equitable access to quality blue-green space.

The transition towards flood resilient cities is also dependent on changing how integrated systems of BG+G and planned, delivered and maintained. Ongoing comparative research into SuDS implementation under a) strengthened English planning policy, which, to date, has resulted in suboptimal uptake, and b) introduction of Schedule 3 in Wales in January 2019, will reveal interesting insights into the effectiveness of these approach to governance, and help policy-makers and practioners understand where future challenges, and opportunities, lie. LAAs are also advocated as frameworks to help make the aspirations of multi-objective planning policies deliverable in practice by bringing together a range of invested stakeholders to debate, contest and ultimately co-produce multifunctional BG+G solutions to current challenges related to flood and water management, sustainability, wellbeing and climate change adaptation. The signing of the 'Newcastle Declaration on Blue and Green Infrastructure' by Newcastle LAA member organisations is positive proof that UFR research is being delivered through the LAA in a way that results in transformative change and supports Newcastle's' progress towards becoming a flood resilient city.

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