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Spatial Evaluation of Multiple Benefits to Encourage Multi-Functional Design of Sustainable Drainage in Blue-Green Cities

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Abstract: Urban drainage systems that incorporate elements of green infrastructure (SuDS/GI) are central features in Blue-Green and Sponge Cities. Such approaches provide effective control of stormwater management whilst generating a range of other benefits. However these benefits often occur coincidentally and are not developed or maximised in the original design. Of all the benefits that may accrue, the *relevant dominant benefits* relating to specific locations and socio-environmental circumstances need to be established, so that flood management functions can be co-designed with these wider benefits to ensure both are achieved during system operation. The paper reviews a number of tools which can evaluate the multiple benefits of SuDS/GI interventions in a variety of ways and introduces new concepts of *benefit intensity* and *benefit profile*. Examples of how these concepts can be applied is provided in a case study of proposed SuDS/GI assets in the central area of Newcastle; UK. Ways in which SuDS/GI features can be actively extended to develop desired relevant dominant benefits are discussed; e.g., by (i) careful consideration of tree and vegetation planting to trap air pollution; (ii) extending linear SuDS systems such as swales to enhance urban connectivity of green space; and (iii) managing green roofs for the effective attenuation of noise or carbon sequestration. The paper concludes that more pro-active development of multiple benefits is possible through careful co-design to achieve the full extent of urban enhancement SuDS/GI schemes can offer.

Keywords: Sustainable Drainage Systems; green infrastructure; Blue-Green cities; Sponge Cities; multiple benefits; benefit intensity

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1. Introduction

The purpose of this paper is to examine how the multiple benefits arising from urban drainage systems that incorporate elements of green infrastructure can be pro-actively considered during the design and selection process. This is important if flood mitigation benefits and the potential for wider positive impacts are to be simultaneously achieved.

In urban areas Sustainable Drainage Systems (SuDS) may form part of a network of Green Infrastructure (GI) that provide elements of the natural environment through provision of areas of vegetated open space. Such water management and flood mitigation interventions can deliver a wide range of other benefits which contribute to environmental, economic and social improvements in urban areas. For example, SuDS/GI solutions can contribute to ecosystem services and provide other benefits such as cost effective public health measures [1,2]. For example, it has been suggested the frequency of exposure to natural settings and the extent of vegetation cover may be important in improving human well-being, specifically in the realm of mental health [3]. A recent UK briefing note identifies the following benefits for urban green infrastructure: urban temperature regulation, improving air quality, reducing surface water flooding, reducing pollution of urban water courses, noise reduction, carbon storage, habitat and urban biodiversity, pollination and provision of community food [4]. Other benefits which can be important drivers for developers adopting SuDS/GI infrastructure are uplift in property value adjacent to Blue-Green space and enhanced amenity and recreational opportunities for residents [5]. CIRIA have summarised these multiple benefits as having the potential to provide direct economic value, amenity or aesthetic value, added environmental and ecosystem value, and social value [6]. Some of these benefits (such as pollination) accrue to the immediately adjacent urban areas. Others (such as carbon storage) may contribute less directly, but are exerted over longer time periods at regional, national and international scales.

Trends in urban drainage design have moved towards source control measures using natural drainage processes through vegetated above ground features such as swales, storage ponds and rain gardens. Therefore these wider potential benefits are being more actively discussed in the discourse around Blue-Green cities in Europe [7], Sponge Cities in China [8] and Water Sensitive Urban Design in Australia [9] (as defined in Table 1).

Table 1. Comparison of terms commonly used in different geographic regions.

Term	Short Definition
Blue Green Cities	A Blue-Green city aims to recreate a naturally oriented water cycle while contributing to the amenity of the city by bringing water management and green infrastructure together [10].
Sponge Cities	A Sponge city refers to sustainable urban development including flood control, water conservation, water quality improvement and natural eco-system protection in which a city's water system operates like a sponge to absorb, store, infiltrate and purify rainwater and release it for reuse when needed [8].
Water Sensitive Urban design	Water Sensitive Urban Design encompasses all aspects of integrated urban water management and is significant shift in the way water related environmental resources and water infrastructure are considered in the planning and design of cites, at all scales and densities [11].

The benefits that are most relevant in a given location will depend on the contextual environmental, social and economic characteristics of the immediate area being served. It has been suggested that communities are more likely to support green interventions if they enhance cultural services [12]. However, trade-offs may have to be made between the level of provisions of different benefits [13,14]. It should also be accepted that not all green infrastructure interventions have positive outcomes. Some negative effects potentially may arise, for example from the introduction of pests and diseases and perceived increases in crime in areas with increased vegetation cover [15]. Also inequalities in terms of the section of a community to which benefits accrue have been recognised based on factors such as age, gender and socioeconomic status [16].

In the UK co-ordinated strategies to foster the multi-functional benefits of green infrastructure solutions are being encouraged [4]. However only 48% of local authorities have current green space strategies (reducing from 76% in 2014) and even less have green infrastructure strategies for the creation of new sites. Nevertheless cities such as Birmingham, Manchester and London are producing green infrastructure plans as adaptation measures to manage flooding, climate change and other risks. But maximising the wider range of benefits achievable from green infrastructure requires the right physical interventions in the right place. However, little collaboration has been found between the statutory and non-statutory players in GI planning and the group of organisations managing SuDS. In particular the complex interdependencies between the urban components and stormwater management using SuDS/GI have not yet effectively been translated into governance interactions between the variety of responsible agencies and wider stakeholders [15].

Often urban infrastructure components are analysed on different scales and frequently this is done independently to other components. This is highlighted by the fact that in the UK there are no policies/documents concerning the integration of both SuDS and GI elements. Furthermore there are no planning rules on urban forms which are based on the available evidence for ecosystem service provision [4]. Fundamentally this results from a failure to act at a systems level, partly arising from the administrative arrangements reflecting discrete responsibilities for different types of asset groups. The lack of effective UK legislation, such as a UK SuDS Approval Body (SAB) as intended in the 2010 Flood and Water Management Act, and little regulatory control on SuDS design, construction and maintenance, are also cited as significant barriers that hamper progress [17].

Despite the known benefits of SuDS/GI to urban drainage and flooding problems, widespread implementation of such schemes has been restricted by uncertainties regarding hydrological performance and service delivery, and a lack of confidence that decision makers and communities will accept, support and take ownership of such infrastructure [18]. Barriers to sustainable water management include scientific, technological/technical, institutional, legal, managerial, political, monetary and social, but with social-institutional barriers typically posing the greatest hindrance. Sheer resistance to change represents a particularly relevant socio-institutional barrier for more widespread uptake of SuDS/GI [10]. Surprisingly in the UK these approaches are still regarded as "novel", despite the many successful schemes that are in operation.

A study of barriers to the uptake of SuDS/GI in Newcastle, UK was undertaken through a series of semi-structured interviews with 19 professional stakeholders, with the 5 most prevalent barriers being classified as socio-political [10]. Respondents were asked how these barriers could be overcome. The most prevalent response (63%) was the promotion of multifunctional space and identification of the multiple benefits. Respondents commented that:

> "If [a SuDS scheme] is similar in cost but you can highlight all these other benefits that link with our sustainability target, our air quality improvements, then straight away they would be happy to sign off as a project".
>
> And
>
> "... you need to think about the multi-functional use of space!".

This raises the challenge of how the multiple benefits of SuDS/GI can be identified and quantified (and monetised), particularly with respect to the benefits that accrue during the everyday non-flood state (e.g., carbon sequestration, habitat and amenity improvements). This state has been defined as the first domain in the 3 Point Approach to urban flood management, reflecting day-to-day performance when there is little or no rain [19]. The optimal approach to creating multifunctional and resilient infrastructure may be through changing how SuDS/GI are planned and delivered towards greater collaborative working and co-funding from organisations and departments with a wide range of remits [10]. Most significantly this multi-functionality should be acknowledged at the institutional level.

The remainder of this paper examines how the potential multifunctionality of SuDS/GI assets can be actively embraced in the design process, first by drawing on a range of tools to identify where the most important benefits lie and then discussing examples of how specific modifications to different kinds of installation can be made to deliver such enhanced performance.

2. Propositions to Address Benefits in SuDS/GI Design

The foregoing provides a background context to three propositions which will be explored in detail in the remainder of this paper. These are listed as follows:

2.1. Proposition 1: Multiple Benefits from SuDS/GI Assets Emerge Coincidentally

Systematic procedures for pro-actively developing drainage infrastructure to deliver a specified range of predetermined desirable multiple benefits are rare. For example in the UK, in developing Sustainable Drainage Systems little if any direct attention is given to the planning of wider benefits that can be expected to be associated with a mature installation. The focus is on achieving the primary function of capturing, storing and infiltrating rainfall and reducing surface runoff flows. Thus multiple benefits may emerge sporadically, coincidentally or even accidentally from SuDS/GI interventions.

GI approaches to achieve general urban greening and improving visual and recreational amenity is at the heart of water sensitive urban design. However consideration of wider potential performance is beyond the remit of most SuDS designers who may wish to see specific evidence of possible benefits, before explicitly addressing how these may be actively delivered. A range of benefit evaluation tools exist to support suitable choices at the design stage, and these are briefly reviewed Section 3, where new concepts of benefit intensity and benefit profile are also introduced. A stronger justification for implementing SuDS/GI approaches can be made if a simultaneous and explicit case can be demonstrated for the wider multiple benefits they can achieve, rather than relying that they may occur fortuitously once an asset has been installed.

2.2. Proposition 2: Agreement Is Needed on Relevant Dominant Benefits

It is clear from many studies that not all benefits occur simultaneously, and some benefits may preclude the establishment of others [14,20]. For example, in a flood plain restoration scheme in the Johnson Creek watershed in Portland Oregon, recreational benefits were found to be in direct conflict with habitat and biodiversity benefits [21]. Therefore not all the multiple benefits from SuDS/GI are realisable all of the time. What is important is to establish a smaller subset of benefits that provide the greatest benefit uplift, uniquely agreed for each site's location specific circumstances. The uplift in each benefit category should be referenced against initial prevailing condition states based on local and contextual environmental performance which already pre-exist in a given location. In this way the **dominant** benefits which provide the greatest discernible change can be established. Just as importantly the principal beneficiaries of this change can be identified. A methodology for achieving this is outlined later in this paper.

A parallel activity would be to engage with local stakeholders to explore priorities and preferences through engagement in Learning and Action Alliances (e.g., [22]) and other forum. It is then a simple step to weight the benefit categories following a systematic survey of the communities and users who will be affected by the flood mitigation proposal. This modification to a neutrally weighted analysis, could help define which are the **relevant** benefits in each location.

2.3. Proposition 3: Systems Should Be Co-Designed to Deliver Both a Flood Control Function and Wider Multiple Benefits

The purpose of refining the benefit evaluation is to create a positive feedback loop into the asset design (Figure 1). The notion of circular or iterative design is not new, and the adjusted or refined design can thus be informed by an understanding of the relevant dominant benefits that might be achieved from a proposed SuDS solution. This will allow the principle drainage function of SuDS/GI to be co-designed with the delivery of the subset of relevant dominant benefits pertaining to site specific contexts and circumstances. In this way the important benefits may be actively enhanced through initial design modifications and the specification of subsequent maintenance and management strategies. Examples of how such refinements could be made are discussed towards the end of this paper in Section 5.

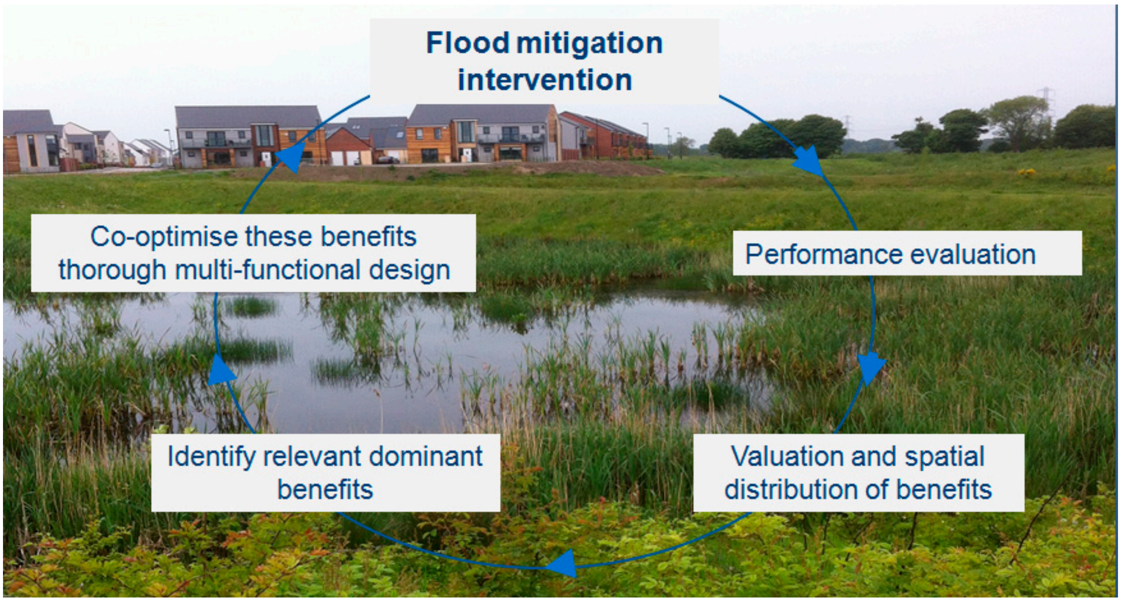

Figure 1. A positive feedback loop to reinforce multi-functional design of relevant dominant benefits in urban drainage systems that incorporate elements of green infrastructure's (SuDS/GI).

3. Benefit Evaluation Tools

A range of methodologies and tools have been proposed to establish and quantify the range of benefits discussed earlier. Such tools are required to evaluate both the primary functions of SuDS/GI and their wider benefits so these kind of assets can be proactively co-ordinated to achieve multi-functionality. Much useful analysis can be found in the literature on ecosystem services to help improve the understanding of multiple benefits which emerge from aspects of urban greening. For example it is now understood that the multi-functional and multi-scale nature of green urban infrastructure can lead to interactions between these benefits at different scales [23].

Methodologies which have been used include life cycle assessment [24,25], scenario planning [26], expert knowledge [27] and modelling using tools such as i-Tree and EnviroAtlas [28,29]. Jayasooriya. and Ng reviewed 20 modelling tools for managing urban flooding and the economics of GI practices. They noted there is a trend for recent tools to include a Geographic Information System (GIS) interface, and called for more tools to incorporate the range of ecosystem services and social benefits which SuDS/GI practices can provide [30]. Recently techniques have begun to emerge which represent the spatial distribution of ecosystem services by normalising each benefit value to a common scale and aggregating these spatially in a GIS platform [31–33].

A novel example of this kind of spatio-temporal approach to Blue-Green infrastructure design and modelling has been produced by the Urban Europe Green/Blue Cities Project. This is based on an integral, multi-scalar and adaptive Blue-Green infrastructure design methodology [34]. By focusing specifically on Kiruna in Sweden and Zwolle in the Netherlands a set of design principles were developed to support the delivery of 'nature' in cities. This was considered at a range of scales to utilise the wider opportunities 'natural systems' can bring to create and sustain better places for people and ecosystems. A decision support system was provided combining both spatial and temporal modelling so the additional value that Blue-Green infrastructure delivers to the quality of urban living could be advanced in terms of identifying the innovation practices required. In both cities a water sensitive urban structure was modelled showing priorities of investment and transformation of the built environment. The range of ecosystem services brought by Blue-Green infrastructure were considered crucial components for the mainstreaming of SuDS/GI solutions.

Some tools provide a cost benefit analysis through a structured assessment to help quantify and evaluate the monetary value of each benefit. However, Spengenberg and Settele have cautioned that monetised results are context and method dependent, and can fail to reflect complex interactions between benefits, and where value transfer is adopted large uncertainties can accrue [35].

A recent tool to help make the business case for SuDS has been developed in the UK by CIRIA (Benefits of SuDS Tool: BeST) (http://www.susdrain.org/resources/best.html) which enables a financial assessment of related Blue-Green solutions to be made [6]. BeST provides a structured approach to evaluating a wide range of benefits and is based on a simple structure, that begins with a screening and qualitative assessment to identify those benefits to evaluate further. On completion of the evaluation, the tool provides a series of graphs and charts based on Ecosystem Services (ESS) and Triple Bottom Line (TBL) (criteria. (N.B. Ecosystem Services criteria relate to supporting, provisioning, regulating, and cultural services); Triple Bottom Line criteria relate to environmental, social and economic domains). BeST doesn't account for every individual circumstance or site specific nuance, relying on the user to contextualise the scheme into the framework of the tool, nor does it provide a detailed distributional analysis of where the benefits will accrue. Application of the tool in the UK has revealed that many of the more substantial benefits from SuDS/GI are not those related to flood, drought or water quality, but those which accrue to amenity and human health, especially for distributed interventions across a catchment [5]. Reinforcing the propositions made earlier in this paper, these authors conclude that opportunities to maximise wider benefits to society are lost where the approach to 'drainage' uses the traditional paradigm of just getting the water away quickly and safely.

To help determine which are the **relevant** benefits to actively pursue in a given location, an Adaptation Support Tool has been developed by van de Ven [36] This can be used to inform stakeholders on the adaptation options they have and where and how effective and costly these would be. The tool contains 72 blue, green and grey adaptation measures to choose from and provides an effectiveness appraisal based on performance metrics detailing storage, peak flow reduction, heat stress reduction, water quality effects and calculates the costs of each adaptation measure and of the total package. Through using a touch-table with a professional facilitator, participants become fully aware of the ecological, recreational and social effects and co-benefits of specific adaptation solutions. The spatial, social, ecological and economic consequences of proposed measures are extensively discussed and decisions on the value of a range of co-benefits of Blue-Green infrastructure can be collectively generated to guide specific designs.

4. Spatial Evaluation Using Concepts of Benefit Intensity and Benefit Profile

Benefit evaluation can be particularly effective when it is used to assess the benefit uplift in a specific location against a chosen initial condition state, or against an alternative (e.g., piped) drainage strategy. This can help make a rational comparison between the magnitude of benefits that can be achieved and hence can identify those benefits that are worth actively pursuing and enhancing through multi-functional design. Furthermore if the spatial distribution of benefits are analysed then it is possible to identify where (and to whom) the overall aggregate benefit occurs and how this is valued by community stakeholders and beneficiaries can be established.

In developing such a methodology Hoang, Fenner and Skandarian emphasise 5 key points [20]:

(i) The general impacts of SuDS and associated Blue-Green infrastructure may include both benefits and dis-benefits and these are context-dependent.

(ii) Trade-offs may occur between different benefit categories for a range of installation types, and these in turn are also influenced by specific local contexts and prevailing background environmental conditions.

(iii) Many of the added benefits are incremental and need to be assessed in relation to the level of similar services which pre-existed in each specific location (i.e., in relation to an initial condition state), and the rate they develop over time.

(iv) It can be difficult to compare directly across non-commensurate benefit categories to establish the relative contribution that each can deliver in specific of local circumstances, individual site characteristics and against preferences of local communities.
(v) Benefits can accrue to different stakeholder groups other than the asset owner and these are distributed across spatial scales from local to regional to global.

The benefits or dis-benefits arising from SuDS and Blue-Green Infrastructure can span various categories. Each of these categories can be characterised by a different metric. This makes direct comparison of the relative performance of benefits difficult. Furthermore, the absolute values of each metric offer little insight to the contribution of each benefit, in relation to pre-existing services/benefits in a specific location. Normalising the benefits according to each location's conditions and context helps identify the extent of the benefit uplift relative to an initial condition state and this allows a balanced comparison across the categories to be made.

One approach has been to normalise ecosystem services on a scale of 0 to 10, by representing the ecosystem service relative to the maximum value achieved in any single discrete land parcel across the site of interest [32]. This technique of normalising as a ratio to the maximum value attainable in the site of interest is transferable to representing benefit categories across grid squares in a GIS platform.

Benefit Profile and Benefit Intensity

Building on this approach, Morgan and Fenner [37] have introduced concepts of benefit profile and benefit intensity, described here as follows:

A Benefit Profile can be created by comparing the normalised impacts across multiple benefit categories to reflect the relative extent of the benefit uplift and the total area affected in each category, combined with the effectiveness/potential of each benefit achieved.

The normalised values could be computed as simple ratios, depending on the purpose of the evaluation, such as:

- Benefits from SuDS/GI infrastructure solutions: benefits from alternative (piped?) solutions.
- Benefits after installation of an asset: pre-existing benefits before the installation of an asset.
- Potential benefits at some future time: realised benefit occurring now, etc.

The benefit profile can be presented as a bubble chart which incorporates the concept of how much potential benefit is realised by the scheme (Figure 2). This allows both the *size* of each benefit to be compared together with the *extent* to which it is accruing. Some benefits might be restricted to small local areas only whilst others may be more widely distributed across a wider area of the overall site. Each benefit category can also be represented as a dis-benefit, so for example, habitat creation may also raise concerns over the possibility of harbouring disease vectors.

The total benefit score for each benefit category is the 'headline' figure accumulated across all grid squares and identifies if there has been an improvement or not beyond the initial condition state. This is plotted against the area over which a benefit is generated so the extent over which each benefit has influence can be compared. The size of each bubble then represents the effectiveness of the benefit related to its specific location. A small bubble suggests that in the specific location being considered there is only a low potential for improvement in that benefit category. For example, despite extensive planting of vegetated surfaces and the increase in leaf area which provide the potential for significant pollutant trapping, little uplift in pollution mitigation would be seen if air quality was initially already in a good state, (with no pollutants in the atmosphere to trap as the site is far from high densities of road traffic). A large bubble approaching the full size indicates that all the potential benefit is being realised across the site. From this representation, it becomes clear which are the dominant benefits worthy of actively pursuing through the design process. In the hypothetical example shown in Figure 2 this would be flood mitigation (being the primary function of the drainage installation) and access to green space.

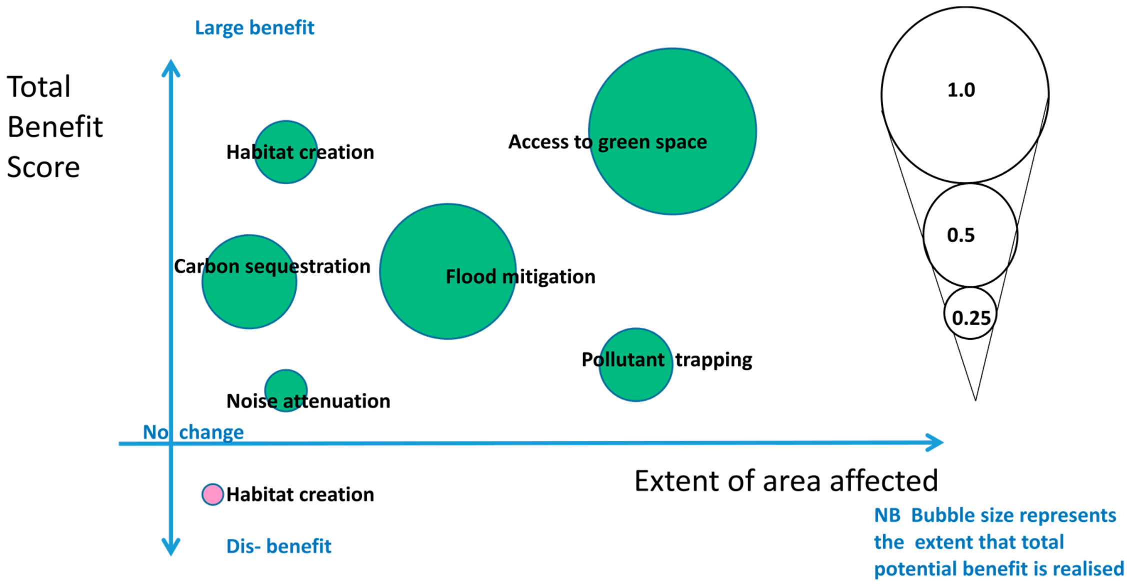

Figure 2. Idealised Benefit profile represented as a bubble chart.

Benefit Intensity is the spatial distribution of the unweighted accumulation of multiple benefits emanating from a SuDS/GI intervention(s) over the adjacent urban area. It is generated by the summation of all the normalised benefit scores in each grid square. As a further refinement, a weighted spatial distribution can also be developed to reflect the way local communities and stakeholders prioritise the importance/significance of each benefit category.

A set of benefit evaluation tools for ArcGIS 10.X has been developed, from which the above parameters can be calculated. The tools are designed to work with Ordnance Survey data commonly available in UK cities and are available at available at: http://www.bluegreencities.ac.uk/bluegreencities/index.aspx. The grid square resolution over which the calculations are performed can vary from 1 m × 1 m to 30 m × 30 m, depending on the purpose and scope of the analysis. These tools have been used to generate benefit intensities and benefit profiles arising from flood mitigation interventions in a number of cities including Portland, USA [20] and Newcastle, UK [37]. In the latter location, six benefit categories were modelled to demonstrate the approach, including access to greenspace, air pollution trapping (PM_{10}), carbon sequestration, flood damage avoided, habitat size and noise attenuation.

Simple computer models were used to identify the extent of each of these benefits in each grid square which were pre-existing under an initial condition state. The calculations were then repeated to compute the level of benefits which could be achieved after the introduction of the SuDS/GI asset(s). Scores in each grid square were then generated for each benefit based on the relative change between these two states.

Raster maps were produced for each benefit category showing both the before and after condition preceding and following the SuDS/GI drainage intervention. For access to green space a raster cost distance calculation was performed twice for all green space greater than 500 m^2 and for all green space between 50–500 m^2. Pollutant trapping was based on the dispersion of PM_{10} taking into account distance from the road network, with different land covers absorbing or blocking PM_{10} particles. Carbon sequestration was also based on twelve land cover types with higher values assigned to woodland and lower rates to grassland, and man-made surfaces assigned a zero score. Flood damage avoided was computed utilising the CityCat Urban Flood Model (developed by Newcastle University, Newcastle, UK) and multiple return periods were considered to find the annualised damage risk. Different depth-damage curves were constructed for each land use and building class data. Habitat size considered the value of having connected green spaces and the GIS tool identified clusters of interconnected green space and estimated the number of species supported by each cluster, with large areas calculated as supporting species density of around 500/m^2 while smaller areas could be as low as 15/m^2. Finally noise attenuation was based on traffic noise emanating from the road network and a cost-distance calculation was performed for each of seven noise levels based on attenuation with distance, terrain and surface material and obstacles.

Each of the six individual benefit distributions can then be added together for an overall multiple benefit distribution, to portray the Benefit Intensity across the area where the SuDS/GI infrastructure is currently or intended to be installed.

This approach provides two advantages to existing methods of benefit evaluation. Firstly, the spatial distribution of benefits is considered allowing beneficiaries to be identified in the adjacent communities. Secondly, the benefits are context specific. For example, a small addition of green space in an area with little green space may derive a greater benefit uplift than a large addition of greenspace in an area that is already very green; such as in areas having the presence of pre-existing park land.

The primary output of the tool are maps of benefit intensity identifying where the greatest improvements have been achieved for each benefit category individually and for all the benefits collectively. These maps can be interrogated for information on specific locations or presented as aggregate benefit profiles so that the relevant dominant benefits in a given location can be clearly identified. Once these benefits are established (and confirmed as having merit and meeting the needs of the local community) design and site management practices for the SuDS installation can be adjusted or modified where necessary to optimise the benefits which have been identified as having the most impact.

An example is shown in Figure 3 of how the distribution of individual benefits arsing from a range of proposed interventions (including green roofs, permeable paving, swales, and street trees) in the urban core of Newcastle city centre can be cumulatively depicted as an overall benefit intensity. A further step would be to weight the different benefit categories on the basis of stakeholder preferences following a systematic survey of the communities and users affected by the proposals. This modification to the neutrally weighted analysis presented here could help confirm which dominant benefits should be optimised through initial design and subsequent maintenance and management strategies.

Figure 4 shows the benefit profile for the Newcastle urban core. In this case, a small but effective increase in carbon sequestration is achieved from the increase in natural surfaces such as green roofs. There is a moderate increase in access to greenspace, as green roofs were assumed to be publically inaccessible and so did not contribute to the access benefit score. Finally, a moderate reduction in flood damage is generated, mostly attributable to the performance of the proposed swale along St James' Boulevard. (N.B. The minor flood dis-benefit shown in the benefit profile is caused by a slight misalignment between the flood modelling and the land use map).

The approach is flexible such that other benefit layers could be easily added provided they can be represented by a spatial component. The method can also be adapted to incorporate more advanced models of the benefit categories considered. The method can identify beneficiaries and which parts of a community receives the benefits and can be used to contrast multiple design options rapidly. In doing so it would be suitable for use in the early stages of designing a SuDS/GI scheme. The benefit intensity maps produced may also be useful during consultation with stakeholders and for wider urban planning purposes.

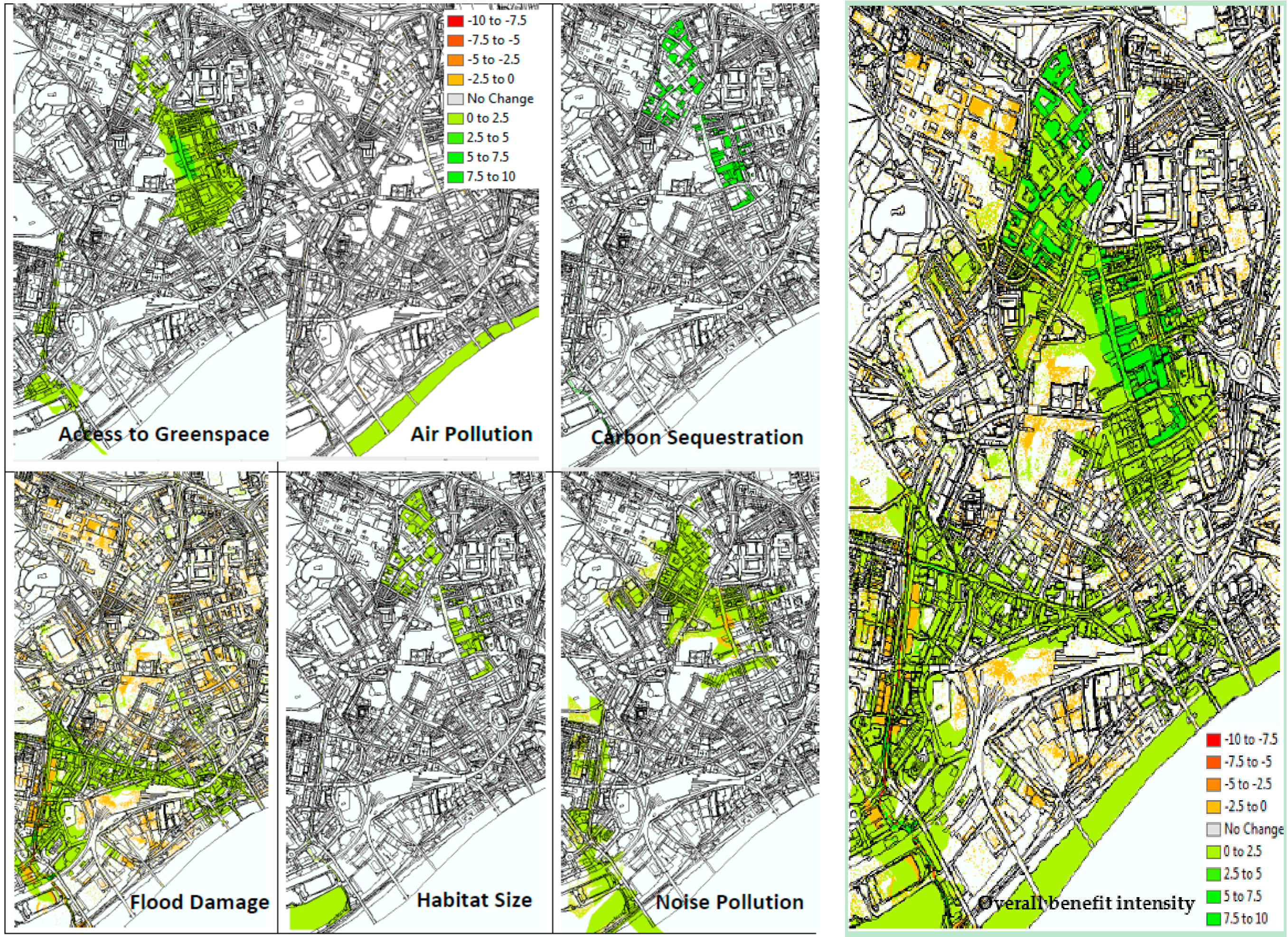

Figure 3. Spatial distribution of individual benefits and accumulation into an overall benefit intensity of SuDS interventions in Newcastle urban core.

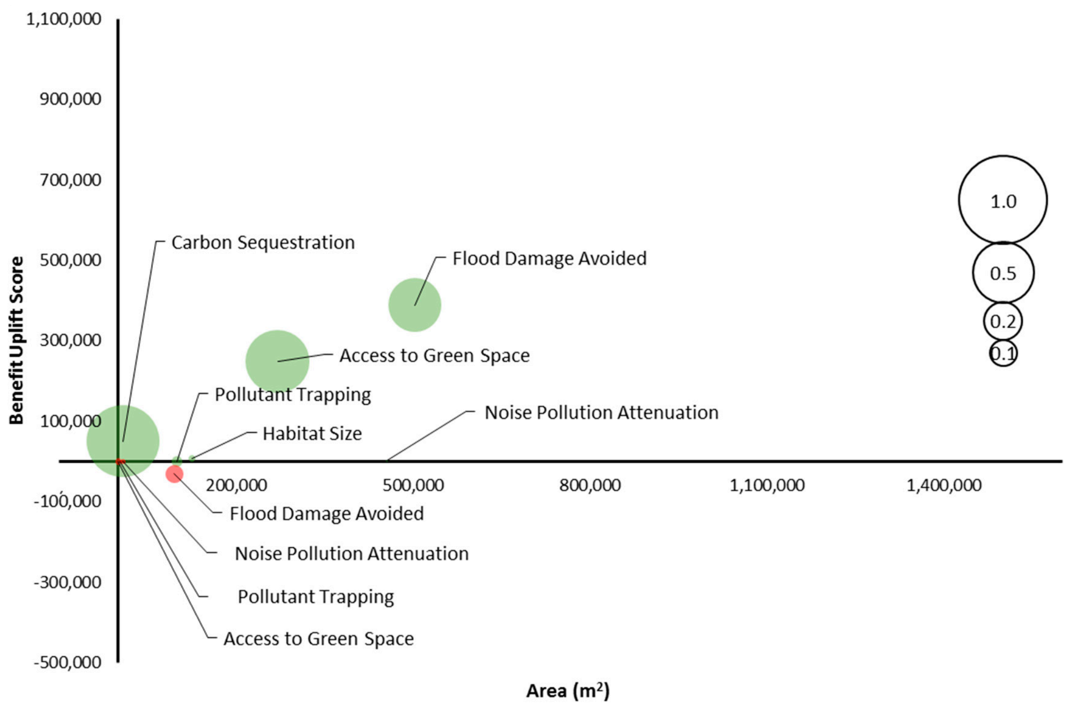

Figure 4. Benefit profile for Newcastle urban core (after Morgan and Fenner [37]).

5. Discussion of Design Modifications for Typical SuDS/GI Assets

Proposition 3 suggested that stormwater management systems should be co-designed to deliver both a flood control function and wider multiple benefits. The first step in achieving this requires the identification of a focussed subset of site specific **relevant dominant benefits**, which can be selected by using the tools described above. The next step is to co-design systems from this broader perspective to achieve these desirable multiple benefits. The nature of the design modifications which may need to be made to achieve this are discussed below for three typical SuDS/GI schemes: green streets, bioswales and green roofs.

5.1. Green Streets: Pollutant Trapping Benefits

Green streets are frequently designed for stormwater management purposes, but they also have the potential to reduce air pollution through trapping on leaf surfaces. In areas that suffer from significant levels of PM_{10} air pollution due to the close proximity to high levels of road traffic, this potential for pollutant trapping may be considered as an important additional benefit. However the installation of street trees must be carefully designed and maintained to enhance, and not worsen, local air quality. Studies have shown that adding vegetation, especially trees, to hot-spots of air pollution (e.g., poorly ventilated areas along streets) can *increase* pollutant concentrations by further restricting air flow and exchange [38]. Conroy has shown the strategic placement and design of green infrastructure is necessary to enhance PM_{10} capture and to prevent the possibility of green infrastructure inadvertently worsening air quality [39]. When trees are planted within street canyons, careful management of the crowns, including pruning, is recommended to promote air flow [40]. Recommendations include: adequate space between the tree crowns and nearby walls, tree height shouldn't exceed the height of nearby buildings, and planting fewer trees is better [38,41]. For green streets within street canyons, designers may want to limit the number of trees in bioretention cells and suspended pavement systems and focus on using stormwater measures based on herbaceous vegetation (e.g., bio-retention cells and bio-swales). The close proximity of the vegetation to the PM_{10} emission sources maximizes the efficiency of interception and deposition; also, the smaller size of vegetation in installations such as street gardens does not significantly hinder air flow within the street [42].

Care must be taken not to limit the upward flow and dispersion of air and pollutants, therefore it is vital for stormwater and air quality researchers to determine the performance, optimal design, and best placement of vegetated stormwater control measures within green streets with regard to reducing PM_{10} concentrations [39].

5.2. Marginal Additional Investments: Leverage Multiple Benefits

Actively seeking a wider set of enhanced benefits can sometimes be achieved by small marginal additional investments [43]. By applying the BeST tool in Roundhay, Ashley showed that the value provided by a SuDS scheme was mostly from benefits other than those directly managing stormwater [5]. 43% of the financial benefits for Roundhay accrued from increased property values. Analysis of the potential for leveraging further benefits for Roundhay by marginal additional investments showed that increasing the numbers of trees from 250 to 1000, increases residents' views over green space for up to 500 people, and health benefits increased proportionally to some 25% compared with the original 6% of total value. Nevertheless, for Roundhay, flood risk reduction provided the largest continuing benefit longer-term, as the amenity benefits no longer were considered part of the overall benefits after the first year, as these benefits accrue immediately following construction [5]. Furthermore the scheme has to be adequately maintained to prevent a decline of amenity values in the future.

5.3. Swales and Linear SuDS/GI Installation: Greenspace Connectivity Benefits

Urban green infrastructure usually consists of a fragmented mosaic of diverse smaller patches of vegetation with different uses within which large areas such as parks are set. Connecting such areas together in the form of urban corridors can have substantial benefits both in amenity terms and for the linear movement of wildlife. With some additional thought at the design stage some linear SuDS/GI schemes such as swales might be marginally extended to provide the mechanism for linking these patches together. The new development in Camborne, Cambridgeshire, UK linked three villages, Upper Camborne, Greater Camborne and Lower Camborne, and was built on 40 ha of former arable land. The master plan for the development protected the remaining areas of semi-natural habitat and linked them together with a variety of new green infrastructure, such as woodland planting, meadows, lakes, amenity grassland, playing fields, allotments and formal areas [4]. The scheme includes 10 miles of new hedgerows and green infrastructure which accounts for 240 ha of the development such that the levels of biodiversity on the site are now higher than when it was arable farmland.

A useful tool to quantify this ability to join up areas of green space is the Integral Index of Connectivity (*IIC*) defined by Pascual-Hortal L. and Sauroa S., and is expressed as [44]:

$$IIC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i \times a_j}{1 + nl_{ij}}}{A_L^2}$$

where: a_i = Area of each habitat patch
nl_{ij} = Topological distance between patches I and j
A_L = Area of Study

Within the Camborne development is Lamb Drove, a small area devoted to the introduction of a range of SuDS measures, which have been systematically monitored over a long period of time. Applying this index to the Lamb Drove installations showed a benefit uplift in the connectivity of 1.34, from the SuDS interventions in the immediate area [45]. Co-designing SuDS/GI schemes to provide both a flood mitigation benefit and improved green space connectivity is a clear example of where multi-functionality can be achieved.

5.4. Green Roofs: Noise Attenuation and Carbon Sequestration Benefits

Hoang and Fenner showed the benefits that can accrue from green roofs will be dependent on how the installations are managed [13]. These benefits can include hydrological performance regarding runoff retention and storage, carbon sequestration, noise attenuation, building and urban cooling, pollutant trapping, food production, biodiversity and social and amenity benefits. However different functions of a green roof can prevail under different conditions. The main determining factors of these conditions are the heat and water budget of the roof. The functions have strong dependencies on soil moisture and characteristics of the vegetation and the soil cover. Also different green roof functions prevail under different physical conditions and that green roof functions may occur in phases or continuously. In particular, high soil moisture can diminish the functioning of noise attenuation, and limits the capacity for stormwater uptake but could enhance photosynthesis, carbon sequestration and heat exchange of the roof. The nature and density of planting are other important variables which can achieve different outcomes. So again an element of co-design is required to achieve the relevant dominant benefits required.

6. Conclusions

Ashley R. et al. have made the following observation [5]:

> "If the added benefits to society that can be provided by using SuDS/GI are to be realised then the 'drainage' perspective needs to be supplanted by one in which Blue-Green infrastructure is seen as a starting point for the planning of land use and property development or renovation; i.e., it is no longer 'drainage' that we need; rather what can be achieved is too valuable to be so pigeonholed".

This paper has argued that more needs to be done to pro-actively consider the wider outcomes and benefits that can provide multiple positive gains from the implementation of SuDS/GI solutions for urban drainage and urban flood mitigation. This will involve a systematic appraisal of which benefit opportunities offer the most potential gain in a given location, and meet the expectations and desires of local stakeholders. Such an approach will avoid such benefits being left to occur coincidentally or by chance and so maximise the case for the adoption of SuDS/GI assets by addressing the aims and goals across a wider urban planning framework. To make this case sufficiently convincing the tools that are being developed to evaluate the multiple benefits from SuDS/GI need to be regularly applied so that these **relevant dominant benefits** can be identified for each location and context specific circumstances. This can drive more effective co-design so that areas of truly multi-functional green space can be realised in so many urban locations.

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