A conceptual approach for evaluating the multiple benefits of urban flood management practices

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DOI: 10.1111/jfr3.12267

Key words
Benefit dependency; benefit intensity; benefit profile; flood management; floodplain restoration; green infrastructure; urban flooding.

Abstract

This paper focuses on the spatial distribution of the dominant and relevant benefits of urban flood management based on context- and location-specific evaluations. We explore the conceptual rationale and describe a detailed methodology for assessing the *benefit profile*, *benefit intensity*, and comment on *benefit dependencies* arising from urban flood management practices that utilise green infrastructure. A case study is described which demonstrates the application of the concepts in Portland, Oregon, USA. A Geographic Information System approach is developed to evaluate some of the multiple benefits of the East Lents Floodplain Restoration Project. Results are presented in the form of a comparative benefit profile, and a spatially distributed benefit intensity. The paper concludes with the implications of the methodology for future multiple benefit evaluation of urban drainage and flood management systems.

Introduction

An important principle in the design of sustainable infrastructure is to seek multifunctionality in asset performance. In justifying approaches to flood risk management which prioritise the use of green infrastructure (GI) and restored natural systems over alternative pipe and concrete channel solutions, there is a need to understand the wider benefits that such approaches can deliver and where and to whom they accrue. This need is particularly pressing for flood risk reduction applications, because constructed solutions tend to have larger volume storage and flood reduction/mitigation capabilities than the individual small-scale assets designed to manage water from more frequent storms. Their potential wider benefits, therefore, can be more extensive.

Many practitioners seek to monetise the disparate range of multiple benefits, which can accrue for incorporation in conventional cost-benefit balance sheets, and tools have recently been developed that attempt this (e.g. CIRIA RP993, 2015). To complement these methods, the approach described here is to place the benefit appraisal in a local context (as a relative uplift from an initial existing condition state) and to completely understand their spatial distribution and aggregated impact on a range of stakeholder groups and beneficiaries. Furthermore, it is important to balance such analysis by explicitly assessing the possible disbenefits that can arise from some installations. This represents a first step towards incorporating such a benefit appraisal into a multi-criteria decision format, for example, by using a simple approach based on the Analytical Hierarchy Procedure, through systematic pairwise comparison of benefits.

The literature on urban storm water management, flood management, Sustainable Drainage Systems (SuDS), and Best Management Practices (BMPs) increasingly refers to the variety of multiple benefits which can be provided by assets based around vegetative surfaces and GI (Benedict and McMahon, 2012; Walker *et al.*, 2012, Ellis, 2013). GI can be considered as an interconnected network of multifunctional green spaces and the flood risk management services, such GI projects provides, have been utilised over a range of urban areas in the United States, Australia, and Europe. Meanwhile, SuDS are increasingly regarded as an approach to realise the wider benefits of managing surface water beyond their flood risk and drainage function, such as offering multifunctionality in water quality and wildlife habitat (Henry, 2012; Walker *et al.*, 2012). Such installations are collectively referred to here as SuDS/GI.

However, effective integration of SuDS/GI into the existing urban fabric requires further understanding of SuDS/GI hydrological, ecological, and social benefits as well as trade-offs, where they interact with other aspects of urban infrastructure (Hoang and Fenner, 2016). A meta-study of the literature by Demuzere *et al.* (2014) showed that the multifunctional and multiscale nature of green urban infrastructure also leads to interactions between these benefits at different scales. For example, at the small scale of a single green roof, Hoang and Fenner (2014) have shown that several benefit categories can be dependent on the same controlling variables but may respond in different ways to variations in those variables. So, low soil moisture enhances water retention but reduces noise attenuation capacity and vice versa. This suggests in many circumstances, co-optimising all potential benefits simultaneously is not achievable.

Designing these kinds of assets to achieve multifunctionality requires decision support tools to evaluate both SuDS/GI primary functions and their wider benefits. Various tools and methodologies have been proposed, such as life cycle assessment (Casal-Campos *et al.*, 2013; Flynn and Traver, 2013), scenario planning (Hilde and Paterson, 2014), expert knowledge (Kopperoinen *et al.*, 2014), cost-benefit analysis through a structured assessment to help quantify and evaluate each benefit (CIRIA RP993, 2015), modelling using tools such as i-Tree and EnviroAtlas (Kim *et al.*, 2015; Pickard *et al.*, 2015).

Jayasooriya and Ng (2014) reviewed 20 modelling tools for managing urban flooding and the economics of GI practices and noted the trend for recent tools to include a Geographic Information System (GIS) interface, calling for more tools to incorporate the range of ecosystem services and social benefits which GI practices can provide. Techniques are emerging 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 (Dobbs *et al.*, 2014; Lauf *et al.*, 2014; Turner *et al.*, 2014). However, Spengenberg and Settele (2010) 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.

With this background, this paper proposes a new integrated methodology that highlights the relevant and dominant benefits of urban flood management adopting SuDS/GI using a GIS approach. The methodology emphasises four key points. Firstly, general impacts of SuDS/GI assets may include *both* benefits and disbenefits and these are *context-dependent*. The significance of each benefit must be assessed in relation to socioeconomic circumstances and environmental conditions prevailing in the local area, where each urban flood management solution is installed. Controlling factors for each benefit category vary and can enhance or inhibit benefit outputs. Examples of such site specific factors are the climatic conditions and connectivity to other urban flood management facilities and existing green spaces.

Secondly, *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 background environmental conditions. The services provided by the SuDS/GI flood management assets may not occur homogeneously and could even create negative impacts in some categories, in exchange for the benefits accrued in other categories.

Thirdly, 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, and the rate they develop over time. As such, a better understanding is required of the proportional contribution added within each benefit category, for each particular context. While the physical magnitude and scale of benefits can be analysed using rigorous models and scientifically based functions, it is more difficult to compare across benefit categories to establish the relative contribution that each can deliver in specific local circumstances and individual site characteristics.

Lastly, benefits can accrue to different stakeholder groups other than the asset owner and these are distributed across different spatial *scales*, from local to regional to global.

This paper seeks to illustrate these four key points, demonstrating the fundamental approach using a specific example of the East Lents Floodplain Restoration Project in Portland, Oregon. The output from this analysis is a GIS-based methodology to normalise the benefits in a non-dimensional form for direct comparison across benefit categories. The paper proposes and utilises three concepts to characterise the impacts, namely benefit profile, benefit intensity, and benefit dependency. Results of the analysis could then be used to: (i) provide practical advice to practitioners on the relative magnitude and (as a subsequent refinement to the procedure) the significance of a range of benefits under a given set of prescribed conditions and (ii) illustrate how the design of installations can be modified to enhance those benefits which are relevant and dominant, and what trade-offs may have to be made. Such analysis could then be linked to stakeholder preferences for maximising certain benefit categories and design approaches developed to enhance multifunctionality beyond just an installation's urban flood control role.

Concepts of benefit profile, benefit intensity, and benefit dependency

The core *functions* of SuDS/GI installations relate primarily to surface run-off attenuation and storage, and in some cases to water quality improvements through mechanisms such as phytoremediation, biodegradation, filtration, and sedimentation. The ability of any installation satisfactorily to perform these *functions* is essential to meeting the purpose for which they were installed in the first place. However, the focus here is on developing a broader understanding of how the wider multiple *benefits*, encompassing both a range of ecosystem services and socioeconomic services, are distributed.

Benefit normalisation

The benefits or disbenefits of urban flood management practices can span across various categories, and each of these categories can be characterised by a different metric. As a result, comparing the relative performance of each benefit across a range of categories has been difficult. Furthermore, the absolute values can offer little insight into the meaning of each benefit contribution, in relation to the pre-existing benefits/services in a specific location. For instance, Nowak *et al.* (2013) estimated that the magnitude of carbon storage per square metre of tree cover is 7.69 kg/cm^2 in urban areas. However, the significance of 1 m^2 of tree cover in a densely populated urban area with little green space area might be much more than in a townscape which already has extensive green areas. Normalising the impacts according to each location's conditions and context could therefore help highlight such enhancements relative to an initial condition state and allow a rational comparison across the categories to be made. This paper follows Lauf *et al.*'s (2014) approach for normalising ecosystem services contributions on a scale of 0–10, with 0 denoting *no contribution* and 10 denoting *maximum service contribution* achieved in an individual land parcel. The normalised values could be negative if impacts in the benefit category are less than an acceptable threshold or pre-existing condition, (i.e. creating a disbenefit). Further details of the normalisation process will be described in *The East Lents floodplain restoration case study* section.

Benefit profile

A benefit profile can be created using normalised impacts across categories. The benefit profile displays a set of impacts and their relative contribution to the area of interest, in the form of a radar chart (Figure 1). This can be achieved by computing benefits as simple ratios, for example:

- benefits from GI solutions: benefits from other flood management solutions;
- benefits after installation of an asset: benefits before installation of an asset;
- potential benefits at some future time: realised benefits occurring now, etc.

The radar chart demonstrates a hypothetical comparison between a range of benefits from an urban flood management scheme and a reference condition. The reference condition can be the pre-existing condition, a business-as-usual condition, or a scenario using alternative urban flood management solutions.

In the schematic example in Figure 1, all impacts have been normalised using a piecewise linear transformation to a scale of 0–10 and then compared against the reference condition using Eqn (1).

$$\text{ImpactScore} = \begin{cases} 10 \; if \; S_{\text{ref}} \leq 0, \; S_{\text{case}} > 0 \\ \dfrac{S_{\text{Case}} - S_{\text{ref}}}{|S_{ref}|} * 10 \; if \; S_{\text{ref}} * S_{\text{case}} > 0 \\ -10 \; if \; S_{\text{Ref}} \geq 0, \; S_{\text{Case}} < 0 \\ 0 \; if \; S_{\text{ref}} = S_{\text{case}} = 0 \end{cases} \tag{1}$$

with S_{ref} and S_{case} being the reference and the GI condition.

These impact scores allow a direct comparison across the entire benefit profile. For instance, in Figure 1, air quality improvement is readily seen as the dominant benefit while health has been shown as a disbenefit, due to allergies and pests. (The values used in this example, whilst realistic, are indicative only and chosen to demonstrate the methodology).

Benefit intensity

The benefit profile facilitates benefit comparison across categories. However, it does not reveal how the benefits

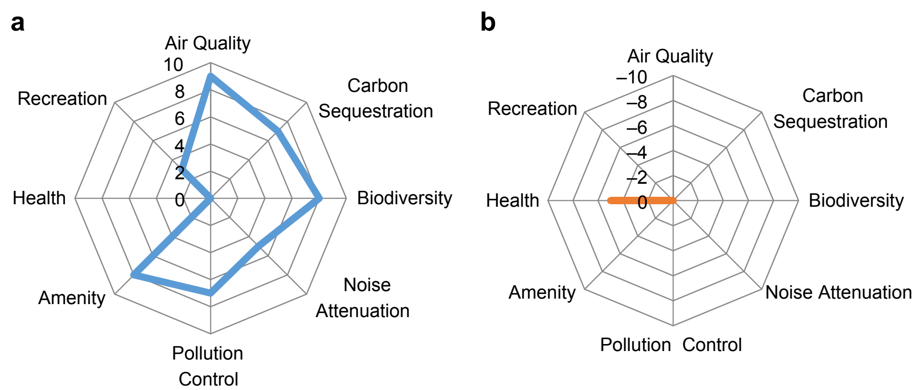

Figure 1 Schematic of an illustrative benefit profile that illustrate the normalised score of the benefit (a) and disbenefit (b).

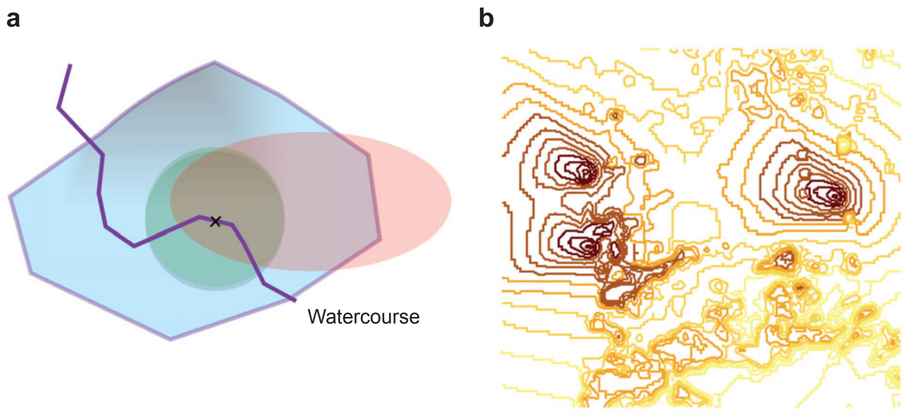

Figure 2 Benefit intensity (a) as layer overlay and (b) as contours.

may aggregate spatially. Benefit intensity illustrates the extent and distribution of cumulative benefits over space, and is displayed either as a series of overlay layers or overall contours of the benefit surface (Figure 2). The overlaying of these benefit ratios in a GIS platform can lead to the identification of where benefits accrue and whether significant benefit 'hotspots' are generated by the SUDS/GI installation. As a further step (not developed in this paper), these benefit layers can then be linked to significance weightings provided by a review of stakeholder preferences, established by appropriate dialogue with the communities served. This can help to highlight where, and to whom, the maximum benefits of an installation accrue.

The scale of analysis and resolution of the GIS grid squares may be determined by data availability and the different databases from where information may be taken. Aggregation or disaggregation to different spatial scales may influence the overall analysis, with flood models tending to report to 1 m^2 resolution, whereas land use variability may only be available over larger areas. Such influences need careful consideration when interpreting potential benefit hot spots, with some benefit categories capable of extending well beyond the site boundary, whereas others are limited to immediate local effects only (for example, reduction of adverse water quality impacts in a distant receiving water compared to direct pollutant trapping adjacent to a highway).

Benefit dependency

Benefit dependency analyses the complementarity and exclusivity of impacts across categories. It emphasises key variables determining the magnitude of impacts and when/where they occur. This is essential for determining the extent to which multiple benefits can be simultaneously co-optimised and where trade-offs need to be recognised. Recent work has shown that such trade-offs can occur between cultural and regulating ecosystem services, and provisioning ecosystems services (Turner *et al.*, 2014). The intention is to develop evaluation mechanisms which can facilitate the understanding of complex cause-and-effect relationships between benefit categories, flood management decisions, and controlling environmental variables. In this way, relevant, dominant benefits can be identified and fed back into the design of urban flood management schemes to enhance their overall performance.

The East Lents floodplain restoration case study

Johnson Creek is a free-flowing stream in Portland, Oregon, USA, managed by the Portland Bureau of Environmental Services (BES) and is considered one of Portland's most important resources (BES, 2015). The East Lents Floodplain Restoration Project (Figure 3) is one of several large-scale floodplain restoration projects implemented to support the Johnson Creek Restoration Plan (BES, 2001) with the goal of reducing nuisance impacts from fluvial flooding – so called *nuisance flooding* (flooding of high frequency, such as 1 in 10 years, which causes public inconvenience) (BES, 2001; Foster Lents Integration Partnership, 2014). Previous to the project, the area was subjected to flood events that affect residential, commercial, and industrial areas, such as the case of the January 2009 flood, which was classified as a 1-in-29-year event (Foster Lents Integration Partnership, 2014). The project and the wider Johnson Creek Restoration Plan (BES, 2001) are amongst relevant policies and plans that enhance Green Infrastructure opportunities in Portland, such as the Portland Watershed Management Plan, Portland Climate Action Plan, and Foster Green Ecodistrict (Foster Lents Integration Partnership, 2014).

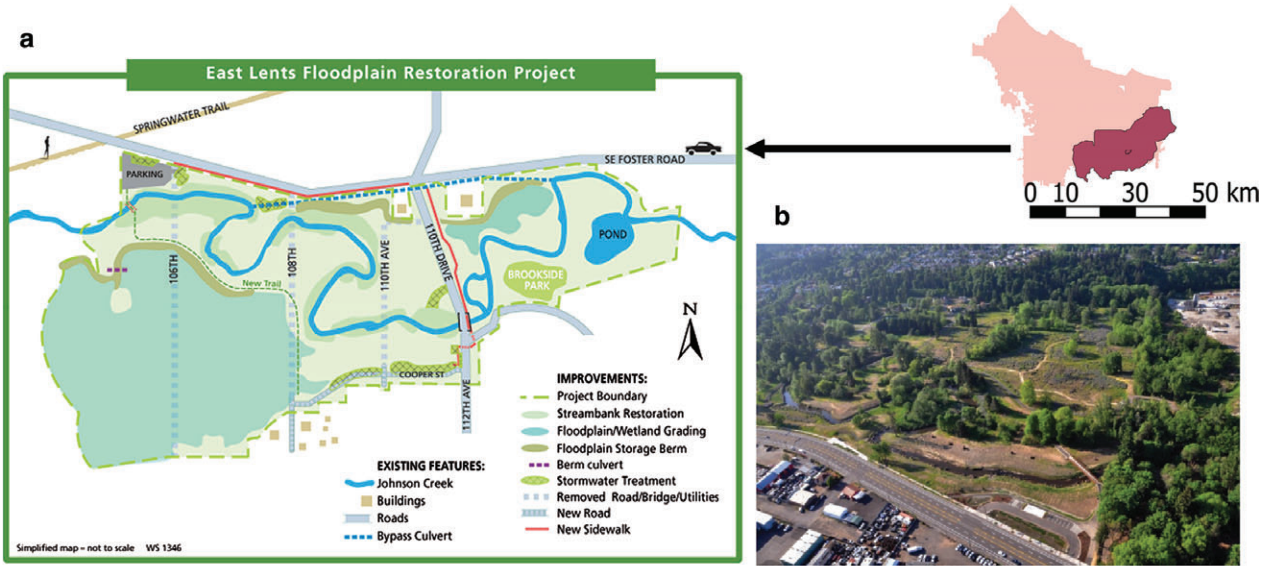

Figure 3 (a) Location of the East Lents Floodplain restoration project within the Lower Johnson Creek catchment (dark pink) and the city of Portland (light pink) and schematic map of improvements done by the project. Source: Bureau of Environmental Services (2015) – Note: schematic map not to scale. (b) Project at completion (2013) looking South East. Courtesy of Bureau of Environmental Services.

The East Lents project was completed in late 2013–2014. The project is bounded on the north by SE Foster Road, a four-lane arterial road, and on the west by a 40.5 hectare industrial area. To the east, it is within close proximity to other green spaces such as Leach Botanical Garden and Zenger Farm. The main objectives of the project in addition to reducing nuisance flooding were to improve water quality and habitat in Johnson Creek. Through the Willing Seller Program (BES, 2001), the project moved 60 families out of the 1-in-100-year floodplain and transformed the site into a natural area for flood storage. Additionally, three roads and bridges were removed and replaced with accessible trails and a pedestrian bridge. As part of the project, several ponds and wetlands were installed. Potential benefits of the project therefore extend beyond the primary flood mitigation function and are likely to provide other improvements into the surrounding area. In this paper, we compare the pre-existing and the final condition (hereafter referred to as the GI condition) of the project, and investigate six benefit categories to evaluate how the distribution of impacts within and beyond the site can be effectively represented.

The road network and land use type within the restoration site were modified as a result of the East Lents project (Figure 4). Under pre-existing conditions, residential patches within the site were categorised as low to medium intensity developed land (Category 22 and 23 in the National Land Cover Database 2011 – refer to Homer et al., 2015). After the restoration, these patches were reclassified as open space developed land (Category 21), which are areas with vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes (Jin et al., 2013). The vegetation layer was also expanded to the whole site. Under flood conditions (for the 1-in-10-year event), inundated patches have been reclassified as water cells. The vegetation structure was deduced from LiDAR data; under flood conditions, vegetation that is shorter than the flood level and therefore inundated has also been reclassified as water cells.

Benefit evaluation methodology

Six example benefit categories were selected to demonstrate the application of the evaluation strategy for the East Lents Floodplain Restoration Project. These benefits were chosen based on the initial aims of the East Lents project and other relevant schemes towards social and ecological development in the area (as described in the Portland Watershed Management Plan, Portland Climate Action Plan, and Foster Green Ecodistrict – refer to BES, 2014 for more details). In essence, the main function of the East Lents project is flood mitigation, as described in the project's aims (BES, 2004), but the project has also been listed under the Foster Lents Integration Partnership as contributing to habitat enhancement, and neighbourhood improvement such as landscape connectivity and sense of place. The Portland Climate Action Plan proposes that Portland residents should be able to walk or bicycle to amenities within 20 min. The benefit categories therefore are as follows:

- habitat connectivity,
- recreational accessibility,

Figure 4 Changes in vegetation cover and road layout before and after the East Lents project. The dash outline shows the extent of the project and the thin dash outline shows where roads were removed.

- traffic movement,
- noise propagation,
- carbon sequestration, and
- pollutant trapping.

For a summary of the detailed methodology adopted in computing each benefit, refer to the Appendix S1, Supporting Information, at the end of the paper.

Although possible, the analysis utilises physically based methods and models to avoid using value transfer from evaluation studies elsewhere. Where no physically based methods are available, parameters derived from Portland-based studies have been included. It is acknowledged that the selected categories do not reflect the full range of multiple benefits which might be considered. However, in this paper, they were chosen mainly to illustrate the dynamics of benefit distribution and their potential interactions. The computation framework of the benefit categories is depicted in Figure 5.

A GIS-based tool was developed with the purpose of demonstrating the concepts proposed in this paper (for description of the tool, refer to the Appendix S1, Supporting Information B). The tool was written in Python and has a Guided User Interface in QGIS version 2.2 and above. It utilises GRASS, SAGA, and other geoalgorithms in the processing component in QGIS. The tool facilitates automated analysis of different impact categories of urban flood management, ranging from flood mitigation to pollutant trapping. It allows automation of many of the tasks described in the computation framework and therefore speeds up benefit evaluation, especially when there is a need to repeat the calculation for multiple conditions and scenarios.

Analysis methods: Normalisation, benefit intensity, and benefit profile and benefit dependency

The paper follows Lauf et al. (2014)’s methodology to normalise the benefits. This normalisation methodology identifies the full range of benefit levels over a site of interest and uses this range as a baseline to rescale the benefit score to 0–10. Score 0 reflects no benefit and score 10 is the maximum level of benefits in that category for the site. The relative benefit level in the before and after condition is then compared and used to compute an overall benefit score. In general, a positive benefit score means that the benefit level has improved from the before condition (initial state) and a negative score means that the benefit level has reduced compared to the before condition. As the benefit scores are normalised to dimensionless value, they are then able to be compared across the benefit categories.

Overall, the process of converting benefit estimation to benefit intensity, benefit profile, and benefit dependency is depicted in Figure 6. Normalising each benefit category into a common scale allows summing across the categories and so highlighting locations where the overall benefit concentrates or peaks, which can be displayed in an aggregated layer of benefit intensity. For each category, the benefit values of the reference and the GI scenarios are combined following Eqn (1) to produce a comparative value that

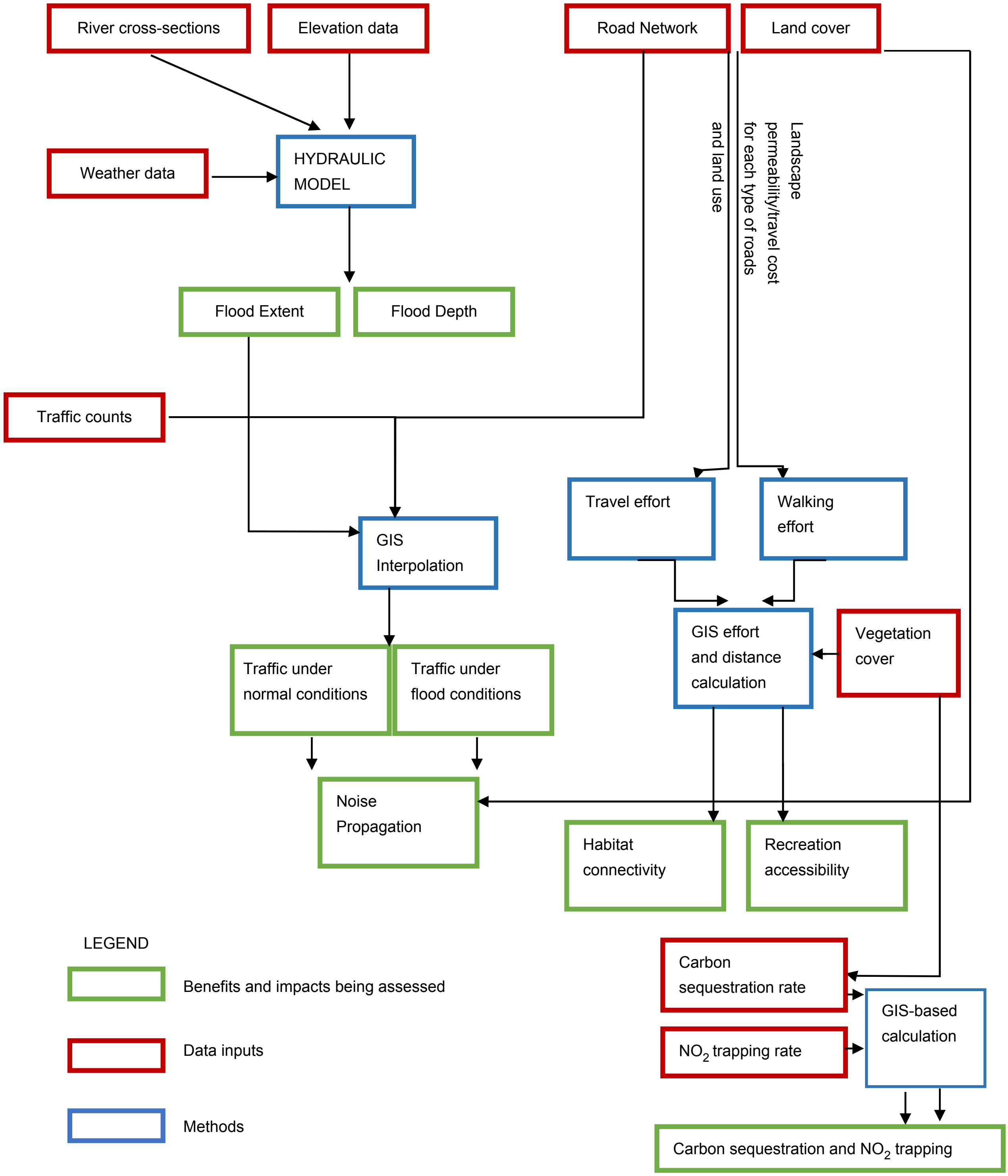

Figure 5 Computation framework of the benefit categories.

reflects whether the benefit services are improved or worsened in each location. If the benefit value in the reference condition is the same as the estimated benefit value after the adoption of a GI flood management solution (e.g. due to extensive pre-existing vegetation cover in that location), then no uplift due to an installation is achieved and the net benefit is recorded as zero. The benefit profile then displays the relative changes in each category in a radar chart, which

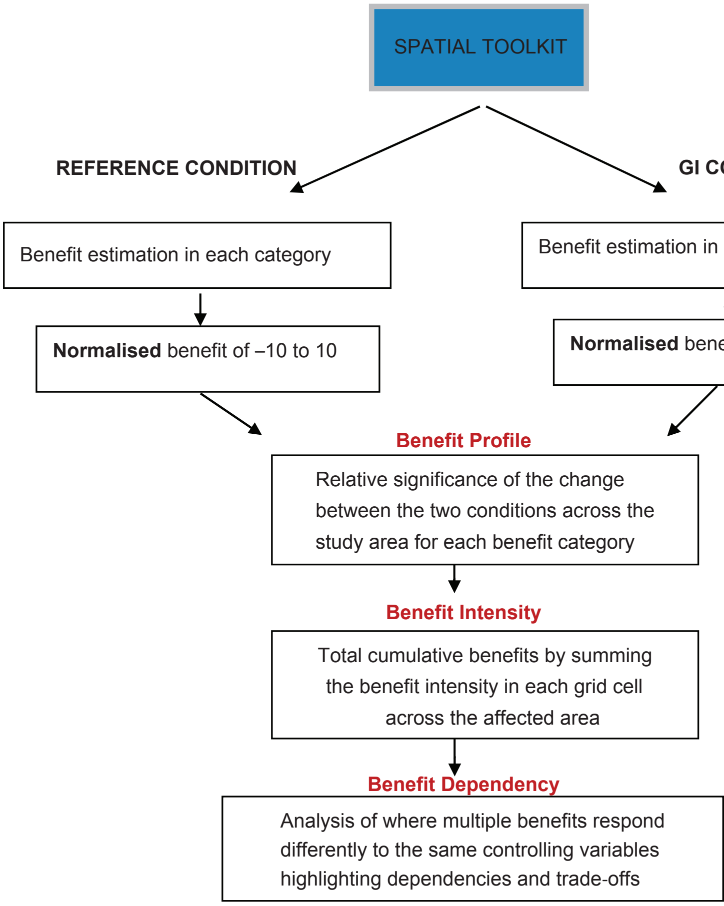

Figure 6 Flow chart of benefit analysis.

helps indicate the benefit categories with a dominant uplift. These uplifts might be interdependent and controlled by a common variable, such as by changes in vegetation coverage or flood extent. Analysing their common control variables or benefit dependency, then highlights ways to co-optimise the benefits and indicate potential trade-offs.

Analysis and discussion

Flood mitigation function of the East Lents Floodplain project

The analysis first considers the ability of the East Lents project to perform its primary flood *function*; the following section then appraises the wider multiple *benefits* that can be associated with the installation.

HEC-RAS modelling results show that the East Lents project makes changes to the flood depth for events of 1-in-10-year, 1-in-50-year and 1-in-100-year return periods (Figure 8). The 'before' and 'after' values represent the range of flood depths under the two conditions, and the difference values show the relative performance improvements arising from the completed project. For these rainfall return periods, the areas of increased flood depth mainly fall within the project area, demonstrating that the project has achieved its design goal of concentrating flood water into the swales in the restored floodplain area. Land areas outside the project mainly experience a reduction in flood depth. Figure 7 also demonstrates that across a range of storm frequencies, the project has the most relative significance for the 1-in-10-year nuisance event. For storms of greater magnitude, while the impacted areas are larger, the relative change is less significant – which is reflected by the lighter shade of benefit intensity.

Multiple benefits associated with the East Lents Floodplain Restoration Project during nonflood and flood conditions

Analysis of the selected benefit categories shows that the East Lents project contributes positively beyond the project area. Landscape connectivity and amenity accessibility are

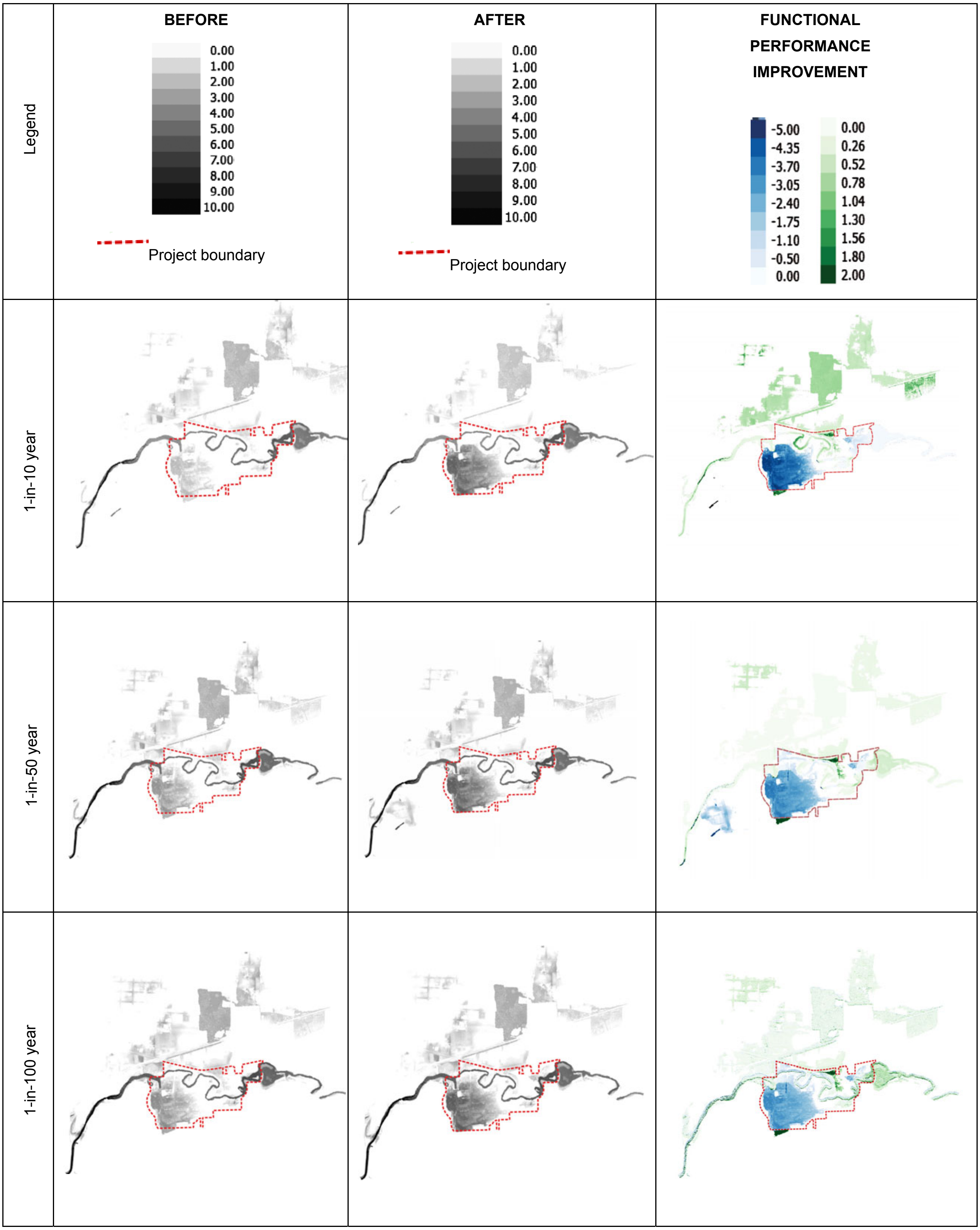

Figure 7 Flood depth (feet) in the Before and After condition and the benefit intensity of the flood function.

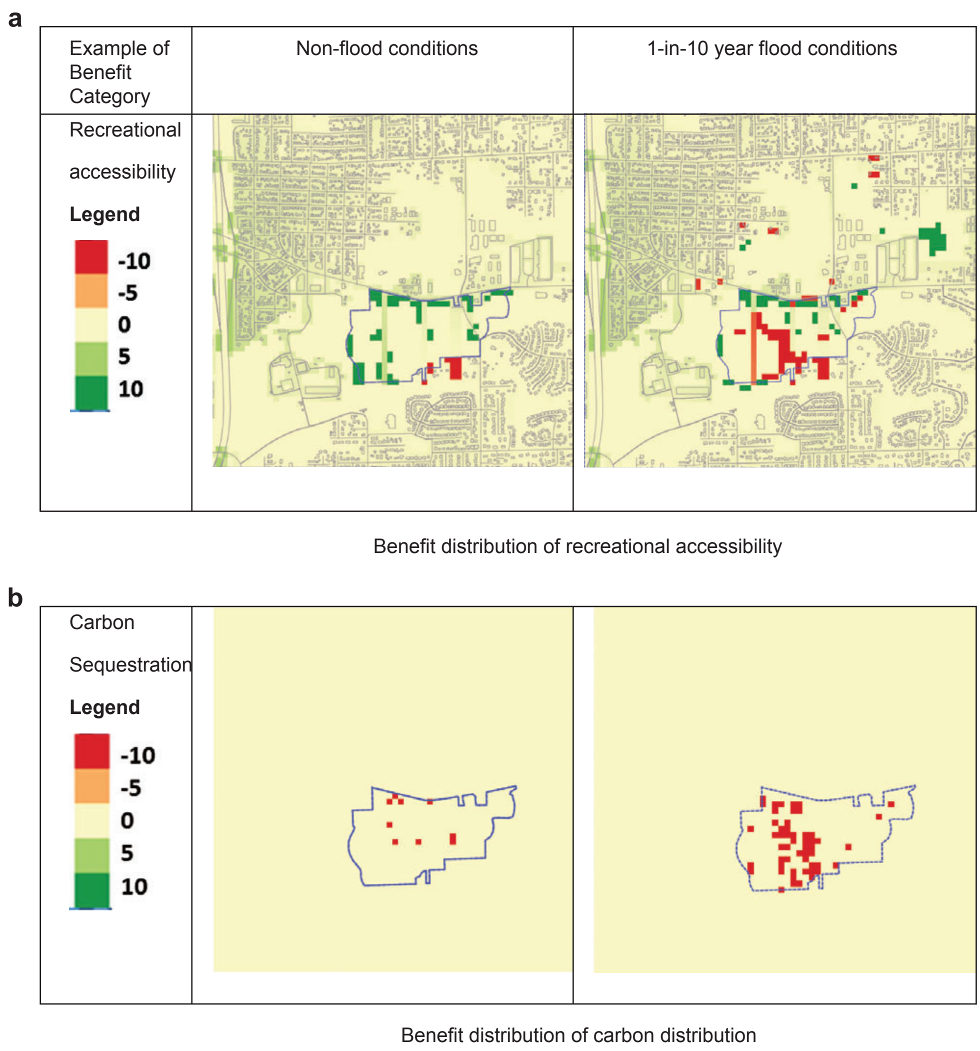

Figure 8 Benefit distribution of (a) recreational accessibility and (b) carbon distribution.

in general improved due to the change in land use of the site (from low intensity developed land to a restoration area) and the removal of three onsite roads. Improvements to habitat accessibility occur both within and beyond the site, because the green space within the site is no longer fragmented and is much more connected to surrounding green elements. Amenity accessibility is also improved, due to the site now being accessible without pedestrians having to travel through the onsite residential roads. Under the flood condition, accessibility to the site is temporarily lessened due to the site being used for flood water storage – which is its main function (Figure 8(a)).

The analysis has shown that compared to pre-existing conditions, carbon sequestration declines due to the removal of vegetation and some tree cover within the project site as part of the restoration activity (Figure 8(b)). A similar decline is found for NO_2 trapping. Nevertheless, these are temporary impacts and expected to recover once vegetation cover matures according to the project impact assessment (BES, 2006). Noise attenuation changes were found to be minimal and could not be detected by comparing the before and after conditions, both in the nonflood and flood conditions. Regarding traffic movement, the area shows improvement where the three roads and houses have been removed as part of the restoration project.

Benefit profile of the East Lents Floodplain Restoration Project

The benefit profile (generated as a ratio of the uplift and the before condition on and off the site according to Eqn (1)) is shown in Figure 9. This is based on the mean performance calculated across the whole Lents area as depicted in Figure 3. Maximum values recorded in any single

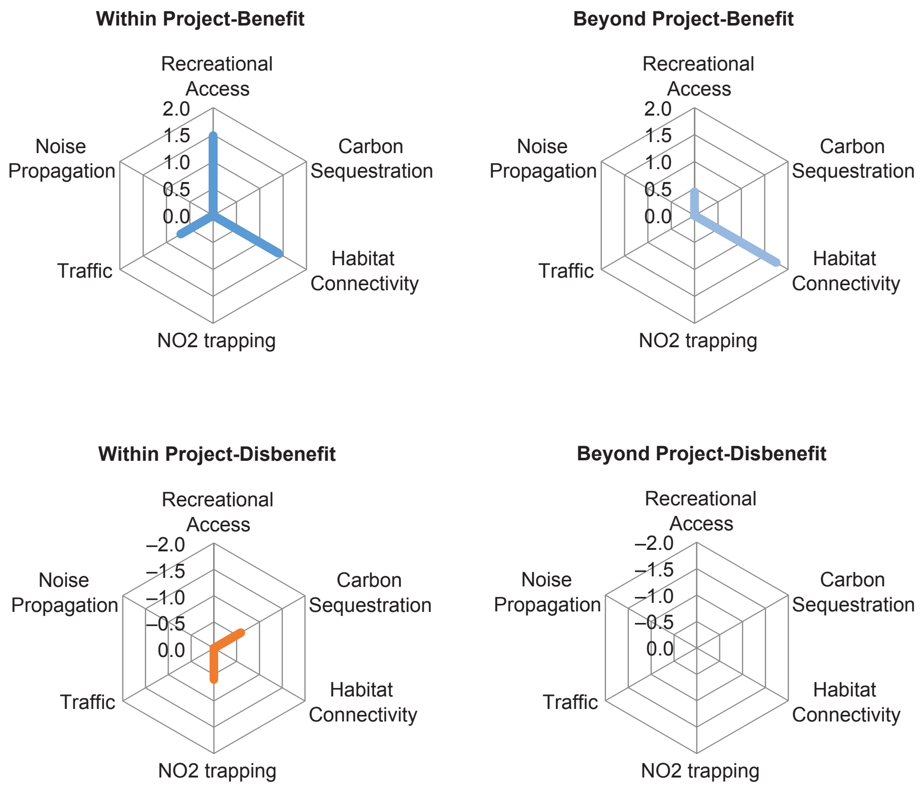

Figure 9 Benefit profile of the East Lents project under nonflood condition. Because no benefit category exceeds a score of 2, the scale is shrunk to 0–2 or −2 for clearer view of the changes.

$30 \times 30\ m^2$ grid are also shown in Figure 10 as a bar chart. A clear uplift can be seen in the categories of recreational access and habitat connectivity both within and beyond the project site. While the benefit profiles show current disbenefits in carbon sequestration and NO_2 trapping, these do not extend beyond the project boundary and overall, the East Lents project poses no significant disbenefits on the surrounding areas.

Figure 10(a) and (b) shows the max and min values of benefit in the cells within and beyond the East Lents site. They indicate that both within and beyond the site, there are hotspots of benefits and disbenefits (to a value of 10 and −10).

Benefit intensity of the East Lents Floodplain Restoration Project

The overall unweighted spatial distribution of the accumulated benefit – disbenefit intensity in East Lents is displayed in Figure 11 under the nonflood condition and the 1-in-10-year condition. These are drawn on a red-green gradient, with red depicting disbenefits and green depicting benefits. The diagram demonstrates that under the nonflood condition, the northern side and western side beyond the site receives net positive benefits due to improved habitat connectivity and recreational accessibility. Furthermore, the figure shows a few local hotspots of multiple benefits occur within the site, together with some net disbenefits where vegetation has been removed.

Under the 1-in-10-year Flood condition, the benefit uplift diminishes due to the site being used for its primary flood storage function. Inundated vegetation will have a reduced rate of carbon sequestration and cannot trap NO_2 due to submerged leaves. The services of carbon sequestration and NO_2 trapping are reduced within the site during these episodes. Similarly, as open water is more inaccessible than green spaces to migratory woodland birds and pedestrians, habitat connectivity and recreational accessibility are both reduced under the flood condition.

The East Lents project and potential beneficiaries

Overall, the East Lents project has shown potential benefits aside from its main function of flood mitigation. The extent of benefits arising from the project spreads beyond the project boundary and as such, can accrue to different stakeholder groups other than the asset owner.

For the flood mitigation function, an overlay of the land use and flood extent (e.g. for the 1-in-10-year event) (Figure 11), shows that before the project flooding, largely

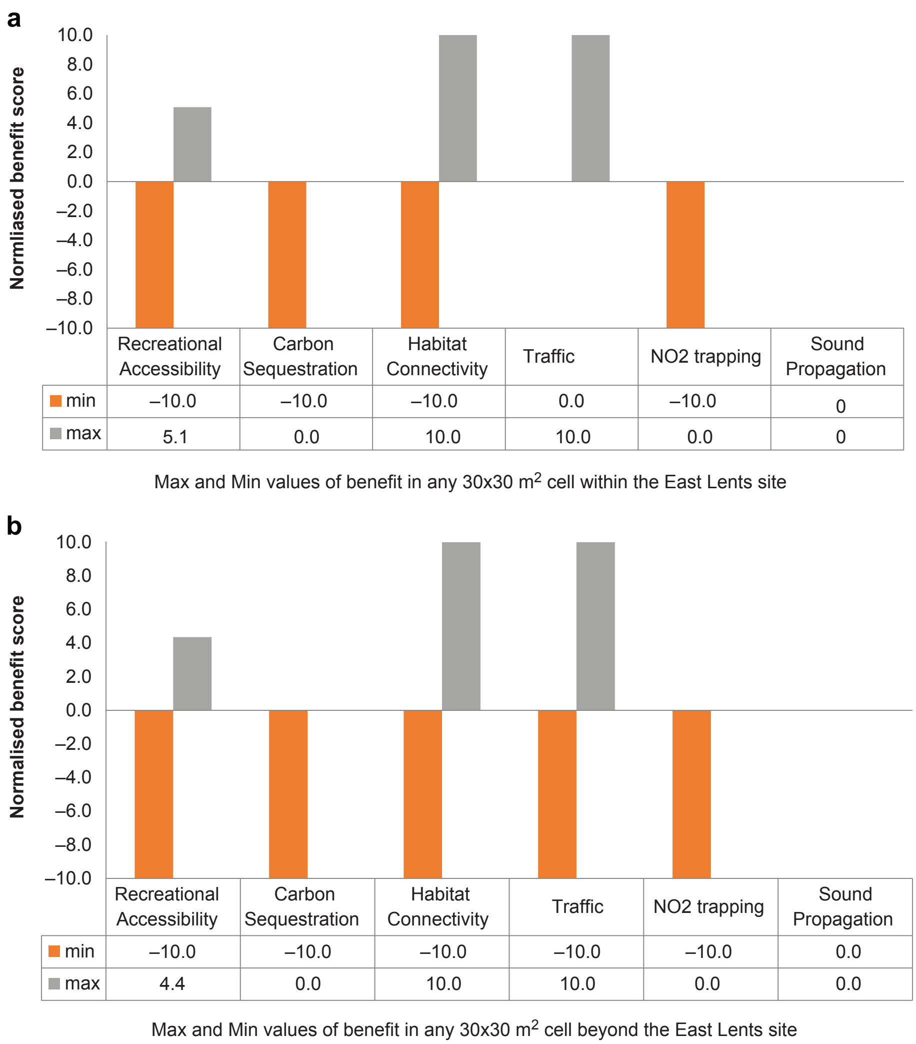

Figure 10 Maximum and Minimum values of benefit in any 30×30 m^2 cell (a) within the East Lents site and (b) beyond the East Lents site.

coincided with vacant and undeveloped areas. Indeed the Lents 5-year Action Plan (Foster Lents Integration Partnership, 2014) identified flooding as a major cause of land and property underutilisation in the Lents area (Figure 12).

Analysis of the changes in flood extent and depth due to the East Lent Floodplain Restoration Project shows that the areas mostly relieved are located in this undeveloped land, followed by commercial, single-family residential, and other land use types including roads (Figure 13). Overall, the areas that are negatively affected by the project are much smaller than the benefited areas. As such, the beneficiaries of the flood mitigation function include owners of the undeveloped land, businesses, single-family residents, and road users.

The results demonstrate that impacts on 'beneficiaries' can vary under both the non -flood and flood conditions. In particular, the project improves the conditions for undeveloped areas that were previously subjected to frequent flooding. Therefore, the project assists the Lents area by creating opportunities for development. Other benefits such as increased recreational accessibility and habitat connectivity are both positive improvements for Lents residents and many wildlife species such as the migratory song birds. These results are in agreement with a previous study of potential ecosystem service of the East Lents floodplain restoration project, which also highlighted these improvements and estimated the monetised value of avian habitat improvement for wintering/migratory species as $402 per acre per year and recreational opportunity as $4.00 per day per user (BES, 2004). While the East Lents ecosystem service study emphasises the dynamic linkages across the benefits, our study demonstrates the spatial variation of the benefits and the context-dependent nature of such linkages.

These are distributed across different spatial *scales*, from local to regional to global. Through multiple interactions

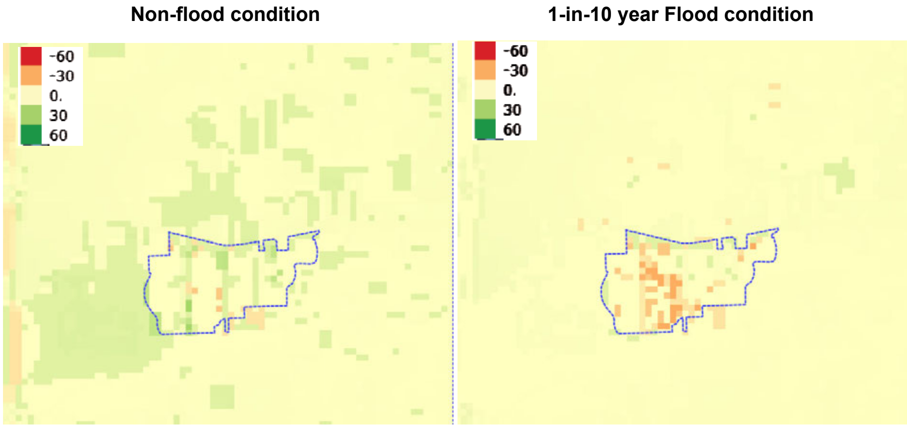

Figure 11 Benefit intensity within and beyond the East Lents Floodplain Restoration site under normal nonflood condition and 1-in-10-year flood condition.

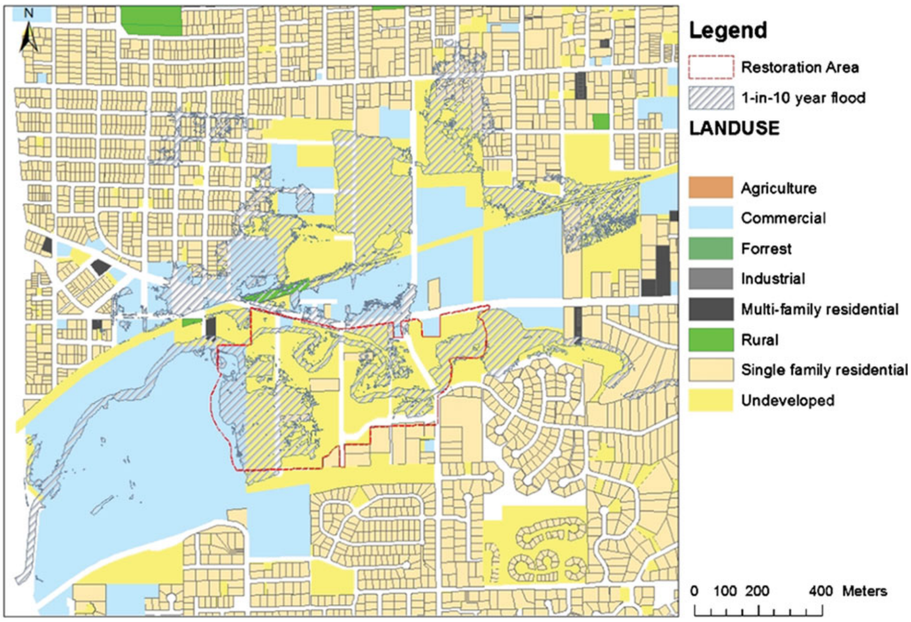

Figure 12 Modelled 1-in-10-year flood extent imposed on land use map in the Before condition.

and feedbacks, such as by reducing flood damages in undeveloped areas – therefore, opening up opportunities for development (BES, 2014), improving habitat quality and recreational access, the benefits are accrued to both Lents businesses and residents. While the majority of the beneficiaries are local, there are potentials for wider contribution, albeit modest, to air quality, recreational accessibility, and habitat connectivity at the city scale.

The monetary cost (through project investment) here occurs to the city bureaus, in particularly, BES. However, this project contributes towards BES' goals of improving environmental services in the area. At a wider scale, the project benefits the residents in the Lents area, in particularly those living in the land parcels that have previously been flooded or those who have benefitted from more accessibility to green spaces.

Discussion

Incremental/cumulative benefits of urban flood management practice

Overall, the study proposes a methodology that enables the *dominant*, *relevant* benefits for a given location to be established. While the primary intended function was flood

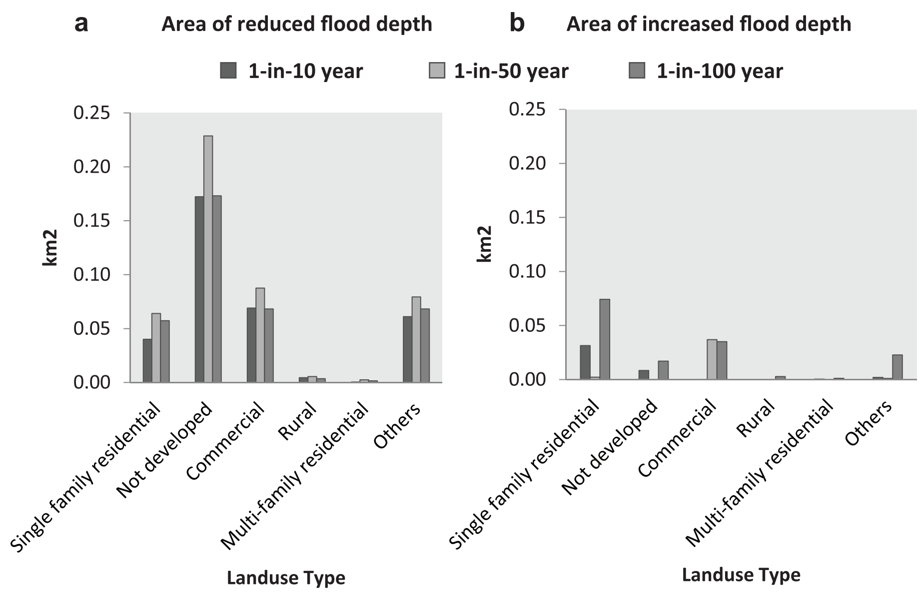

Figure 13 Land use type of areas with reduced (a) and increased (b) flood depth outside the project boundary.

mitigation, recreational accessibility and habitat connectivity are the dominant wider benefits from the East Lents project (from the categories considered). These benefit concepts can be applied to evaluate a completed scheme, such as the East Lents project, or codesign the benefits of a future scheme.

Overall benefits from several installations might accumulate nonlinearly, due to benefit interactions and the relative significance of each (as judged locally). For instance, Portland already has a high density of urban green space and hence the net multiple benefits in such circumstances may therefore be less than in local areas dominated by grey infrastructure. As illustrated in Figure 11, the benefits distribute unevenly over space, and so adding new SuDS/GI installations could lead to high uplift in some areas and minor uplift in other. This uneven spatial distribution of physical benefits implies that the benefits could accrue to different groups of beneficiaries other than the asset owners, other residents in the neighbourhood and management agencies, as well as wildlife groups such as birds (and fish and mammals not investigated here).

Uncertainty and constraints

The study identifies that there are uncertainties associated with the scale of analysis, the thresholds used to define the impacts and appropriate levels of data resolution. Firstly, the extent and resolution of the analysis may lead to variations of the results if reconducted at a different scale and spatial extent. Each benefit layer need a different spatial and temporal resolution to capture the range of benefits and its key elements, for instance in this study, a range of data and different resolutions have been used to illustrate the additional benefits of the East Lents project, ranging from 1×1 m^2 for flood analysis to 30×30 m^2 for noise propagation analysis. The study recognises that data resolution and data availability could be a limiting factor, such as evaluating noise attenuation and habitat connectivity were conducted at the scale of 30×30 m^2 due to the resolution of the US National Land Cover Dataset. For the overall benefit intensity, the 30×30 m^2 resolution was chosen because it is the finest resolution that all benefit layers could be aggregated without further processing. Yet, the benefits are computed for a single moment and under current prevailing conditions, and therefore have not fully addressed the temporal variation as the site and surrounding area matures and changes in the future. Illustrating the dynamics of SuDS/GI benefits through time would further expand the understanding of how to codesign the benefits across a range of conditions and scales.

As well as monitoring the development of time-dependant benefits as vegetation matures to its full extent, changes in organisational complexity and political will also represent transient opportunities for the acceptance of certain types of solution. In a parallel study related to that reported here a range of institutional stakeholders were interviewed regarding their expectations and experiences of the Foster Road Flood Plain Restoration scheme, revealing irregular time intervals when they became involved and therefore when they had opportunity to influence the implementation of the scheme.

Secondly, an assessment of significance of the benefits can be achieved as a refinement to the procedure in a second stage by applying weightings to each category reflecting how different benefits are ranked by the communities they serve through local knowledge and priorities. Some further effects that have not been considered here relate to the positive effects of periodic inundation of the floodplain which beneficially provides groundwater recharge, sediment deposition, food source for salmonids, and other aquatic species that would previously have been limited in the former residential areas on the site.

Thirdly, the thresholds used to define the impacts could be another source of uncertainty. In this study, the distance that pedestrians walk to access recreational spaces was assumed to be 100 m while the travelling range of migratory bird was taken as 3000 m, (See Table S1 of Appendix S1, Supporting Information). Yet, such thresholds vary from individual to individual due to their different preference and physical ability. Therefore in further applications, there will need to be justification of why a particular threshold is selected, such as based on general policy standards or data obtained from the study area.

The study acknowledges that there are unavoidable trade-offs due to the exclusive nature of certain benefits. This could necessitate a decision process to establish benefit priority that would identify which should be the primary benefits, which reflect the drivers for project development and implementation, and which meet objectives across a spectrum of functionalities.

Next steps

The conceptual approach in this paper enables further refinement of the aggregated benefit distribution (unweighted or weighted by stakeholder preferences) into a GIS toolbox, where users can input benefit categories that are relevant to particular circumstances and to visually identify where benefit hotspots occur across urban spaces. The method explored, in particular the normalising routine, can further be implemented in the planning process to compare flood risk alternatives and rationally extend the choice criteria which form the basis on which decisions are made.

Moreover, the intention is to establish positive feedback into the design process so that flood risk management assets can be designed and operated to achieve both their primary flood mitigation function while being configured in ways that co-optimise the most relevant dominant benefits that can provide desirable additional environmental and social uplift to a given area. Part of this process will utilise a pairwise comparison of benefits based on a survey of stakeholder preferences to provide a rank order of the multifunctional aspects of a scheme which are most appropriate in a specific location. A technique to achieve this is the Analytical Hierarchy Procedure (Saaty, 2008) which is the basis for ongoing work based on similar considerations for sites in the UK. In addition, such spatial visualisation of multiple benefits can inform wider urban planning, specifically by encouraging landscape connectivity where SuDS/GI asset can be linked into green corridors for amenity and biodiversity enhancement.

Whilst the example used in this paper has considered an assessment of the multiple benefits emanating from a large flood alleviation scheme, the method proposed can be applied to smaller individual or cumulative SuDS interventions in an urban setting and used to assess the benefit uplift achieved by retrofitted assets (as described for Newcastle, UK by Morgan and Fenner, 2016).

Conclusion

This paper proposes the concepts of benefit profile and benefit as key concepts for assessing the benefits of SUDS/GI installations. Such benefits and disbenefits need to be considered with regard to the context and location of the installation, and in particular, with regard to the pre-existing services at the site. The interdependencies between benefits also need to be considered.

The study has demonstrated the application of these concepts in a case study in Portland, Oregon, USA. Results show that benefits and disbenefits vary across the site with traffic reduction, habitat connectivity, and recreational accessibility being the key benefits in addition to the flood mitigation function being achieved. Carbon sequestration and NO_2 trapping are temporarily reduced, due to the removal of some vegetation. The cumulative net benefit intensity helps establish where the maximum overall effects spatially accrue.

While flood alleviation mainly accrues to adjacent undeveloped areas, wider benefits can spread beyond the owners of the undeveloped land, to businesses, single-family residents, and road users, as well as wildlife species and Portland residents. The study recognises that incremental/cumulative benefits might accumulate nonlinearly due to benefit interactions and changes in the significance with which each benefit is judged or desired by the recipient communities. Finally, the study acknowledges uncertainties and constraints in data resolution, data availability, and the scale of analysis. Nevertheless, the methodology proposed by this study could be of use to practitioners for recognising trade-offs and co-optimise the multibenefits of urban flood management practices.

Acknowledgements

This research was performed as part of an interdisciplinary project programme undertaken by the Blue-Green Cities (BGC) Research Consortium (www.bluegreencities.ac.uk) and Portland-Vancouver ULTRA (Urban Long-term Research Area) project (PVU, www.fsl.orst.edu/eco-p/ultra), as part of the 'Clean Water for All' initiative. The BGC Consortium is funded by the UK Engineering and Physical Sciences Research Council under grant EP/K01366 1/1, with additional contributions from the Environment Agency and Rivers Agency (Northern Ireland) and National Science Foundation.

Associated research data can be downloaded from: http://dx.doi.org/10.17639/nott.26.

Supporting Information

Additional supporting information is available in the online version of this article.

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