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A spatial framework to explore needs and opportunities for interoperable urban flood management

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Abstract

Managing current and future urban flood risks must consider the connection (i.e. interoperability) between existing (and new) infrastructure systems to manage stormwater (pluvial flooding). Yet, due to a lack of systematic approaches to identify interoperable flood management interventions, opportunities are missed to combine investments of existing infrastructure (e.g. drainage, roads, land use, and buildings, etc) with Blue-Green Infrastructure (BGI) (e.g. sustainable urban drainage systems (SUDs), green roofs, green spaces). In this study, a spatial analysis framework is presented combining hydrodynamic modelling with spatial information on infrastructure systems to provide strategic direction for systems-level urban flood management (UFM). The framework is built upon three categories of data: (i) flood hazard areas (i.e. characterise the spatial flood problem); (ii) flood source areas (i.e. areas contributing the most to surface flooding); (iii) the interoperable potential of different systems (i.e. which infrastructure systems can contribute to water management functions). Applied to the urban catchment of Newcastle-Upon-Tyne (UK), the study illustrates the novelty of combining spatial data sources in a systematic way, and highlights the spatial (dis)connectivity in terms of flood source areas (where most of the flood management intervention is required) and the benefit areas (where most of the reduction in flooding occurs). The framework provides a strategic tool for managing stormwater pathways from an interoperable perspective that can help city-scale infrastructure development that considers UFM across multiple systems.

Introduction

Cities are complex spaces formed by interactions between people, infrastructure, and the environment. Water is central to many of these interactions; its availability sets the condition of living and working in urban environments, while its presence also influences the urban climate, biodiversity, and amenity. In that same urban space, excessive rainwater can lead to flooding and high associated costs (1). Urban flood management (UFM) is therefore essential to mitigate the potential impacts of pluvial flooding, while also addressing the complex interactions and functions of water in urban spaces (2–4). UFM requires 'systems-thinking' to manage connections, i.e. interoperability, between existing (and new) infrastructure systems to manage stormwater in an integrated way. Interoperability explicitly considers links between urban systems and their capacity to deal with excess water, so that enhancing interoperability involves storing and transferring stormwater along its pathway across different infrastructure systems (e.g. drainage, roads, land use, and buildings, etc.) (5). Interoperability to enhance flood risk management exists in many forms, often as an integration of existing infrastructure (e.g. roads and the drainage system) with Blue-Green Infrastructure (BGI) (e.g. sustainable urban drainage systems (SUDs), green roofs, green spaces) (6).

Despite the range of BGI flood management solutions available, city planners and flood management practitioners often lack a spatially-based, holistic understanding of the opportunities different urban systems could offer to manage excess surface water in an interoperable way (7,8). A major challenge in considering a holistic perspective on the urban catchment is the alignment of spatial information with the complex and inter-disciplinary decision-making process in urban flood management (and wider urban planning). Decision-making on locations and solutions for flood management is not a streamlined process; it is fragmented and inconsistent and depends on the interplay of known and unknown social, technically, political and economic considerations (5), and often remains based on scenario-testing and limited information on wider system functioning and opportunities for wider benefits (9). Thus, decision-making for UFM across urban catchments is challenging, which hampers the systematic uptake of interoperable flood management solutions and the development and connection of multiple infrastructure systems at the city-scale. It has been acknowledged that there is a

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need for application-oriented, transdisciplinary approaches that synthesise the urban system holistically, which would include identification of the flood problem and flood water pathways, alongside the evaluation of priorities, opportunities and challenges for integrated management (10–12). To this end, Wee (13) advocates the creation of 'recipes for resilience planning', based on data-driven and science-informed decision-making to enhance reproducibility across different spatial scales and locations.

While tools exist to select different types of flood management solutions depending on a specific location, they are often informed by a single aspect of urban flooding such as flood risk (e.g. 14-16); infrastructure and services likely to be at risk (e.g. 17-20); or the potential benefit(s) associated with specific adaptation measures (e.g. 21- 26). Very few approaches are available that explicitly link the source of the flood problem, its potential impact, and specific flood management interventions within the existing urban system. Gersonius et al. (27) developed a conceptual model (4RAF) that approaches this thinking: along stormwater pathways within urban areas the flood problem can be defined as a hazard (i.e. excess water that cannot be managed) or can cause actual exposure to vulnerable infrastructure and people. The nature of the flood problem (i.e. the hazard or exposure) dictates the preferred type of flood management intervention. For example, the flood hazard can be reduced at the source through implementing strategies to retain surface runoff (e.g. green roofs), or relieve pressure on overwhelmed drainage systems (e.g. diversion of flows), and exposure to flooding can be limited using strategies that resist flooding (e.g. flood defences) (27).

Approaches such as the 4RAF model (27) are useful in terms of conceptualising flood-water pathways and linking them to existing flood management solutions. However, there is a lack of clear guidance on how to translate this conceptual thinking into an actual approach to develop UFM at the city-scale. As a result, opportunities are missed to develop interoperable adaptation solutions and combine infrastructure investments which will create well-functioning and flood resilient cities (5,9). In response to this need, a spatial analysis framework is developed that aims to systematically guide strategic decision-making for interoperable UFM. The increasing amount of spatial data on urban areas (e.g. infrastructure, environmental data and flood risk) and computational modelling techniques presents an opportunity to combine flood modelling with spatial data on infrastructure systems to create a data-driven framework. The framework presented here, therefore, utilises freely accessible spatial datasets and combines hydrodynamic flood modelling to map and identify priority areas and opportunities for infrastructure system-integration. By bringing together this information in a systematic way, the framework aims to guide researchers and practitioners in considering urban areas from an interoperable perspective and strategically identify the potential connections between infrastructure systems which can lead to more collaborative urban planning.

Spatial Analysis Framework

An essential part of interoperable UFM is identifying and utilising the potential of actively managing stormwater in urban areas along its pathways across different infrastructure systems (e.g. drainage network, roads, buildings, etc.). To this end, a spatial analysis framework was developed to guide system integration in flood management (Figure 1), consisting of three objectives: (i) identify flood hazard areas (i.e. characterise the spatial flood problem); (ii) identify flood source areas (i.e. areas contributing the most to surface flooding); (iii) identify the interoperable potential of different infrastructure systems (i.e. which systems can contribute to water management functions). In a final part of the framework, the spatial data derived from the objectives are combined to characterise (i) flood intervention zones based on the source-to-hazard flood information and (ii) interoperability opportunities. In what follows, the framework is applied to a case study to illustrate what type of information it can provide and how it can used in the context of existing and future urban development projects to identify priorities and opportunities for interoperability.

Case study application of the framework

The spatial analysis framework is applied to the City of Newcastle-upon-Tyne in northeast England. The study area (9.15 km2) comprises the urban core of Newcastle (Figure 2), which is characterised by a steep topography, falling from the west towards the southeast as for as the River Tyne along the southern border of the study area. The upper study area is dominated by open green space (Town Moor), while the downstream part is highly urbanised. With much of its extent being vulnerable to pluvial flooding, Newcastle City Council has been involved in multiple research projects (28) and signed a declaration on BGI to engage in the prioritisation of the approach in flood management. These efforts are for example reflected in the presence of several SUDs at the newly-developed Helix site of Newcastle University (29) (Figure 2). The SUDs are mainly developed to retain and relieve as much stormwater as possible, through infiltration ponds and grass gullies respectively. This study applied the proposed framework to investigate whether the location of these types of measures align with the potential flood problem within this area. Furthermore, to test the added value the framework can have as part of the implementation of future developments within the city, two development sites were selected: (i) East Pilgrim Street, an urban regeneration project (30,31); and (ii) Arthur's Hill and Fenham, a transport project (32) (Figure 2).

Data input & classification

Flood hazard areas

The potential flood problem can be defined in different ways depending on the objectives of a study or assessment. Most often, a flood problem is expressed in terms of risk to property (33), people (34), in terms of infrastructure and economic damage that flooding can cause (35), or in terms of other impacts such as water quality (36). Because this study focuses on the potential of managing stormwater pathways rather than assessing stormwater impact, the flood problem is defined as the flood hazard (i.e. potential flood depths given a particular rainfall event and duration). To identify locations with the highest flood hazard, the hydrodynamic model CityCAT (37) was used to simulate model flood depths for a 1/50 year flood event (with a duration of 1 hour). Maximum depths during the simulated event were derived for each location. A single flood event was considered in this study, representing an event beyond the designed drainage capacity where water exceedance is guaranteed (38). The resulting modelling of the urban core of Newcastle (Figure 3a) indicates that areas most prone to deep flooding (highest estimated maximum flood depths) are situated centrally in the study area (urban centre) and, to a lesser degree, the lower part near the Tyne River.

Flood source areas

Due to topographical and land use differences across a catchment, surface runoff is often generated in upstream parts of the catchment causing flooding downstream. However, as a result of local infrastructure failures and soil cover characteristics (e.g. impermeable surface), flooding can also be generated locally. Identifying flood source areas can therefore help guide spatial prioritization for flood management intervention (i.e. target locations which have the most impact on reducing flood hazard). To this end, an experimental model design was developed to identify locations where the most floodwater is likely to originate (39). The model design is based on a systematic cell-dependency analysis using CityCAT by dividing the study area into cells (37 in total, Figure 2) and running CityCAT 37 times while each time setting the rainfall in one of the cells to zero (i.e. to simulate a situation where all rainfall is captured within that grid). By subtracting these scenarios from the baseline scenario (i.e. rainfall equal in entire catchment), a map was produced showing the contribution of each grid to the flood extent downstream in terms of area and depth (39). Flood source areas were then calculated by taking the product of the maximum depth and the flood extent generated by each cell (as deep flooding caused the highest damage to residential property and hazard to people, while flood extent indicated how far the effect of a certain source area reaches within the catchment). Contrarily to the flood hazard areas, the areas that generate the most flooding are scattered across the study area (Figure 3b). For example, one cell in the upper part of the catchment has one of the largest contributions to flood depths further downstream, while in the lower part of the catchment there are also some cells that generate significant flooding.

Classifying infrastructure systems for interoperability

Enhancing interoperability for flood management implies that physical interdependencies within and between infrastructure systems are used to contribute to the overall system performance to deal with stormwater. Analogous to the 4RAF model, the function of existing infrastructure systems for stormwater management are classified under two main processes: retain and relieve. The infrastructure systems most considered in urban areas that can potentially be (re)designed to retain water are green spaces (40,41) and buildings with green roofs (42). The main urban infrastructure that can help relieve surface water are roads by transferring water (38), and open spaces (e.g. sports and recreational areas as temporary flood storage (43)). There is also infrastructure that cannot be used as a secondary water management function because of the need to resist stormwater on account of its vulnerability or criticality in urban functionality (44,45).

Within Newcastle, infrastructure systems were classified having a ‘retain’ or ‘relieve’ function, or as buildings that require resistance (i.e. resisting) against stormwater based on Ordnance Survey topographic data and the city’s Development and Allocations Plan (NCCDA) for 2015-2030 (46). For simplicity, all residential and commercial buildings and green spaces were classified as opportunity areas to ‘retain’ stormwater (e.g. SUDs such as green roofs, rainwater harvesting, detention basins etc.), while minor roads and opens spaces were classified as areas that have the potential to ‘relieve’ stormwater (Table 1). As part of the NCCDA, Newcastle City Council identified a retail center within a wider heritage conservation area, which is classified as a ‘resist’ areas (Figure 2, Table 1). Furthermore, emergency and educational facilities, major roads (primary and secondary distributor roads, and public transport corridors) and utilities (power substations) were also classified as ‘resist’ areas (Table 1). Mapping out this classification approach shows that (technically) there are many places where surface water can be managed by existing infrastructure assets (Figure 3c). For example, the Town Moor in the upper part of the catchment presents a major opportunity to retain rainwater, while to the east of the catchment there are many minor roads along open spaces which presents opportunities to relieve the pressure of surface water towards nearby open or green spaces (38,47–49).

Data output & intervention zones

As part of the framework outlined in Figure 1, information on flood dynamics (problem and source) needs to be combined with the infrastructure systems information to identify flood management intervention zones and interoperability opportunities. To this end, a two-step spatial data overlay was designed to (i) characterise flood intervention zones based on the source to hazard flood information, and (ii) map interoperability opportunities based on the existing infrastructure (plans) within each intervention zone.

Spatial overlay 1: Source-to-hazard flood intervention zones

Within the conceptual 4RAF model, flood risk components are linked to specific flood management interventions (27). Similarly, to link flood risk components (reducing flood hazard versus reducing flood exposure) to a spatial location within the study area, data on flood hazard (Figure 3a) and flood source areas (Figure 3b) are combined, i.e. inform which type of intervention is most appropriate in which location. The data overlay is performed by reclassifying both maps into three classes (i.e. low, medium, high flood hazard versus minimal, medium and significant flood source) and creating a combined map consisting of four new intervention types (Table 2, Figure 3c).

The first of the intervention classes is characterised by areas (or cells) that contribute minimally to flood hazard across the catchment, and also have a low flood hazard. These areas are therefore determined to require no intervention at present, i.e. for the flood hazard modelled (i.e.1/50 yr flood event). The next intervention type is characterised by a low to medium hazard combined with a minimal to medium source of flooding. The most appropriate flood management measures in these zones are interventions that aim to 'relieve' stormwater through transferring water along existing infrastructure systems (e.g. pavements, etc.) towards areas that are able to store additional water. The third intervention zone type is determined when the flood source (contribution) of an area to wider catchment flooding becomes significant. In these areas, the focus on 'retaining' stormwater is essential to reduce potential flood hazard and exposure downstream. Finally, when flood hazard in an area becomes higher, using other infrastructure systems to relieve or retain stormwater could cause additional exposure (45). In these high hazard areas, the priority should therefore be to reduce flood exposure and thus install intervention measures to 'resist' stormwater.

By applying this classification of intervention across the catchment (Figure 3), the results indicate that the upper-eastern area of the catchment is characterised by low potential flood hazard, while as a source, the rainfall in this area has a limited impact on surface water generation further downstream. From a catchment perspective, this area has the lowest priority for flood management intervention. Alternatively, priority for intervention should be directed in the areas that contribute significantly to flood levels (locally or downstream), and thus the locations where retaining rainwater as much as possible, or relieving to a new retaining intervention, is recommended. The dominant 'retain' zones are located across the catchment, both upstream and in the lower urban area, while the 'relieve' zones are mostly located in the upper-west of the catchment. Finally, the central area of the catchment is predominantly classified as a 'resist' zone due to the deepest potential flooding occurring in these locations.

Spatial overlay 2: Interoperability opportunities

Within each source-to-hazard intervention zone (i.e. Figure 3c), different infrastructure systems are present that can be considered to assist an intervention that helps manage stormwater (see Table 1 for classification), and/or assist critical infrastructure protection (i.e. transport, energy, communications). To highlight the opportunities for interoperability within each zone, the classified infrastructure map (Figure 3d) was combined with the source-to-hazard intervention zones in a second data overlay which only displays the corresponding infrastructure system class with the matching source-to-impact intervention zone (e.g. retain infrastructure within the retain zone). The output is presented in Figure 3e. This additional step reveals that green space (provided by Town Moor) in the upper catchment offers a significant opportunity to capture water locally within the 'retain' zone (e.g. by enhancing retention and infiltration). Alternatively, there are areas within the 'retain' zone that have no green space. In these cases, capturing water through rainwater harvesting techniques could be an alternative approach to consider in terms of interoperable interventions (51). The 'relieve' zones identified correspond well with the availability of open spaces and minor roads (Figure 3f), which can provide opportunities to investigate the design of interoperable solutions that utilise the transport network better for flood management (e.g. temporary channels in extreme conditions) (38,47–49). Finally, the 'resist' zones (Figure 3g) coincide with many vulnerable or critical infrastructures (e.g. major road, heritage sites, and retail zones), which indicate that flood protection measures such as raising curbs or flood defences are likely to be necessary in these areas.

Overall, by combining the source of flooding with the infrastructure systems into a spatial overlay, the outcome provides a clear system-based approach to managing water at an urban catchment scale. Put into the context of the urban developments discussed in this study (Figure 3e-g), the newly developed Helix site of Newcastle University is located within the 'retain' zone, and this analysis supports the decision to focus on a range of SUDs to protects buildings locally as well as reduce runoff into the city centre further downstream. In future developments, focus could be given to integrate this site with the existing green spaces to optimize the amount of stormwater retained. Alternatively, the transport development scheme (Arthur's Hill and Fenham) sits within a 'relieve' intervention zone, presenting an opportunity to investigate the co-development of a transport/flood scheme that focuses on adaptations to reduce the pressure on the drainage system (e.g. diversion of flows) in the area (Figure 3f). Finally, the urban regeneration project (East Pilgrim Street) (Figure 3g) can be clearly located within a 'resist' intervention zone, thus all present/future developments in this area should have a shared strategic outcome of resistance (protection) from the impacts of stormwater (among other key benefits of the restoration project).

Discussion

To guide the development of interoperable UFM, a framework has been developed by combining three objectives: (i) the identification of the potential flood problem, (ii) identification of priority areas for intervention, and (iii) identification of the interoperable potential of existing infrastructure systems. In doing so, this study has provided a key contribution to challenges raised by the field of UFM which call for more systematic approaches to guide the development of flood resilient cities (i.e. 5, 9, 13). More specifically, this study highlights two key aspects. Firstly, interoperable urban planning can be a facilitator for promoting urban flood resilience at a city-system scale, and the framework presented in this study will assist the operationalising of this. The spatial priority areas identified in this study (Figure 3e-g) can help direct the development interoperable systems by identifying proximal infrastructure, planned schemes, and stakeholders to steer integrated planning and the co-development of strategic investment. In addition to aiding the identification of location, the process of classifying and indicating areas based on intervention type (e.g. resist, relieve, retain) outlined in this paper, provides a clear focus for approaching interoperable solutions.

The second key finding highlighted by this study is a spatial disconnect between flood source and flood impact. Specifically, the framework and its results indicate a clear disconnect between the most efficient locations for investment in flood management (upper catchment) and locations where the majority of flooding and impacts can occur i.e. the middle to lower urban area (and thus where the benefits of investment are located). The disconnection between intervention and benefits can be overcome to some extent by focussing on the multiple benefits BGI can offer beyond flood management (e.g. water recycling, climate regulation) (52,53). Yet this still remains challenging for more conventional appraisal tools (e.g. 48) used by practitioners. With wider guidance on valuing interdependence and resilience in infrastructure systems progressing (54), this framework will provide evidence-based connections that can help overcome this spatial benefit challenge. UFM is already occurring across cities worldwide in many different forms, but with a more formal process or framework to help guide this, planners may be able to consider UFM more holistically within wider strategic planning (e.g. master planning). It should be acknowledged that the framework presented has methodological limitations and uncertainties, which will need to be addressed in future research. Firstly, identification of source-to-hazard intervention zones is dependent on the flood model used (e.g. spatial resolution, duration of rainfall event, inclusion of artificial drainage network) and the design of the cell-dependency analysis (e.g. size and shape of the cells), which requires further model testing in different urban settings (39). Presently, the recommendation is for the selection of the model and model design to align with the objectives of the study (e.g. spatial scale, type of flooding). Secondly, research should focus on the classification of different infrastructure systems in terms of their interoperability capacity for interventions. For example, through combination with more specific infrastructure data (e.g. dedicated routes for emergency services, type/age of buildings, property ownership) or with approaches that identify infrastructure interdependencies (55). Finally, utilising this framework does not guarantee an interoperable scheme will be developed, as the planning process is complex and challenging, especially when introducing multiple stakeholders. Thus, the framework will require further application within practice to help align it to activities that result in collaborative infrastructure developments that consider interoperability along stormwater pathways. This could also include further development of the approach to express the flood component (i.e. hazard contribution) as a more focused flood risk contribution (38,56).

Conclusion

This study presented a spatial analysis framework designed to help explore the needs and opportunities for interoperable urban flood management (of stormwater) by combining three categories of data: (i) flood hazard areas (i.e. characterise the spatial flood problem); (ii) flood source areas (i.e. areas contributing the most to surface flooding); (iii) the interoperable potential of different systems (i.e. which infrastructure systems can contribute to water management functions). Applied to the urban catchment of Newcastle-upon-Tyne (UK), the findings illustrated the potential prioritisation of interventions based on combining data sources in a systematic and spatial way. The framework could be utilised in urban planning as a strategic starting point to promote system-based infrastructure development and consider (through interoperability) prior to developing infrastructure investment plans and stormwater alleviation schemes at a city scale. Furthermore, the output of the framework is especially important to highlight the spatial (dis)connectivity in terms of flood source areas (where most of the flood management intervention is required) and the benefit areas (where most of the reduction in flooding occurs), and therefore creating a basis for increased collaboration across these areas.

Additional Information

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Data Accessibility
All data is available from open access sources. Ordnance Survey data was downloaded using the Digimap platform (https://digimap.edina.ac.uk/). Flood data was produced using the open-source, hydrodynamic flood model CityCAT (https://www.ncl.ac.uk/ceser/research/integrated-systems/cities/citycat/). Visual outputs from the study are available on request.

Authors' Contributions
David A. Dawson (conception and design, writing, critical revision of content); Kim Vercruysse (conception and design, data processing, mapping, & writing); Nigel Wright (conception and design, critical revision of content).

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Tables and captions

Table 1. Classification of infrastructure systems according to potential opportunities to retain or transfer water

Intervention type	Infrastructure systems	Data source
Retain	Residential buildings Commercial buildings Green spaces	OS data © Crown copyright and database right 2018
Relieve	Open spaces Minor roads	OS data © Crown copyright and database right 2018
Resist	Emergency Education facilities Utilities	OS data © Crown copyright and database right 2018
	Retail centers Major roads Heritage assets	Newcastle City Council, 2019

Table 2. Classification of four source-to-impact flood dynamic areas. NI = no intervention.

Source \ Hazard	Low	Medium	High
Minimal	NI	Relieve	Resist
Medium	Relieve	Relieve	Resist
Significant	Retain	Retain	Resist

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Figures and captions

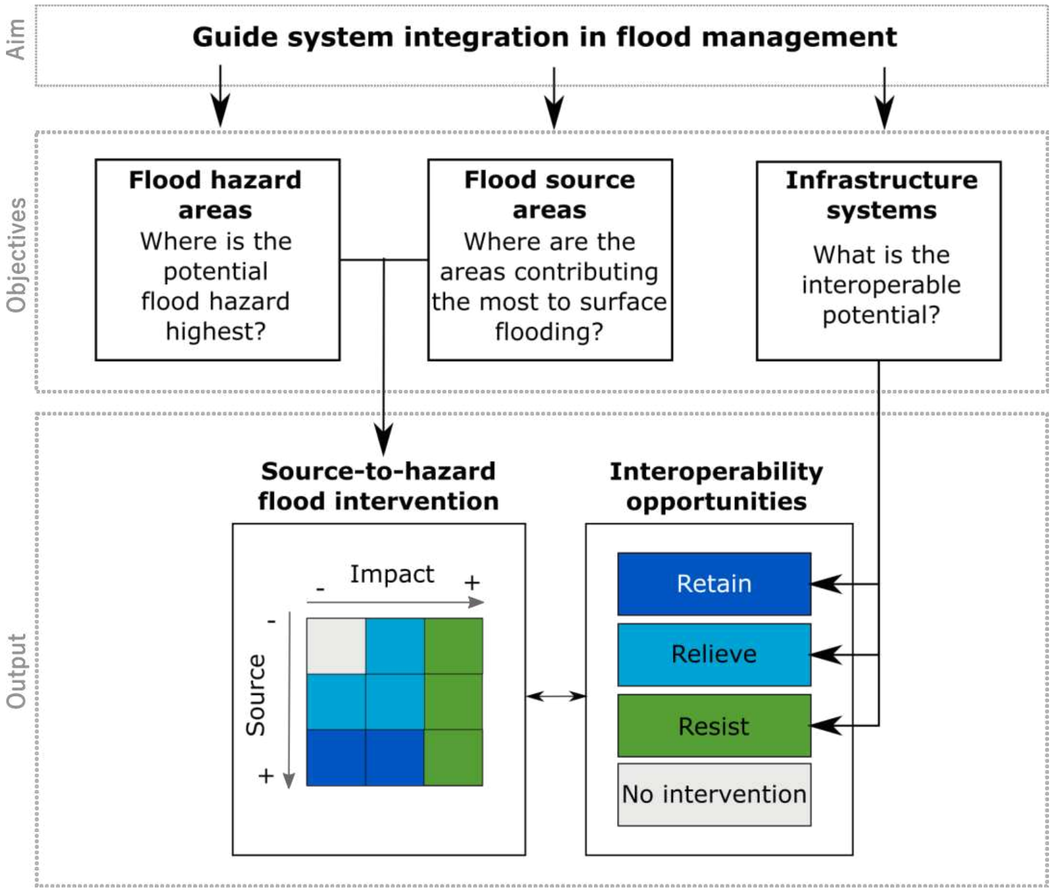

Figure 1. Spatial analysis framework for interoperable flood management

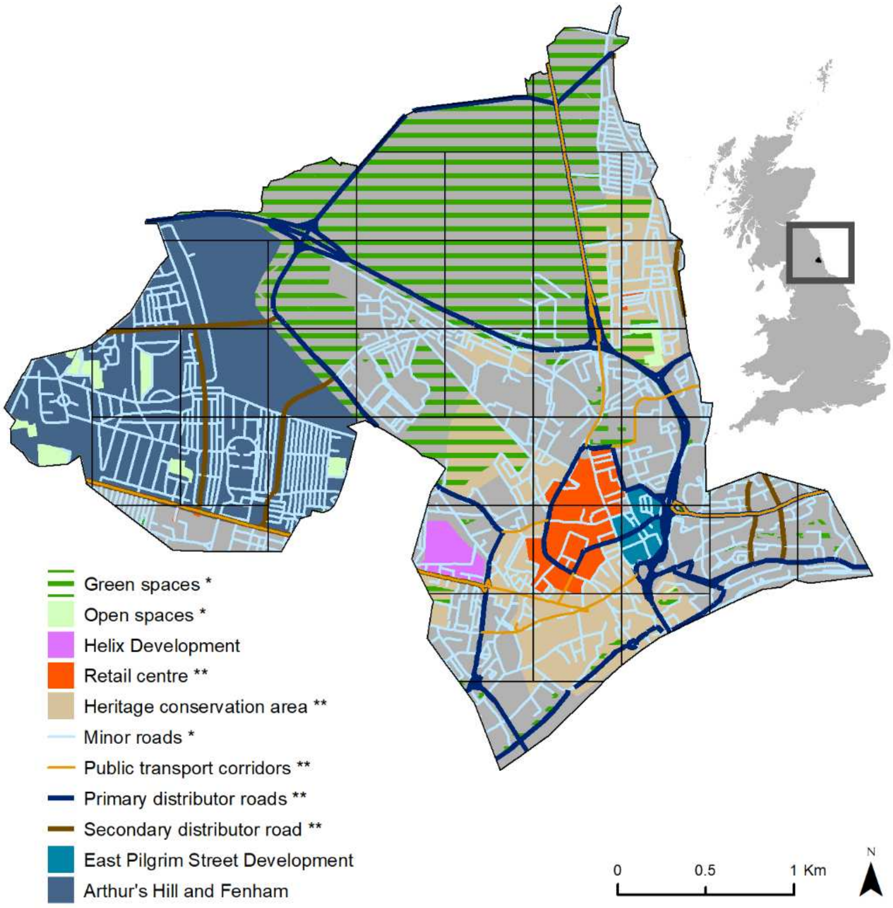

Figure 2. Study area in Newcastle-upon-Tyne, UK (Data sources: * OS data © Crown copyright and database right 2018; ** Newcastle City Council Development and Allocations Plan (NCCDA) 2015-2030)

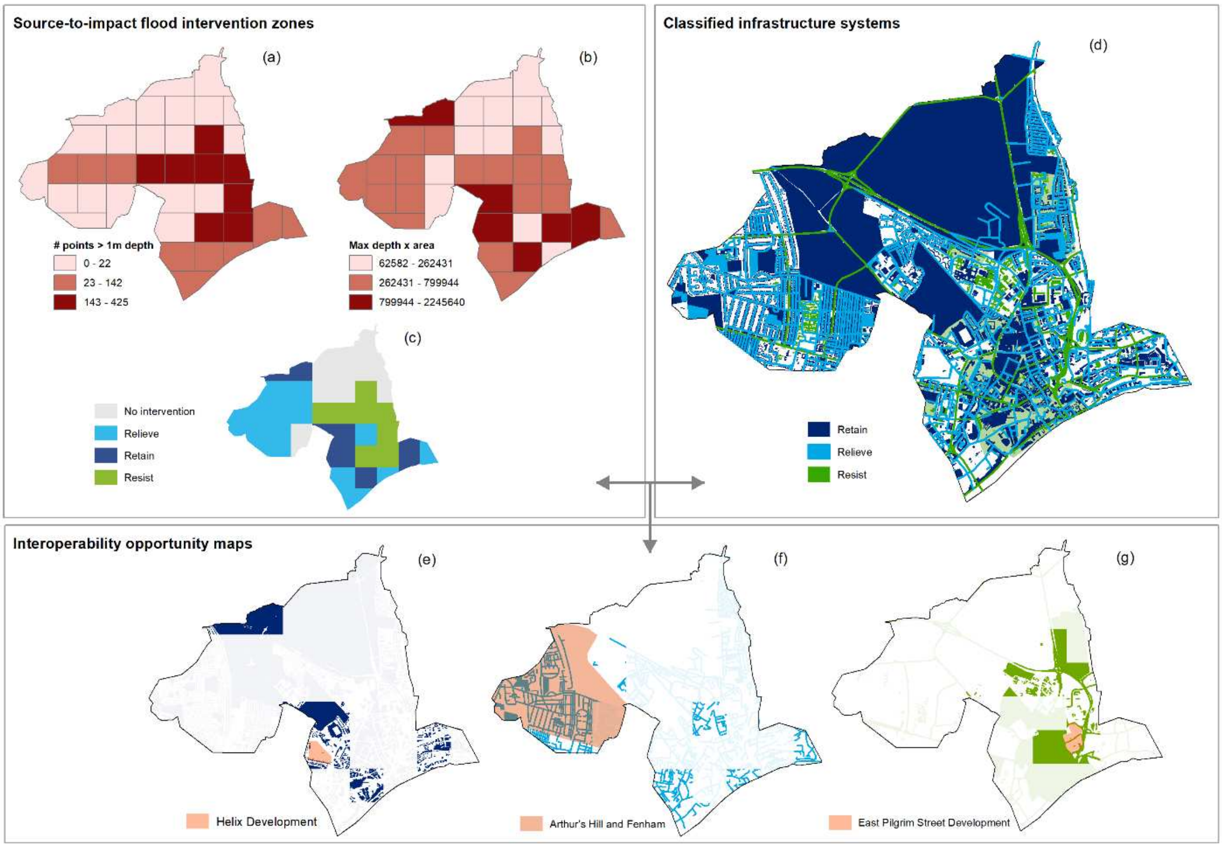

Figure 3. Results of the spatial analysis framework: (a) flood impact areas, (b) flood source areas, (c) source-to-impact flood intervention zones, (d) infrastructure systems classified according to interoperability potential, (e) potential infrastructure to retain water in retain zone, (f) potential infrastructure to relieve water in relieve zone, (g) infrastructure to protect in resist zone (contains OS data © Crown copyright and database right 2018).