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Developing a spatial analysis framework to guide interoperable urban flood management

Kim Vercruysse[1], David Dawson
University of Leeds

Nigel Wright
Nottingham Trent University

ABSTRACT

Integrated approaches are needed to make cities resilient to flooding, while aligning with the complex functioning of cities. Central to this integrated thinking is the importance of interfaces and connections, i.e. interoperability, between existing (and new) infrastructure systems to store and transfer stormwater. Yet, it remains challenging to identify how and where connecting different technical solutions and existing infrastructure systems will contribute to flood resilience. There are a lack of approaches to systematically assess flood adaptation options from an interoperable perspective. Nevertheless, the increasing amount of spatial data on urban areas (often publically available) presents an unprecedented opportunity to consider urban areas holistically. The research question addressed in this study is how spatial data can be combined to inform decision-making in flood management at the systems-level. A spatial analysis framework is presented that aims to synthesize four aspects essential to system-oriented urban flood management: (i) flood hazard; (ii) intervention efficiency; (iii) opportunities for interoperability; and (iv) barriers to system-integration. By considering these aspects together, further development of the framework into an accessible mapping tool will facilitate engagement among researchers and flood management practitioners in integrating multiple infrastructure systems to increase urban flood resilience.

Keywords: urban flood resilience, systems-approach, mapping tool, spatial data

INTRODUCTION

Flooding is the most widespread natural hazard, causing the highest economic damages worldwide (UNISDR, 2015), which is likely to exacerbate even more due to climate change and increasing urbanisation (IPCC, 2014; United Nations, 2016). Due to the complex functioning of cities and their interactions with the wider catchment, integrated flood management is increasingly required to make urban areas more resilient to flooding (CaBA, 2018; Falkenmark, 2004; iCASP, 2018; Pattison and Lane, 2012; WWF, 2016). Central to this integrated thinking in flood management is the importance of interfaces and connections, i.e. interoperability, between existing (and new) infrastructure systems to manage stormwater. Interoperable flood management aims to store and transfer stormwater along its pathway across different infrastructure systems (e.g. roads,

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[1] Corresponding Author: Kim Vercruysse, *University of Leeds, UK, k.vercruysse@leeds.ac.uk*

green spaces), which becomes especially important in cases when the capacity of existing drainage systems (e.g. sewer or SUDs) is exceeded (Vercruysse, Dawson and Wright, [accepted]).

To design interoperable systems and enhance system integration for flood management, a thorough understanding of the hydrological, environmental and socio-political functioning of a city is required. Specifically, information is needed about where along the "stormwater cascade" intervention for flood management is most efficient, and which infrastructure systems can tolerate additional water. To this end, the increasing amount of spatial data on urban areas (e.g. infrastructure, socio-economic aspects, environmental data and flood risk) presents an unprecedented opportunity. The combination of spatial data and different types of modelling techniques have been used in previous studies to investigate networks, vulnerabilities, and interdependencies of infrastructure systems in the context of flooding (Peerenboom and Fisher, 2007; Balica, Douben and Wright, 2009; Eusgeld, Nan and Dietz, 2011; Ouyang and Dueñas-Osorio, 2011; da Silva, Kernaghan and Luque, 2012; Pregnolato, Ford and Dawson, 2015; Beevers, Walker and Strathie, 2016). Alongside technical data, another body of research had focussed on collection socio-political data in the context of flood management to identify barriers to the adoption of sustainable water management solutions (van Herk et al., 2011; Fratini et al., 2012; Ernst and Preston, 2017; O'Donnell, Lamond and Thorne, 2017; Staddon et al., 2017).

However, to date few studies combine data from these different disciplines in flood management (e.g. flood modelling, infrastructure and design, and socio-political aspects) towards systematically guiding actual integrated urban flood management (Morrison, Westbrook and Noble, 2018; Pearson et al., 2018). Furthermore, despite the wide range of available flood adaptation solutions, including single "hard" engineered infrastructure solutions (e.g.flood defences), and blue-green infrastructure (BGI) solutions that include networks of natural and designed landscape components such sustainable urban drainage systems (SUDs), green roofs, and storage areas (Ghofrani, Sposito and Faggian, 2017), city planners and flood management practitioners often lack a holistic understanding of the city needed to identify how and where linking different technical solutions and existing infrastructure systems can contribute to flood resilience (Ahern, 2013). There is a lack of frameworks to guide systematic assessment of adaptation options for urban flood management that consider an interoperable perspective (Preston, Mustelin and Maloney, 2013; Hansen and Pauleit, 2014; Look and Field, 2017; Meerow and Newell, 2017). In other words, there is a need for application-oriented approaches that conceptualise the urban system, the flood risk problem, and the opportunities and challenges to adaptation (da Silva, Kernaghan and Luque, 2012). Insights into how the growing data-availability in urban areas can be combined with hydrological modelling approaches and the vast range of multifunctional and innovative options for urban water and flood management, is therefore one of the key research needs to fully operationalise integrated flood management (Vercruysse, Dawson and Wright, [accepted]).

Therefore, the research question addressed in this study is how spatial data can be systematically used to inform and guide researchers and practitioners in considering the urban area from an interoperable perspective for flood management. An interdisciplinary, spatial analysis framework is developed that synthesizes four essential questions relevant to system-oriented urban flood management: (i) where is the potential flood hazard highest (defining the problem), (ii) where will flood management intervention be most efficient; (iii) which infrastructure systems can tolerate additional stormwater and which systems cannot (interoperability); and (iv) what are potential barriers for system-integration?

The development of the spatial analysis framework is ongoing work, therefore, a simplified version of the analysis framework is used here to explain the concept and illustrate the purpose. The study is applied to Newcastle Upon Tyne (UK) and described in the next section. This is followed by an overview of the conceptual analysis framework, the selected spatial input data, and a discussion of how the results can contribute to guiding integrated, interoperable, flood management. In the conclusion the key findings are presented, including recommendations for further research.

METHODOLOGY

Case study

The study is applied to the City of Newcastle-Upon-Tyne in north-eastern England, UK. While Newcastle is vulnerable to both pluvial (surface) and fluvial (River Tyne) flooding, pluvial flooding has been the focus in multiple studies as part of the Blue-Green Cities and Urban Flood Resilience research projects of which Newcastle is a principal case study (Blue-Green Cities Research Project, 2016; Urban Flood Resilience Research Project, 2018). The Newcastle Learning Action Alliance was established in 2014 by the Blue-Green Cities Research Project to create a platform for stakeholders to develop a Blue-Green vision that includes flood risk and surface water management alongside the delivery of multiple diverse ecological, socio-cultural and economic benefits (Urban Flood Resilience Research Project, 2018). The current study is part of the Urban Flood Resilience project, which is a follow-up project of the Blue-Green Cities project, focusing on the knowledge and tools necessary to adopt a systems-approach to urban flood management.

The study area is comprised of the urban core of Newcastle, with an area of 9.15 km^2 (Figure 1). The upper part of study area is dominated by open green space (Town Moor), while the downstream part is strongly urbanised, characterised by dense commercial and historical buildings in the centre and residential areas to the east and west. The city is characterised by a relatively steep topography, sloping down from the west towards the south-east until the River Tyne along the Southern border of the study area.

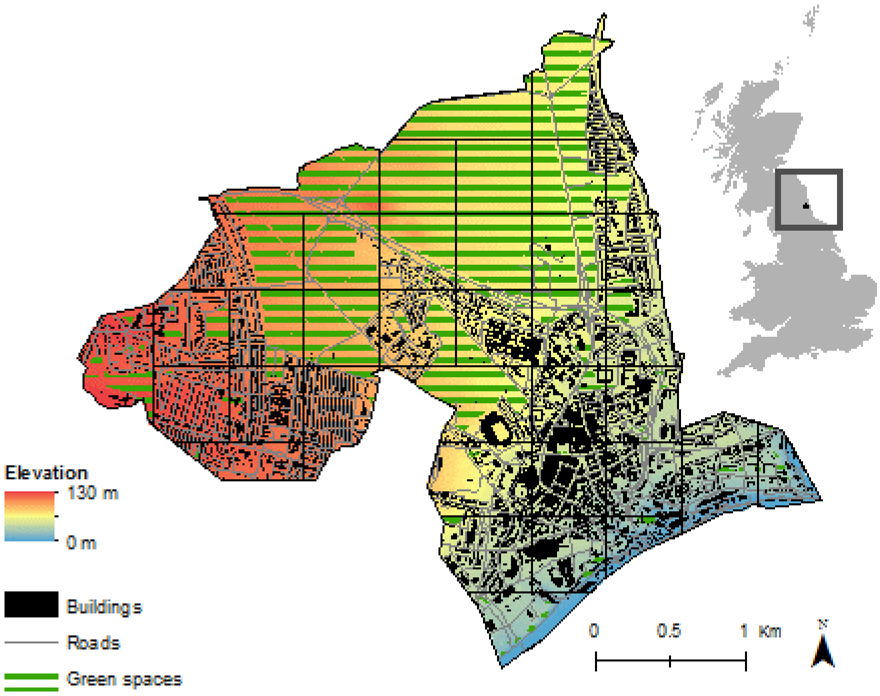

Figure 1. Urban core of Newcastle Upon Tyne (UK) (OS data © Crown copyright and database right 2018)

Spatial analysis framework

As mentioned in the introduction, interoperable design for flood management requires a thorough understanding of not only the potential flood hazard in a city, but also the hydrological and socio-political functions and interactions within a city. Stormwater can cross different infrastructure systems (e.g. drainage network, roads, buildings, etc.), while also crossing socio-political boundaries, making it possible to either store/transfer water along its pathway, or actually preventing stormwater from flowing somewhere. To address these aspects, a spatial analysis framework is being developed, consisting of four main steps (Figure 2).

The first step is to identify the potential flood hazard under a specific scenario: where is flood hazard likely be the highest? In a second step, this flood hazard information is compared to the locations where flood management intervention is likely to be the most efficient in reducing flood hazard; what is the connection between location with a high potential flood hazard and locations contribution to this hazard? This information then feeds into the third step, which aims to identify where stormwater can go (for store or transfer) and equally important, where it cannot go (e.g. due to emergency routes, utilities, etc.). This step aims to identify opportunity areas to manage stormwater and, if no opportunities can be identified, indicate where additional/new infrastructure will likely be required. Finally, alongside the opportunities, it is equally important to identify where other socio-political factors might form potential barriers for integrated flood management so that appropriate stakeholders can be involved or alternative solutions can be developed. In what follows, these four steps are further discussed, starting with an overview of the selected spatial input data (Table 1).

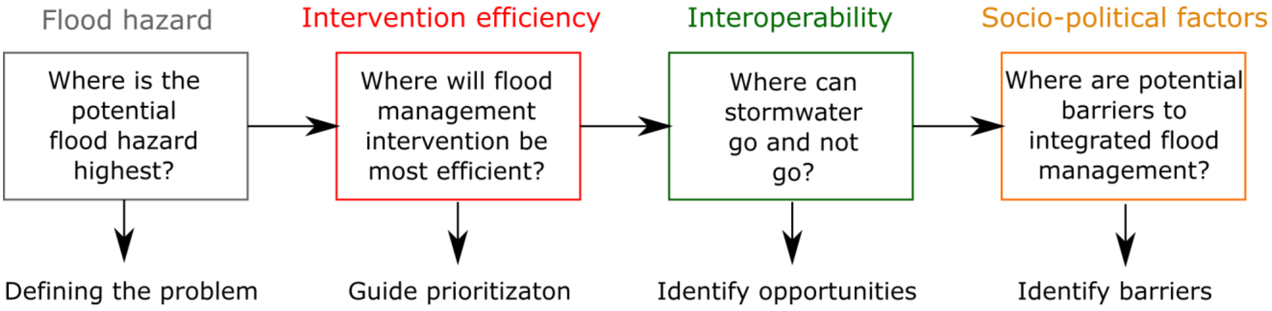

Figure 2. Conceptual illustration of spatial analysis framework for interoperable flood management

Flood hazard

To assess flood hazard for a particular location and rainfall event, a wide range of pluvial flood models have been developed in the past decades (Sanders, 2017). Hydrodynamic models are often the most useful in the context of interoperability, because the high level of detail in those models allows to simulate interactions between different infrastructure systems. In this study, CityCAT, a hydrodynamic model developed by Newcastle University (Bertsch, Glenis and Kilsby, 2017), was used. The model has previously been applied to evaluate the impact of BGI and other infrastructure modifications on flood depths (Morgan and Fenner, 2017), or the impact of flooding on transport disruption (Pregnolato, Ford and Dawson, 2015; Pregnolato et al., 2017). In this study, CityCAT was applied to 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.

Intervention efficiency

Locations with high flood risk are not necessarily the locations where flood management intervention is the most efficient or has the most impact. Source areas “causing” flooding downstream are often different than the locations characterised by high estimated flood depths, so that if these source areas (i.e. the locations which would have the most impact on reducing flood hazard) can be identified, it can be used to guide prioritization for flood management intervention. To this end, an experimental model design was developed as part of this study to assess locations where most floodwater is likely to come from (Vercruysse et al., [in preparation]). The model design is based on a systematic sensitivity testing of CityCAT through dividing the study area into grids (Figure 1). The outcome of this analysis is a map showing the contribution of each grid to flood volumes downstream, so that the locations contributing the most to flooding can be identified.

Interoperability

Enhancing interoperability for flood management implies that physical interdependencies within and between infrastructure systems can contribute to the overall system performance to deal with stormwater (Ouyang and Dueñas-Osorio, 2011). In general, the function of existing infrastructure systems for stormwater management can be classified under two main processes: store and transfer stormwater to a safer/more suitable location. The most considered infrastructure systems in urban areas that can be interoperable are green spaces (retain water locally) (e.g. Schuch et al., 2017; Sheffield City Council, 2018) and roads (transfer water) (e.g. Balmforth et al., 2006). Furthermore, in some locations carparks or leisure areas are also being redeveloped or considered as temporary flood storage areas (e.g. De Urbanisten, 2012). In this study, the location of green spaces and carparks are used as an example of opportunities to store water, while roads are considered opportunities to transfer water. Additionally, locations were identified where it is assumed that additional stormwater can cause harm or expose critical infrastructure to the impacts of flooding. For example, using roads to transfer water near a hospital or utility infrastructure might impede access (Coles et al., 2017). In this study, major roads (A-roads and motorways on the OS Mastermap 2018) were identified as roads not to be purposely used to transfer stormwater, as well as locations near hospitals and energy substations.

Socio-political factors

Implementation of interoperable solutions for flood management goes beyond the physical flooding system and also requires consideration of socio-political factors. Multiple infrastructure systems are involved, and therefore also different sectors, which makes it challenging to transfer knowledge, address different needs and opinions, pinpoint responsibility, and quantify the value and potential benefits of interventions (Hoang and Fenner, 2016; Hickford et al., 2017). Therefore, it is important to acknowledge potential barriers for interoperability, so that the feasibility of technical solutions can be weighed against possible external challenges. In this study, property boundaries were used to represent barriers posed by the multitude and complexity of stakeholders involved.

Table 1. Sources of input data for simplified spatial analysis framework

	Flood hazard	**Intervention efficiency**	**Interoperability**		**Barriers**
			Manage water	***No water***	
Data	Maximum flood depths 1/50 year event	Flood volume contribution per grid	Green spaces	Utilities	Property boundaries
Source	CityCAT	CityCAT	OS data © Crown copyright and database right 2018	OS data © Crown copyright and database right 2018	OS data © Crown copyright and database right 2018
Data			Roads	Medical buildings	
Source			OS data © Crown copyright and database right 2018	OS data © Crown copyright and database right 2018	

RESULTS AND DISCUSSION

In general, potential flood hazard for the modelled 1/50 year rainfall event is highest in middle and the lower eastern part of the catchment (Figure 3a). However, these locations with high flood hazard are not the locations that contribute the most to flooding (Figure 3b). Furthermore, combining the four steps within the proposed analysis framework allows to identify different classes for flood management, which can guide prioritization about where and which interoperable intervention is likely to be most suitable. In what follows, this is illustrated with four selected locations.

Location A in the upper part of the catchment is characterized by a low potential flood hazard (low amount of points with estimated flood depths >1m) (Figure 3a), but the intervention-efficiency sensitivity analysis shows that this area contributes significantly to flood volumes downstream (Figure 3b). In other words, capturing and storing the stormwater within location A will have a significant impact on reducing flood depths downstream. Furthermore, due to the high percentage of green space in this area, location A presents an opportunity to retain water locally by enhancing infiltration and creating stormwater storage ponds to avoid runoff further downstream (Figure 3c). Therefore, adjusting the current infrastructure (e.g. levees and culverts to keep water on green spaces) could be a potential high-impact intervention. In relation to the socio-political factors, there are very little number of properties within location A, which could potentially reduce the stakeholder complexity related to managing this land (Figure 3d). However, an important dataset to be included in further development of the framework will be ownership of land and other administrative information, as the amount of properties only provides a simplified indication of the socio-political complexity within an area.

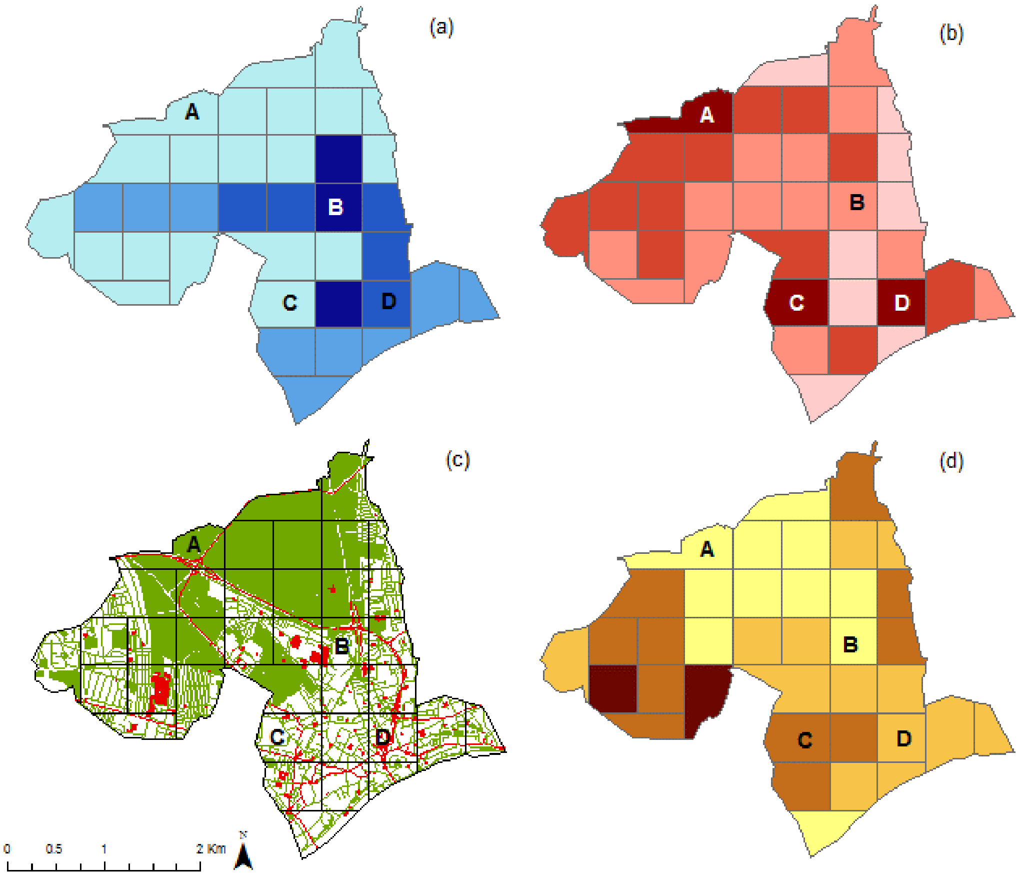

Figure 3. Analysis framework output maps: (a) flood hazard (dark = highest number of points with estimated flood depth > 1m), (b) intervention efficiency (dark = highest potential impact on flood reduction), (c) interoperability opportunity (green=green spaces and minor roads, red=major roads, medical buildings and utilities), (c) barriers (dark = highest socio-political complexity).

Similar to location A, location C is characterized by low potential flood hazard, while it also contributes significantly to flood volumes downstream (Figure 3a-b). However, compared to location A, this location does not present great opportunities to capture and store water using the current infrastructure (Figure 3c).

Nevertheless, this area is currently under development as part of Newcastle University, with specific attention for SUDs (Helix, 2019), and has therefore important strategic importance to alleviate flood depths within the city center. If the relative stakeholder complexity can be overcome (Figure 3d), additional interoperable solutions could be to transfer stormwater along the road network towards the River Tyne (Balmforth et al., 2006) or investigate the impact of water harvesting techniques to capture stormwater locally (Huang et al., 2015).

Contrarily, location B is characterized by very high potential flood hazard, but contributes relatively little to flood volumes downstream (Figure 3a-b), i.e. the flood hazard in this area is caused by areas upstream of this location. Therefore, adding additional green space will likely not solve the source of the flood problem, but will only offer local protection. Furthermore, this area poses significant barriers for interoperability, as it is characterized by a high percentage of medical buildings and a major road crossing (Figure 3c). As a result, while the stakeholder complexity in terms of number of properties is relatively low in this area (Figure 3d), it would nevertheless be more suitable and effective to manage stormwater in upstream areas rather than dealing with it locally.

Finally, location D is both characterized by high potential flood hazard and high contribution to flood volumes (mostly local as this is one of the most downstream located areas within the catchment) (Figure 3a-b). These results illustrate that it is essential to manage stormwater locally to prevent local flooding. The strategic importance of this area in terms of its potential to reduce local flooding is reflected within the redevelopment plans for this area of Newcastle City Council, which specifically focusses on BGI (Lawless, 2016a, 2016b). Additionally, there are a few carparks in the area which could offer an interoperable solution to temporarily store water (Digman et al., 2014), given that the major road that runs through location D is taken into account (Figure 3c).

CONCLUSION AND FURTHER RESEARCH

This study presented a first concept of a spatial analysis framework that aims to combine spatial information from different disciplines within urban flood management and research to help guide the systematic, city-scale system-integration for flood management. To this end, flood modelling was used to identify locations of flood hazard as well as locations contributing the most to this flood hazard to better understand the hydrological interaction between different spatial locations within an urban catchment. Through a four-step approach, the proposed framework combines the flood hazard information with data on infrastructure and socio-economic factors that can present opportunities and barriers for interoperable flood management.

It is recognized that the current approach is based on an oversimplification of reality and that important input data is missing. However, the aim of this initial study is to illustrate what the framework aims to deliver. Therefore, the initial results presented here should be considered as an example to show the potential of considering multiple data-layers together to get a more holistic image of the problem, the opportunities and the challenges for system-oriented urban flood management. In further research, the data-input and analysis will be further refined, partly through interactive workshops with experts in the field of urban flood management and city-planning.

Further development of the framework into an accessible mapping tool will facilitate engagement among researchers and flood management practitioners in integrating multiple infrastructure systems to increase urban flood resilience, and help guide prioritization and better targeting of flood management interventions and investments in urban development.

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