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Interoperability: A conceptual framework to bridge the gap between multifunctional and multisystem urban flood management

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Abstract
Urban flood management is increasingly expected to be multifunctional to integrate with the existing functioning of cities. Locally, this led to the development of sustainable urban water drainage designs, while at larger scales, blue-green or water-sensitive cities are considered as examples for how cities should function. Upscaling local designs to city-scale flood resilience is not straightforward, however, due to the complexity of physical infrastructure and socio-economic interactions within urban systems and requires "system-of-systems" thinking. To this end, we introduce the concept "interoperability" to guide transition from local multifunctionality to city-scale multisystem flood management, through actively managing connections between infrastructure systems to convey, divert, and store flood water. While flood management is already based on these connections, interoperability is about explicitly emphasising them to explore and create opportunities to facilitate the integration of systems for flood management. The main research need arising from this conceptualisation is to determine how spatial data on infrastructure, environment, and social characteristics in urban areas can serve as a basis to identify opportunities and barriers for interoperability. By introducing interoperability and the research needs arising from it, a framework is created to facilitate and encourage practical thinking and discussion about system integration in urban flood management.

KEYWORDS
integrated flood risk management, resilience, urban drainage, water sensitive urban design

1 | INTRODUCTION

1.1 | Urban flood resilience

Cities are areas with highly connected and dense networks of people, resources and infrastructure, resulting in urban systems that work at an increased efficiency. At the same time, urban networks and people are very vulnerable to the impacts of flooding (pluvial and fluvial), which causes widespread economic, environmental, and social damages. Furthermore, continuing urbanisation and the likely increase in intense rainfall events as a result of climate change, will exacerbate the impact of urban flooding and decrease the extent to which traditional drainage infrastructure provides flood protection (Haghighatafshar et al., 2018; IPCC, 2014a; UNISDR, 2015; United Nations, 2016). To address these threats of flooding in an uncertain future, adaptation becomes essential to create flood resilient cities (Balsells, Barroca, Becue, & Serre, 2015; Jha, Bloch, & Lamond, 2012; Wise et al., 2014).

Urban flood resilience (UFR) is the term commonly used to refer to the whole urban system (i.e., from physical structures to people) and its capacity to cope with flooding, specifically, to maintain significant levels of efficiency in its social, economic, environmental, and physical functions during and after flood events (Balsells et al., 2015; Cousins et al., 2017; Hammond, Chen, Djordjević, Butler, & Mark, 2015; OECD, 2014; Parsons et al., 2018; Staddon et al., 2018). An advantage of (re)orienting urban flood management through the concept of resilience (as opposed to flood mitigation only), is that it encourages creative thinking and flexible adaptation strategies focussing on dynamic, systemic, and integrated approaches (Balsells et al., 2015). Central to UFR is "multi-functionality," which refers to deliberately combining ecological, social, and/or economic functions in urban flood management strategies (Ahern, 2013), while using the limited urban space more effectively (Hansen & Pauleit, 2014; Merz, Hall, Disse, & Schumann, 2010) and potentially reducing costs in comparison with traditional water management measures (Ashley et al., 2013).

At the local scale, the idea of multifunctionality has been rapidly adopted by the urban drainage research community (Fletcher et al., 2015), and has resulted in a fast growing range of innovative multifunctional solutions for flood management that provide various benefits across multipurpose designs (Lawson et al., 2014; Morgan & Fenner, 2017; Zareba, 2014). These designs are often referred to as sustainable urban drainage systems (SUDSs), water sensitive urban designs (WSUDs), or simply blue-green infrastructure (BGI) (Fletcher et al., 2015; Ghofrani, Sposito, & Faggian, 2017; O'Donnell, Thorne, & Yeakley, 2018). For example, with multifunctional BGI (e.g., bioswales, retention ponds, rain gardens, green roofs), opportunities are created to extend the benefits of the designs beyond flood management (Demuzere et al., 2014; Jha et al., 2012; Morgan & Fenner, 2017; Peng & Jim, 2015). BGI can provide ecosystem services such as reducing water pollution by filtering runoff water, improving air quality by increasing carbon sequestration, or enhancing biodiversity by creating suitable habitats for fauna and flora (Lamond, Rose, & Booth, 2015; Woods Ballard et al., 2015). Well-established multipurpose interventions are, for example, retention basins that can store water in times of flooding, which are used for leisure or as buildings during other times. Examples of multifunctional designs for flood management are found in cities across the world (Table 1).

However, the spatial extend of the effect of single (local) multifunctional designs in terms of reducing surface runoff (and creating wider benefits) often remains limited (Haghighatafshar et al., 2018). Particularly when larger-scale UFR is aimed for, it is essential to combine multiple urban systems to manage excess water (Voskamp & Van de Ven, 2015; Zevenbergen, Veerbeek, Gersonius, & Van Herk, 2008). The "system" benefit of such approaches is significant, for example, in Uganda, modelling the effects of implementing suitably designed water harvesting systems at a catchment-scale, showed the potential of increasing resilience to flooding by up to 25%, and also providing up to 30% of the household water supply requirements (Mugume, Melville-Shreeve, Gomez, & Butler, 2017). Similarly, simulations with overland flow hydrodynamic models in Malmö, Sweden, showed that a system of BGI can reduce the total flooded surface by 70% (Haghighatafshar et al., 2018). The idea that the principles for local multifunctional designs (i.e., intercepting, storing, slowing, and reusing excess water) can be applied at wider spatial scales is reflected in the emergence of concepts such as "blue-green cities" (Lawson et al., 2014), "water-sensitive cities" (Radhakrishnan, Pathirana, Ashley, Gersonius, & Zevenbergen, 2018), or "sponge cities" (Jiang, Zevenbergen, & Fu, 2017). These concepts have been translated into concrete city-wide retrofitting/developing plans to make cities more water resilient by creating a more natural water balance through the upscaling of BGI and sustainable urban drainage designs (Table 1). Nevertheless, despite several examples of city-wide retrofitting or development, alongside a wide range of possible designs for more sustainable urban flood management, large-scale implementation of these solutions generally remains slow (Balsells et al., 2015; Meerow & Newell, 2017; O'Donnell, Lamond, & Thorne, 2017; Serre, Barroca, Balsells, & Becue, 2018).

TABLE 1 Examples of multi-functional designs and multi-system initiatives involving urban flood management

Multi-functional designs	Multi-system initiatives
Outdoor school auditorium Malmö, Sweden (Digman et al., 2012)	*Ekostaden Augustenborg* Malmö, Sweden (Climate-ADAPT, 2014)
Waterplein Benthemplein Rotterdam, the Netherlands (Rotterdam Climate Initiative, 2018)	*Amsterdam Rainproof* Amsterdam, the Netherlands (Amsterdam Rainproof, 2018)
Multipurpose retarding basin Machida City, Japan (Jha et al., 2012)	*Green City, Clean Waters* Philadelphia, USA (Philadelphia Water Department, 2018)
SMART tunnel Kuala Lumpur, Malaysia (Jha et al., 2012)	*Sponge Cities* Several cities, China (Li et al., 2018)
Endcliffe Park flood storage area Sheffield, UK (Sheffield City Council, 2018)	*Ebbsfleet Garden City* Ebbsfleet, UK (Ebbsfleet Development Corporation, 2018)

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1.2 | Urban flood management strategies

A key challenge in upscaling single multifunctional designs to multisystem urban flood management, is understanding the interaction between social (e.g., communities, properties, authorities) and infrastructure (e.g., transport, green spaces, buildings, energy) systems (existing and new), and their combined performance characteristics to manage excess water and offer multiple functions (Ahern, 2013; Haghighatafshar et al., 2018; Hoang & Fenner, 2016). Because cities are such complex "systems-of-systems" there is a need to approach urban flood management from a systems perspective and further explore and evaluate the possibilities and challenges related to using both existing and new infrastructure (and social) systems to manage flood risk in urban areas.

The problem in this context, however, is that the majority of flood management strategies fall short in considering the urban environment holistically. For example, the most basic strategy to flood management starts from a preselected location (Figure 1a). Site selection can happen for any number of reasons, for example, in a newly built area with sustainability goals (e.g., Ebbsfleet Development Corporation, 2017), as part of urban regeneration projects (Zevenbergen, Veerbeek, Gersonius, Thepen, et al., 2008), or through community support (McLean, Beevers, Waylen, Wright, & Wilkinson, 2015; WMO, 2017). Following this strategy, a set of adaptation measures is then designed for the specific site. However, measures that are technically most effective to reduce flooding and deliver additional benefits, do not necessarily address the locations most at risk of flooding and/or the most vulnerable groups (Johnson, Penning-Rowsell, & Parker, 2007). Thus, a second strategy is to use the estimated risk of flooding to guide flood management (Figure 1b), where the risk of flooding is often interpreted as the combined effect of the flood hazard and the system vulnerability to flooding (Balica & Wright, 2010). Many decision support approaches have been developed based on this risk driver, and have been extended to include the associated costs (e.g., European Commision, 2016; Fratini, Geldof, Kluck, & Mikkelsen, 2012; Zhou, Mikkelsen, Halsnæs, & Arnbjerg-Nielsen, 2012) or infrastructure and services likely to be at risk (e.g., Coles, Yu, Wilby, Green, & Herring, 2017; Gonzva, Barroca, Gautier, & Diab, 2017; Pregnolato, Ford, & Dawson, 2015; Zevenbergen et al., 2018). Alternatively, flood management strategies can also be based primarily on the potential benefit(s) associated with specific adaptation measures (Figure 1c). Most often the focus is on a single benefit (e.g., reduce a local scale flood problem or increase access to green spaces), but multiple benefits are increasingly being considered. This is reflected in the development of decision support approaches to evaluate competing and complementary ecosystem service priorities at the city-scale to systematically identify locations where BGI would be most needed (e.g., Alves, Sanchez, Gersonius, & Vojinovic, 2016; Casal-Campos, Fu, Butler, & Moore, 2015; Digman, Horton, Ashle, & Gill, 2016; Meerow & Newell, 2017; Morgan & Fenner, 2017; Vandermeulen, Verspecht, Vermeire, van Huylenbroeck, & Gellynck, 2011).

In short, with multiple strategies being used to guide the implementation of flood management measures, it is unsurprising that there are numerous approaches directly aimed at assessing these different aspects of urban flood management (e.g., risk, costs, benefits). While some of these approaches do consider the city as an entity, that is, including system interactions, most do not explicitly consider the existing systems at the city-scale and how these can be utilised, and combined with other or new infrastructure, to manage excess water (Kuller Bach, Ramirez-Lovering, & Deletic, 2017; Serre et al., 2018). As a result, opportunities are missed to fully make use of existing urban systems and integrate adaptation solutions within the urban environment, which prevents the systematic application of flood management measures to achieve UFR. The question therefore remains as to how the urban environment "as a whole"

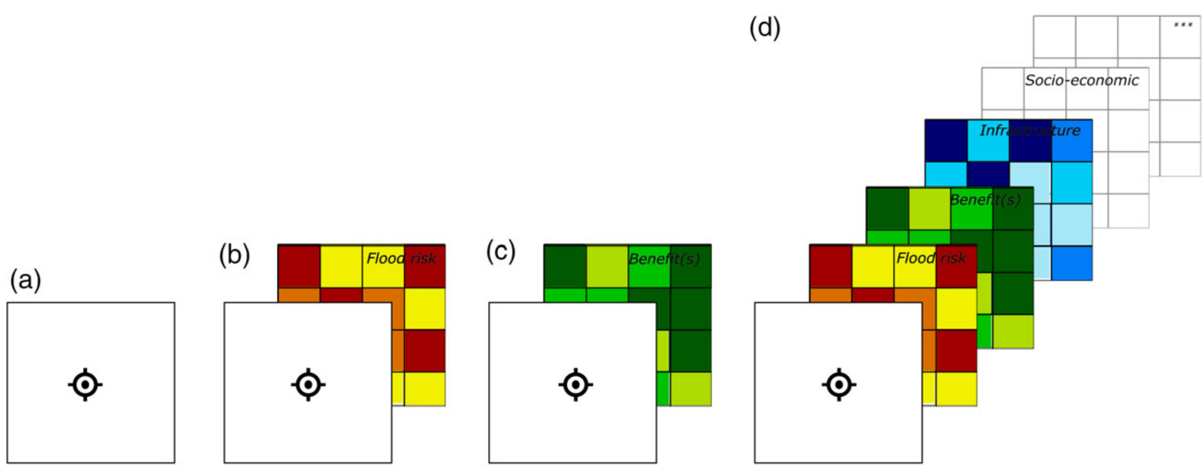

FIGURE 1 Conceptual illustration of urban flood management strategies. Adaptation measures can be developed based on: (a) a preselected location; (b) the estimated flood risk; (c) the potential (multiple) benefit increase; (d) the multiple systems within a city

can become the basis for strategies that guide and support more system-based flood management (Figure 1d).

In this paper, we directly address this critical research agenda by proposing a new concept, "interoperability," which especially considers the city, and its interconnections, as a whole (as part of a wider catchment) in the development of flood management strategies. Through this new concept, we aim to provide a framework for how to operationalise systems-thinking into urban flood management using the urban "system-of-systems" as a basis. First, we describe the concept of interoperability in detail (section two) and discuss how the more explicit consideration of system connections can provide drive and opportunities for more integrated, system-based approaches to flood management (Section 3). Then, we propose a conceptual approach to embed interoperability in a systematic data analysis of urban systems and identify critical research needs to achieve this (Sections 4 and 5).

2 | INTEROPERABILITY: TOWARDS SYSTEM-BASED STRATEGIES TO URBAN FLOOD RESILIENCE

As stated, the need for "integrated, holistic approaches" to flood management are increasingly being advocated as the solution to achieving UFR (Balsells et al., 2015; Jha et al., 2012; Zevenbergen, Veerbeek, Gersonius, & Van Herk, 2008). While few tools are available to achieve this at the city-scale, integrated, systems-thinking is gaining momentum in catchment sciences, whereby the entire catchment is being increasingly recognised as an essential scale to manage water across its pathway by emphasising the many ecosystem and socio-economic interactions (e.g., CaBA, 2018; Falkenmark, 2004; iCASP, 2018; Pattison & Lane, 2012; WWF, 2016).

We apply similar thinking to the "city catchment" by introducing the concept of "interoperability" to more explicitly consider the linkages between different systems and their capacity to deal with excess water, that is, the ability of any water management system to redirect water and make use of other system(s) to maintain or enhance its performance function during exceedance events. In other words, by assessing the complex topological properties of the urban infrastructure systems, particularly the interoperability between the drainage system, existing multifunctional (blue/green) solutions, and other urban systems (e.g., infrastructure such as transport or land use), it could be possible to expand the capacity of the overall system towards achieving improved UFR (Ouyang & Dueñas-Osorio, 2011). In doing so, interoperability becomes the basis to develop strategies to guide the adaptive design process of developing from a system with single multifunctional assets towards an interoperable "system-of-systems" capable of achieving UFR (Figure 2).

In practice, a wide range of examples exist whereby connections between different infrastructure systems are actively

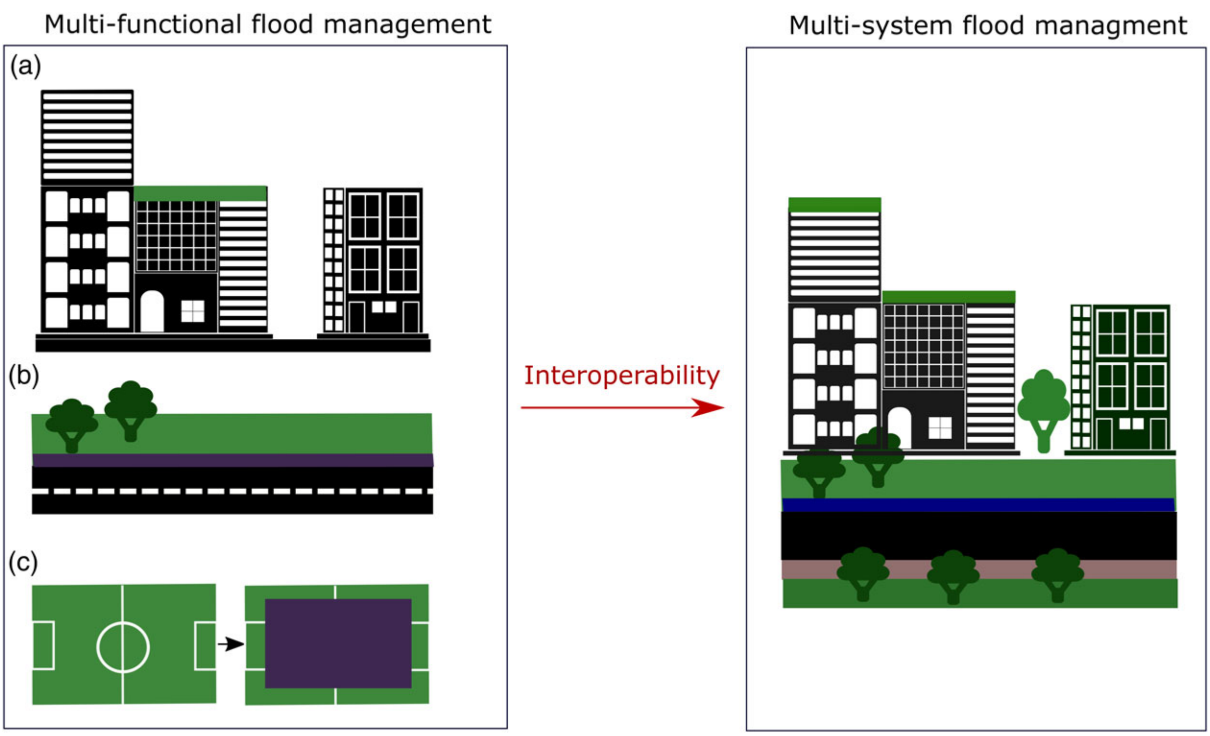

FIGURE 2 Illustration of interoperability as a transition from implementing individual multifunctional designs (e.g., (a) green roofs; (b) swale; (c) retention) to system-integrated flood management (e.g., Blue-Green cities or Sponge Cities)

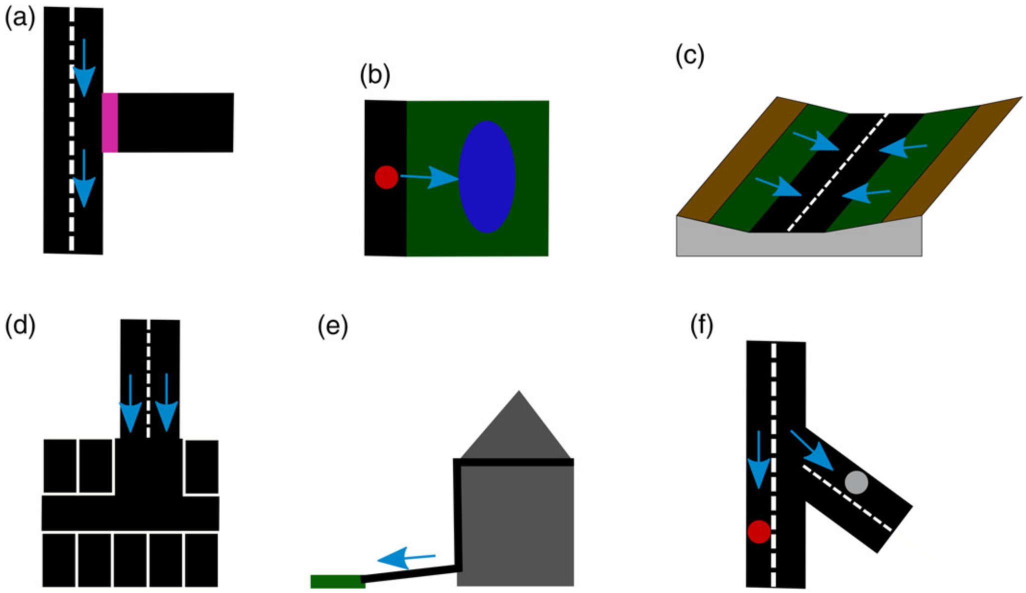

FIGURE 3 Potential types of interoperability (blue arrows indicate the transfer of water from one system to another): (a) drainage to road; (b) sewer to blue-green infrastructure; (c) blue-green infrastructure to road; (d) road to open space; (e) housing/roofs to blue-green infrastructure; (f) road to underused road gully (grey dot) away from frequently overwhelmed gully (red dot)

managed to deal with flood water. In the United Kingdom, the concept and guidance of "design for exceedance" (Balmforth, Digman, Kellagher, & Butler, 2006) promotes the use of highways, footpaths, swales, car parks, or vegetated channels in urban areas to have a secondary function of conveying flood water. Figure 3 illustrates some simplified examples of interoperability to enable efficiency gains through system integration. Adjustments to the local transport infrastructure can divert water from a residential area and storing excess water on the highway (Digman Ashley, Hargreaves, & Gill, 2014) (Figure 3a). Further examples include the upsizing of local sewers alongside the construction of an overflow system into a nearby local park (Figure 3b), were existing ornamental ponds can be used for extra water storage (including oil interceptors) (Digman et al., 2012). Alternatively, the connectivity between SUDs or BGI and the road network can be enhanced, so that the road can serve as an additional runoff channel when the capacity of the SUDs is reached (Figure 3c) (Ramboll Studio Dreiseitl, 2015). Following this principle, water can also be diverted along the road network towards open spaces (e.g., parking spaces) for temporary storage (Figure 3d), from roof drains towards green spaces (Figure 3e) or towards gullies that are underused compared to gullies which are often overwhelmed (Figure 3f).

The above cases are just a few existing examples where urban systems that are not necessarily built to manage water (temporarily) serve as additional water management assets. The intention of collecting these examples under the umbrella of interoperability is to create a framework which can be applied to consider these connections in a more standardised way. In other words, while flood management is in essence already based on the connections between systems to convey, divert, and store water, interoperability is about explicitly emphasising system connections as a way to explore and create opportunities to facilitate the integration of systems for flood management. In what follows, some of these opportunities are further discussed.

3 | OPPORTUNITIES THROUGH INTEROPERABILITY

The most significant role interoperability can play in flood management lies in promoting the capture and transfer of water along different points of the "stormwater cascade." As illustrated in the examples in Figure 3, interoperable connections especially become important when the capacity of existing systems (drainage or BGI) is exceeded. Furthermore, locations with highest flood risk are not necessarily the locations that would benefit the most from intervention for flood management. Instead, it could be more effective to install measures along the pathway of the water to avoid water building up and becoming a high risk for people and infrastructure. In this context, examining the potential interoperability within a city could lead to the identification of locations to intercept flood water during a rainfall event.

More explicitly managing connections between infrastructure systems can also reduce the pressure on vulnerable points in the system. Interdependence between infrastructure systems has become a major research area in the last 30 years, and by exploiting the capacity between systems we could increase the potential for cascading failures through the system; amplifying small disruptions into large disruptions (Balica, Douben, & Wright, 2009; Beevers, Walker, & Strathie, 2016; da Silva, Kernaghan, & Luque, 2012; Eusgeld, Nan, & Dietz, 2011; Ouyang & Dueñas-Osorio, 2011; Peerenboom & Fisher, 2007; Pregnolato et al., 2015). For example, hydrological model simulations in Malmö, Sweden, have also shown that the efficiency of a BGI system in mitigating flooding can be strongly limited if implemented in an area with a hydraulically overloaded piped sewer network (Haghighatafshar et al., 2018). Progressing from these types of analyses, interoperability offers a way to practically use information on infrastructure vulnerabilities to develop integrated design solutions for flood management that limit the risk of cascading failures. For example, by systematically considering multiple systems and their functions together, critical points or vulnerabilities within infrastructure systems can be avoided while focusing on parts of the systems that are underused, for example, water can be diverted from points in the system that is often overwhelmed to locations that are "underused" (Figure 4a,b).

Finally, considering interoperability in adaptation strategies also creates opportunities for different adaptation pathways at different timescales. Embedding interoperability within a "system-of-systems" flood management approach could allow adaptations to be adjusted or enhanced depending on changing conditions (i.e., climate change or society). This flexibility in adaptation and resilience-based decision-making helps to account for uncertainty in the future and is advocated by organisations nationally and globally (IPCC, 2014b). For example, the road network can initially be modified to divert water away from a residential area towards an open space where it can be temporarily stored (Figure 4b). Over time, if climate worsens or society wishes to pursue a more sustainable future (Haasnoot, Kwakkel, Walker, & ter Maat, 2013; Wise et al., 2014), this established connection can be further developed and integrated with more BGI (Figure 4c).

4 | EMBEDDING INTEROPERABILITY: DATA DRIVERS

The introduction of interoperability in the flood management context is, at present, a theoretical idea not yet supported by empirical evidence. To apply interoperability as a practical means to facilitate system integration for flood management and achieve the opportunities we argue it can bring in terms of UFR and adaptation, a thorough understanding of the hydrological, environmental, and socio-economical functioning of a city is required.

The growing number of data sets on multiple aspects of urban environments (e.g., land use mapping, environmental monitoring, census), and models and tools to process these data (e.g., flood modelling, spatial, and network analysis), present an unprecedented opportunity in this context. Especially in European cities, a wealth of information is often publicly available (e.g., on land use, road networks, building types, property boundaries, topography, climate, flood risk, etc.), which could theoretically inform decision-making for flood management at the systems level. The central question therefore becomes: how can (spatial) data on infrastructure, environmental, and socio-cultural and economic characteristics in urban areas serve as a driver to identify opportunity areas for interoperability and in doing so develop a systemic strategy for flood management at the city-scale (Figure 5)?

Insights into how the growing data-availability 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

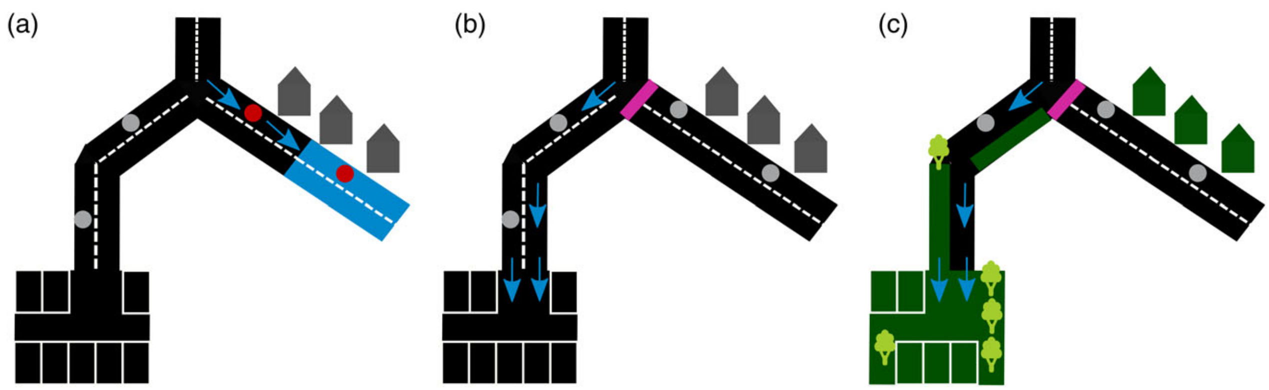

FIGURE 4 Illustration of transition to multisystem flood management through interoperability: (a) surface water naturally flows through a residential area where street gullies are often overwhelmed (indicated in red); (b) street hump prevents excessive surface water to flow in residential area and is diverted along road towards open (e.g., parking) space for temporary storage; (c) blue-green infrastructure is fitted which is integrated with the additional flow

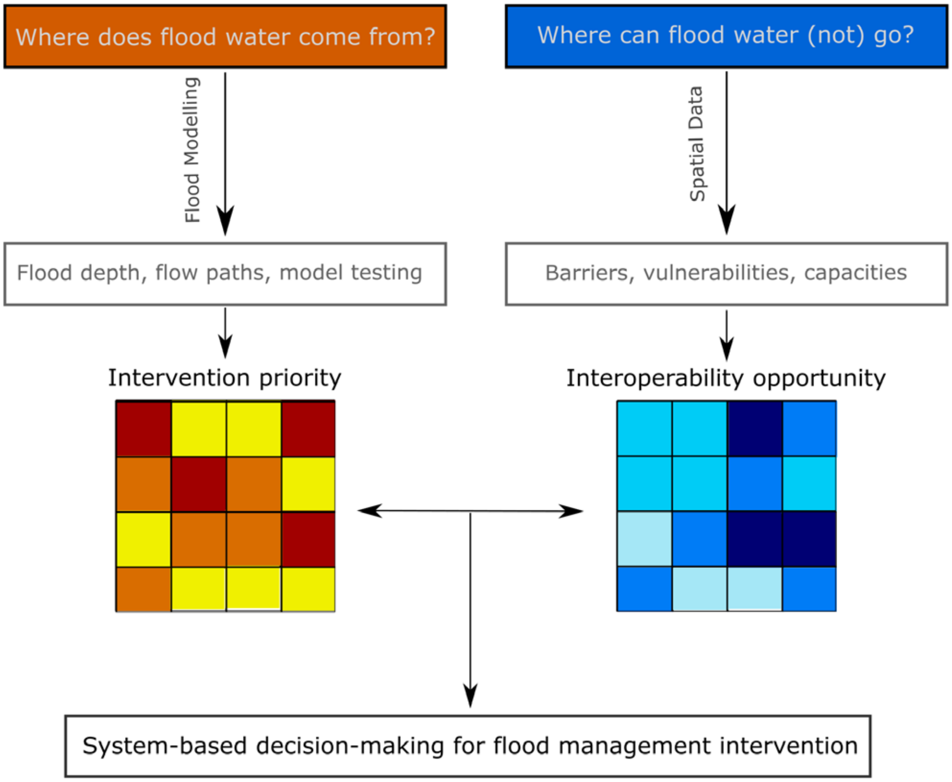

FIGURE 5 Conceptual architecture of a spatial mapping tool for system-based flood management aiming to combine two main aspects: (a) where does flood water come from and how can intervention priority areas be identified, and (b) where can flood water (not) go based on the existing infrastructure and socio-economic systems that create opportunities and barriers for interoperability

key research needs to fully operationalise integrated flood risk management that aims to achieve UFR. More specifically, given a specific urban area and its characteristics, there are two main areas in which detailed information will be needed to achieve this: (a) which areas contribute the most to the flood hazard, that is, where is intervention a priority, and (b) which areas or systems can tolerate additional flood water and where can flood water not go (Figure 5).

First, it is essential to better understand the origins of where flood water comes from to make interoperable connections effective, that is, without causing any additional risk related to high water levels and flowing water. As stated earlier, simply identifying locations with high flood risk limits the possibilities of managing the water before it becomes a risk. Alternatively, to make interoperability work in the context of UFR, "source to impact" information is needed so surface water flooding can be addressed efficiently along its entire pathway. To this end, a wide range of hydrodynamic models are already available, which can predict with variable detail where and when surface flooding can occur in urban areas (Bertsch, Glenis, & Kilsby, 2017; Sanders, 2017; Teng et al., 2017). However, these models are yet to be applied in a systematic "source to impact" way, that is, to identify priority areas for flood management intervention at the city-scale.

Second, as well as understanding the origins of flood water, building systemic UFR and actively managing system connections through interoperability requires an understanding of system capacities and opportunities, but also the barriers. For example, knowing where can additional water in the system be tolerated (e.g., a sewer, green space, a road), and where can additional water not be tolerated (e.g., areas with potential adverse economic, environment, and social impacts). Insights into these interactions and dynamics are therefore needed to help determine which urban assets and systems facilitate or limit the potential of increasing interoperability. An understanding of the capacity of different systems to transfer and store water is essential, as well as understanding the socio-economic (e.g., location of emergency services, property boundaries) and environmental (e.g., sewer overflow locations) characteristics of urban areas. Furthermore, to avoid increasing vulnerabilities and (cascading) system failures, it is crucial to identify the vulnerable points in the system (e.g., easily overwhelmed sewer inlets or energy substations) (Evans et al., 2018; Ouyang & Dueñas-Osorio, 2011; Pregnolato et al., 2016).

5 | CONCLUSION AND FURTHER RESEARCH

To achieve higher UFR, integrated strategies for flood management are essential to not only consider all relevant stakeholders, but also the many interdependencies between infrastructure systems. Many design options already exist to increase system-integration through multifunctionality, however, the uptake of these options and upscaling them to the city-scale still remains challenging. In this context, interoperability was introduced as a transitional step to facilitate this transition from multifunctionality to multisystem urban flood management. This paper has provided a conceptual introduction to interoperability and outlined the potential opportunities it can create when transitioning to system-based flood management in a concrete and practical way.

By introducing the concept and its merit, this paper will open-up discussion regarding the operationalisation of UFR and through application (in forthcoming research) help embed system-approaches into standard practices and design standards. The conceptual framework developed in this paper has also highlighted two main research needs. First, hydrological flood models need to be applied in a "source to impact" context to better understand flood/surface water pathways and prioritise areas for interoperable flood management interventions. Second, a synthesis is required of the (spatial) variables that facilitate or limit interoperability between urban systems to deal with excess water locally and along its pathway. By combining these two research areas, it will be possible to develop decision-support approaches that can guide city planners and developers to develop more system-based flood management strategies and consider interoperability explicitly within present and future planning.

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