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Urban Water Journal

ISSN: 1573-062X (Print) 1744-9006 (Online) Journal homepage: http://www.tandfonline.com/loi/nurw20

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To cite this article: L. Hoang & R.A. Fenner (2015): System interactions of stormwater management using sustainable urban drainage systems and green infrastructure, Urban Water Journal, DOI: 10.1080/1573062X.2015.1036083

To link to this article: http://dx.doi.org/10.1080/1573062X.2015.1036083

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Urban Water Journal, 2016
http://dx.doi.org/10.1080/1573062X.2015.1036083

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RESEARCH ARTICLE

System interactions of stormwater management using sustainable urban drainage systems and green infrastructure

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(*Received 24 February 2014; accepted 12 March 2015*)

This study explores system interactions of stormwater management solutions using Sustainable Urban Drainage System (SuDS) and Green Infrastructure (GI) within the wider urban landscape. A series of interdependencies between urban components relating to stormwater management are identified. These include physical interdependency, geographical interdependency, cyber interdependency and logical interdependency, as defined by Peerenboom (2001). Stormwater management using SuDS/GI are viewed according to their Hydrological, Ecological and the Built Environment functions during events up to the design rain (non-flood condition) and during controlled exceedance and uncontrolled inundation (flood condition). The inclusion of SuDS/GI into the urban fabric is shown to modify urban functional and relational interdependencies under both these conditions. Within the context of the UK, there are fragmented responsibilities across planning scales created by SuDS/GI solutions which have not addressed the relational complexities that exist between agencies and competent authorities. The paper identifies the key barriers towards effective adoption of SuDS/GI within the context of the UK as physical barriers, perception/information barriers and organisational barriers.

Keywords: sustainable urban drainage systems; green infrastructure; urban landscape; complex urban systems

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1. Introduction

As cities have expanded through rapid urbanisation, natural green spaces have been lost to hard surfaces and often concrete flood defences (Asakawa et al., 2004). This has enabled further development adding to the greying of urban landscapes and compounding the decline in urban green spaces. It has been widely recognised that such pockets of residual green space provide valuable features to mitigate human impacts and enhance general quality of life in the urban environment (Hickman, 2013). Both Green Infrastructure (GI) and Sustainable Urban Drainage Systems (SuDS) can help restore natural features within the urban environment landscape (Ellis, 2013; Winz et al. 2011).

Green Infrastructure, which is the interconnected green pathways and blue spaces formed of surface water bodies within the urban domain, has been strongly promoted as a smart approach to preserving and enhancing remaining natural spaces (Benedict & McMahon, 2006). Such pathways act as corridors and refugia that sustain natural ecosystems, which may have been heavily modified and fragmented due to urbanisation. Green Infrastructure is also a key feature for improving the urban aesthetic and the overall functioning of towns and cities (Fabos, 2004). The Garden City movement (Howard, 1902) was an early example of employing green-belts to provide food, amenity, recreation and leisure spaces within cities. The parks movement in London in the 1870s and 1880s viewed urban green spaces as places of health (Hickman, 2013). In several countries Green Infrastructure has often been implemented as part of long-range planning measures that are designed to improve the urban ecosystem and human living conditions at the city scale. However this can lead to competing goals of ecocentric versus anthropocentric planning (Kambites & Owen, 2006; Wright, 2011).

Meanwhile, SuDS are stormwater management installations based on natural hydrological processes which often utilise vegetated land surfaces (Woods-Ballard et al., 2007). These SuDS components help attenuate flood impacts by temporarily storing water, often filtering the pollutants at source and encouraging infiltration of stormwater into the ground. The design of SuDS can often be geared towards improving water quality and reducing impacts across the flood pathways and at distant impact sites further down a catchment.

Due to their primary focus and function – as well as their associated scale differences – GI and SuDS can be considered as providing natural features into the urban fabric through centralised strategic planning (top-down) or localised urban drainage practices (bottom-up) approaches, respectively. Research from both the urban planning and flood management communities has now considered the wider multiple benefits this type of infrastructure can provide, beyond their intended principal functions. For instance, Gobster and Westphal (2004)

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recommended the inclusion of a 'human dimension' in designing urban greenways, while Cameron et al. (2012) showed that domestic gardens could contribute towards flood mitigation and wildlife preservation. Within the SuDS domain, Cettner et al. (2013) and Ashley et al. (2011) have also called for analysing the multiple benefits such non-structural infrastructure can provide, including the provision of ecosystem services and stimulation of social interactions.

Yet urban areas are highly complex and comprise a system of systems (Hall et al., 2012), in which the effects of incorporating GI or SuDS cascade much further than their intended drainage functions. Within this context, this paper looks at both SuDS and GI as stormwater management solutions containing natural elements and considers their physical interdependencies with other city scale infrastructure. In parallel to this the interactions between the various agencies responsible for their management are also examined. In classifying the contrasting complexities which can arise in both the technical and human/organisational systems involved, we adopt the typology defined by Fratini et al. (2012), as follows:

- *Functional complexity*, when complexity is related to the physical dimensions of the urban space and to the range of functions assigned to technical objects (e.g. infrastructures).
- *Relational complexity*, when complexity is related to humans and in particular to the different views and perspectives of the actors involved in the decision making process.

The paper draws on a meta-analysis which has been conducted based on literature drawn from a wide geographical and disciplinary range in order to capture the multiple and varying impacts of SuDS/GI elements. In this paper, non-flood and flood conditions are defined as the condition states when stormwater components function up to their capacity and when their capacity is exceeded, respectively. These represent the performance domains that influence the key interactions between urban drainage installations and other urban components. The paper highlights that SuDS/GI could have multiple inter-related impacts that go beyond the landscape and flood response functions (Ashley et al. 2014). While drawing examples from elsewhere, the paper focuses on potential implications for the UK and highlights key barriers toward efficient adoption of SuDS/GI schemes. The next section of the paper therefore looks at stormwater management and flood consequences within the interdependencies of the urban system. In the subsequent sections, we will look at the potential cascading impacts of SuDS/GI implementation on the performance of other urban components and key infrastructure services, and vice versa. The final section of the paper then draws attention to the physical and organisational barriers in the UK which must be overcome to integrate SuDS/GI into the urban landscape and planning decisions.

2. Interdependencies in the urban system

2.1 *Cascading flood impacts in the urban system*

Floods have widespread impacts on the whole urban system, which consists of both hard and soft infrastructure. The hard infrastructure concerns physical components such as the water and energy delivery networks, communication infrastructure and the transport system. These systems form critical infrastructure to support the soft infrastructure of social linkages and economic production (Bloomfield et al., 2010; Carlsson et al., 2013). In particular, the UK summer floods in 2007, and the more recent winter floods in 2013–2014, exposed some of the interactions across the urban system: flooding blocked roads and therefore disrupted emergency services and the transport of demountable flood barriers, which further delayed effective flood responses (Lyall, 2013). The floods also led to power cuts which impacted other services and their recovery (Booth, 2012), directly affected water treatment works and water delivery services (Chatterton et al., 2010; Welter et al., 2010), destroyed crops (Morris & Brewin, 2014) and perturbed natural ecosystems (Merz et al., 2010). Localised urban flooding from surcharged sewers also exerts impacts on homes and businesses outside coastal and fluvial floodplains (Dawson et al., 2008).

Aside from disruption to physical infrastructure, flood impacts can propagate to social interactions and services by displacing people, interrupting care provision and leaving psychological consequences beyond the duration of the floods (Sims et al., 2009). As a public health risk, floods increase vulnerability to drowning and other accidents (Fewtrell & Kay, 2008), and act as psychological stressors during the impact phase (Mason et al., 2010; Shultz et al., 2013). After floods recede, the impacts still manifest in post-traumatic stress disorder, emotional distress or outbreaks of infectious diseases (Brown & Murray, 2013; Tunstall et al., 2006). Flood impacts therefore extend much further than the spatial and temporal domain of physical flood manifestation and can create lasting economic damage (Merz et al. 2010) through the disruption of key supply chains.

2.2 *Urban interdependencies and impact pathways*

As a dynamic system, an urban area exhibits several types of interdependencies across its components which floods can impact on. Devices for stormwater management are components of such urban systems and can create interdependencies which could turn flooding into a "wicked problem" (Rittel & Webber, 1973) if drainage

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solutions do not consider the whole system impacts and feedbacks.

Peerenboom (2001) classed such interdependencies into four categories:

- physical interdependency,
- cyber interdependency,
- geographical interdependency,
- logical interdependency.

Physical interdependency occurs when one infrastructure installation is dependent on the material output of the other; for instance a railway system may rely on the coal supply from the energy system. *Cyber interdependency* is when one component needs information from another system. *Geographic interdependency* is when critical infrastructures are located at the same site and can be impacted by the same event. Finally, *logical interdependency* is the close link between the states of services between two systems, with a prior event or action determining subsequent levels of performance.

Viewed under this lens, multi-infrastructure disasters including the UK 2007 and 2014 floods have exhibited impacts via urban interdependencies in the form of long-term impacts on neighbouring infrastructure (geographical interdependencies) and intensified resource competitions due to reduced supply capacity during floods (physical interdependencies) (Bloomfield et al., 2010).

2.2.1. *The non-flood and flood conditions*

Recognising the complex nature of urban flooding, Fratini et al. (2012) have proposed the Three Points Approach, which defines three domains that urban flood risk management needs to address (Figure 1a). The horizontal axis shows the flood return period and the vertical axis shows the damage cost of the event. Fratini et al. (2012) use a linear frequency-damage line shown diagonally on a log-log scale to demonstrate the relation between hydrologic events and their damage costs, regardless of whether the risk is mitigated or not. They argue that the

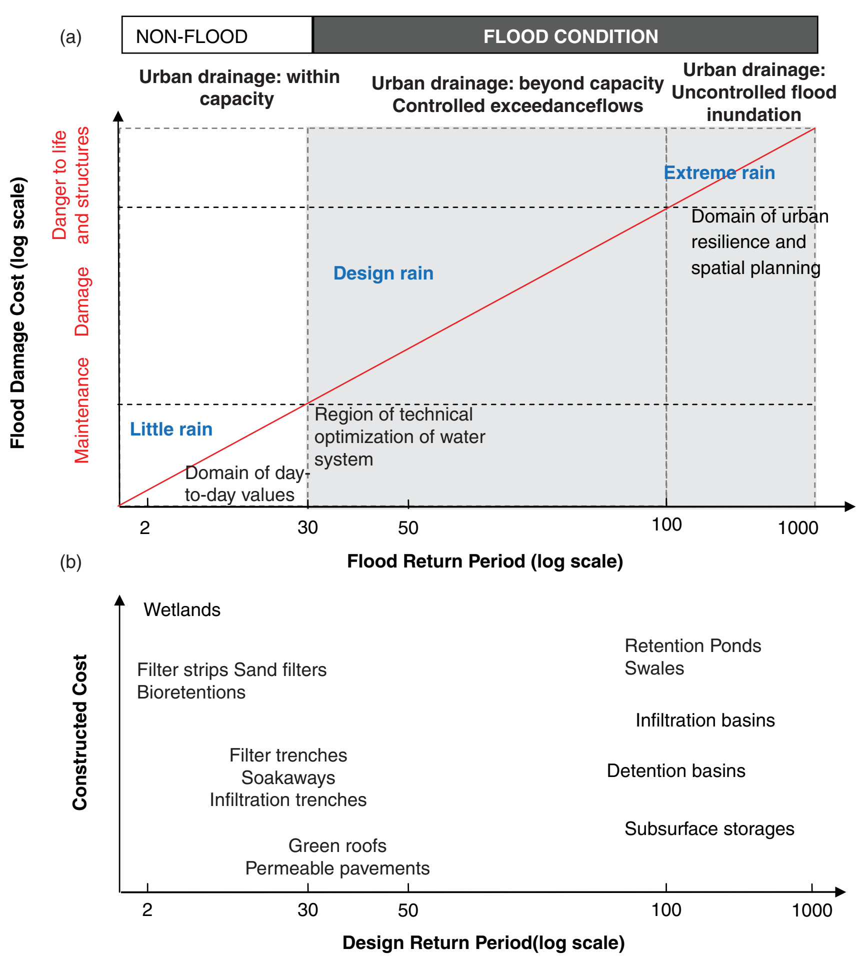

Figure 1. a) The Three Points Approach framework (adapted from Fratini et al. 2012) within the context of urban drainage systems in England and Wales. b) Schematic diagram of the designed capacity of SuDS components according to the UK SuDS manual (Woods-Ballard et al. 2007).

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frequency-damage line remains stable due to the complex evolvement of the risks. In essence, flood damage could be reduced by flood mitigation, but increases again once people and nature adapt to the new equilibrium and vulnerability.

The Figure defines three domains. The first domain refers to the *non-flood* condition state, reflecting day-to-day performance when there is little or no rain. This involves the daily functioning of stormwater management within the urban space, with systems operating within their design capacity. Where there is a change from the *non-flood* to *flood* conditions, systems are operating under technical optimisation. Here, focus is placed on technical solutions to improve drainage capacity with the drainage network operating at its full capacity, based on the design events selected to deliver appropriate levels of service for sewers and other drainage infrastructure. In the *flood* condition state there are two more domains. The middle domain occurs beyond the exceedance point, when coping strategies are shifted toward improving urban resilience and mitigating flood impacts through control of surface flows. Finally, the third domain occurs under extreme rain when flooding becomes uncontrolled inundation. In Figure 1a these domains are defined in relation to the return period of design rain and extreme rain, which in England and Wales is a 1 in 20 to 30 year event for the urban drainage systems and 1 in 100 year event for protection against flooding from watercourses, overland flows and adjacent land (Balmforth, 2006; Woods-Ballard et al., 2007).

Within that context, stormwater management using SuDS (and GI) have emerged as local solutions which form integrated parts of the wider drainage system and attempt to recreate the predevelopment hydrology. Whilst contributing to reducing the impacts of exceedance flows in the flood condition (e.g. by providing attenuation through surface storage zones) they additionally provide multiple functions in the day-to-day non-flood condition (Davies et al., 2006; Perring et al., 2013).

Collectively SuDS/GI solutions vary in their design capacities and therefore fit into different places along the urban drainage non-flood – flood spectrum (Figure 1b). Here the y-axis represents the constructed cost which includes the land cost and the capital cost of the components and the x-axis represents the design rain for these components. Both axes are not to scale. When compared against Figure 1a, the figure shows that each of these components has a design point that can be under or beyond the capacity threshold of the whole urban drainage system. Those components with the design capacity under the 1-in-30 year rainfall event therefore mainly function under the day-to-day domain while others can help alleviate the flood condition in the exceedance and flood inundation domains. Overall the figure shows that SuDS components can form a port-folio of options that contribute to the management of storm water in both the non-flood and flood condition states. Components such as filter trenches, soakaways and green roofs typically are designed to cope with 1 in 10 to 1 in 30 year rainfall events while retention ponds, swales and infiltration basins are frequently designed for the 1 in 100 year events. It should also be noted that these design points are not static. For instance, while the capacity of many below ground urban drainage systems are often designed for a 1 in 30 year event, these systems can cope with more severe rain if other stormwater management practices are also in place.

2.2.2 The hydrological, ecological and built environment roles of stormwater management

The utilisation of urban components in SuDS/GI-based stormwater management necessitates a review of existing urban structures and what functions they may provide. The main role of cities is to support human inhabitants and their socio-economic activities; yet urban areas are still catchments and also a part of the wider ecosystem (Brown et al., 2008). While traditional flood defences often require new construction, SuDS/GI could leverage the existing green and blue spaces within the urban domain. Such spaces are increasingly being recommended as areas of temporary storage to hold exceedance flows which occur when conventional below ground systems exceed their design capacity (Woods-Ballard et al., 2007). SuDS/GI potentially create new interdependencies on these spaces, which might not have previously been designed for flood functions. Therefore efficient stormwater management needs to maintain the intended functions and performance of these green components while deploying them for flood mitigation.

While both Green and Grey Infrastructure are diverse and contested concepts, Davies et al. (2006) argue that they are not discrete categories and instead exist along a green-grey continuum. Natural Economy Northwest (2009) have broadly defined grey infrastructure as constructed assets whilst green infrastructure consists of natural assets. They grouped each category into typologies identifying the component parts of each form of infrastructure.

Drawing on these conceptual approaches, the role of SuDS/GI can be expanded from solely stormwater management providing water storage and conveyance channels to a triangle made up of hydrological, ecological and built environment functions, which exist both in the non-flood and flood condition (Figure 2a). The dynamics of these hydrological-ecological-built environment functions are not fixed and may change under these different condition states and from installation to installation. The Built-Environment functions include services that support human inhabitants, such as those providing utilities, transport service, and facilitating social and commercial

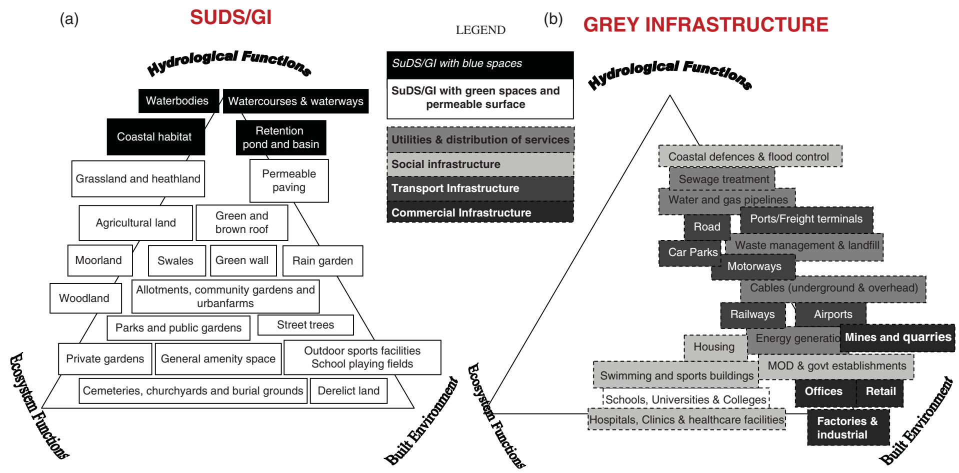

Figure 2. Example of the main functions of urban infrastructure. The list of infrastructure components was collated from "Putting the green in the grey" (Natural economy Northwest, 2009). The boundary of the triangle denotes the urban domain, with components outside of the triangle more common in rural or fringe areas. Figure 2a shows SuDS/GI components and Figure 2b shows the components within the four types of grey infrastructure.

activities. The Hydrological functions provide hydrological services of storing and conveying water flows. The Ecological functions support biodiversity and urban ecology.

The primary intended functions of private gardens and school playing fields are as social infrastructure, but could contribute toward urban ecology, aesthetics and temperature regulation as well as providing a localised flood management function (Cameron et al., 2012; Farrugia et al., 2013). Hence they are placed between the Built Environment function and the Ecological function as their intended benefit is to support human wellbeing via providing aesthetic and activity spaces and other ecosystem services. Similarly, other urban green areas mainly provide leisure space for humans and habitat for urban ecology but could perform the Hydrological functions during floods. Other social infrastructure such as schools, hospitals and housing (Figure 2b) could accommodate urban green space and hence provide ecological functions. Meanwhile, commercial, utility and transport infrastructure are placed at the Built Environment corner of the triangle as they often carry critical services during the time of floods, as discussed in Section 2.1. However in most cases they have not been utilised to provide hydrological functions. Current commercial infrastructure usually has a low density of green and blue spaces (Kaźmierczak & Cavan, 2011) but could potentially enhance their aesthetic and ecological functions by incorporating natural features. Similarly, roads and highways could offer the Hydrological function if employed as exceedance channels (Balmforth, 2006; Woods-Ballard et al., 2007) or Ecological function once coupled with stormwater wetlands (Ahern, 2013).

3. Functional complexity between SuDS/GI infrastructure and other urban components

Based on the functions defined in Figure 2, this section considers the physical interactions between technical systems, first by considering the interactions between urban components in conditions where installations operate within their design capacity (non-flood condition), and secondly during exceedance conditions of controlled and uncontrolled surface flooding.

3.1 Interdependencies within design capacity (non-flood condition)

3.1.1 Influence of urban components on SuDS

3.1.1.1 Main functions. Under the non-flood condition, grey infrastructure continues to provide a Hydrological function but offers little additional Built Environment or Ecological functionality. On the contrary, the Hydrological, Ecological and Built Environment functions simultaneously co-exist for SuDS/GI based strategies. While surface components of grey infrastructure create impervious surfaces in installation such as trapezoidal channels (Burns et al., 2012), SuDS/GI can become linking components and corridors for urban ecology and human activities.

3.1.1.2 Interdependencies. Figure 3 illustrates the urban interdependencies revolving around the Ecological, Hydrological and Built Environment function of SuDS/GI. Due to the localised and passive nature of SuDS/GI, they are not often affected by cyber interdependencies or do not rely on inputs from the energy system for operation. Under the non-flood condition, to provide an ecological

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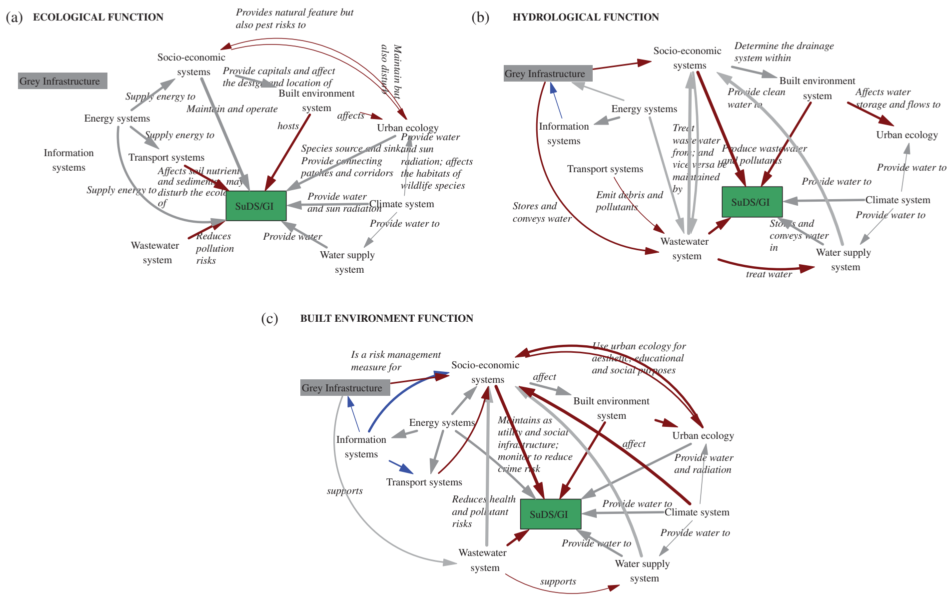

Figure 3. Example of urban interdependencies for Ecological, Hydrological and Built Environment of stormwater management. Grey arrows represent physical interdependencies, brown arrows represent logical interdependencies and blue arrows represent cyber interdependencies.

function, SuDS/GI components require physical inputs of solar radiation (from the climate system), nutrients, and water.

The performance and feasibility of certain components can be limited by the prevailing conditions of the built environment (e.g. road density, infiltration capacity of the area, available drainage networks; and in the case of retrofitted green roofs, the structural strength of buildings to support additional load). In terms of logical interdependency, SuDS/GI can still be dependent on other SuDS components such as pre-treatment systems and source control techniques, since overwhelming one component might affect the functioning of other components. As such, in contrast to traditional grey infrastructure, the interdependencies between SuDS/GI and other urban components remain strong even under the non-flood condition. Moreover, these interdependencies when operating under design capacity can also affect SuDS/GI performance under the flood condition when capacity is exceeded, particularly regarding their hydrological function. For example, SuDS/GI can be further categorised into infiltration-based techniques and retention-based techniques, which have different interdependencies. Fletcher et al. (2013) demonstrated that the performance of the former (such as swales, rain-gardens and permeable pavements) largely depends on site conditions and clogging risks from lack of maintenance while the latter (such as wetlands, ponds and green roofs) depends on climatic factors and the antecedent conditions prior to the rainfall event. As such, infiltration-based techniques might have stronger dependency on site maintenance compared to retention-based techniques.

3.1.2 *Influence of SuDS on urban components*

3.1.2.1 Impacts of Grey Infrastructure and SuDS/GI. Under the non-flood condition, the interdependencies lessen for grey infrastructure. Within the urban system, grey infrastructure continues the water storage and conveyance functions but offers little wider services to the urban system. As hard physical barriers, these structures might even contribute to the impervious areas and occupy valuable space in the urban domain. They can also obstruct the functioning of the urban components: for example, the biodiversity of urban ecology is affected by the construction of dams and other flood defences (Pettifer & Kay, 2012). Winz et al. (2011) examined perspectives on stormwater in New Zealand and showed that the traditional approach of using grey infrastructure create positive feedback loops of more urban development fuelling more stormwater infrastructure construction at the expense of environmental systems.

In contrast, SuDS/GI solutions continue providing services and might enhance the urban environment, its ecology and through this human wellbeing whilst not being called on to provide drainage during times of no rainfall. Studies have shown that the installation of a single SuDS component or a network of GI can trap pollutants and reduce the risk of diffuse pollution (Nicholson et al., 2012; Trowsdale & Simcock, 2011). Pollution reduction in turn improves the performance of

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the food and agriculture systems and also additionally provides pollination services and grazing sites. Regarding physical changes, 5% mature deciduous trees have been shown to reduce mean hourly surface temperatures by 1.0°C over the course of a summer's day in Manchester. Conversely, if all vegetation is replaced by asphalt, temperature might soar by a maximum of 3.2°C at mid-day (Skelhorn et al., 2014). Similar cooling effects of urban green spaces were also found by Qiu et al. (2013), Shashua-Bar and Hoffman (2000) and Vidrih and Medved (2013). The total net carbon sequestration from urban green spaces in Leipzig (Germany) was estimated to be between 137 and 162 $MgCO_2ha^{-1}$ (Strohbach & Haase, 2012). This carbon saving impact is even larger if counting the avoided carbon spent on making and transporting materials required in grey infrastructure solutions, and averting the energy used in their operation. Green solutions could also calm traffic where rain gardens are installed as part of street furniture (Vecchio 2012) and help improve the perception of local residents on the quality of the neighbourhood (Ward Thompson & Aspinall, 2011; Ward Thompson et al., 2013). Ecological changes are demonstrated by changes in biodiversity and species richness (Tzoulas et al., 2007).

3.1.2.2 Potential SuDS/GI interdependencies. Implementation of SuDS/GI can create logical interdependencies to the water, food and agriculture, transportation, energy, health and social systems, for example by providing attractive meeting places. As SuDS/GI also can be sites for social activity and contribute components of urban ecology, they bear geographical interdependencies with other forms of public open space. Gómez-Baggethun and Barton (2013) demonstrated that urban allotments can provide noise reduction, air purification, waste treatment and climate regulation- regulating ecosystem services that translate into logical interdependencies. If located next to major roads, (geographic interdependency), selected planting at SuDS sites can trap damaging particulate matter on to leaf surfaces significantly reducing PM 10 concentrations along major routes (Tiwary et al., 2009).

However, the integration of SuDS/GI into the urban system can also lead to potential problems and disruption (Table 1). The accumulation of debris and pollutants around SuDS locations can make them a risk hotspot to local residents. For example, urban stormwater treatments such as bioretention, while reducing a large amount of zinc, lead and Total Suspended Sediments, can remain a source of copper (Trowsdale & Simcock, 2011). Perring et al. (2013) highlighted the risk of volatile compounds released by certain plants, with the presence of toxic or irritant species and invasive species damaging the native ecology. Fierro et al. (2009) showed negative impacts from GI in Mexico, due to crime and poor park maintenance while MacDonald et al. (2010) demonstrated the increased risk of wild fires and poisonous snakes. Steeneveld et al. (2014) showed that in Rotterdam (Netherlands), water bodies increase rather than reduce the Urban Heat Island effect within a radius of 2 m.

Table 1. Examples of the impacts of SuDS/GI installation on the primary functions of other urban components under the non-flood condition.

Urban components	Services	Potential disruptions
Water supply (sources)	Trap pollutants, reduce water treatment need and can release water back to the water system and underlying ground	Become a pollutant source if not treated properly
Wastewater (conveyance and treatment)	Provide local solution for wastewater treatment	Tree roots can damage sewer pipes
Food and agriculture	Reduce pollutants and provide pollination and grazing sites	Pest and disease hotspot if not maintained properly
Transportation	Traffic calming, traffic noise reduction	May block views if trees are too high, risk of branch and leave falling in strong wind
Energy	Urban cooling from heat island effect, carbon sequestration which might reduce climate change impacts fuelling energy demand	May require energy to maintain such as pumping water
Communication	n/a	n/a
Ecology	Provide corridors and habitats for wildlife species	May host pests and pollutants
Health	Provide spaces for physical activities and relaxation, improve air quality	Pollen allergy, may host disease vectors
Social	Provide space for socialising; crime reduction	May create opportunity for crime at night due to reduced vision, may be aesthetically unpleasant
Buildings	Provide shading (green roof) and reduce carbon footprints via carbon sequestration	Might increase water-related risks around the building and loads on the structural strength of the building
Economic	Provide services that might have economic values such as carbon sequestration	May incur costs for maintenance and cleaning

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Donovan and Butry (2010) reported the negative effects of trees such as blocking views, dropping leaves, occupying space and damaging pavements, infrastructure and buildings due to their root systems. GI could also contribute to pollen allergies, through the planting of exotic species and creating an overabundance of pollen-producing species in urban greens (Cariñanos et al., 2014). Pandit et al. (2013) noted the supporting function and utility of SuDS/GI to economic and social systems reflecting in property price increases with proximity to city centres, parks with lakes and small neighbourhood reserves (and reductions with proximity to main roads, large parks and sport reserves). This can lead to a process of neighbourhood gentrification, as experienced in Portland Oregon, where low income households can no longer afford to remain in some areas and are forced to less attractive zones, often further way from basic services and central urban areas. However these patterns are very site and context specific. Some concern has highlighted a further potential paradox where ecologically successful installations may result in their eventual evolution and designation as protected nature reserves. This has the potential to inhibit maintenance and compromise their primary drainage function.

3.1.2.3 Variation and uncertainty in SuDS/GI impacts. These interactions also vary across seasons, site conditions and socio-demographic circumstances. For example, Hathway and Sharples (2012) found that urban rivers in Sheffield cool temperature by over 1.5°C in spring but less so in summer. Under sustained periods of hot weather, cooling at the river is only manifest during day time and more pronounced in vegetated banks. The cooling effect is further influenced by the river water temperature, incident solar radiation, wind speed, relative humidity and the urban form (enclosed, open square, open street and closed street) on the river bank. Regarding social interactions, Peschardt and Stigsdotter (2013) demonstrated social variation in the usages of SuDS/GI such as small public urban green spaces in Copenhagen

These variations can also stem from geographical features. Within a city, urban residents living at low-lying regions are significantly more susceptible to floods than those in higher areas (Coulthard & Frostick, 2010). Often, the distribution of urban green space is non-uniform across the urban landscape and their functions affect urban residents disproportionately, with the value of their wider positive benefits to different socio-economic income groups also varying considerably. A study in Manchester showed that people living in poverty often reside near major roads, in high density areas and manufacturing areas. They have only limited access to green space other than formal open space (Kaźmierczak & Cavan, 2011) and thus benefit disproportionately from the amenity features SUDS/GI solutions can provide.

3.1.2.4 The role of perception and preference in the overall impacts. The overall impact of SuDS/GI sometimes stem from perception and individual preferences rather than actual physical impacts. For example, people reported feelings of insecurity in dense, unmanaged and view-restricted wildlife environments (Bixler & Floyd, 1997). Some respond well to green roofs but many prefer sedum-dominated extensive green roofs due to a perception of visual messiness in other types of roofs (Jungels et al., 2013). Pandit et al. (2013) found that people prefer to buy houses close to a broad-leaved tree but not a palm tree; houses with trees near the property are not preferred due to the maintenance requirements, risk to building foundations and lower available open space. This diversity of views on the functional complexities of SuDS/GI and the affected groups further transform these interdependencies into the managerial domains, which create relational complexity, arising from the interdependencies between organisations, social interactions and the expectations of different stakeholder groups (see Section 4).

3.2 Interdependencies beyond capacity exceedance (flood condition)

3.2.1 Influence of urban components on SuDS

3.2.1.1 Main functions. As discussed, many types of urban infrastructure can offer a range of Hydrological, Ecological and Built Environment functions. For multi-functional components, the dominant function might switch under changing conditions, such as between the flood and non-flood conditions. Under the flood condition, various components such as soakaways and bioretentions facilitate the Hydrological function via water storage and infiltration. However, under more extreme rainfall, more and more SuDS/GI components may become inundated by providing surface water storage, and so their Ecological function can become limited.

3.2.1.2 Interdependencies. Traditionally, urban drainage systems and grey flood protection installations rely on multiple urban components to perform their Hydrological function (Figure 4). For instance, pipes and concrete channels are connected elements to the whole drainage network. Their performance under controlled exceedance as such is strongly affected by other components in the network and by the flows, debris and pollutants the system carries. Flood protection installations under uncontrolled inundation often receive and transmit flows from surrounding land and watercourses and therefore exhibit strong geographical interdependency with the neighbour-

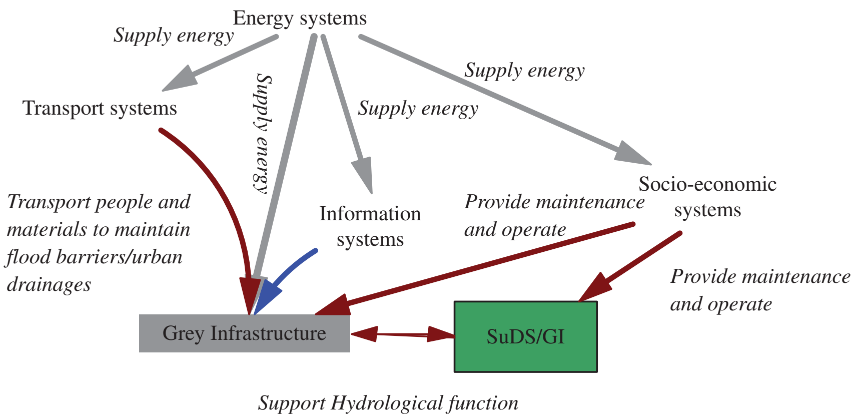

Figure 4. Examples of interdependencies of grey infrastructure and SuDS/GI to perform the Hydrological function under the flood condition. In this diagram and subsequent diagrams, grey arrows represent physical interdependencies, brown arrows represent logical interdependencies and blue arrows represent cyber interdependencies.

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ing infrastructure. They may also require energy for pumping and operation thus, by Peerenboom's definition, bear physical interdependency to the energy system.

The operation of urban drainage systems and flood protection installations often needs information about the flooded areas, together with knowledge regarding event magnitude and progress, and thus relies on cyber interdependency. The importance of cyber and information interdependencies is also increasing as more and more infrastructure operation becomes reliant on ICT services; this further creates new interdependencies around information transfer in 'digital cities' (Price & Vojinovic, 2008; Dawson et al., 2008). Cyber networks in turn are strongly dependent on electric supply, which further fuels the physical interdependency of grey stormwater management on the energy system. These interdependencies then exert extra demand on the energy system, which also serve socio-economic and transport needs.

Under uncontrolled flood inundation, urban drainage services depend on the transport system for delivering mountable flood barriers and people to sites; they consequently have strong logical interdependencies on the state of the transport system. Due to the interactions of these interdependencies, the dependencies of grey infrastructure might form positive feedback loops that magnify risks if either the communication, energy or transport system is impaired.

Compared to traditional drainage infrastructure, SuDS/GI do not heavily rely on the energy and transport systems and therefore avoid these particular physical and logical interdependencies under the flood condition. Apart from geographical interdependency, SuDS/GI exhibit interdependencies on other systems. The interdependencies of SuDS/GI performance under the flood condition are mainly logical interdependencies on the performance of other stormwater management including existing grey infrastructure and natural drainage systems that influence the water flows and pollutant load to the component. SuDS/GI performance is also linked to the logical interdependency of maintenance carried out under the non-flood condition, since infrastructure filled with accumulated debris will be unable to perform their Hydrological function. A 2005 assessment of in-ground SuDS in Scotland found that runoff from un-stabilised areas or construction runoff and the lack of regular maintenance contributed to partial blockage in 30% of the sites and permanent blockages in one site (Schlüter and Jefferies 2005), thus compromising their performance during significant rainfall events.

3.2.2 *Influence of SuDS on urban components*

3.2.2.1 General interdependencies. Many urban components rely on stormwater management to cope with pluvial and fluvial flooding, creating a logical interdependency, as the performance and state of these strategies affect the functioning of the rest of the urban system. The impacts of stormwater management extend widely. For example, raising the flood defence in the Lyth Valley not only protected properties but also a key road from inundation, and thus affected both the built environment and the transport system (Penning-Rowsell & Pardoe, 2012). These interdependencies extend to social interactions and public health, directly via reduced drowning and other health risk, and indirectly via less disruption of critical infrastructure such as the transport networks, electricity supply, waste management, and water and wastewater treatment works (Kaźmierczak & Cavan, 2011).

While both SuDS/GI and grey infrastructure provide the Hydrological function to attenuate exceedance and reduce flood risks, they differ in several aspects. Firstly, they create different risk distribution within the urban domain. Grey infrastructure such as flood levees,

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demountable flood protection devices or urban sewers mainly reduces flood risks by creating hard barriers or conveyances to transfer the water elsewhere. These components thus transfer the risk out of the protection zones, suppressing the risks locally until the design capacity is exceeded. In contrast, SuDS/GI create a more diffused distribution of flood risks over space and time by storing water in their components and attenuating the peak flows.

Secondly, SuDS/GI and grey infrastructure differ in terms of the integration of natural features and processes. SuDS/GI facilitate the natural hydrological cycle and therefore reconnect urban ecology to the natural hydrological cycle and flood pulses. By reconnecting the hydrological cycle, SuDS/GI contribute to groundwater recharge and urban ecology, positive impacts of which extend to the non-flood condition (Bailly et al., 2008; Middleton, 2002). This is not the case with piped grey infrastructure, which either focuses on drainage efficiency or pollutant load reduction whilst neglecting ecological changes (Burns et al., 2012). However, the interactions of SuDS/GI with surrounding areas can also create adverse unintended consequences. Dearden and Price (2011) noted that infiltration-based SuDS/GI could impact the underlying groundwater and certain types of rocks, leading to issues on local groundwater quality, flooding and ground instability. Such impacts might pose challenges, given the diffuse and context-dependent nature of the risks.

3.2.2.2 Unique SuDS/GI interdependencies. These differences highlight the need to consider new interdependencies caused by the physical presence of SuDS/GI, which has not occurred in stormwater management using grey infrastructure. As discussed, flooding is an interconnected phenomenon that affects multiple systems. Conventionally solutions are conceived by the asset managers within the scope of their specific responsibility and expertise. So pipeline owners may see a solution in terms of increasing the capacity of pipe assets. Alternative approaches would tackle the issue, for example, at source using components which may pre-exist at the surface in urban environments. Expanding the boundaries of where such solutions might be sought avoids a perpetuation of narrow technical fixes, but may impose risks to other parts of the urban system.

SuDS/GI solutions may create impacts on other infrastructure components as shown in Table 2. As passive measures to store or attenuate peak flows, SuDS/GI bear geographical interdependency to the urban system and in their inundated state, can obstruct the connectivity and functionality of other parts of the built environment. For instance, car parks or roads, primarily designed as transport infrastructure, could be used for intentional street ponding (Carr & Walesh, 2008) and would not be able to carry their transport function if being used as exceedance or flood water storage areas. During uncontrolled flood inundation, the location of roads and car parks included in SuDS/GI-based stormwater management could have implications on the connectivity of the road networks and the functioning of the emergency services, which further transform into social and economic impacts. Within the exceedance condition, the inclusion of more trees in the cityscape can reduce soil erosion and facilitate infiltration via extra macropores (Bartens et al., 2008; Stovin et al., 2008). However, extreme floods and strong winds can damage tree roots and lead to fallen branches and leaves (Lopes et al., 2009). Those fallen branches and leaves can become debris that obstruct the transport networks, block the sewer network and induce concerns from local residents regarding falling tree branches (Schroeder et al., 2006; Sreetheran et al., 2011). Plant debris can further pose a health risk if they become rotten, creating unpleasant smells or nurturing pests and pathogens (Perring et al., 2013). GI components such as urban parks and open spaces are often subject to dog, rodent and bird contamination (Ellis, 2004). They thus can contribute to pollution risk if they are used for exceedance water storage and then surpassed under uncontrolled flooding. Furthermore, while SuDS components such as wetlands and vegetated retention basins could reduce bacteria loads from stormwater runoff, they could release enteric organisms during high flow periods, particularly under short, intense summer storms (Ellis, 2004). Aside from water quality issues, SuDS/GI installations can also alter receiving water response such as prolonging attenuation flows and changing the current minimum flows, impacts of which remain uncertain on stream hydrology and ecology. Fletcher et al. (2013, p. 261) recognise that "performance of stormwater technologies in restoring the water balance and in removing emerging priority pollutants remain poorly quantified". Furthermore, the multi-functionality of SuDS/GI can obstruct its own functioning. For instance, a case study by Tsavdaris et al. (2015) showed that vegetation in a detention pond could increase turbulence and horizontal recirculation and thus lead to variation in treatment performance.

3.3 Summary

Overall, this section has analysed the functions of SuDS/GI under the non-flood and flood conditions, using traditional urban drainage as a reference. The next section will look at the relational complexity within current responsibilities for stormwater infrastructure in the UK and identify potential gaps for widespread SuDS/GI innovation, through barriers to their efficient adoption and management.

Table 2. Examples of the impacts of SuDS/GI on the urban system under the flood condition including controlled exceedance and uncontrolled flood inundation.

	SuDS/GI	
Systems	Controlled exceedance	Uncontrolled flooding
Water supply (sources)	✓ Facilitate water infiltration enhancing groundwater recharge	× Might transmit pollutants to surrounding areas when surface storage is surpassed
	✓ Pollutant and sediment sink, hence:	× Might prolong attenuation flows, affect minimum flows of receiving waters
	✓ Reduce contamination risks on water sources	× Might affect local groundwater quality and flood mounding
	× Might prolong attenuation flows, affect minimum flows of receiving waters	
	× Might affect local groundwater quality and flood mounding	
Wastewater (conveyance and treatment)	✓ Relieve pressure on downstream treatment	× Might increase debris load and blockage on the urban drainage system
	✓ Reduce pollutant loads	
Food and agriculture	✓ Reduce crops contamination and livestock impacts due to pollutant reduction	× Might spread pathogen and pest risks previously contained
	× May require short term flooding of marginal land	
Transport	× Might affect traffic due to changes in available road surfaces and car parks	✓ Mitigate sediment load and flows on key roads
	× Roads as flow pathways	× Potential to affect network connectivity due to fallen leaves / branches or sites being used for flood purposes
	× Ice risk under low temperature	
Health	✓ Reduce widespread health risks due to restricting and treating pollutants at sources	× Might increase health risks to surrounding areas due to pathogens and pests when surface storage is surpassed
	× Potential for creating unpleasant smells, allergy or health risks due to rotten leaves/ trees or pollens	× Risks of physical impacts from branches and trees falling due to weakened soil structure
	× Possible exposure to waterborne diseases	× Danger from drowning at amenity sites
Energy		× Fallen branches might affect power lines
Communication		× Fallen branches might affect network connectivity
Social	× Potential for temporarily disabling the use of social amenities	× Further disrupt the functioning of social amenities due to more sites being inundated
	× Increase the visibility of exposure to floods	× Can induce psychological impacts due to fear of falling tree branches and pest risks
	× May add to insurance risk	
Ecology	✓ Act as a refugia for wildlife species	× Might spread pest or water-borne diseases onto other ecosystems
	× Might disturb the existing ecosystem	
Economic	✓ Reduce economic impacts via reducing pollution and exceedance risks to property	✓ May reduce flood damages but
		× Could also increase costs regarding subsequent maintenance and other impacts

4. Relational complexity of suds/gi within the urban system

Many urban components are also linked by a range of actors, including organisations and responsible authorities, and the interactions between them form a "relational complexity" (Fratini et al., 2012). For example, the impacts and total economic costs of floods which can be spread widely across the urban system into the remit of different agencies with responsibility for managing the risks and the physical assets.

4.1 Under flood conditions

4.1.1 Main actors

In the UK, relational complexity under flood conditions is summarised in the CIRIA report on Designing for Exceedance (Balmforth, 2006), as well as by Nicholson et al. (2012) and Dawson et al. (2011). For England, the Planning and Policy Statements (PPS), in particular PPS25, PPS11 and PPS1, are amongst the key documents defining the flood response regime. In Scotland, the Scottish Environment Protection Agency has responsibility for

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the regulatory roles (Woods-Ballard et al., 2007). Related organisations that influence flood risks and stormwater management are the Environment Agency for England and Wales; Department of Environment, Food and Agriculture (DEFRA); local authorities; water companies; businesses and agencies managing the affected attributes (such as health, transport and police).

The Flood and Water Management Act (2010) now defines the lead local flood authority for an area as the unitary authority or the county council (DEFRA, 2011). The important roles played by district councils, internal drainage boards, highways authorities and water companies are also recognised in the Act and these bodies, together with the Environment Agency, are identified as risk management authorities. The Act also requires a lead local flood authority to develop, maintain, apply and monitor a strategy for local flood risk management in its area and to be responsible for ensuring the strategy is put in place. This involves consulting on the strategy with risk management authorities and the public, the Local Government Group (LGG) in association with Local Authority representatives, the Environment Agency and DEFRA.

The Act established the principle of a SuDS Approving Body (SAB) at county or unitary local authority levels. The SAB would have responsibility for the approval of proposed drainage systems in new developments and redevelopments, subject to exemptions and thresholds. Approval must be given before the developer can commence construction. However, according to the Sustainable Drainage Centre (2014), implementation of the National Standards for SuDS has been delayed and the anticipated date of October 2014 has not been achieved. It is understood that the earliest date for implementation will now be April 2015 perpetuating the uncertainty around the implementation of SuDS schemes. Alongside these developments, the EU Floods Directive requires the drawing up of Preliminary Flood Risk Assessments which consider impacts on human health and life, the environment, cultural heritage and economic activity. This information is used to identify the areas at significant risk which can then be modelled in order to produce flood hazard and risk maps.

These initiatives have helped integrate SuDS/GI into urban drainage and surface water management and create new relational interdependencies amongst the corresponding agencies. Such changes will have cascading impacts on both functional and relational complexities of SuDS/GI within the wider urban context. Moreover the emphasis on the drainage function is still the foci of this integration, while as demonstrated in the paper, the multi-functionality aspects of SuDS/GI requires further incorporation of the drainage function with the ecological and other functions.

System interdependencies are not only the linkages amongst the organisations managing flood impacts, but also the agencies representing the different affected groups at times of both flood and no flood. These are potential logical interdependencies that will affect the effectiveness of stormwater management. For instance, Chatterton et al. (2010) estimated economic costs from the UK 2007 floods as distributed amongst a range of different groups, as follows:

- households (38%),
- businesses (23%),
- temporary accommodation (3%),
- motor vehicles (3%),
- electricity, gas and water utilities (10%),
- communication and transport (roads, rail an telecom) (7%),
- local government agencies (4%),
- public health, fatalities and distress (9%),
- agriculture (2%),
- Environment Agency (1%),
- Emergency services (<1%).

In addition there was significant uncertainty in estimating intangible damages to individuals, such as impacts from psychological and emotional stress.

Flood damages affect multiple sectors and stakeholders, who might have different coping capacities, recovery times and power influence in the planning process. Within the affected groups, Mason et al. (2010) and Shultz et al. (2013) identified youth and women, particularly pregnant women, as being more susceptible to posttraumatic stress disorder and major depressive disorder. Yet, older adults are also mentally and physically vulnerable to disruptions of access to community services, medical care and stress from the risks of losing friends and family (Bei et al., 2013; Wadsworth et al., 2009). Kaźmierczak and Cavan (2011) and Parker et al. (2009) further highlighted the role of socio-economic characteristics of the population and housing types in creating vulnerabilities to floods. In particular, they emphasised the vulnerabilities of urban residents with limited financial capacity, limited mobility and low access to information due to weak social networks, lack of knowledge of the local area, weak command of the official language, age or mental health.

4.1.2 Interactions and interdependencies

Relational complexity spans both temporal and spatial dimensions. In essence, flood risks of one area can be influenced by the discharge policy of an upstream area, and available runoff storage of nearby farms or catchments (Quinn et al., 2013). Similarly policies of disconnecting downspouts from the drainage network and reducing CSO spills can impact on flow levels being maintained in receiving waters, and attenuation through surface storage can have similar effects.

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These interdependencies further affect the dynamics between the drivers for flood safety, which often dominate the immediate post-flood responses, and the multi-functionality of stormwater management (Warner et al., 2012). Those recently flooded often lobby for visible, hard defences in their immediate local neighbourhood which may be the wrong long term solution when considered at the wider catchment scale. SuDS/GI implementation can thus be impeded by the current high dependency on grey infrastructure and a lack of initial up-take. Penning-Rowsell and Pardoe (2012) showed that flood risk reduction will benefit the uninsured or underinsured population, whilst indirectly benefiting insurance companies and reducing taxpayer spending on additional flood risk management. However in contrast they dis-benefit the unaffected taxpayers and those who provide flood loss repair and replacement services. Such contested views and interests on flood risk solutions highlight the need for a participatory approach in implementing stormwater management.

Figure 5 highlights the different linkages of SuDS/GI and grey infrastructure under flood conditions. Since geographical interdependencies are often context-dependent and physical interdependencies do not apply for managerial linkages, they are omitted in this figure. The figure exhibits logical interdependency, which illustrates the operational and management structure, and cyber interdependency, which represents communication of flood risk information. Cyber interdependency could range from informing, consulting to actual collaboration. While the operation of grey infrastructure and SuDS/GI mainly involves agencies such as the UK's Department of Environment, Food and Rural Affairs (DEFRA), Environment Agency (EA) /Scottish Environmental Protection Agency (SEPA) and water companies, information needed for its effective operation extends much wider and includes linking groups such as Local Resilience Forums and Response Coordinating Groups as well as other utility and transport services, the police and rescue organisations such as the Flood Rescue team of the Royal National Lifeboat Institute (RNLI), and even the Army. Potential complexity created by the implementation of a SuDS Approval Body is shown in dotted line.

Under flood conditions, the operation of grey infrastructure is directly managed by local authorities, local drainage boards and water undertakers. It also relies on managerial decisions from the utility services and the local highway authority, as grey infrastructure functioning is logically and physically dependent on these systems. The communication mechanism regarding grey infrastructure therefore largely reflects the logical interdependencies of its governance. Meanwhile, SuDS/GI management is affected by local authorities, sewerage undertakers and property owners. Since SuDS/GI utilises various components from other urban systems, it is highly dependent on managerial decisions affecting those systems, such as which sites and roads could be used as flow pathways and flood attenuation sites. As such, it needs information from

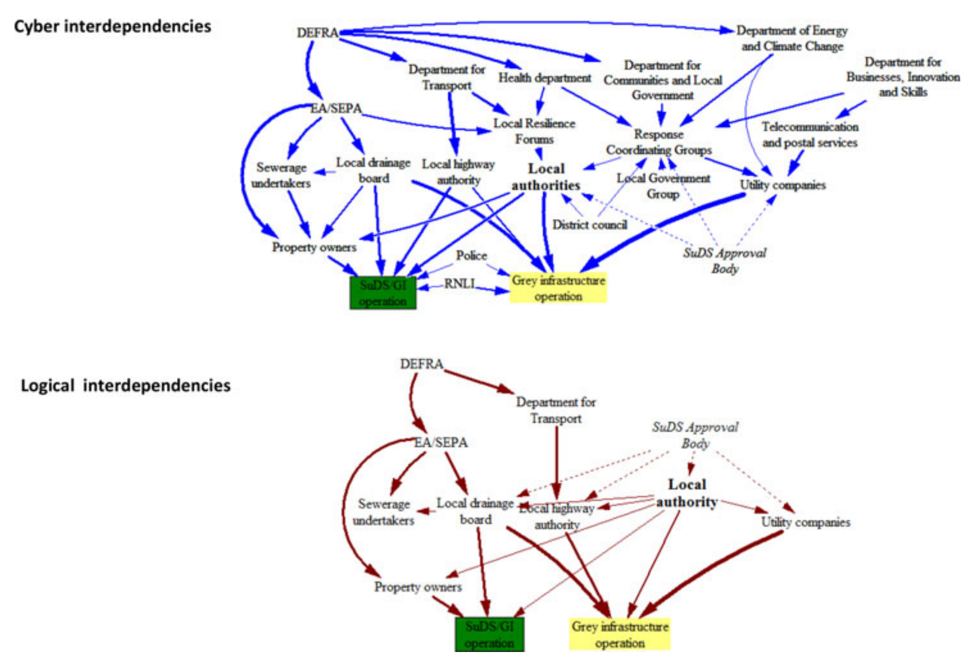

Figure 5. Example of Cyber and Logical organisational dependencies under the flood condition, in which Local Authorities (in bold) is the lead local flood authority as defined by the Flood and Water Management Act 2010 (DEFRA, 2011). Thickness of the arrows reflects the strength of the interactions.

various agencies, including the local highway authorities, property owners, police and emergency services. Nevertheless, the current management structure of SuDS/GI does not reflect this complexity and mainly mimics grey infrastructure management.

4.2 *Under non flood conditions*

4.2.1 *Main actors*

During periods of low rainfall when installations are not exceeded in the non-flood condition, the required management interventions mainly revolve around maintenance of the assets. However such maintenance actions (by whoever is the adopting authority) are framed narrowly often only to sustain the drainage function and not reflecting wider maintenance strategies which could help optimise other secondary functions of the system, such as biodiversity and habitats.

The linkages are different between SuDS and GI, due to their different intended functions and policy drivers. According to the SuDS manual (Woods-Ballard et al., 2007), drainage responsibilities concern local authorities, environmental regulators, sewerage undertakers, highway authorities, private landowners or land managers and internal drainage boards, along with stakeholders such as the Royal Society for the Prevention of Accidents (RoSPA), SuDS contractors, developers, drainage planners and designers, and the insurance industry. Relevant policies to SuDS include PPS 1, PPS 3, PPS 9, PPS 23 and PPS 25 (Woods-Ballard et al., 2007). The development process involves developing the concept, drainage design, planning permission, detailed drainage assessment and approval according to Building Regulation, drainage and road construction, and consent to discharge. Groundwater source hazard assessment for SuDS is not normally required for roof drainage, residential areas, amenity space, car parks, and local roads. Similarly, highway and road runoff does not often require discharge consents. However if discharging to "sensitive" waterbodies (surface or ground), a full risk assessment is required and all major roads coming under the responsibility of the Highways Agency are similarly charged. It is also the case that most new (as well as identified existing polluted SWOs) have consent conditions set by the EA.

The maintenance agreements are established amongst the adopting agency by the local planning authority. They often consist of local authorities, highway authorities and sewerage undertakers. Other related impacts of SuDS are considered via compliance to existing legislation rather than direct consultations with the corresponding agencies. SuDS planning is therefore often site-specific, component-based, quantitative and with water-related objectives based around developing an alternative flood risk strategy.

Meanwhile, GI planning is often driven by the desire to include the human and natural functions of green infrastructure which extends beyond managerial domains and short-term socio-ecological changes (Kambites & Owen, 2006). A key feature of GI is the connectivity and multi-functionality attribute which might provide benefits bigger than the sum of its parts. Therefore, in contrast to the site-specific nature of SuDS, GI planning emphasizes connecting a wider range of stakeholders and covering qualitative criteria such as biodiversity value and human satisfaction (Kambites & Owen, 2006). These new emphases necessitate governance innovation since the impacts might not overlap with the planning horizon and responsibilities of the corresponding agencies (Brunckhorst et al., 2006). Yet, current urban planning still mainly focuses on urban growth and the use of green spaces as supporting infrastructure (Llausàs & Roe, 2012). Planning policies have also been criticised for their urban-centric models in dealing with urban fringe development (Scott et al., 2013). Llausàs and Roe (2012) also identified three major aspects determining GI success as:

(1) the climate,
(2) the social context,
(3) the planning policy drivers.

Changing the policy drivers can change the potential uptakes of GI within current practices. Key statutory and non-statutory players in GI planning involve the Commission for Architecture and the Built Environment (CABE), Community Forests, the Landscape Institute, the Town and Country Planning Association, the Chartered Institute of Water and Environmental Management, the Environment Agency in England and Wales, local authorities, Natural England, NGOs, regional spatial strategy and urban planners (Horwood, 2011; Kambites & Owen, 2006; Llausàs & Roe, 2012). This list suggests there is little overlap with the group of agencies managing SuDS, apart from the agencies with direct responsibility for water functions. Furthermore, wider stakeholders that might be affected by the interdependency cascade of the urban system are often neglected. Thus, the functional complexity between the urban components and stormwater management using SuDS/GI have not yet effectively been translated into governance interactions.

4.2.2 *Interactions and interdependencies*

Figure 6 demonstrates the main interactions and interdependencies of SuDS/GI and grey infrastructure under non flood conditions. These interdependencies require new governance linkages regarding making space for ecology and water. Yet, the figure shows that much of these interdependencies have not been transformed into logical and cyber governance interdependencies. This lack of collaboration and involvement across respective

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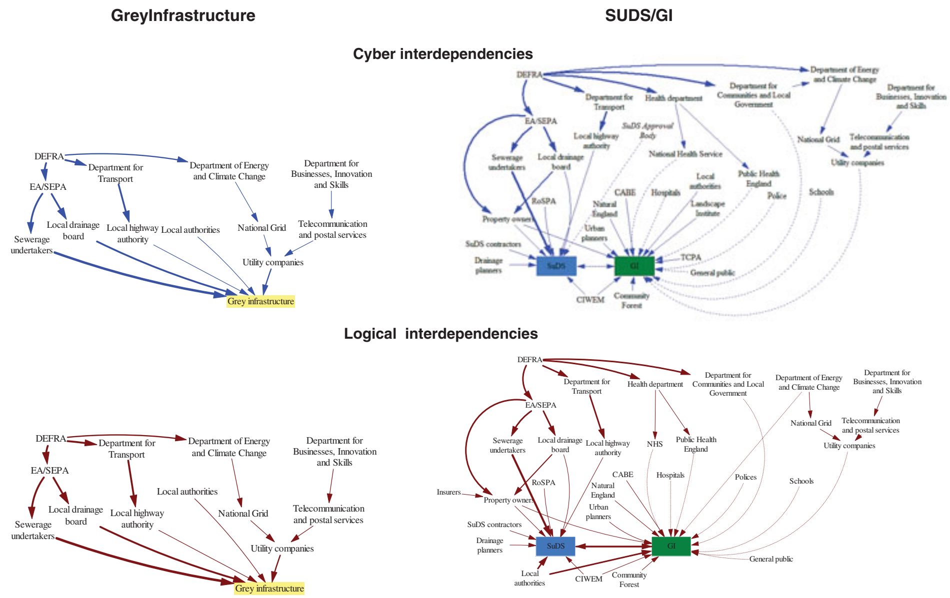

Figure 6. Examples of key cyber and logical dependencies under the non-flood condition for grey and SuDS/GI management. Thickness of the arrows reflects the strength of the interactions and dotted arrows indicate benefits/functional linkages that have not been translated into the relational complexity.

managing agencies can be a barrier toward effective management of potential SuDS/GI impacts regarding their integrated nature and the diversity of related stakeholders. Much of the insurance industry still view non-structural measures as short-term solutions leading to an eventual goal of hard engineered structures (Ball et al., 2013). Adopting these strategies in housing developments can change the insurability of properties, since insurers are still more confident on grey engineered flood defences (Ball et al., 2013). As a flood risk strategy, SuDS/GI has also been affected by the fragmented flood management structure in England and Wales, which until 2010 had no lead control of responsibility for urban surface water flooding (Coulthard & Frostick, 2010).

GI planning documents fail to include a wider group of stakeholders affected by these urban interdependencies. The participatory process of community stream restoration projects also cause delays and potential oppositions for implementation, in contrast to the fast, standard and top-down implementation of conventional solutions (Winz et al., 2011). In the USA, stakeholders such as house owners have shown a willingness to use non-structural measures such as streambank naturalisation and wetlands to reduce stormwater and non-point source pollution (Kaplowitz & Lupi, 2012). Furthermore, such community projects on stream restoration create positive effects on vegetation and raise people's awareness, probably due to communal ownership of the project (Winz et al., 2011). Given the competing interests from different stakeholders, managing these relations via informing, consulting and collaborating remains a key action point (Ashley et al., 2011). New organisational interdependencies need to be recognised to reflect the interconnected nature of SuDS/GI functions and benefits. The use of SUDS/GI solutions, whilst potentially adding to urban green space, does not prevent the competing effects of continuing urbanisation if elsewhere in a catchment bad planning policy control still allows development in the flood plain.

Integration is encouraged by the European Habitats Directive and GI policies from regional planning bodies. Their interactions pose further challenges in understanding and considering the relational complexity of SuDS/GI. In essence, the question of which policies and agencies play the main administrative role may arise when the stormwater management function is in conflict with the habitat/conservation function. As such, there needs to be holistic consideration of how the complexity and functions evolve over time and vary over space. Such consideration of both relational and functional complexity may help optimise the design to realise the potential functions of SuDS/GI, but at the same time address the diverse needs and responsibilities of relating agencies.

5. Barriers and implications for the UK

Many organisational and agency partnerships need to be reframed if SUDS/GI implementation is to be effectively co-ordinated at both the planning and operational stages and potential concurrent benefits of both realised. These organisational dependencies are particularly important to systems performing multiple functions, since effective

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management of such systems require organisational collaboration amongst relevant agencies. Furthermore some benefits do not accrue to the SuDS/GI asset owner and thus may have less immediate priority to those with direct responsibility for SusDS/GI installation and their upkeep. This can give rise to a lack of incentive to pursue such solutions if multiple benefits do not show up on organisational balance sheets.

Hitherto, each urban infrastructure component is largely analysed on different scales and often independently to other components. This is highlighted by the fact that there are no policies/documents concerning the integration of both SuDS and GI elements. Fundamentally this results from a failure to act at a systems level, partly arising from the administrative arrangements reflecting discrete responsibilities for different types of asset groups.

In examining system interactions of stormwater management using SuDS/GI, both functional and organisational impacts have been considered in this paper. A key hurdle emerges in a UK context which is the gap between the planning policies and the interactions of urban components via SuDS/GI. Current structural approaches of flood risk management using grey infrastructure solutions are unsustainable but in order to effectively implement stormwater management using alternative and effective SuDS/GI solutions, the following barriers need to be overcome:

Physical barriers: include potentially negative interdependencies cascading through the urban system under both flood conditions and non-flood conditions; the lack of available land for SuDS/GI implementation; physical limitations of their performance in the UK context; and delays in achieving the full range of benefits due to tree maturity and the strong dependency of SuDS/GI functioning on the maintenance regime. Significant uncertainty exists in the quantification of their impacts and wider benefits and therefore necessitates further research in determining the key physical constraints. Specifically the conditions which enhance each benefit and how they are inter-related needs to be better understood so that tradeoffs can be identified when influencing environmental factors are more favourable to achieve some benefits than others.

Perception/information barriers: refers to SuDS/GI being perceived as short-term solutions with low certainty in the reliability of their functions. Furthermore, these negative perceptions on SuDS/GI can impede their adoption and subsequent maintenances.

Organisational barriers: concerns the split responsibilities and stakeholder groups amongst related agencies managing flood risks and the rest of the urban system. While both SuDS/GI involve the use of natural features and processes, their intended functions and planning scales are different. Mell and Roe (2010) have noted that that information gained from the experiences of Green Infrastructure planning implementation is still fragmented despite the theory and principles being embedded with government initiatives at many levels.

The underlying reasons for the organisational barriers are because organisations are naturally segmented into sectors, with different vested interests and priorities. Meanwhile optimising SuDS/GI performance requires integrated and multi-sectoral involvement. However this will lead to new complexities regarding how to compromise on goals and how decisions on collaboration can lead to long-term gain/loss to each agency. This conflict is inherent and can only be negated by some shared platform of collaboration; because a fully integrated agency might spread itself too thin across the sectors.

In short, there needs to be better linking mechanisms between urban planning and urban drainage management, as well as greater recognition of new relational complexities reflecting the system interdependencies created by SuDS/GI. This extends to the diverse range of beneficiaries who are served by their multi-functional attributes and benefits.

A practical step to achieving the organisational dialogues needed can be developed through Learning Action Alliances, such as the ongoing one currently underway successfully in Newcastle (which has so far met eight times between March 2014–January 2015) and previously advocated by Ashley et al (2012) and van Herk et al (2011). The creation of such LAA's can provide a shared space for joint working where the barriers, uncertainties, controversies and limitations to the benefits of SuDS/GI can be discussed between stakeholders that play an active role in managing specific facilities, without being bound by the need to reach an immediate formal decision. LAA's are vehicles where trust can be built through a mutual gains approach in which a consensus around priorities can be developed and visionary projects explored. Options can be freely discussed outside the constraints of existing formal institutional settings. In Newcastle representatives from relevant stakeholder groups who can influence decisions about the adoption of SuDS/GI strategies across the city have been involved, including major stakeholders representing city council departments, environment (e.g. EA, Natural England), local interest groups, trusts and societies, water companies, academics, and major landowners. Such groups can directly contribute to reducing the barriers which emerge from the relational complexities described earlier in the paper. The lessons learnt from the outcomes, such as those being generated in Newcastle, can be rapidly replicated in other cities through the establishment of similar groups. Further details can be found at: http://www.bluegreencities.ac.uk/bluegreencities/research/learning-and-action-alliance.aspx

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6. Conclusion

This paper has highlighted SuDS/GI as a holistic stormwater management measure that has the potential to enhance benefits in urban ecology, energy, landscape and socio-economic systems. It has been shown that SuDS/GI bears fewer interdependencies on the energy and communication system, but creates new interdependencies not previously existing with grey infrastructure. Within each component, the major interactions and interdependencies also change regarding their hydrological, ecological and built environment function under contrasting non-flood and flood condition states. Furthermore, the literature has reported not only positive impacts of SuDS/GI on the urban system, but also negative impacts that merit attention in their design and management.

In conclusion, this review of existing evidence in the literature has led to proposals for placing stormwater management using SuDS/GI within a new framework of urban interdependencies which explores both their functional and relational complexity. From the original grey-green continuum proposed by Davies et al. (2006), the paper has extended the framework to include the Hydrological, Ecological and the Built Environment functions. The interdependencies amongst the urban components regarding stormwater management have then been viewed according to these functions. Overall, it has been shown that the inclusion of SuDS/GI into the urban fabric can modify functional interdependencies under both flood and non-flood conditions. In particular, SuDS/GI exhibit geographical and logical interdependencies during the time of flood and all four kinds of interdependencies under the non-flood condition.

SuDS/GI implementation could also pose potential negative impacts on the primary functioning of other urban components. For example impeding road use where carriage ways are designated as flow channels under exceedance flow. At the same time SuDS/GI imposes fewer interdependencies on the energy and information systems under flood conditions than traditional grey infrastructure. Under non flood conditions there are opportunities for such assets to offer other multiple functions and benefits. The organisational complexity, however, has not reflected these new interdependencies created by SuDS/GI solutions. In essence, documents concerning SuDS and GI are still largely separated and the stakeholder groups involved in the designing and maintenance of these features are currently not well assimilated, apart from through the agencies with direct responsibility for water management. This state of policy disconnection therefore acts as a key barrier towards effective adoption of SuDS/GI. The paper identified these barriers as physical barriers, perception/information barriers and organisational barriers.

The paper recognises that due to the multi-functionality of SuDS/GI, there has been a national trend toward integrated management. These actions have helped reduce the fragmentation of flood management and enable collaboration amongst the relevant management agencies. However, they also pose new challenges in considering the potential multiple functions of SuDS/GI and communicating and sharing information across agencies with differing primary responsibilities. These are key considerations, particularly when optimising one function could reduce other functions, and thus, creating conflicts amongst stakeholder groups.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work is part of the Blue Green Cities project funded by the UK Engineering and Physical Sciences Research Council, grant EP/K013661/1. The underlying research materials for this article can be accessed at http://figshare.com/articles/GI_Interactions_-rar/1409473.

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