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City-scale accessibility of emergency responders operating during flood events

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Abstract. Emergency responders often have to operate and respond to emergency situations during dynamic weather conditions, including floods. This paper demonstrates a novel method using existing tools and datasets to evaluate emergency responder accessibility during flood events within the city of Leicester, UK. Accessibility was quantified using the 8 and 10 min legislative targets for emergency provision for the ambulance and fire and rescue services respectively under "normal" no-flood conditions, as well as flood scenarios of various magnitudes (1 in 20-year, 1 in 100-year and 1 in 1000-year recurrence intervals), with both surface water and fluvial flood conditions considered. Flood restrictions were processed based on previous hydrodynamic inundation modelling undertaken and inputted into a Network Analysis framework as restrictions for surface water and fluvial flood events. Surface water flooding was shown to cause more disruption to emergency responders operating within the city due to its widespread and spatially distributed footprint when compared to fluvial flood events of comparable magnitude. Fire and rescue 10 min accessibility was shown to decrease from 100, 66.5, 39.8 and 26.2 % under the no-flood, 1 in 20-year, 1 in 100-year and 1 in 1000-year surface water flood scenarios respectively. Furthermore, total inaccessibility was shown to increase with flood magnitude from 6.0 % under the 1 in 20-year scenario to 31.0 % under the 1 in 100-year flood scenario. Additionally, the evolution of emergency service accessibility throughout a surface water flood event is outlined, demonstrating the rapid impact on emergency service accessibility within the first 15 min of the surface water flood event, with a reduction in service coverage and overlap being observed for the ambulance service during a 1 in 100-year flood event. The study provides evidence to guide strategic planning for decision makers prior to and during emergency response to flood events at the city scale. It also provides a readily transferable method for exploring the impacts of natural hazards or disruptions in other cities or regions based on historic, scenario-based events or real-time forecasting, if such data are available.

1 Introduction

Floods are one of the most significant natural hazards, affecting 116 million people globally, causing approximately 7000 deaths and damages in the region of USD 7.5 billion annually (UNESCO, 2010). Within the UK, the Environment Agency (2009) estimated that 5 million people (1/12 of the UK population) occupying 2 million properties are currently at risk from coastal, fluvial or surface water (pluvial) flooding. Following the Pitt Review (Pitt, 2008), the Environment Agency produced UK-wide surface water flood hazard maps and identified flood "hotspots" at direct flood risk. Although considerable work has focused on understanding the UK's direct flood risk, flooding often has associated indirect or cascading impacts that extend beyond the area experiencing inundation. Indirect impacts relate to a series of interconnected or related infrastructural failures that are initiated by a natural hazard or disturbance such as a flood event (Pescaroli and Alexander, 2015). Critical infrastructure, such as utility services, hospitals, emergency service locations (police, ambulance, and fire and rescue stations), and the transportation networks that connect these services are also susceptible to flooding (Douglas et al., 2010; Stålhult and Andersson, 2014). Therefore, inundation may result in spatially diffuse consequences that are often difficult to measure and are perceived as less important when compared to direct flood impacts (Penning-Rowsell and Parker, 1987; Arkell and Darch, 2006). For example, a flooded electricity substation may result in thousands of properties outside of the flooded area losing power. Also, flooded transport infrastructure may affect the transit of vehicles across the network (Gil and Steinbach, 2008; Lhomme et al., 2013; Yin et al., 2016), which is of particular importance to the emergency services (e.g. fire and rescue, ambulance, police) that may be required to respond to emergency calls during flood events.

According to the UK Government's Civil Contingencies Act (2004), responders operating within a Multi-Agency Flood Plan (MAFP) are divided into two categories with separate duties during emergency scenarios. Category 1 responders, including emergency services, lead local authorities (LLAs) and the Environment Agency are at the core of a response, while Category 2 organisations, such as utility and transport services, act as co-operating responders to assist and share information during flood emergencies. In England and Wales, Category 1 and 2 responders act individually or collectively through 42 local resilience forums to respond to major emergency situations, including those related to severe flooding (Defra, 2014).

Working in a common framework, local responders are required to make their own decisions about what planning arrangements are appropriate considering the local circumstances and priorities. For flood-related incidents, a MAFP is required by the Civil Contingencies Act (2004) to outline a framework for planning, response and recovery. The successful implementation of a MAFP requires the key operational and stakeholder organisations (e.g. fire and rescue service, ambulance service, city council and police) to provide efficient and functional services during flood conditions collectively. To a large extent, this depends on the continued functioning of critical infrastructure nodes and networks pertinent to flood emergency planning and response, including vital services such as fire and rescue stations, hospitals, telecommunication networks and the transit network (Lumbroso et al., 2008; Dawson et al., 2011; Lumbroso and Vinet, 2012; Wilby and Keenan, 2012; Bosher, 2014). Currently, decision making during flood events and knowledge of flood-prone areas is informed by planning exercises coordinated by emergency responder organisations, local understanding and past experience of areas prone to flooding, as well as identification of flood hotspot areas based on flood modelling studies (see Sect. 2.1). However, these approaches only show the locations of direct flood risk and cannot be used to understand the indirect impacts of flooding on emergency responder operation and accessibility. An applied understanding of the spatio-temporal impacts of flood events on emergency responder accessibility may enhance existing contingency planning frameworks by providing foresight into the potential bottleneck locations across the city, which may ultimately increase emergency responder resilience and preparedness during flood events.

Emergency responders in the UK are required by legislation to conform to strict time frames in which they must respond to incidents. For example, ambulance and fire and rescue services are required to reach 75 % of "Red 1" incidents in less than 8 and 10 min respectively from when the initial report was logged. These include incidents that may elicit high-priority blue-light responses such as cardiac arrest, life-threatening and/or traumatic injury, road traffic collisions, and individuals trapped in floodwaters. However, these response targets might be unachievable under certain flood situations that limit the ability of emergency responders to navigate a disrupted road network (Albano et al., 2014).

Gil and Steinbach (2008) evaluated the indirect impact of flooding on an urban street network, demonstrating the consequences of localised and larger-scale spatial accessibility during disruptive events. Findings suggested that, although the effects of a specific flood event may be concentrated or isolated in one location, other areas may still be affected. An urban transport network may be able to cope with small changes of state (i.e. minor flood events where depths are low and spatial extent is limited). However, more severe flooding may result in the transport network reaching a "tipping point" where network routing is considerably impacted (Sakakibaral et al., 2004; Dawson et al., 2011; Albano et al., 2014). According to Gil and Steinbach (2008), locations during floods may become (i) "islands", completely cut off with no access; (ii) "peninsulas", with a single critical access route; (iii) "peripheral areas" that are more difficult to access or (iv) "refugial areas", which are still accessible and play an important role for coordinating and managing response efforts. These indirect, cascading impacts may be more detrimental to the functioning of a city than the immediate, directly apparent impacts and may result in substantial difficulties for road users, including Category 1 emergency responders, to navigate during flood events.

This paper describes a novel approach to modelling and evaluating the impacts of surface water and fluvial flood events of varying magnitudes on emergency responders operating at the city scale using readily available datasets and functions within a GIS software package (ArcGIS). The city of Leicester was selected as a case study, with a specific focus on emergency response mapping of two Category 1 responders, namely the Leicestershire Fire and Rescue Service and the East Midlands Ambulance Service.

2 Methodology

2.1 Case study area

Leicestershire, including the city of Leicester, UK, has experienced a history of localised flooding (Shackley et al., 2001) with council records indicating that annual fluvial flood damages amounted to ~GBP 90 000 between 2000 and 2010 (Climate East Midlands, 2012). In addition, surface water flooding also poses serious problems to the city of Leicester, with Leicester being ranked 16th out of 4215 settlements assessed within England in terms of surface water flood risk (Defra, 2009). The Environment Agency also estimates that approximately 36 900 properties in Leicester's principle urban area occupy flood-prone areas (Leicester City Council, 2012).

Anecdotal information is available on historic flood events within Leicester although details on specific flood mechanisms, severity and areal extent are largely absent. Based on the total number of historic incidents collated by Leicester City Council, the flood events that occurred in July 1968 and June 1993 appear to be the most severe historical events, with reports indicating that the July 1968 flood event affected up to 1800 properties and 28 factories within the city (Leicester City Council, 2011). More recently (June 2012), Leicester experienced severe surface water flooding following a short, intense period of precipitation where ~30 mm of rainfall fell in 20 min, overwhelming the city's drainage and resulting in widespread flooding across the city.

Since the Flood & Water Management Act (2010), Leicester City Council has completed a number of flood risk studies, including a Preliminary Flood Risk Assessment (2011), Flood Risk & Hazard Mapping Report (2013) and Local Flood Risk Management Plan (2015). These studies identified 26 surface water flood hotspots, including the main hospital, Leicester Royal Infirmary, as well as a number of densely populated, low-income areas of the city (Fig. 1) and have been important in informing flood planning and instigating flood management efforts within the city. However, research has focused largely on the direct impacts of flooding in the city and has not studied the indirect impacts of flooding, for example, on emergency response and accessibility.

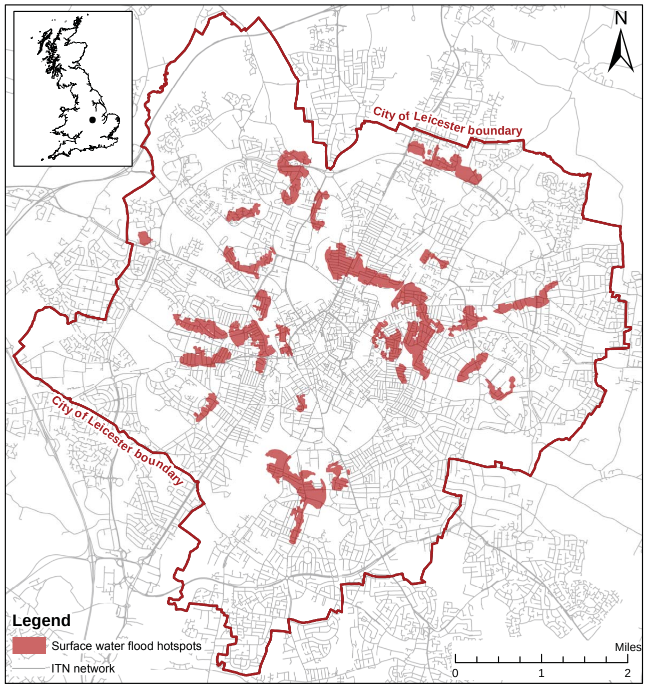

Figure 1. Distribution of the 26 locations identified as surface water hotspots in Leicester, UK.

2.2 Data collation

2.2.1 Road network and critical infrastructure

Leicester's transport network was represented using Ordnance Survey Integrated Transport Network (ITN) data, which, in addition to including detailed road network geometry and routing information, include metadata that outlines standard road restrictions that may inhibit or delay the traversing of a vehicle across a specific section of road. The same ITN data are also used in emergency responder control centres and within emergency vehicles to aid navigation to incidents (Ordnance Survey, 2008). Restrictions contained within the ITN included height and weight limits, speed restrictions based on national speed limits, mandatory turn restrictions (i.e. no right turns) and one-way roads. Although it is likely that congestion and human behavioural changes may affect the routing of emergency vehicles during flood events, the network analysis undertaken did not consider congestion or the impact of traffic. Although congestion data could be implemented into the modelling framework based on historic traffic data (Winn, 2014; Cho and Yoon, 2015), which were available for the city of Leicester from Leicestershire County Council, congestion data were not used due to uncertainties associated with how human behaviour and patterns of congestion may differ under flood conditions when compared to normal conditions on which the traffic data were based. Furthermore, emergency vehicles are able to bypass the majority of congestion when responding to incidents that elicit a blue-light response. Still, because congestion data were not implemented in the modelling conducted, the results presented demonstrate a "best-case" scenario, ignoring potential delays associated with other road users.

The Environment Agency National Receptor Database (NRD) was used to identify critical infrastructure nodes and vulnerable locations in the study area, including hospitals, ambulance stations, and fire and rescue stations. Six fire and rescue stations (Birstall, Western, Southern, Central, Eastern and Wigston) and five ambulance and hospital locations (Goodwood Ambulance Station, Leicester Royal Infirmary, Gorse Hill Ambulance Station, Narborough Ambulance Station and Leicester General Hospital) were identified as points of origin for modelling emergency response zones.

2.2.2 Flooding scenarios

The impact of surface water and fluvial flooding on Leicester's emergency response times for ambulance and fire and rescue were both considered. Existing surface water and fluvial inundation datasets associated with flooding of various magnitudes were obtained directly from the Leicester City Council and Environment Agency respectively. Fluvial and surface water flood events with return periods of 1 in 20, 100 and 1000 years were assessed.

High-resolution (1 m horizontal, ±0.25 m vertical), city-wide surface water inundation depth data derived from a hydrodynamic inundation model (TUFLOW), conducted as part of Leicester's Surface Water Management Plan (2012), were obtained from the Leicester City Council. This resource allowed the extraction of spatially referenced flood depth data at multiple points in time throughout the flood event. The modelling involved applying spatially uniform precipitation associated with specified return periods, namely 1 in 20, 1 in 100 and 1 in 1000 years, calculated for design storm hyetographs of 6 h duration (Fig. 2). Distributed roughness values classified according to Ordnance Survey MasterMap© land uses (e.g. 0.02 for roads, 0.03 for buildings, 0.04 for gardens and/or vegetation) were applied in the modelling process. The modelling included a uniform drainage rate of $12\,\mathrm{mm\,h^{-1}}$ to account for drainage and/or infiltration to natural, permeable surfaces and artificial drainage systems such as sewers and manholes, as recommended by the Environment Agency (2012). Further information on the surface water inundation modelling used in this study can be found in Leicester City Council's Surface Water Management Plan (2012).

Fluvial inundation data for the River Soar and associated tributaries within Leicester were obtained from the Environment Agency. As flood depths were not available for fluvial flooding, flood hazard data were used to derive flood restrictions. Flood hazard is a function of flood depth (m), velocity ($\mathrm{m\,s^{-1}}$) and potential for entrainment of debris within floodwaters (HR Wallingford, 2006), all factors that could inhibit vehicle passage. The spatially distributed flood hazard data were classified into four categories based on the flood hazard rating calculated using the FD23211 guidance document proposed by HR Wallingford (2006): (i) low – shallow flowing water or deep, standing water, (ii) moderate – dangerous for some with deep, fast-flowing water, (iii) significant – dangerous for most with deep, fast-flowing water and (iv) extreme – deep, fast-flowing water that is dangerous to all.

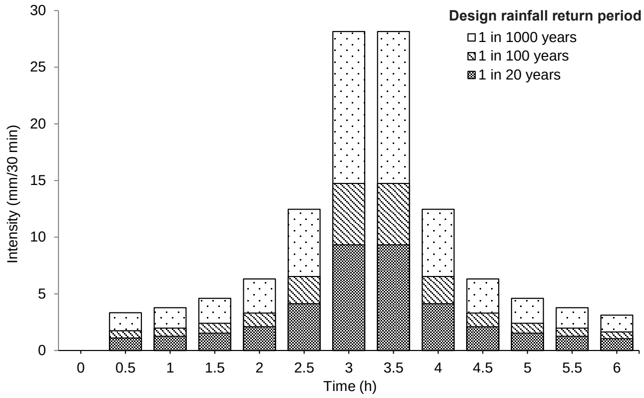

Figure 2. Design rainfall scenarios for the 1 in 20-, 1 in 100- and 1 in 1000-year surface water flood modelling conducted by the Leicester City Council.

2.3 Methods

2.3.1 Network restrictions

First, flood restrictions were defined using the data detailed in the previous section. A study by the Automobile Association (2014) recommended that regular motorists (i.e. small or medium cars) should avoid driving through floodwaters ≥ 15 cm depth as this may be sufficient to stall a car or result in loss of control, while water depths exceeding 30 cm may be sufficient to move vehicles. Additionally, depths ≥ 15 cm may conceal submerged hazards (e.g. overflowing drains or large debris), which could prevent vehicles from successfully traversing floodwaters. Despite this, emergency vehicles have a greater tolerance for travelling through floodwaters than standard vehicles.

Semi-structured interviews conducted with Leicestershire Fire and Rescue Service revealed that water depths of approximately 25 cm (lower than the wheel arch of the vehicle) may be traversed during an emergency situation due to the size, weight and power of emergency vehicles – a fire appliance weighs approximately 12 T and drivers are trained to traverse through floodwaters. This threshold depth value is also consistent with previous research (HR Wallingford, 2006; Dawson et al., 2011; Pregnolato et al., 2016). Although high velocities may hinder emergency responders from successfully traversing floodwaters, modelled flow velocities were typically $< 1\,\mathrm{m\,s^{-1}}$ due to ponding in topographic hollows. Therefore, depth was selected as the principal factor when evaluating the sites of network restrictions. Hence, a threshold water depth of 25 cm was set for the surface water flood scenarios, with water depths ≥ 25 cm being treated as restrictions to emergency vehicle flow along a specific road section.

Surface water flood depths ≥ 25 cm were then processed to remove additional polygons that did not overlap or intercept with the ITN and would not be used for analyses (i.e. in

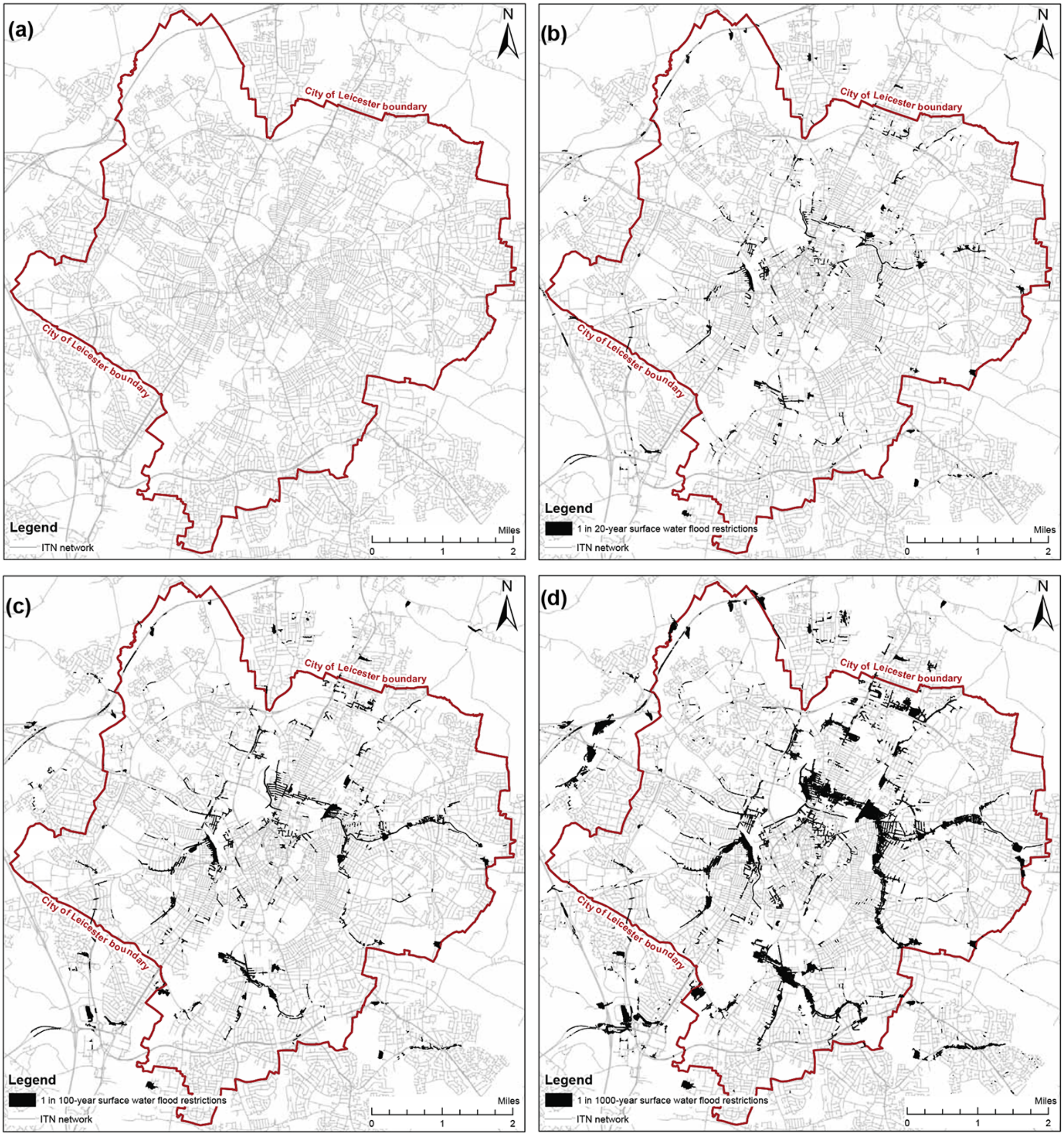

Figure 3. ITN network under **(a)** normal no-flood conditions and overlain with restrictions under **(b)** 1 in 20-year, **(c)** 1 in 100-year and **(d)** 1 in 1000-year surface water flood scenarios showing the extent of flooding above a 25 cm threshold that intersects the ITN network.

areas that would not affect network routing since their extent did not extend to the road network). Additionally, network restrictions were manually inspected to ensure realistic emergency response zone calculation. Processing included the removal of obstructions due to (i) isolated pixels of inundation less than $10\,m^2$ in area that would likely be traversable and (ii) artefact-inundated areas over raised transport features such as bridges and bypasses that may not have been correctly represented in the DEM. Preprocessing of network restrictions used for the surface water flood scenarios improved computational speed and performance significantly, with the 100-year surface water flood event having 201 065 polygons to treat as restrictions prior to inspection but only 10 557 afterwards. Figure 3 illustrates the no-flood restriction transport network as well as the transport network with overlain surface water flood depths greater than 25 cm under the three flood magnitude scenarios: 1 in 20 years, 1 in 100 years and 1 in 1000 years.

To create fluvial inundation restrictions, all fluvial flood hazard categories with the exception of the "low" flood hazard category were treated as barriers and restrictions in all return period scenarios. Low flood hazard polygons were removed as restrictions because it was reasonable to assume that emergency vehicles would be able to traverse floodwaters in this category (Sect. 2.2.2). Category 1 responders suggested that emergency vehicles could have some issues passing through floodwaters in the "moderate" flood hazard categories and above, especially due to the possibility of submerged obstacles. Therefore, flood hazard ratings of moderate and above were treated as restrictions within the modelling. Figure 4 highlights the flood hazard data used to create restrictions for fluvial inundation under the 1 in 20-, 1 in 100- and 1 in 1000-year flood scenarios.

2.3.2 Network routing

To quantify accessibility and evaluate service coverage, quickest routing (based on time taken to travel between two points when traversing the Integrated Transport Network), as opposed to shortest-path routing (based on the distance between two points), was selected since this algorithm considers road restrictions and impedances. Quickest routing between facility and destination was based on Dijkstra's (1959) shortest-path algorithm with network routing weighted by travel time rather than distance, allowing the inclusion of travel impedances and restrictions. Quickest routing was applied because the shortest route by distance may not necessarily be the quickest traversable route because a shorter path may be more weighted due to a restriction. For example, a length of arterial road with a lower UK standard speed restriction of 20 mph (32.2 km h^{-1}) may be traversed more quickly than a longer route such as a motorway with a UK standard speed restriction of 70 mph (112.7 km h^{-1}). Routing based on Dijkstra's algorithm was chosen due to the algorithm being a computationally efficient and widely accepted method of solving vehicle routing problems and conducting network analyses (Sniedovich, 2010). Furthermore, the method was easily interfaced with the GIS framework, allowing the implementation of weighted restrictions and impedance data contained within the ITN metadata the network analyses conducted.

All network analyses took into account ITN road restriction and impedances specifically for emergency vehicles, as defined by the UK government's Traffic Signs Regulations and General Directions Act (2002). Vehicle qualifier information, metadata imbedded within the ITN dataset, which indicates whether a restriction or impedance applied to a

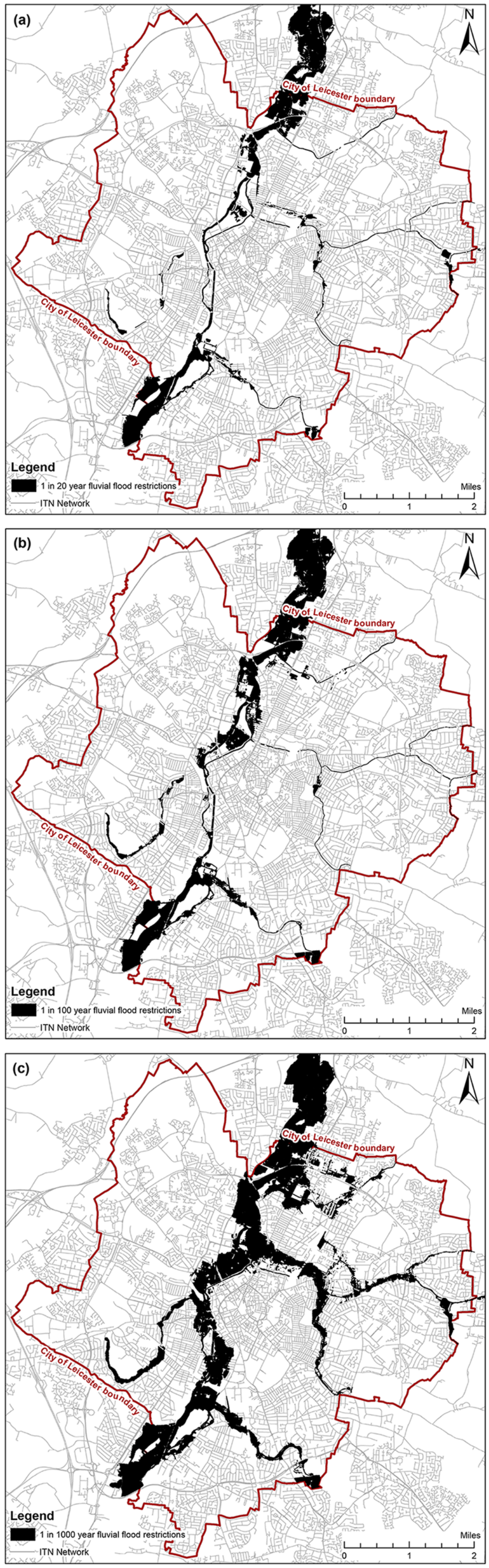

Figure 4. Fluvial flood restrictions under **(a)** 1 in 20-year, **(b)** 1 in 100-year and **(c)** 1 in 1000-year scenarios.

specific vehicle depending on its use, load and type (e.g. taxi, bus, wide-load heavy goods vehicle, emergency vehicles, hazardous or dangerous loads), was set to "emergency vehicles" to reflect the motoring regulations that emergency vehicles are exempt from during blue-light response.

Basic origin of destination "A-to-B" routing between two points and response zone calculation was undertaken for key fire and rescue and ambulance nodes identified using the National Receptors Database. To calculate A-to-B routing, an origin node (A) was identified (i.e. fire and rescue station) and a destination node (B) was highlighted where an emergency vehicle may have to attend, i.e. an evacuation centre where affected persons would be gathered in the event of an emergency. Quickest routing between both points was then calculated to give a journey duration under normal no-flood conditions. Flood restrictions were then overlain over these routes and routing was recalculated to understand the specific impact of flooding on an origin-to-destination routing.

Next, to calculate polygon response zones of emergency responders, relevant nodes (i.e. fire and rescue stations, ambulance stations and hospitals) identified from the National Receptors Dataset were treated as "facilities" within an ArcGIS Network Analyst framework. Using these facilities as starting points for vehicle routing, polygon response zones highlighting all road network locations lying within a 10 min (fire and rescue) or 8 min (ambulance) radius were calculated for each individual station, based on legislated response time frames for "Red 1" high-priority incidents. Individual station service polygon areas were then combined and overlain to visualise and evaluate the zonal emergency service coverage for the whole city under unimpeded no-flood conditions. Flood restriction data for surface water and fluvial flood scenarios could then be input into Network Analyst and the response polygons could be recalculated for different magnitude surface water and fluvial flood scenarios to understand the impact of flooding on emergency response.

3 Results and discussion

3.1 Origin–destination routing

Using a simple origin-to-destination routing, a route between the Western Fire and Rescue Station and St. Andrew's Methodist Church, an evacuation centre within a close proximity to the Western Fire and Rescue Station, was calculated. Figure 5a highlights the modelled quickest route under normal conditions when no flood restrictions were present, demonstrating that fire and rescue services responding from the Western station would be able to reach the destination within a 5 min time frame, travelling a distance of 4.6 km (2.86 miles). However, when flood restrictions derived from a 1 in 100-year fluvial flood event were integrated into the model, journey travel times were shown to increase to 8 min (+60 %; Fig. 5b) under a "flood-informed" scenario, where responders are prepared and informed of network restrictions before responding and are able to plan an alternative route before leaving the station, and 15 min (+200 %; Fig. 5c) under an uninformed scenario, where impassable floodwaters are encountered by responders en route. This demon-

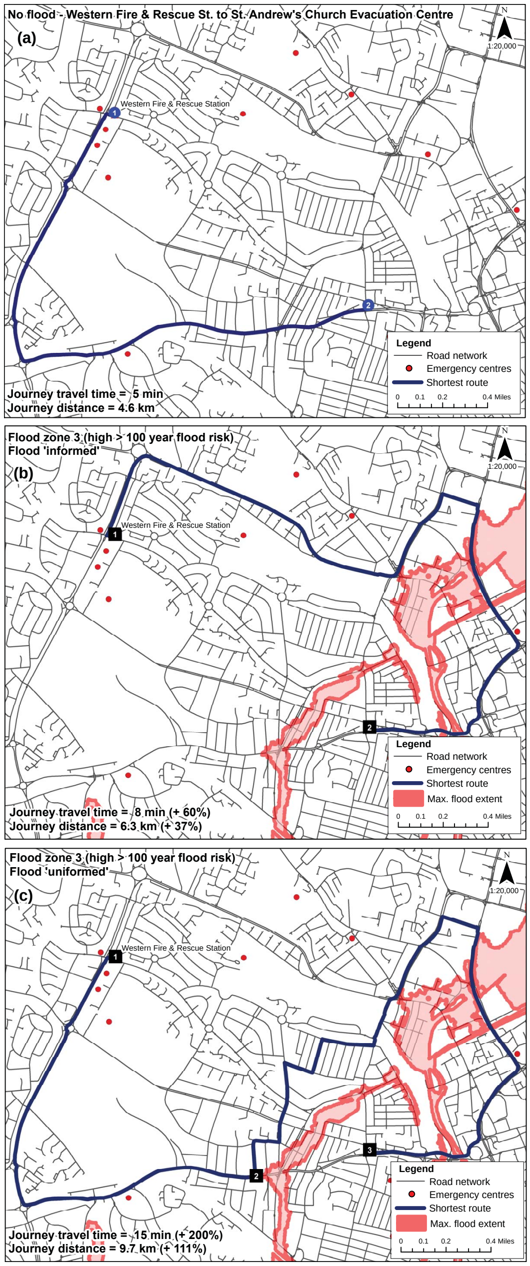

Figure 5. Quickest routing between the Western Fire and Rescue Station and St. Andrew's Methodist Church (evacuation centre, 300-person capacity) under **(a)** normal conditions and high (> 100 year) fluvial flood risk scenarios. **(b)** A prepared and "informed" scenario where first responders are aware of network restrictions before responding, whereas **(c)** shows a "uniformed" scenario where impassable floodwaters are encountered by responders en route.

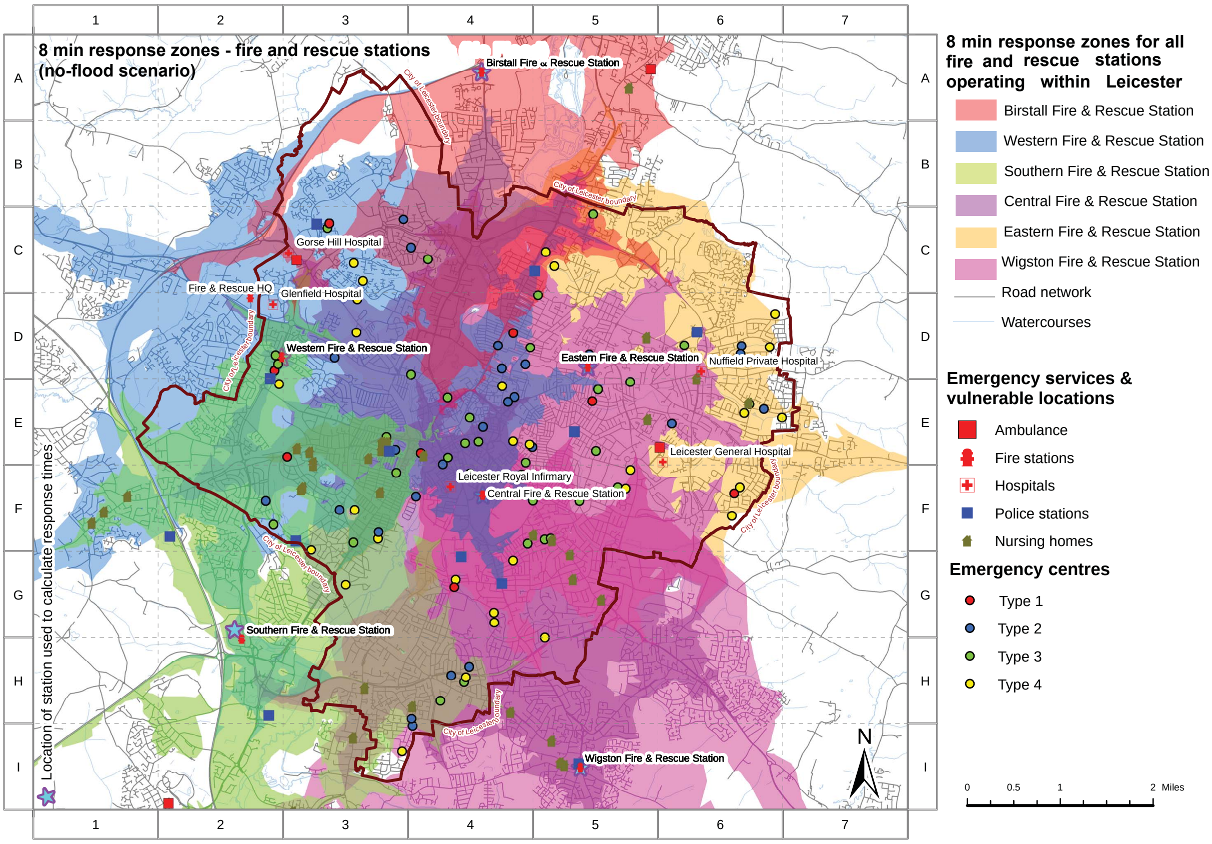

Figure 6. City accessibility (within 10 min) for fire and rescue service stations under normal no-flood conditions.

strates the impact that flood events may have upon origin-to-destination routing for emergency responders, as legislated response times may be unachievable under potential flood situations, which may limit the efficiency of emergency responders traversing a disrupted road network, resulting in affected individuals being at greater risk (Arkell and Darch, 2006). Furthermore, the importance of preparedness is critical because emergency responders may be able to respond more rapidly if up-to-date information on the extent of flood-related network restrictions is available.

3.1.1 Zonal response: no-flood conditions

The network analysis undertaken suggests that Leicestershire Fire and Rescue Service (LFRS) would be able to reach 100 % of the city road network within 10 min when operating under normal conditions (i.e. no flooding or disruptions present), meeting the 10 min legislative time frame (Fig. 6). Furthermore, significant areas of the city are shown to be within a 10 min response zone from one or more fire and rescue stations as there are numerous areas across the city where overlap in station coverage exists. This indicates that the fire and rescue stations are strategically placed to maximise station coverage, and some contingency overlap exists when operating under optimal conditions to ensure resilient operation.

The response zones for the East Midlands Ambulance Service (EMAS) for an 8 min-or-less (for immediately life-threatening incidents) scenario returned similar findings. Under normal conditions when no flood restrictions were present, it was predicted that 89 % of the city would be reachable within 8 min or less (Table 1; Fig. 7). Areas that were predicted to be unreachable within an 8 min time frame were mostly situated around the city boundary. However, unlike the fire and rescue service, which is more dependent on remaining at their stations between incidents (e.g. due to requiring different personal protective equipment, depending on the incident, and because of the size of the emergency vehicle), ambulance services are more mobile in their operations and have strategic standby points that they are able to occupy between incidents, based on statistical and historic incident records, often only returning to the ambulance depot at the end of a shift.

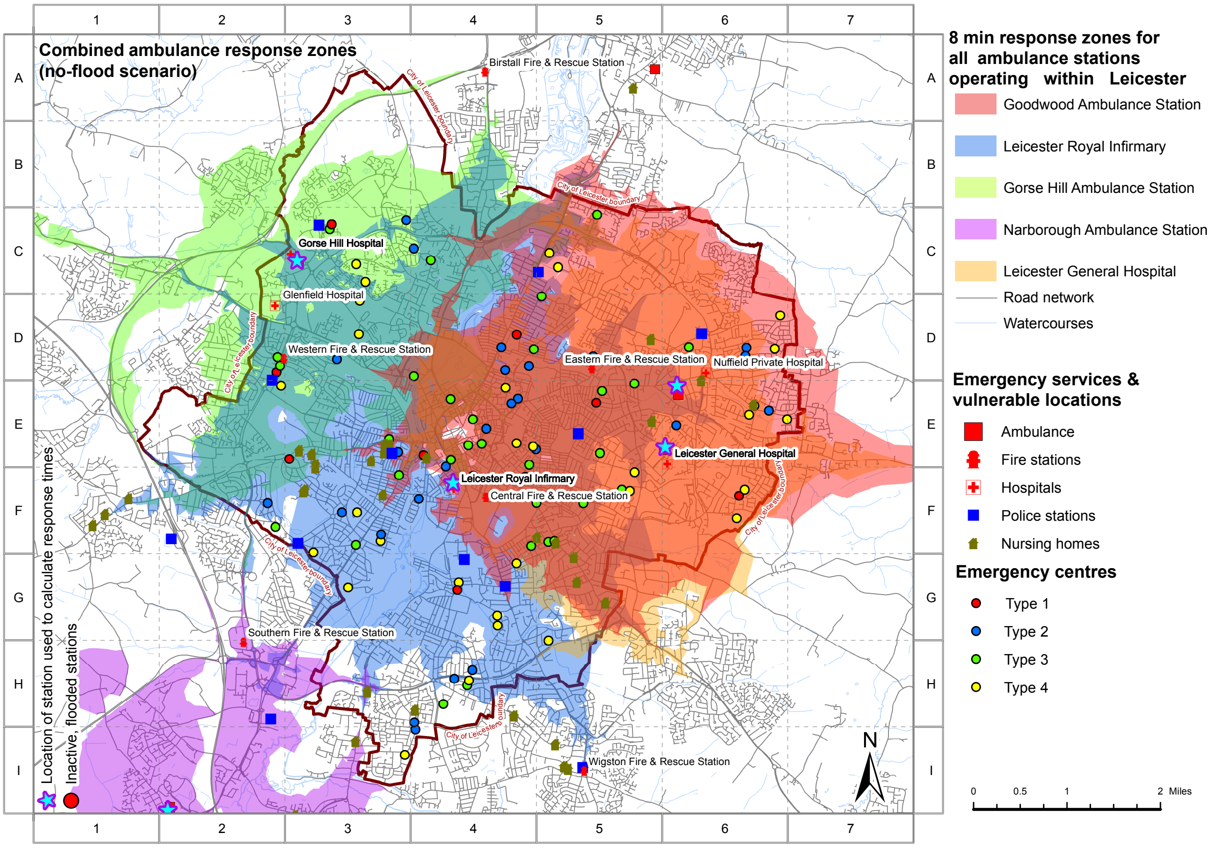

Figure 7. Accessibility of the city (8 min) for ambulance service stations operating under normal no-flood conditions.

Table 1. Percentage of area accessible to fire and rescue and ambulance service stations under normal and flood scenarios.

Flood scenarios	Fire and rescue service		Ambulance service	
	Accessible in 10 min	Inaccessible	Accessible in 8 min	Inaccessible
No flood	100 %	0 %	88.9 %	0 %
1 in 20-year SW	66.5 %	6.0 %	50.7 %	2.6 %
1 in 100-year SW	39.8 %	12.7 %	39.8 %	12.5 %
1 in 1000-year SW	26.2 %	31.0 %	26.8 %	30.9 %
1 in 20-year Flv	97.6 %	1.9 %	84.1 %	3.5 %
1 in 100-year Flv	96.2 %	1.9 %	82.9 %	3.5 %
1 in 1000-year Flv	74.3 %	13.8 %	56.0 %	13.1 %

NB “SW” is surface water flooding scenarios; “Flv” is fluvial flooding scenarios.

3.1.2 Impact of surface water flooding

Fire and rescue service

When restrictions derived from the 20-year surface water flood scenario were incorporated into the model, the fire and rescue service was shown to experience a 34 % reduction in service coverage, resulting in 66 % of the road network being accessible in 10 min or less (Table 1; Fig. 8a). This reduction in service coverage appears to be due to difficulties in access due to a decrease in the road network connectivity along primary, high-hierarchy road linkages (i.e. A-roads), which are intended to provide large-scale transport links within or between areas, as opposed to lower-hierarchy arterial roads, which are intended for local traffic to smaller housing estates (Department of Transport, 2012). Large parts of the south-west of the city appear to be inaccessible within a legislated 10 min time frame due to key access roads (e.g. A5460, A563 and M1 motorway) surrounding the Southern Fire and Rescue Station experiencing floodwaters overlaying the ITN, re-

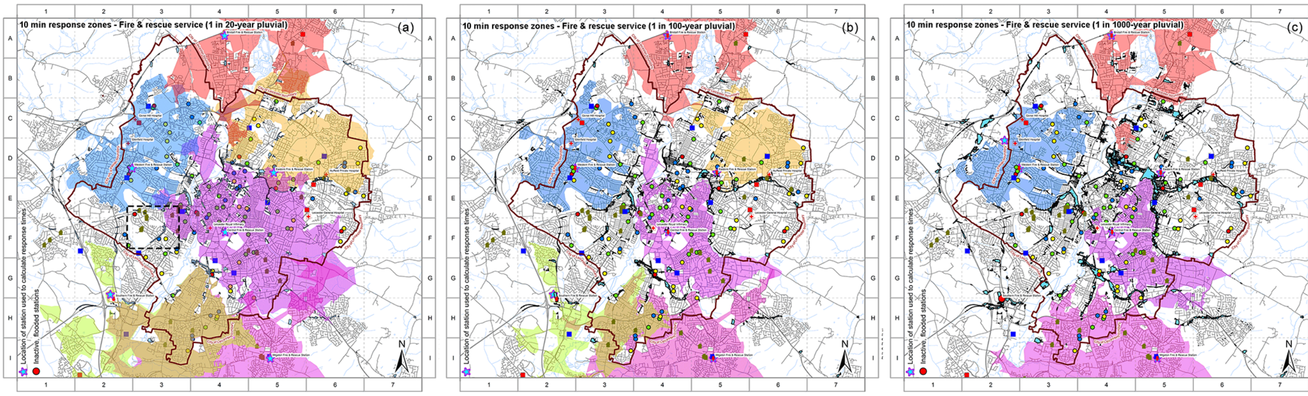

Figure 8. City-scale accessibility (within a 10 min time frame) for fire and rescue service stations: **(a)** 1 in 20-year, **(b)** 1 in 100-year and **(c)** 1 in 1000-year surface water flooding scenarios. New Parks Lane, referred to in the text, is highlighted in the rectangle in Fig. 8a. See Fig. 6 for key.

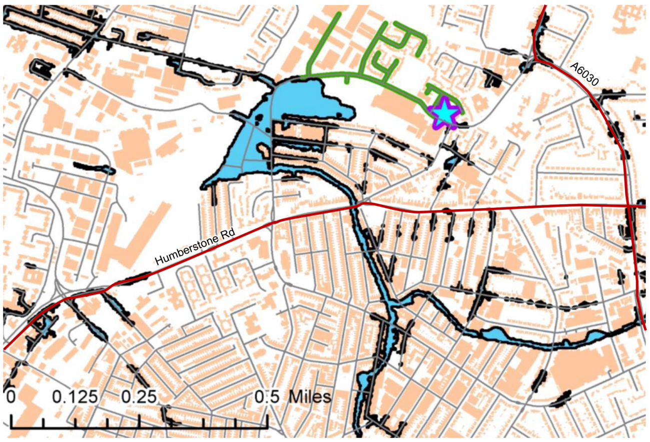

Figure 9. The Eastern Fire and Rescue Station during a 1 in 100-year flood event shows the surrounding roads experiencing inundation, predominantly surrounding Willow Brook (centre). The green line indicates the accessible road network without mitigation measures. Floodwaters surrounding Willow Brook were removed at the Humberstone Road intercept because a large bridge passed over the brook. Floodwaters blocking access to the A6030 were also removed since these would likely be pumped.

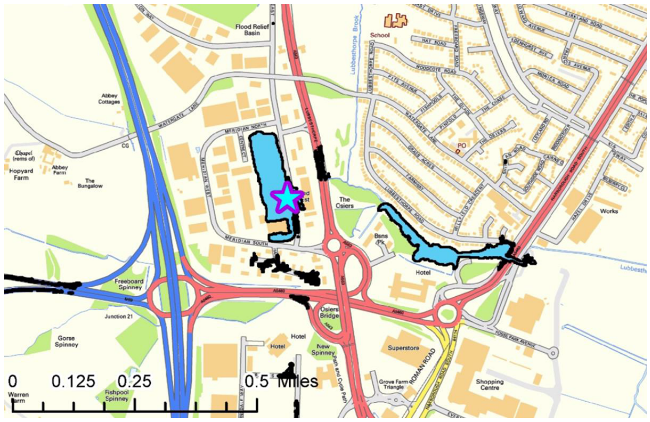

Figure 10. The Southern Fire and Rescue Station during a 1 in 100-year flood event shows that the station is directly at risk of flooding and if sufficient mitigation measures are not taken during a flood of similar or greater magnitude, functioning of the station could be compromised.

sulting in a reduction in service coverage (Fig. 10a). Additionally, ITN blockages along primary access roads, including New Parks Way (A563) by Hinkley Road roundabout and the A47, result in the Western and Central Fire and Rescue stations becoming unable to access areas located within the south-west of the city. Moreover, 6 % of the city area was predicted to be completely inaccessible or "islanded", either due to floodwater occupying the road network directly or due to zones of the city being isolated and surrounded entirely by floodwaters.

Under a 1 in 100-year surface water flood scenario, the modelling suggested that 40 % of the city would be accessible within 10 min and 13 % of the city would be completely inaccessible (Table 1; Fig. 8b). The analysis conducted was based on a best-case scenario, assuming that localised pumping of floodwaters would be conducted at the Eastern and Southern Fire and Rescue stations since these stations would be directly or indirectly affected by a flood event of this magnitude; the Eastern Fire and Rescue Station may experience disruptions in service because of difficulties in accessing the key access routes, Humberstone Road (A47) and the A6030, due to the surrounding road network being inundated by floodwaters (Fig. 9), while the Southern Fire and Rescue Station may experience direct flooding if floodwaters are not managed (Fig. 10). In the analysis, smaller restrictions surrounding these stations were removed, assuming that the fire and rescue stations would focus resources on ensuring that these facilities were functioning efficiently. However, it is possible that the Eastern and Southern Fire and Rescue sta-

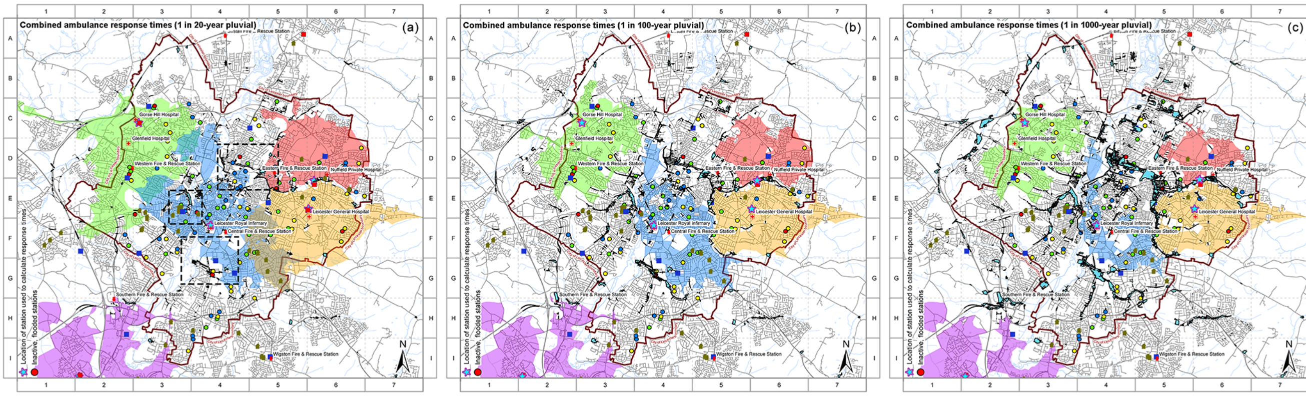

Figure 11. City-scale accessibility (within an 8 min time frame) for ambulance service stations under **(a)** 1 in 20-year, **(b)** 1 in 100-year and **(c)** 1 in 1000-year surface water flooding scenarios. The key access roads referred to in the text are highlighted in the rectangles in Fig. 11a. Refer to Fig. 7 for key.

tions could be rendered inoperable under a 1 in 100-year surface water flood event if sufficient mitigation measures were not conducted.

Under the most extreme 1000-year surface water flood scenario, the model predicted that almost three-quarters of the city would be inaccessible to the fire and rescue service within a 10 min time frame, with 26 % of the city being accessible by the fire and rescue station in under 10 min (Table 1; Fig. 8c). Additionally, 31 % of the city was predicted to be completely inaccessible to the fire and rescue service using the city's road network. Therefore, other means of transport (e.g. foot, boat or helicopter) would be required to access large areas of the city. Moreover, under this extreme flood scenario, the Eastern and Southern Fire and Rescue stations would be fully compromised by floodwaters and would be required to divert their operations and resources to alternative stations across the city.

The model also predicts that there would be no overlap in fire and rescue station coverage during a 1 in 1000-year surface water flood event and that many vulnerable parts of the city, including the main hospital (Leicester Royal Infirmary), would be either directly inundated by floodwaters or inaccessible due to key access routes throughout the city experiencing network restrictions.

Ambulance service

When flood restrictions were introduced into the ambulance service response model, high-priority response coverage in 8 min or less was shown to decrease in relation to an increase in flood magnitude, similar to the fire and rescue service response. Over half of the city (51 %) was projected to be accessible in 8 min or less under a 1 in 20-year surface water flood scenario, 40 % under a 1 in 100-year scenario and 27 % under a 1 in 1000-year scenario (Table 1; Fig. 11). Although the east of the city surrounding Leicester General Hospital and Goodwood Ambulance Station appears to maintain much of its accessibility, areas to the north and south of the city become inaccessible during a 1 in 20-year flood event due to flood restrictions causing a bottleneck and restricting transit on a number of primary access roads throughout the city, including Melton Road (A607), Aylestone Road (A426), Welford Road (A5199) and Hinkley Road (A47).

Furthermore, areas of absolute inaccessibility were also shown to correlate with flood magnitude. Under a no-flood scenario, the entire city was accessible by road, while 2.6, 12.5 and 30.9 % of the city was shown to be inaccessible by the ambulance service under 1 in 20-, 1 in 100- and 1 in 1000-year surface water flood scenarios respectively (Table 1).

3.2 Impact of fluvial flooding

When compared to the surface water flood scenarios, incidences of fluvial flooding within Leicester were shown to have a minor impact on emergency response under the 1 in 20- (Fig. 12a) and 1 in 100-year (Fig. 12b) fluvial flooding scenarios, with fire and rescue and ambulance service emergency response only becoming significantly impacted under an extreme 1 in 1000-year fluvial flood scenario (Fig. 12c). This could be due to the large capacity of the River Soar and associated tributaries passing through the city centre, which were engineered into culverts and linear compound channels to convey floodwaters rapidly and efficiently, meaning a large magnitude flood would be required to cause significant disruption. Additionally, it is likely that the impacts of fluvial flooding on emergency response are limited at lower magnitudes when compared to surface water flood events of similar magnitude. This is because the spatially concentrated footprint of fluvial flooding surrounds watercourses, meaning disruptions are more confined and less widespread. The assessment suggests that emergency responders operating within Leicester are resilient to fluvial flood events of low to medium magnitude, with such events having limited impact on emergency response times and accessibility

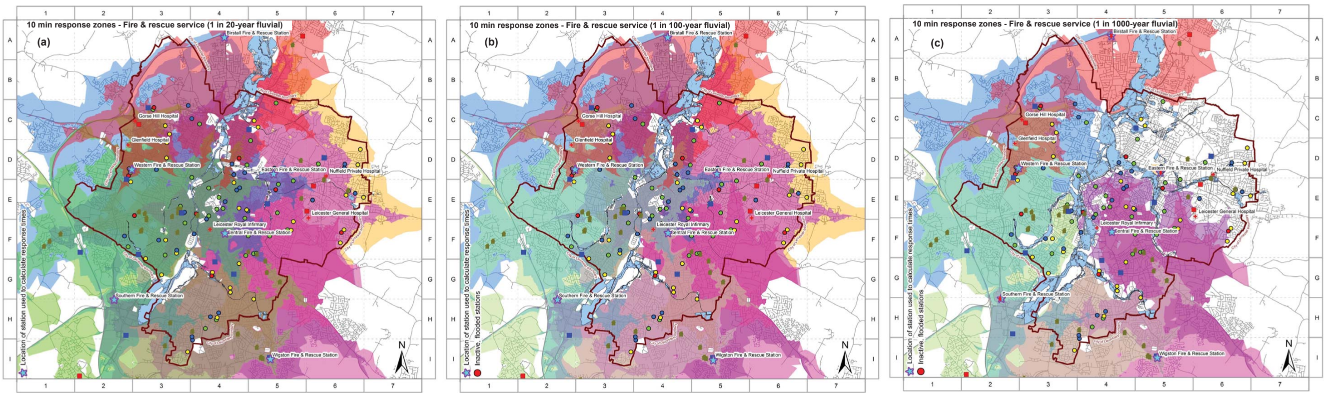

Figure 12. City-scale accessibility (within a 10 min time frame) for fire and rescue service stations under **(a)** 1 in 20-year, **(b)** 1 in 100-year and **(c)** 1 in 1000-year fluvial flooding scenarios. Refer to the key in Fig. 6.

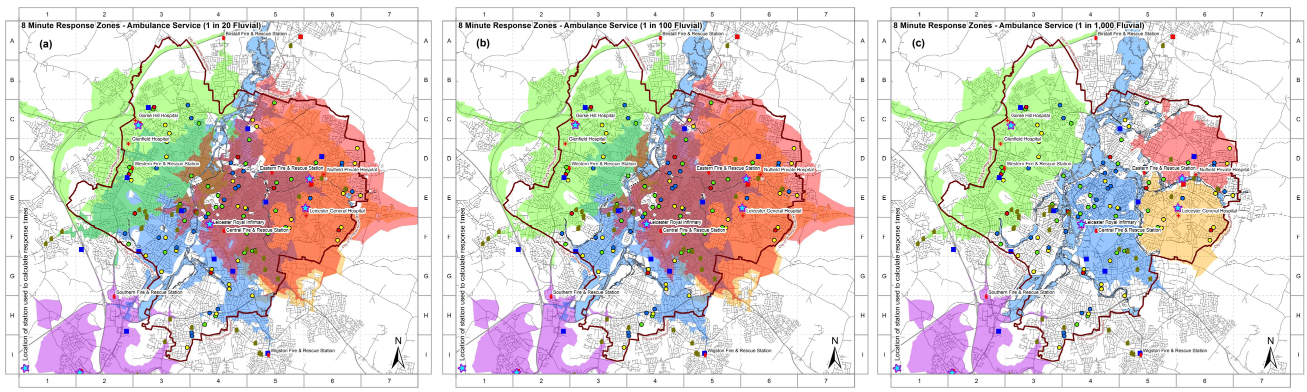

Figure 13. City-scale accessibility (within an 8 min time frame) for ambulance service stations under **(a)** 1 in 20-year, **(b)** 1 in 100-year and **(c)** 1 in 1000-year fluvial flooding scenarios. Key access roads referred to in the text are within grid reference E4 in **(c)**.

across the city. However, the 1 in 1000-year (Fig. 12c) fluvial flood scenario was shown to significantly impact emergency response and accessibility, with some stations becoming compromised by floodwaters. The fire and rescue service scenario suggested that the Eastern Fire and Rescue Station would be severely impacted by fluvial flooding from Willow Brook, resulting in the station only being able to respond to localised incidents, similar to the situation depicted in Fig. 9. Additionally, the ambulance service scenario suggested that Leicester Royal Infirmary would be inundated by floodwaters, rendering the hospital's ambulance station inoperable, and large areas in the north, north-east, south and south-east of the city would become inaccessible within an 8 min response time (Fig. 13). Furthermore, the 1 in 1000-year fluvial flood scenarios show a partitioning of the city into two separately functioning entities divided into east and west along the River Soar, where emergency resources would be unable to be exchanged by road because of key access roads crossing the River Soar (e.g. the A-roads surrounding Frog Island are the A47, A50, A6) becoming blocked with floodwaters.

3.3 Temporal evolution of accessibility through a surface water flood event

The sections above show a static representation of emergency response under maximum flood depths. However, it is also likely that the accessibility of emergency responders operating at a city scale during flood conditions may evolve through the duration of a flood event. It is likely that accessibility will change between 0 h, when no disruptions are present (i.e. no-flood conditions), and the maximum extent of floodwaters (outlined in the surface water flood scenarios above). Therefore, emergency response accessibility may change over time as the city's road network is compromised.

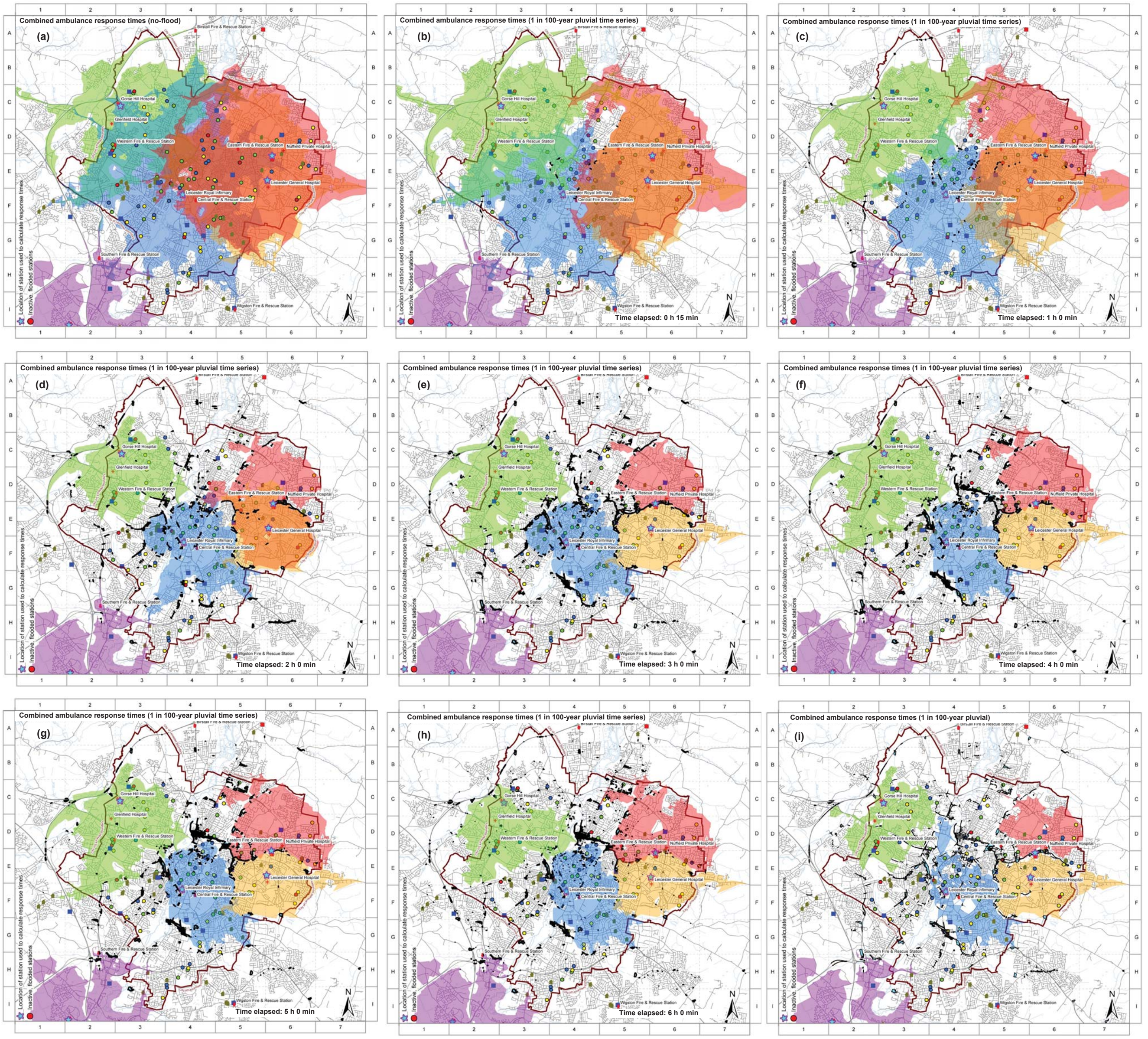

Figure 14. Combined ambulance service response zones during a 1 in 100-year surface water flood event. **(a)** No-flood conditions prior to the flood event, **(b)** 0.25 h, **(c)** 1.0 h, **(d)** 2.0 h, **(e)** 3.0 h, **(f)** 4.0 h, **(g)** 5.0 h, **(h)** 6.0 h, at the end of the rainfall event and **(i)** static maximum flood depths recorded during the event. Refer to key in Fig. 7. Please see the Supplement for an animated version of Fig. 14.

To further understand the temporal evolution of accessibility during a surface water flood event, the ambulance service 8 min response during a 1 in 100-year flood event was examined. Surface water flood depths were extracted at multiple points in time throughout the flood event (namely 0, 0.25, 1, 2, 3, 4, 5, 6 h and the maximum flood depths that were recorded during the design rainfall event; Fig. 2). Next, surface water flood depths were processed into flood restrictions and inputted into the ambulance service response model. Figure 14 shows the temporal evolution of ambulance 8 min response zones throughout a 1 in 100-year surface water flood event.

Results from the temporal inundation modelling demonstrate that the influence of flooding on emergency response is dynamic through a surface water flood event. Rapid onset impacts are witnessed within the first 15 min of the event, with service coverage overlap within the city centre being shown to reduce. Goodwood, Leicester Royal Infirmary, Gorse Hill and Leicester General Hospital stations are all shown to experience a reduction in their service areas, and overlap between station coverage is shown to decrease very early on during the flood event. Notably, the model predicts that inundation extent over the depth threshold value increases (> 25 cm) dramatically between 1 and 2 h, affecting many of the primary access routes around the city and causing ambulance accessibility and service coverage overlap to decrease considerably. Because surface water flood events are often unpredictable and have short lead times, this highlights the requirement for emergency responders to be aware and prepared for rapid-onset flood events.

4 Conclusion

Under normal operating conditions, both emergency services considered were shown to reach the majority of the city (100 and 89 % for fire and rescue services and ambulance services respectively) within the legislated response times for Red 1 incidents (8 or 10 min), suggesting that the stations are strategically situated to provide efficient response during an emergency. In addition, there is sufficient overlap in the polygonal response zones of each emergency responder station, indicating a degree of resilience if one station was unable to respond due to being occupied with another emergency situation. However, when surface water and fluvial flood situations of different magnitudes are introduced into the model, wider ramifications of localised flooding on city-scale emergency response times become apparent. Specifically, surface water flood mechanisms are shown to exert significant disruption to emergency response due to floodwaters (i) being spatially distributed and widespread across the city; (ii) having areal extents and depths that are sufficient to cause restrictions to road users, even at lower magnitudes, and (iii) occupying many of the key access routes (i.e. primary A-roads) and critical areas needed to traverse the city road network.

In contrast, the impacts of fluvial flooding on emergency response are limited, especially for lower-magnitude events. This is principally due to the spatially concentrated nature of the fluvial inundation footprint in the city, and the large channel capacity of the River Soar and its associated tributaries. The River Soar running through the city centre was engineered into a linear compound channel with a large channel capacity, meaning that high flood flows are conveyed rapidly and efficiently downstream and beyond the city boundaries. Bridges and overpasses built over watercourses in the city are generally higher than the bank full channel capacity, thus allowing the transport network surrounding the River Soar to continue to be operational under small to medium flood events. Under fluvial flood conditions, the key risk to emergency responders is the direct flooding of emergency responder locations, resulting in the stations becoming inoperable. This is apparent in the 1 in 1000-year flood scenario when the Goodwood Ambulance Station and the Eastern Fire and Rescue Station become compromised by floodwaters (Figs. 12c and 13c).

Findings suggest that it is important to ensure that primary access locations within the city road network, predominantly the higher-hierarchy roads (e.g. A-roads identified in the analyses above) are kept restriction free, and specific effort should be focused on ensuring that these locations do not become blocked. Furthermore, the ambulance service should ensure that they are situated at strategic stand-by points during flood conditions to minimise the impact of a blocked road network on delaying emergency response to vulnerable locations.

Although findings indicate that Leicester's emergency service could be under pressure during certain flood scenarios when responding to high-priority incidents, the modelled response times are considered conservative since congestion and behavioural factors were not incorporated in the analysis. As such, travel times during flood events of the presented magnitudes may be greater and emergency responders may encounter forms of disruption that the model is unable to represent. Further work could seek to incorporate traffic modelling and consider human behaviour, although this may prove difficult to assess without congestion data available during observed flood events. Additionally, the analysis conducted does not consider future climatic changes in precipitation regimes that may result in the occurrence of more frequent and severe flood events resulting in a more impacted emergency response (Wilby et al., 2008; Whitfield 2012; Kendon et al., 2014; Watts et al., 2015). Moreover, although the use of accessibility maps based on Environment Agency and local council flood hazard return periods can be useful, particularly for planning purposes, their utility in flood emergencies can be limited due the spatial and temporal heterogeneity of rainfall distribution, which may differ between flood events. Further study may be directed at coupling nowcast meteorological data (e.g. radar, rain gauge or river flow data) with city-scale hydrodynamic inundation models to provide real-time flood restriction data for the network analysis framework. This could be used to inform operational response and decision making during actual flood events. Additionally, future work could be undertaken to assess the impact of flood events (or other natural hazards, such as tsunamis, landslides, wildfires, bridge closures or collapses, etc.) on vulnerable infrastructure nodes (such as emergency centres or nursing homes) to develop contingency plans and/or analyse site preparedness for flooding (Liu et al., 2016). Although vulnerability analyses were conducted as part of this study using care homes as indicators of high densities of vulnerable persons, the data could only be communicated internally to project partners due to confidentiality of data. Thus, vulnerability analyses have been excluded from this paper, but they offer an effective method of communicating indirect flood risk to vulnerable people and locations.

5 Data availability

The Ordnance Survey ITN dataset used to represent the transport network in the modelling framework and the base mapping layers used in this study were downloaded through the Edina Digimap (2016) data repository (https://digimap.edina.ac.uk/os).

Flood restriction data inputted into the Network Analyst model can be obtained from the UK Government (2016) data repository (https://flood-warning-information.service.gov.uk/long-term-flood-risk/map?map=Reservoirs). High-resolution surface water flood outputs and associated files (e.g. input precipitation, distributed roughness data, national receptors database) can be requested for the city of Leicester (Leicester City Council, 2012) (http://www.leicester.gov.uk/media/178251/swmp-main-report.pdf), but similar UK-wide surface water maps are freely available from the the UK Government (2016) data repository.

The Supplement related to this article is available online at doi:10.5194/nhess-17-1-2017-supplement.

Competing interests. The authors declare that they have no conflict of interest.

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