Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-309, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 28 September 2016

Natural Hazards and Earth System Sciences
Discussions

Flood Impacts on Emergency Responders Operating at a City-Scale

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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-minute legislative targets for emergency provision for the Ambulance and Fire & Rescue services respectively under 'normal', no flood conditions, as well as flood scenarios of various magnitudes (namely the 1 in 20 year-, 1 in 100-year and 1 in 1,000-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 & Rescue 10-minute 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 1,000-year surface water flood scenarios respectively. Furthermore, total inaccessibility was shown to increase with flood magnitude, increasing from 6.0 % to 31.0 % under the 1 in 20-year and 1 in 100-year surface water flooding scenarios respectively. Further, the evolution of emergency service accessibility through a surface water flood event is outlined, demonstrating the rapid onset of impacts on emergency service accessibility within the first 15-minutes of the surface water flood event, with a reduction in service coverage and overlap being witnessed for the Ambulance service under 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 and provides a readily transferable method to explore the impacts of natural hazards or disruptions on additional cities or regions based on historic, scenario-based events or real-time forecasting if such data is available.

Key words: Surface water flooding, fluvial flooding, emergency response, network analysis, inundation modelling, emergency planning, accessibility, GIS, transport modelling.

1 Introduction

Floods are one of the most significant natural hazards, affecting 116 million people globally, causing approximately 7,000 deaths and damages in the region of $7.5 billion annually (UNESCO 2010). Within the UK, the Environment Agency (2009) estimated that five million people (one twelfth of the UK population), occupying 2 million properties are currently at risk from coastal, fluvial or surface water flooding. Following the Pitt Review (2008), the Environment Agency produced UK-wide surface water flood hazard maps, as well as identifying and assessing flood 'hotspots' which are 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 which extend beyond the area experiencing inundation. Indirect impacts relate to a series of interconnected or related infrastructural failures which 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 & Rescue services) and the transportation networks which connect these services are also susceptible to flooding (Douglas *et al.* 2010; Andersson and Stålhult 2014). Therefore, inundation may result in spatially diffuse consequences which are often difficult to measure and are perceived as of lesser importance 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 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), which may be required to respond to emergency calls during flood events.

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

Working to 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 MAFP requires the key operational and stakeholder organisations (e.g. Fire & Rescue Service, Ambulance Service, City Council and Police) to provide efficient and functional services during flood conditions collectively. This, to a large extent, depends on the continued functioning of critical infrastructure nodes and networks pertinent to flood emergency planning and response, including vital services such as Fire & Rescue stations, hospitals, telecommunication networks and the transit network (Dawson *et al.* 2011; Lumbroso et al. 2011; Wilby and Keenan 2012; Bosher 2014). Emergency responders in the UK are required by legislation to conform to strict timeframes in which they must respond to incidents. For example, Ambulance and Fire & Rescue services are required to reach 75 % of 'Red 1' incidents in less than 8 and 10 minutes respectively from when the initial report was logged. These include incidents which may elicit high priority blue light responses such as cardiac arrest, life-threatening/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 demonstrating 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' whereby 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; *(i)* '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 One emergency responders, to navigate during flood events.

This paper describes a novel approach to evaluate and forecast 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 One responders, namely the Leicestershire Fire & Rescue Service and the East Midlands Ambulance Service.

2 Methodology

2.1 Case Study Area

Leicestershire, including the City of Leicester, UK (Fig. 1), has experienced a history of localised flooding (Shackley *et al.* 2001) with council records indicating that annual fluvial flood damages amounted to ~£90k 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 4,215 settlements assessed within England in terms of surface water flood risk (Defra 2009) and the Environment Agency estimating that approximately 36,900 properties in Leicester's principle urban area occupying 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 which 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 1,800 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 minutes, 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 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 have 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. These have been important in informing flood planning and instigating flood management efforts within the City but have focused largely on the direct impacts of flooding in the City and have not studied the indirect impacts of flooding, for example, on the emergency response and accessibility.

2.2 Data Collation

2.2.1 Road Network and Critical Infrastructure

The City of Leicester's transport network was represented using Ordnance Survey Integrated Transport Network (ITN) data, which, in addition to including the road network geometry and routing, included metadata which outlined standard road restrictions which may inhibit or delay the traversing of a vehicle across a specific section of road. 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 was available for the City of Leicester from Leicestershire County Council, congestion data was not used due to uncertainties associated with how human behaviour and patterns of congestion may differ under flood conditions when compared to normal conditions in which the traffic data was based on. Furthermore, emergency vehicles are able to bypass the majority of congestion when responding to incidents which elicit a blue light response. Still, because congestion data was not implemented into 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 and Ambulance and Fire and Rescue stations. Six Fire & 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 the City of Leicester's emergency response times for Ambulance and Fire & 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 1,000-years were assessed.

City-wide surface water inundation depth data were obtained from Leicester City Council, conducted as part of Leicester's Surface Water Management Plan (2012). The modelling involved applying spatially uniform precipitation associated with specified return periods, namely 1 in 20-, 1 in 100- and 1 in 1,000-year, calculated for design storm hyetographs of six-hour 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/vegetation etc.) were applied in the modelling process. The modelling included a uniform drainage rate of 12 mm/hr to account for drainage/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 was used as flood hazard is a function of flood depth (m), velocity (m/s) and the debris potential; all factors which could inhibit a vehicle passage through floodwaters. The flood hazard data used consisted of four categories (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 which is dangerous to all.

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 AA (2014) recommended that regular motorists (i.e. small/medium cars) should avoid driving through flood waters ≥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. surcharged drains or large debris) which could prevent vehicles from successfully traversing floodwaters. Despite this, emergency vehicles have a greater tolerance to travelling through flood waters than standard vehicles.

Semi-structured interviews conducted with Leicestershire Fire & Rescue Service found that water depths of approximately 25 cm may be suitable to travel through during an emergency situation. Therefore, a threshold water depth of 25 cm was set for the surface water flood scenarios, with water depths <25cm being removed as restrictions and water depths ≥ 25 cm being treated as restrictions to the flow of traffic along a specific road section.

Surface water flood depths ≥25cm were then processed to remove additional polygons which did not overlap or intercept with the ITN and would not be used for analyses (i.e. in areas which would not affect network routing as 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 10m^2 in area which would likely be traversable; and *(ii)* artefact inundated areas over raised transport features such as bridges and bypasses which may not have been correctly represented in the Digital Elevation Model (DEM). Pre-processing 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 25cm under the three flood magnitude scenarios; 1 in 20-year, 1 in 100-year and 1 in 1,000-year.

To create fluvial inundation restrictions, all fluvial flood hazard categories with the exception of the 'low' flood hazard category were treated 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 based on the description (Section 2.2.2.2). Category One 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 so flood hazard ratings of 'moderate' and above were treated as restrictions within the modelling undertaken. 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 1,000-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 as 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 (e.g. a length of arterial road with a lower speed restriction of 20 mph) than a longer route (e.g. a motorway with a speed restriction of 70 mph).

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 specific vehicle depending on its use, load and type (e.g. taxi, bus, wide-load HGV, emergency vehicles, hazardous/dangerous loads etc.) was set to 'emergency vehicles' to reflect the motoring regulations which emergency vehicles are exempt from during blue light response.

Basic origin to destination 'A to B' routing between two points and response zone calculation was undertaken for key Fire & 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 & 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 re-calculated to understand the specific impact of flooding upon an origin to destination routing. Next, to calculate polygon response zones of emergency responders, relevant nodes (i.e. Fire & Rescue stations, ambulance stations and hospitals) identified from the National Receptors Dataset were treated as 'facilities' within an ArcGIS Network Analysis framework. Using these facilities as starting points for vehicle routing, polygon response zones highlighting all road network locations lying within a 10-minute (Fire & Rescue) or 8-minute (Ambulance) radius were calculated for each individual station, based on legislated response timeframes 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 inputted into Network Analysis and the response polygons could be re-calculated 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 Western Fire & Rescue station and St. Andrew's Methodist Church, an evacuation centre within a close proximity to Western Fire & Rescue station was calculated. Figure 5a highlights the modelled quickest route under normal conditions when no flood restrictions were present, demonstrating that Fire & Rescue services responding from Western station would be able to reach the destination within a 5-minute timeframe, 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 minutes (+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 minutes (+200 %; Fig. 5c) under a uniformed scenario, where impassable floodwaters are encountered by responders en-route. This demonstrates the potential impacts which 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 across a disrupted road network, resulting in affected individuals being at greater risk (Arkell and Darch 2006). Furthermore, the importance of preparedness is shown to be of critical importance, as emergency responders may be able to respond more rapidly if up-to-date information on the extent of flood-related network restrictions is available.

3.2.1 Zonal Response: No Flood Conditions

The network analysis undertaken suggests that Leicestershire Fire & Rescue Service (LFRS) would be able to reach 100 % of the City road network within 10-minutes when operating under normal conditions (i.e. no flooding or disruptions present), meeting the 10-minute legislative timeframe (Fig. 6). Furthermore, significant areas of the City are shown to be within a 10-minute response zone from one or more Fire & Rescue stations as there are numerous areas across the City where overlaps in station coverage exist. This indicates that the Fire & 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 East Midlands Ambulance Service (EMAS) under an 8-minute 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 minutes or less (Table 1; Fig. 7). Areas that were predicted to be unreachable within an 8-minute timeframe were mostly situated around the City boundary. However, unlike the Fire & Rescue service which are more dependent on remaining at their stations between incidents (e.g. due to requiring different personal protective equipment [PPE] 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 which 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.

3.2.2 Impact of Surface Water Flooding

3.2.2.1 Fire & Rescue Service

When restrictions derived from the 20-year surface water flood scenario were incorporated into the model, the Fire & Rescue service was shown to experience a 34 % reduction in service coverage, resulting in 66 % of the road network being accessible in 10-minutes 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 southwest of the City appear to be inaccessible within a legislated 10-minute timeframe due to key access roads (e.g. A5460, A563 and M1 motorway) surrounding Southern Fire & Rescue station experiencing floodwaters overlaying the ITN resulting in a reduction in service coverage (Fig. 8a). Additionally, ITN blockages along primary access roads, including New Parks Way (A563) by Hinkley Road Roundabout and the A47 result in Western and Central Fire & Rescue stations becoming unable to access areas located within the southwest of the City. Moreover, 6 % of the City area was predicted to be completely inaccessible or ‘islanded’, either due to flood water 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 39 % of the City would be accessible within 10 minutes 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 Eastern and Southern Fire & Rescue stations as these stations would be directly or indirectly affected by a flood event of this magnitude; Eastern Fire & 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 (Fig. 9), while Southern Fire & 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 & Rescue stations would focus resources on ensuring that these facilities were functioning efficiently. However, it is possible that Eastern and Southern Fire & Rescue stations 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 1,000-year surface water flood scenario, the model predicted that almost ¾ of the City would be inaccessible to the Fire & Rescue service within a 10-minute timeframe, with 26 % of the City being accessible by the Fire & Rescue station in under 10 minutes (Table 1; Fig. 8c). Additionally, 31 % of the City was predicted to be completely inaccessible to Fire & Rescue service using the City's road network. Therefore, other means of transport (e.g. foot, boat or air) would be required to access large areas of the City. Moreover, under this extreme flood scenario, Eastern and Southern Fire & Rescue stations would be fully compromised by floodwaters, hence inactive so 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 & Rescue station coverage under a 1 in 1,000-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 due to inundation.

3.2.2.2 Ambulance Service

When flood restrictions were introduced into the Ambulance service response model, high-priority response coverage in 8-minutes or less was shown to decrease with an increase in flood magnitude in a similar manner to the Fire & Rescue service response. Over half of the City (51 %) was projected to be accessible in 8-minutes 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 1,000-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 under 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 a 1 in 20-, 1 in 100- and 1 in 1,000-year surface water flood scenarios respectively (Table 1).

3.3 Impact of Fluvial Flooding

When compared to the surface water flood scenarios, incidences of fluvial flooding within Leicester were shown to exert minor impact on emergency response under the 1 in 20- (Fig. 12a) and 1 in 100-year (Fig. 12b) fluvial flooding scenarios, with Fire & Rescue and Ambulance service emergency response only becoming significantly impacted under an extreme, 1 in 1,000-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 have been hard 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 due to the spatially concentrated footprint of fluvial flooding surrounding watercourses, meaning disruptions are more confined and less widespread. The assessment suggests that emergency responders operating within the City of Leicester are resilient to fluvial flood events of low to medium magnitude, with such events having limited impact on emergency response times and accessibility 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 & Rescue service scenario suggested that Eastern Fire & 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. 8, while 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 becoming inaccessible within an 8-minute response time (Fig. 13). Furthermore, the 1 in 1,000-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; A47, A50, A6) becoming blocked with floodwaters.

3.4 Temporal Evolution of Accessibility through a Surface Water Flood Event

The above sections show a static representation of emergency response under maximum flood depths. However, it is also likely that the accessibility of emergency responders using a City's road network during flood conditions may evolve through the duration of the flood event, from 0 hours where no disruptions are present (i.e. no flood conditions), to the end of the rainfall event where the maximum flood depths, as outlined in the surface water flood scenarios above, are experienced and emergency response is compromised.

To further understand the temporal evolution of accessibility through a surface water flood event, the Ambulance service 8-minute response under a 1 in 100-year flood event was examined. Surface water flood depths were extracted at multiple points in time through the flood event (namely 0hrs, 0.25hrs, 1hrs, 2hrs, 3hrs, 4hrs, 5hrs, 6hrs and the maximum flood depths 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-minute response zones through 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 minutes of the event, with service coverage overlap within the City centre being shown to be reduced. 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, very early on during the flood event. Notably, the model predicts that inundation extent increases dramatically between 1 and 2 hours, 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 & Rescue and Ambulance services respectively) within the legislated response times for 'Red 1' incidents (8- or 10-minutes), 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 which 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 associated tributaries. The River Soar running through the City Centre has been hard-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, which is apparent in the 1,000-year flood scenario when Goodwood Ambulance station and Eastern Fire & Rescue station become compromised by floodwaters (Fig. 12c & 13c).

Findings suggest that it is important to ensure that primary access locations within the City's road network, predominantly the higher hierarchy roads (e.g. A-roads identified in the above analyses) are kept restriction free and specific effort should be focused on ensuring that these locations do not become blocked. Furthermore, the Ambulance service could ensure that they are situated in 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 the City of Leicester's emergency service could be under pressure during certain flood scenarios when responding to high-priority incidents, the modelled response times are considered to be conservative as 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 which 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 Environment Agency and local council flood hazard return period based mapping of accessibility 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 with city-scale hydrodynamic inundation models to assist operational response and decision making during actual flood events in real time. Additionally, further study could also focus on analysing the impact of flood events (or other natural hazards, i.e. tsunami, landslide, wildfire etc.) on vulnerable infrastructural nodes (i.e. emergency centres or nursing homes) to develop contingency plans and analyse site vulnerability to 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 confidentially of data. Thus, vulnerability analyses have been excluded from this paper but offer an effective method of communicating indirect flood risk to vulnerable people and locations.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

The project was funded by the UK Natural Environment Research Council (*NE/M008770/1*) under its Environmental Risks to Infrastructure Innovation Programme. The authors would like to thank the strong support received from the project partners, Leicester, Leicestershire & Rutland Local Resilience Forum, Leicester City Council, Leicester Fire & Rescue Service, Environment Agency and East Midlands Ambulance Service prior to and during the project, without which this project would have not been possible. In particular, we gratefully acknowledge the support from Martin Fletcher, Nira Sumaria and Chryse Tinsley from Leicester City Council and Garry Mawby from East Midlands Ambulance Service for their contribution to the research undertaken and to AECOM and the Environment Agency for producing the flood data used as inputs for the analyses conducted.

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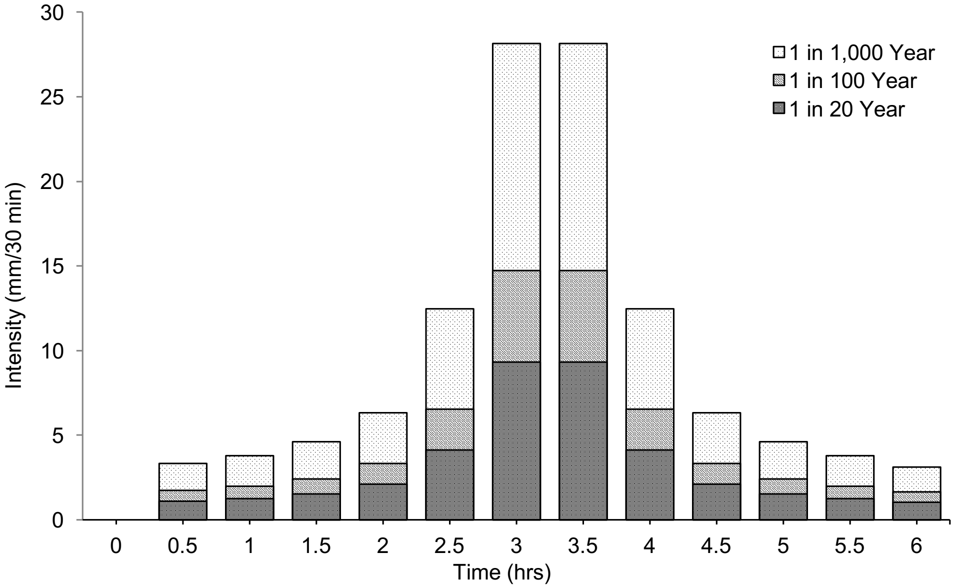
Table 1: Percentage of area accessible to Fire & Rescue and Ambulance Service stations under normal and flood scenarios.

Flood Scenarios	Fire & Rescue Service		Ambulance Service	
	Accessible in 10-minutes	Inaccessible	Accessible in 8-minutes	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 1,000-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 1,000-year Flv	74.3 %	13.8 %	56.0 %	13.1 %

N.B. ‘SW’ = surface water flooding scenarios; ‘Flv’ = fluvial flooding scenarios

570 *Figure 1: Location of the City of Leicester, United Kingdom.*



575 **Figure 2: Design rainfall scenarios for the 1 in 20-, 1 in 100- and 1 in 1,000-year surface water flood modelling conducted by Leicester City Council.**

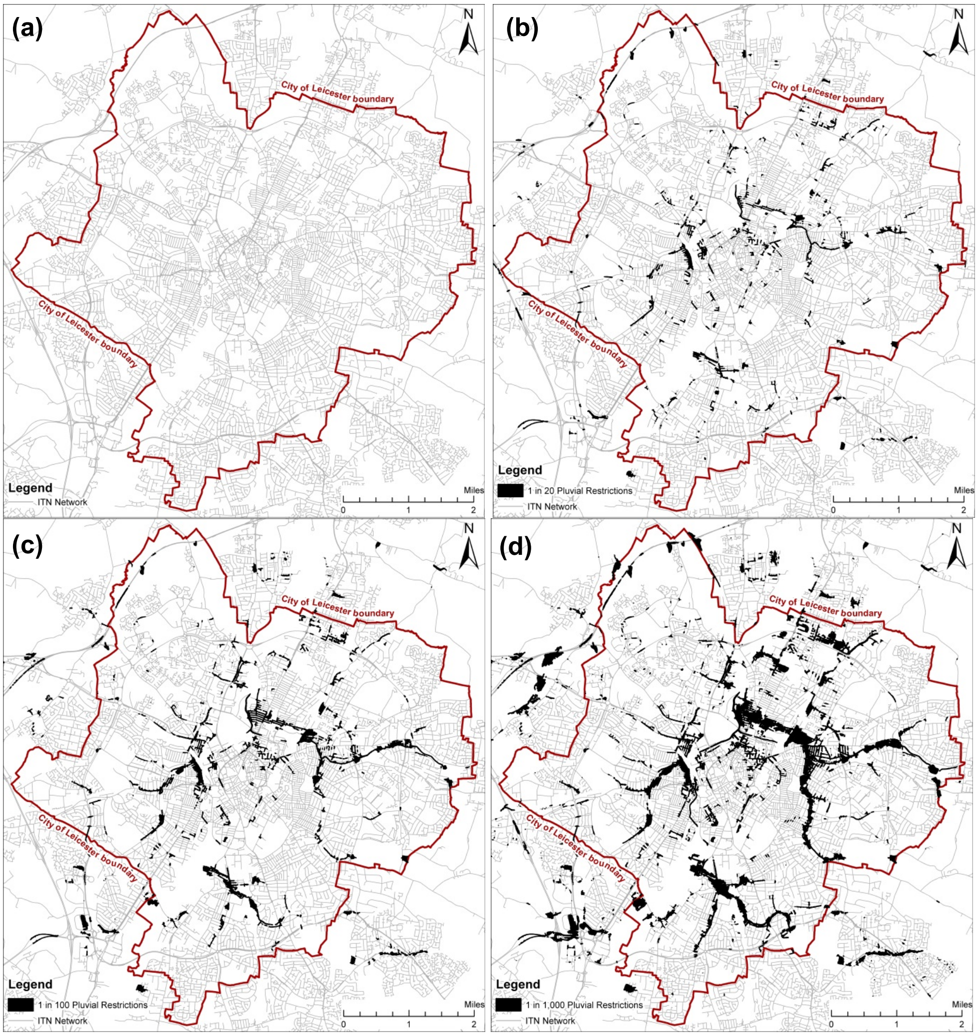


Figure 3: ITN network under: (a) 'normal', no flood conditions, and overlain with restrictions under a: (b) 1 in 20-year, (c) 1 in 100-year, and; (d) 1 in 1,000-year surface water flood scenarios showing the extent of flooding above a 25 cm threshold which intersects the ITN network.

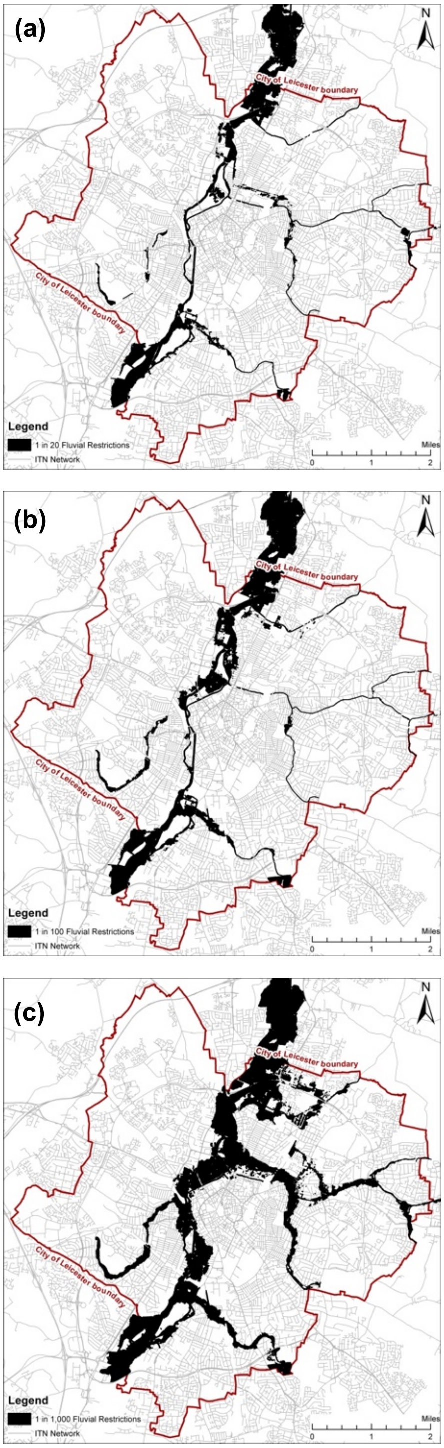


Figure 4: Fluvial flood restrictions under (a) 1 in 20-year; (b) 1 in 100-year; and (c) 1 in 1,000-year scenarios.

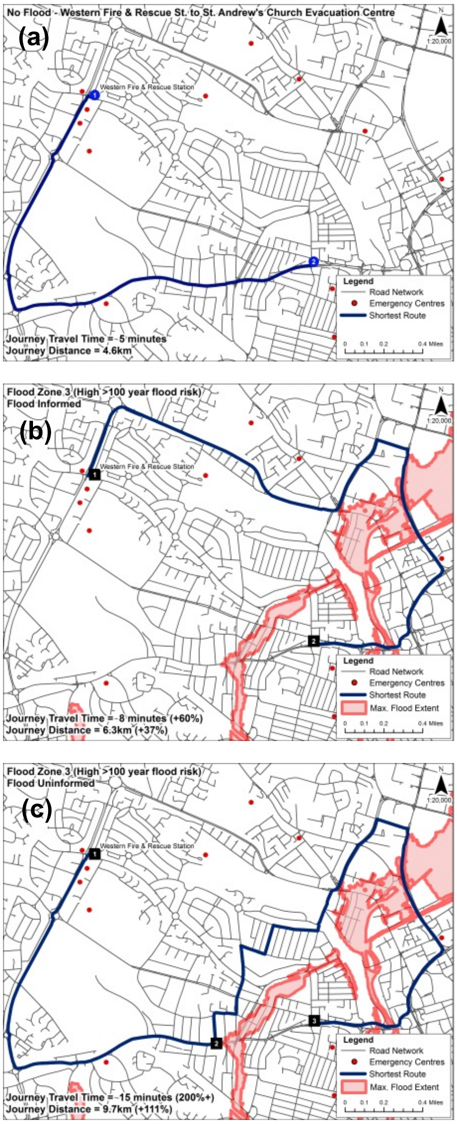


Figure 5: Quickest routing between Western Fire & Rescue Station and St. Andrew's Methodist Church [Evacuation centre; 300 people capacity] under: (a) normal conditions, and; high (>100 year) fluvial flood risk scenarios. (b) shows a prepared and 'informed' scenario whereby fire appliances are aware of network restrictions before responding, whereas (c) shows an 'uniformed' scenario where impassable flood waters are encountered by responders en-route.

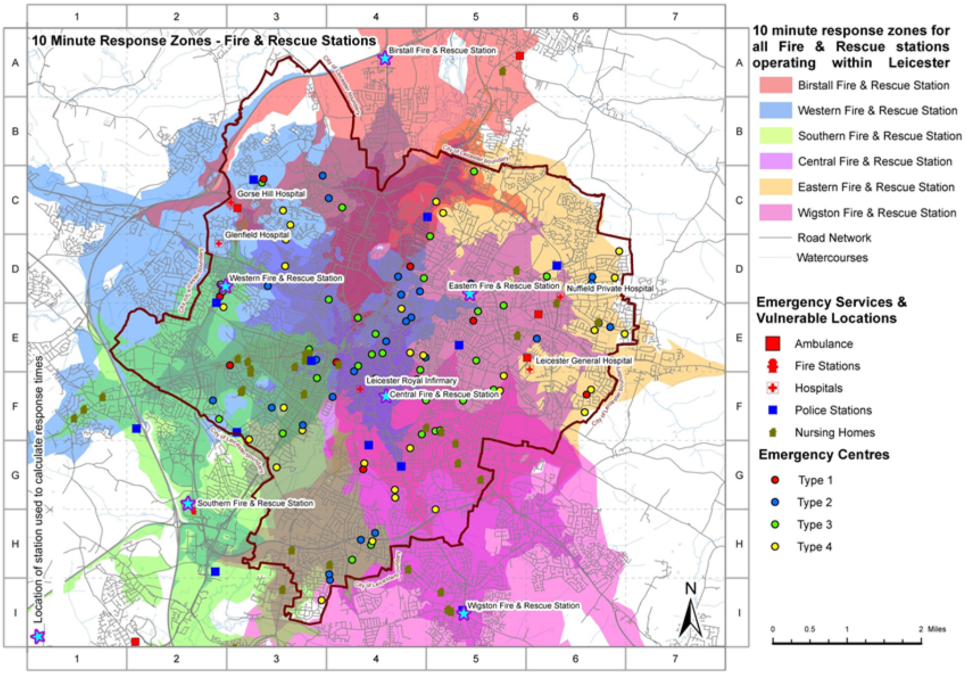


Figure 6: City accessibility (within 10-minutes) for Fire & Rescue Service stations under 'normal', no flood conditions.

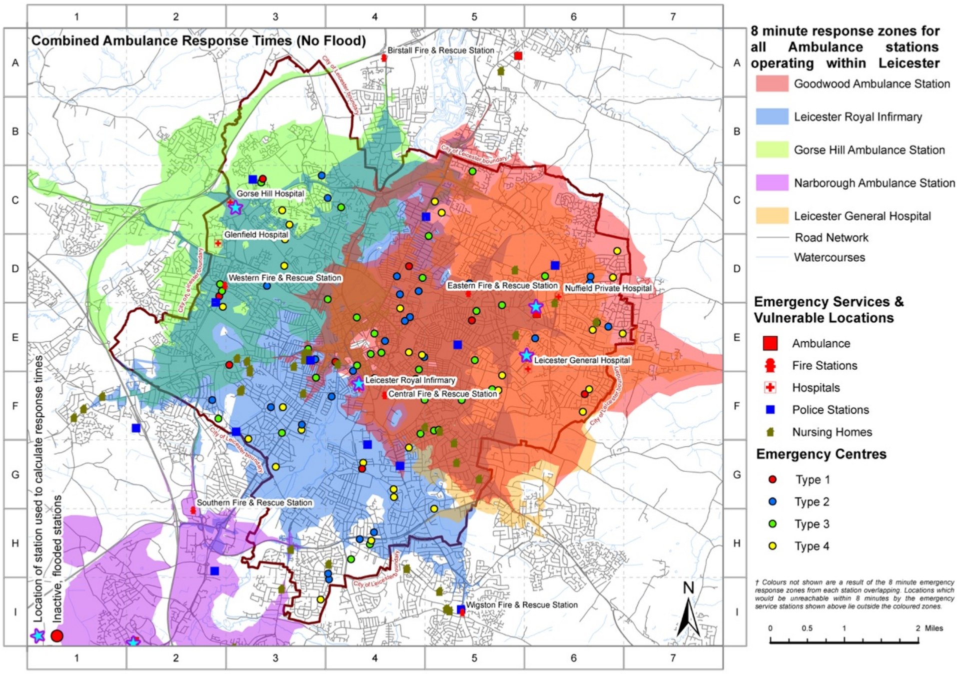


Figure 7: Accessibility of the City (8-minutes) for Ambulance Service stations operating under 'normal', no flood conditions.

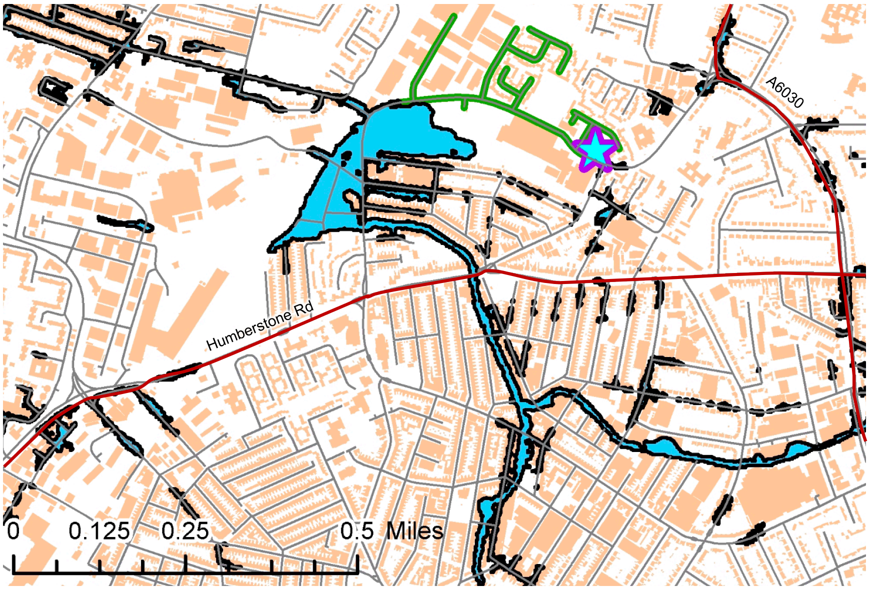


Figure 8: Eastern Fire & Rescue station under a 1 in 100-year flood event shows the surrounding roads experiencing inundation, predominantly surrounding Willow Brook (centre). The green line indicates the accessible road network without mitigation measures. Floodwaters surrounding Willow Brook were removed at the Humberstone Road intercept because a large bridge passed over the Brook. Floodwaters blocking access to the A6030 were also removed as these would likely be pumped.

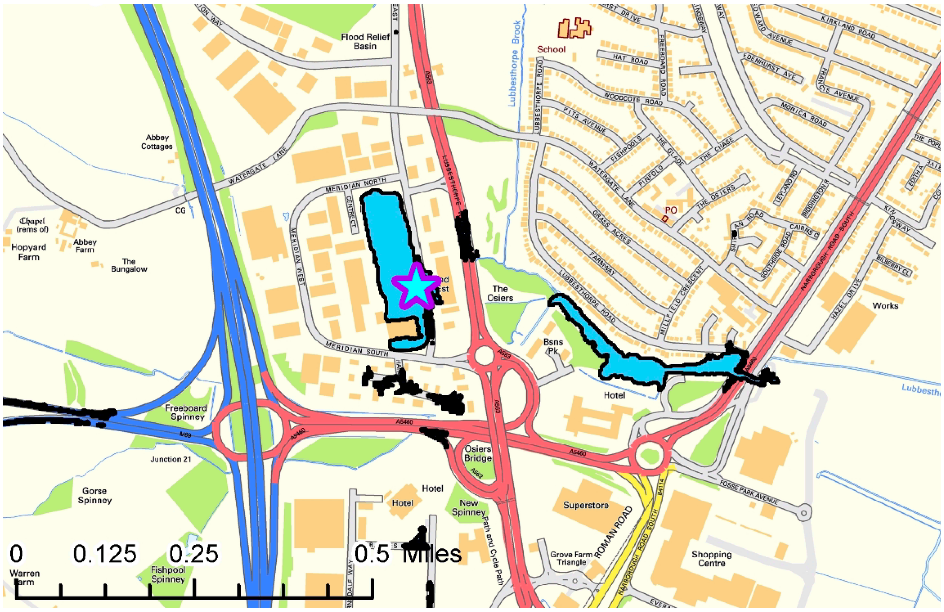


Figure 9: Southern Fire & Rescue station under a 1 in 100-year flood event shows that the station is directly at risk of flooding and if sufficient mitigation measures are not taken during a flood of similar or greater magnitude, functioning of the station could be compromised

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Published: 28 September 2016

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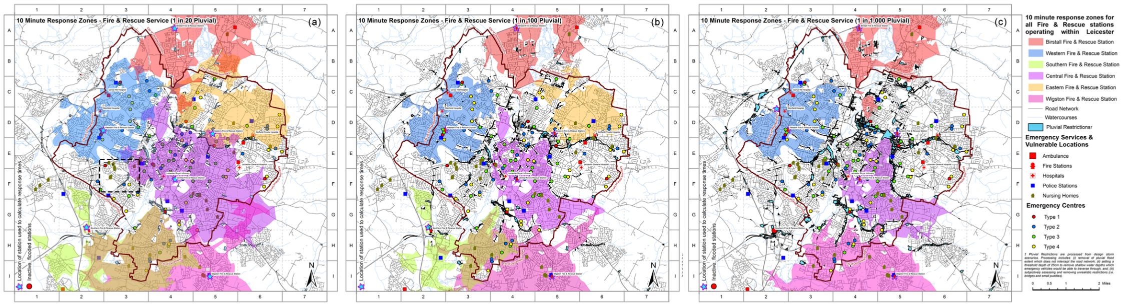

Figure 10: Accessibility of the City (within a 10-minute timeframe) for Fire & Rescue Service stations: (i) 1 in 20-year; (ii) 1 in 100-year, and; (iii) 1 in 1,000-year surface water flooding scenarios. New Parks Lane, referred to in the text, is highlighted in the rectangle in Figure 10a.

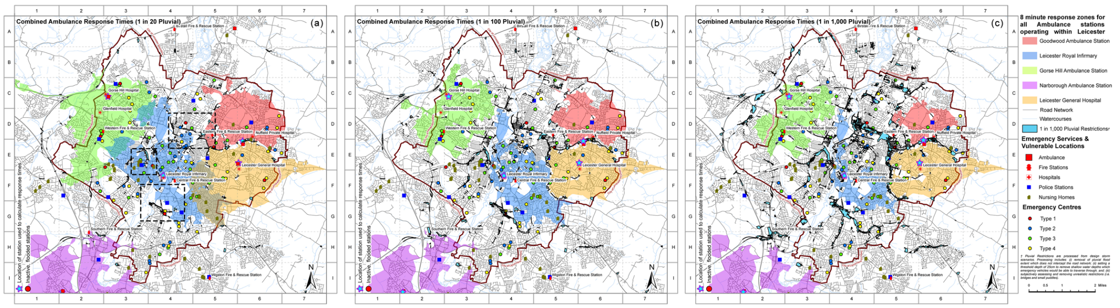

Figure 11: Accessibility of the City (within an 8-minute timeframe) for Ambulance service stations under: (i) 1 in 20-year; (ii) 1 in 100-year, and; (iii) 1 in 1,000-year surface water flooding scenarios. The key access roads referred to in the text are highlighted in the rectangle in Figure 11a.

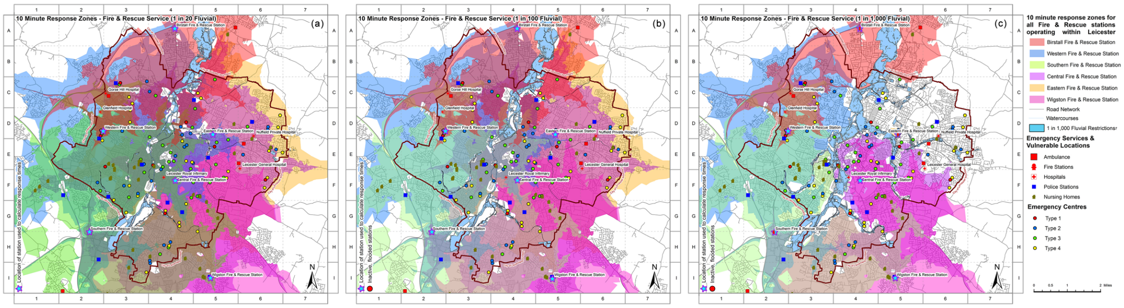

Figure 12: Accessibility of the City (within a 10-minute timeframe) for Fire & Rescue Service stations under: (i) 1 in 20-year; (ii) 1 in 100-year, and; (iii) 1 in 1,00-year fluvial flooding scenarios.

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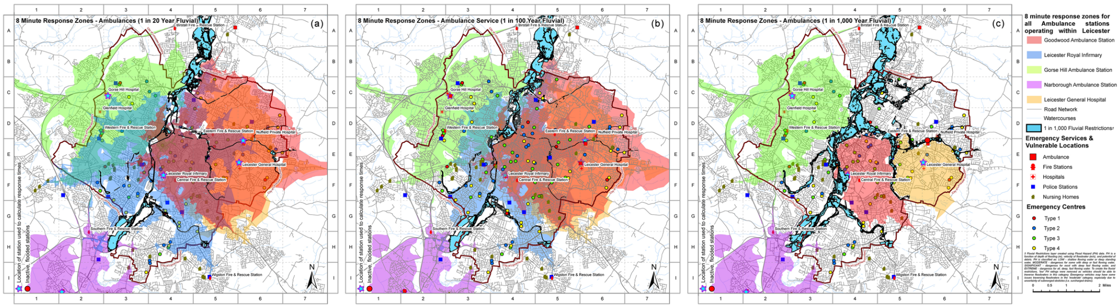

Figure 13: Accessibility of the City (within an 8-minute timeframe) for Ambulance Service stations under: (i) 1 in 20year-; (ii) 1 in 100-year, and; (iii) 1 in 1,000-year fluvial flooding scenarios. Key access roads referred to in the text are highlighted in the rectangle in Figure 13c.

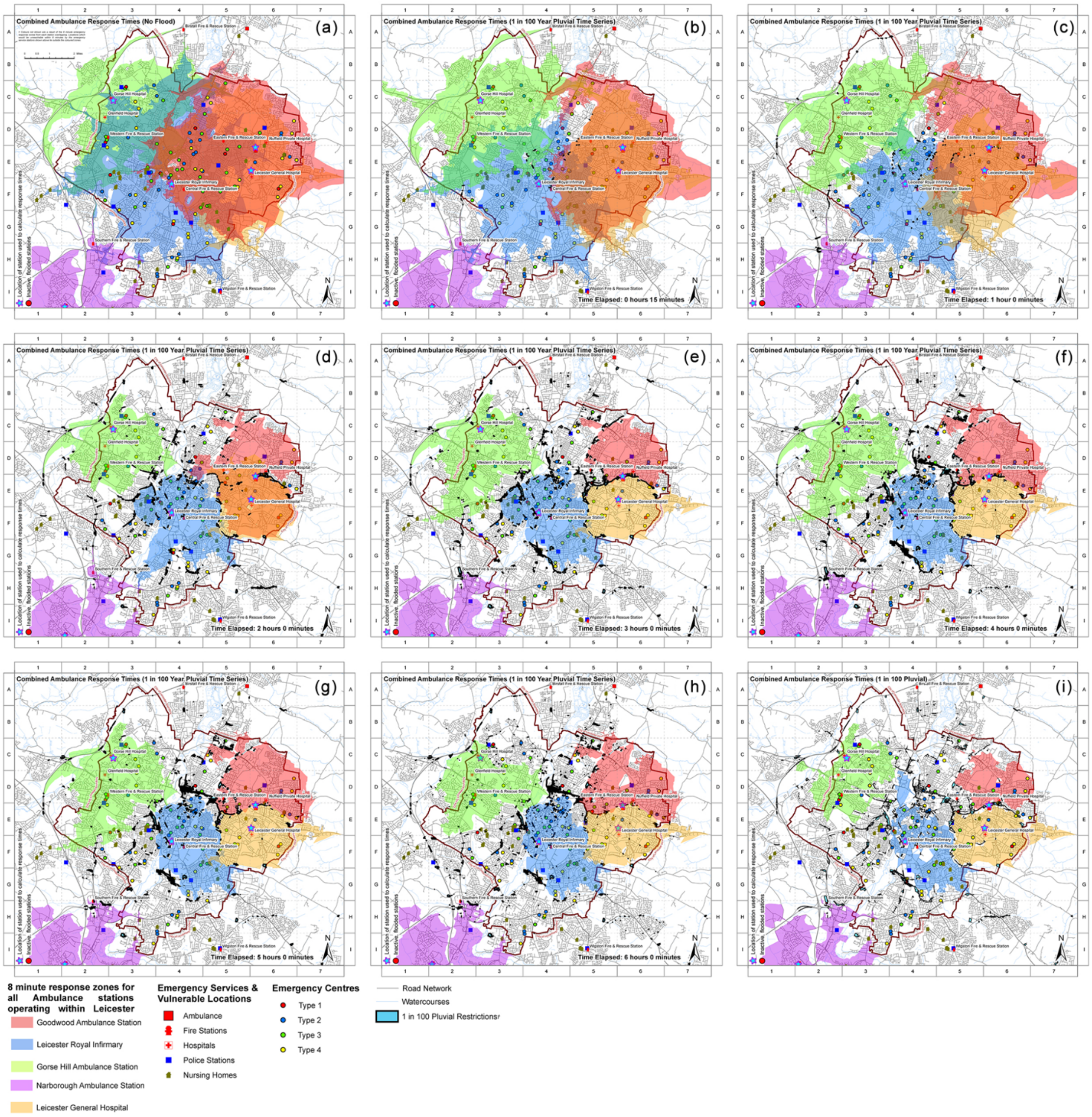

Figure 14: Combined Ambulance service response zones during a 1 in 100-year surface water flood event; (a) No flood conditions, prior to the flood event; (b) 0.25hrs; (c) 1.0hrs; (d) 2.0hrs; (e) 3.0hrs; (f) 4.0hrs; (g) 5.0hrs; (h) 6.0hrs (end of rainfall event, and; (i) Static maximum flood depths recorded during the event.