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Interactive comment on "Flood Impacts on Emergency Responders Operating at a City-Scale" *by* Daniel Green et al.

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In the following response, the comments of the referee are printed in **black** and author replies in **blue**. **Red** text refers to proposed changes to the manuscript text.

1. General comments:

Emergency responder accessibility during natural disaster and extreme weather is a major issue. This paper addresses this problem by proposing a method to evaluate emergency responder accessibility during flood events within the City of Leicester. This is an applied research based on existing tools and datasets. Method is well depicted and can be easily reused.

Thank you. The aim of this research was indeed to work with project partners using existing tools and datasets to assess accessibility during flood events within Leicester. We focus on developing a methodology that is potentially transferrable.

We are glad that you recognise the importance of understanding emergency responder accessibility during

natural disasters and extreme weather conditions and that you also see that the framework could be readily applied to other case studies or locations.

Nevertheless, state of the art concerning accessibility assessment could be more exhaustive in order to improve methodology. Indeed, as the network analysis undertaken did not consider congestion or the impact of traffic, it will be interesting to use more innovative method for assessing accessibility.

Although data on congestion were available for the city (under non-flood conditions), this was not included within the present analyses due to uncertainty about how to implement congestion within the modelling framework (e.g. difficulties in predicting human behaviour and where congestion might occur during flood conditions which has been discussed on Lines 137 – 146).

The word "accessibility" should appear in the title of the paper.

The authors like this suggestion as the paper focuses strongly on city-scale accessibility. The title of the paper has now been revised from "Flood Impacts on Emergency Responders Operating at a City-Scale" to "City-scale Accessibility of Emergency Responders Operating during Flood Events".

2. Specific comments:

2.1 In this research, it is required to assess accuracy of quickest routing calculation. Indeed, using GIS software in order to calculate quickest routing may produce inaccurate results. A comparison between GIS results and quickest routing achieved tanks to reference tools is required. For instance, Google Map give very accurate results, so it will be interesting to assess correlation between GIS results and Google Map results.

Dijkstra's algorithm is a computationally efficient, widely used and accepted algorithm to solve vehicle routing problems and conduct network analyses, which many of the cited publications within the manuscript apply.

The following has been added at Line 221 at the end of paragraph to affirm the use of Dijkstra's algorithm: "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 into the GIS framework, allowing the implementation of weighted restrictions and impedance data contained within the ITN metadata into the network analyses conducted." This now leads nicely onto the following paragraph which discusses vehicle-specific road restrictions.

Regarding using Google Maps to conduct routing, network analyses undertaken within the GIS framework using the Ordnance Survey Integrated Transport Network (ITN) data took into consideration road restrictions and impedances included within the meta-data which allowed routing suitable for emergency vehicles (see Section 2.3.2; line 223). Whereas, Google Maps presumably bases routing on a standard car and does not consider emergency vehicle specific factors such as height or width restrictions. The algorithms used to solve routing by Google in their mapping software are not widely published. Routing is most likely calculated using similar/adapted algorithms (i.e.

Dijkstra's algorithm) but the use of Google Maps by emergency responders is untested.

The routing conducted within our GIS modelling framework uses the Ordnance Survey's ITN data which provides comprehensive information about road typology and routing information to many third-party companies under license. Furthermore, the mobile data terminals within many emergency vehicles in the UK are based on routing solutions using Ordnance Survey ITN data (Ordnance Survey 2008). Ordnance Survey data are regarded as the best available in the UK. ITN data has been widely used in other studies looking at road network efficiency within the UK (e.g. Dawson *et al.* 2011; Pregnolato *et al.* 2016). The data are regularly updated every 6 weeks to ensure information is correct and accurate. The ITN data were thoroughly checked by the authors before use and tested on a number of known routes before the full analysis was executed.

Line 132 has been amended to strengthen the case for use of the ITN data: "The City of 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, included metadata which outlined standard road restrictions which may inhibit or delay the traversing of a vehicle across a specific section of road. The same ITN data is also used in emergency responder control centres and within emergency vehicles to aid navigation to incidents (Ordnance Survey 2008)".

Validation of the quickest routing calculation within the GIS framework is included here for the benefit of the reviewer and readers of the supplementary material but has not been added to the paper because of the amendments made to strengthen the case of using ITN data. However, a comparison with Google Maps provides a form of validation, determining whether the network analysis used within the GIS platform performs satisfactorily.

The route from Western Fire & Rescue Station to a nearby evacuation centre presented in Figure 5a was replicated within Google Maps. The GIS platform predicted that the journey of an emergency vehicle would take 5 minutes and the journey distance would be 4.6 km. Google Maps predicted that journey travel time for a regular vehicle would be 7 minutes (+2 minutes) without traffic and journey distance would remain as 4.6 km. Although both algorithms are realistic in their calculation of journey duration, a journey duration of 5 minutes is more realistic under a 'blue lights' response situation when the majority of traffic can be bypassed.

2.2 Hypothesis about capabilities of emergency vehicles to travelling through flood waters should be validated. Moreover, it would be necessary to take into account velocity and not just the flood depths.

This is a valid point. Velocity and the presence of debris (including submerged debris/obstacles) as well as water depth are all factors that would inhibit emergency vehicles traversing through flooded areas.

The Automobile Association (2014) recommend that regular motorists should not travel through flood waters. However, emergency vehicles have a greater tolerance to flood water than standard vehicles. Therefore, a depth of 25 cm was deemed appropriate and is consistent with the threshold level used in other studies (e.g. HR Wallingford 2006; Dawson *et al.* 2011).

Furthermore, interviews with Leicestershire Fire & Rescue Service confirmed that fire appliances are very resilient and that water velocity at a depth of 25cm (lower than the wheel arch of the appliance) would need to be extremely high to affect the traversing of a 12-tonne fire appliance. Although the risk would be assessed on a case-by-case basis by crew members, the majority of flood waters with a depth of 25 cm could be traversed and, in the case of an emergency situation where loss of life is possible, the risk of damaging an emergency appliance is of secondary concern. Nonetheless, 25 cm could also still be hazardous if the water conceals or obscured other hazards (i.e. open manholes). Recognition of this limitation is included at Line 183 and 208.

Furthermore, surface water flood velocities are likely to be relatively low velocity due to ponding in topographic hollows. Modelled velocities for the most extreme surface water flood magnitude considered (1 in 1,000-year) were typically < 1 m/s.

Future studies could seek to combine numerical modelling outputs of depth and velocity over a specific threshold (e.g. 25 cm depth and 2.5 m/s velocity or greater), or even flood hazard as defined by HR Wallingford (2006). However, in the present study, depth was considered to be a useful first metric for designating road restrictions.

References to previous research applying a depth threshold of 25 cm have been added in the manuscript, along with more justification on the use of the depth threshold value:

"Semi-structured interviews conducted with Leicestershire Fire & 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 tonnes 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 flood waters, modelled flow velocities were typically < 1 m/s due to ponding of floodwaters 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 $\geq$ 25 cm being treated as restrictions to emergency vehicle flow along a specific road section."

2.3 Concerning impact of fluvial flooding, it will be interesting to study the case where bridges are closed, even if they are not flooded. For instance, in France during a 1/100 flood, bridges are generally closed in order to prevent major accident. Indeed, fluvial flooding can weaken the structure of the bridge.

Bridge closure/collapse was beyond the scope of the paper but the methodology could be used for this application in further study. Fluvial flooding can most certainly weaken the structure of a bridge and bridge failure during flood events can be a major issue (e.g. December 2015 UK floods in which a number of bridges failed, such as a bridge crossing the River Wharfe in Tadcaster, North Yorkshire on the 29th December 2015). However, this has not occurred in the City of Leicester before.

Although bridge closure was not considered in the analysis, many of the bridges in the 1 in 100- and all in the 1 in 1,000-year fluvial flood zone became 'inactive' because areas surrounding the River Soar and tributaries were submerged, thus restricting access to some of the bridges in the city.

Bridge closure/failure during natural disasters represents an interesting avenue for further research and may be more applicable in other city contexts. This could be implemented within the modelling framework by adding point blockages on the road network to prevent access to bridges.

Hence, reference is now made to how the methodology could be adapted to understand the impact of bridge closure or collapse in line 446 of the conclusion:

"Additionally, further study could be undertaken to assess the impact of flood events (or other natural hazards, such as tsunami, landslide, wildfire, bridge closure/collapse 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)."

3 Technical corrections:

3.1 Line 65: First sentence of the paragraph should become the last sentence of the paragraph.

This has been amended within the manuscript text.

3.2 Line 67: Multi-Agency Flood Plan (MAFP).

The abbreviation of Multi-Agency Flood Plan (MAFP) has been added.

3.3 Line 129: A map with the 26 surface water flood hotspots will be more interesting than the Figure 1.

The authors agree that a map showing the spatial distribution and extent of the surface water flood hotspots across the city would be a useful addition to the paper. The original Figure 1 (location of the City of Leicester within the United Kingdom) has been inset into a figure showing the distribution of the surface water flood hotspots as suggested. The figure is attached at the end of this document.

3.4 Line 170: You can indicate if a specific tool had been used for the modelling surface. You can also specify that is possible to extract depth at multiple points in time through the flood event.

The TUFLOW model was used by Leicester City Council to conduct high resolution (1 m horizontal, +/- 0.25 m vertical) surface water inundation modelling. This created spatially distributed ASCII files containing depth (m) and velocity (m/s) maps at the resolution of the LiDAR topography data used (1 m horizontal resolution). Only depth was extracted and used for the present analyses.

The following has been added at the beginning of the paragraph to reflect this:

"High resolution (1 m horizontal, $\pm$ 0.25 m vertical), city-wide surface water inundation depth data derived from a hydro-dynamic inundation model (TUFLOW), conducted as part of Leicester's Surface Water Management Plan (2012), were obtained from Leicester City Council. This resource allowed the extraction of spatially-referenced flood depth data at multiple points in time throughout the flood event"

3.5 Line 171 to 174: This paragraph need to be clarified.

This paragraph has now been revised to read more clearly and clarify the use of Environment Agency flood hazard data. A reference to HR Wallingford (2006) has been added, which identifies the equation used to calculate flood hazard.

"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 (m/s) and potential for entrainment of debris within flood waters (HR Wallingford 2006), all factors which 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 which is dangerous to all."

The following section (2.3.1; lines 203 – 211) expands upon this and defines how flood hazard data for the fluvial flood events was processed to create restrictions on the road network.

3.6 Line 180: What is AA?

The AA refers to the British Automobile Association (AA), which provides breakdown cover, insurance and route planning to drivers travelling within the UK. The acronym is now defined in-text and the end of text reference has been updated to reflect this change.

3.7 Line 235: Two paragraphs should be a better choice to allowing readers to well understand than you developed two approaches.

The authors agree that this is a long paragraph and separating this at Line 235 would clarify the difference between the initial A to B (origin-destination) routing and the zonal polygon response zones. This material has now been divided into two paragraphs.

References:

Pregnolato, M., Ford, A., Robson, C., Glenis, V., Barr, S., Dawson, R. (2016) 'Assessing Urban Strategies For Reducing the Impacts of Extreme Weather on Infrastructure Networks', The Royal Society Open Science, 3: 160023.

Ordnance Survey (2008) 'Reducing Response Times', [Online]. Available at: http://webarchive.nationalarchives.gov.uk/20100402134053/ordnancesurvey.co.uk/âĂÍ oswebsite/products/osmastermap/layers/itn/casestudies/terrafix

Dawson, R.J., Peppe, R. and Wang, M. (2011) 'An Agent-Based Model for Risk-Based Flood Incident Management', Natural Hazards, 59(1): 167 – 189.

The Automobile Association (2014) 'Floods and Heavy Rain: Advice from the AA's Flood Rescue Team' [Online]. Available at: http://www.theaa.com/motoring_advice/seasonal/floods-and-wet-weather.html.

HR Wallingford (2006) 'Defra & Environment Agency – R&D Outputs: Flood Risks to People Phase 2, FD2321/TR2 Guidance Document'.

Liu, J., Shi, Z. & Wang, D. (2016) 'Measuring and Mapping the Flood Vulnerability Based on Land-use Patterns: a Case Study of Beijing, China', Natural Hazards, 83: 1545 – 1565.

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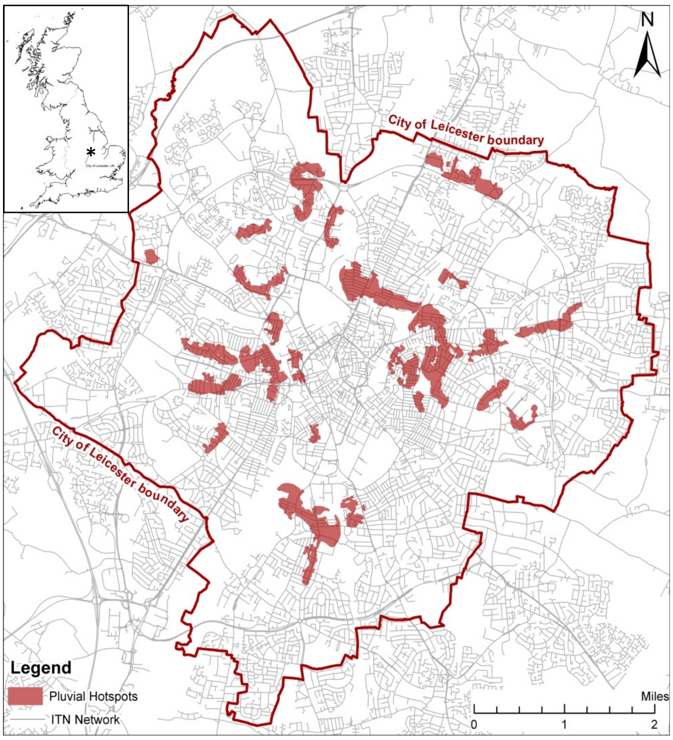

Fig. 1. Distribution of the 26 locations identified as surface water hotspots in the City of Leicester, UK