Disruption of emergency response to vulnerable populations during floods

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Emergency responders must reach urgent cases within mandatory timeframes, regardless of weather conditions. However, flooding of transport networks can add critical minutes to travel times between dispatch and arrival. Here, we explicitly model the spatial coverage of all Ambulance Service and Fire & Rescue Service stations in England during flooding of varying severity under compliant response times. We show that even low magnitude floods can lead to a reduction in national-level compliance with mandatory response times and this reduction can be even more dramatic in some urban agglomerations, making the effectiveness of emergency response particularly sensitive to the expected impacts of future increases in extreme rainfall and flood risk. Underpinning this sensitivity are policies leading to the centralisation of the Ambulance Service and decentralisation of the Fire & Rescue Service. The work provides opportunities to identify hotspots of vulnerability (e.g. care homes, sheltered accommodations, nurseries and schools) for optimising the distribution of response stations and/or developing contingency plans for stranded sites.

Vulnerable groups such as the elderly, young children and people with poor health are disproportionately affected by natural disasters such as flooding (Ngo, 2001; Nick *et al.*, 2009; Walker *et al.*, 2010). One 'adaptation tracking' study (Lesnikowski *et al.*, 2015) examined evidence of policy change between 2010 and 2014 in 41 high-income countries and found no progress in the reported inclusion of vulnerable populations in climate adaptation policy design. Understanding who gains and who loses from climate change impacts (as well as from adaptation policies) is an important step towards resolving potentially disproportionate consequences for vulnerable and disadvantaged populations and the development of more socially-just adaptation measures (Adger, 2006).

In the U.K., Ambulance and Fire & Rescue Services are the primary emergency responders to extreme flood events, during which demands for services often rise significantly. Spikes in demand during major flood events can affect multiple health care facilities simultaneously (Arent *et al.*, 2014), thereby requiring additional 'surge capacity' within health care units (Banks *et al.*, 2007; Hess *et al.*, 2009). Surge capacity should also be considered for emergency responders, factoring in the rising demand and adverse impacts of flooded transportation networks on access to and evacuation of vulnerable population and facilities. However, a prerequisite to considering surge capacity (and indeed other coping strategies for emergency services) is to understand the socio-economic and geographic distributions of vulnerability to service provision (hereafter termed "hotspots"). Such vulnerability is a function of two parameters. First, concentrations of people (e.g. young children or the elderly), or facilities (e.g. nurseries or care homes) where personal circumstances may create barriers to obtaining/ understanding information and/or reacting to flood events compared with the general population (Iowa Department of Public Health, 2009), or where emergency responders become proportionately more critical in providing emergency services; and second, the spatial distribution of emergency responders. Both are non-stationary, for instance, the U.K. has witnessed progressive centralisation of Ambulance Services over recent decades. Flood events have the capacity to change the relationship between these two parameters through both primary impacts (e.g. flood-impassable roads) or secondary consequences (e.g. development of traffic congestion). Climate change may impact the magnitude and frequency of flood events, and so both the primary impacts and secondary consequences, which makes the identification of vulnerability hotspots crucial if emergency response systems are to adapt to future flood risk.

In this paper, we identify vulnerability hotspots within flood-sensitive patterns of emergency services coverage for England. We focus on: (i) three population groups that are most dependent on emergency services during flooding (the elderly, young children and people with very poor health) and (ii) facilities with high concentrations of vulnerable people (care homes, nurseries, schools and sheltered accommodation; Supplementary Information, S1). Quantitative assessment is based on compliance rates against timeframes (Supplementary Information, S2) for reaching incidents of different categories (including life-threatening cases), a key performance indicator for emergency response services in England. Spatial accessibility (Weiss, *et al.*, 2018) to vulnerable populations and facilities is mapped explicitly for every Ambulance and Fire & Rescue station in England, using their mandated timeframes for specified incidents and navigation-grade transport network dataset for routing (see Methods and Supplementary Information, S3). Performance is measured in terms of areal coverage and population that can be reached within given response times, under various authoritative flood scenarios (see Methods and Supplementary Information, S4), compared with no-flood baseline conditions. Specifically, flood vulnerability hotspots for the three population sub-groups, and four types of facilities are identified with the most detailed census data and exact facility locations (over a million points) in England. The analysis reveals the extent to which even low magnitude/high frequency floods can significantly impact emergency response times.

Results

Areal and Population Coverages

Areas covered by individual Ambulance, and Fire & Rescue stations were derived for the baseline, coastal/fluvial and surface water flood conditions of various magnitudes. For example, Figure 1 shows the spatial coverage of all Fire & Rescue stations in England (inset) and Southeast (main) under local 100-year surface water flood events, for the 5-, 8-, and 10-minute timeframes under normal traffic (see Methods and Supplementary Information S2). Equivalent maps for Ambulance stations are shown in the Supplementary Information (Supplementary Figure 3). Statistical analysis of the accessibility mapping under various conditions is presented next.

Figure 2 summarizes the percentage coverage by Ambulance Service stations in England, in terms of: (i) total area, (ii) total population, (iii) population over 75 (elderly), (iv) population under 5 (young children); and (v) population with Very Bad Health (people with VBH) as defined in the 2011 census. Coverages are given for coastal, fluvial and surface water flood events for various Annual Exceedance Probabilities (AEPs), and within the 7-minute timeframe for Ambulance Services in England (see Methods and Supplementary Information S2). Complete results for other timeframe targets are given in Supplementary Table 1. Equivalent results are given for the Fire & Rescue Service in the Supplementary Information (Supplementary Table 2).

Spatial Disparity

Whilst the Ambulance Service 7-minute percentage areal coverages are low (37%), on a national scale, the coverages of both the total population and individual population groups in the baseline condition are above 80%. County-level statistics reveal the spatial disparity. Variabilities of the Ambulance Service 7-minute coverages are illustrated in the scatter plots (Figure 3) which compare baseline coverage with those under fluvial/coastal flood conditions for the 47 ceremonial (geographic) counties in England (City of London is included in the Greater London). Counties with less than 60% coverage, and most dramatic reduction from baseline are labelled in the plots (Figure 3). Equivalents for Fire & Rescue Service 5-minute statistics show a similar pattern. Apart from several counties where under both the baseline and flood conditions, populations coverages are notably low, East Riding and Berkshire see the most dramatic reduction in population coverage in all categories, with total population coverage reducing from 65% and 80% respectively to just 9% and 12%.

The impact of flooding on accessibility is demonstrated at both the national (Supplementary Tables 1-4) and county-scale (Supplementary Tables 5-6). The 50th percentiles (Supplementary Figure 10) of Ambulance Service county-level 7-minute coverage for the population groups decrease from 77-82% in the baseline condition to 53-58% in a less than 30-year fluvial/coastal flood, and further down to 41-46% for the 30-100 year event.

Population coverages of the top ten most populated counties by Ambulance Service (Supplementary Table 5) and Fire & Rescue Service (Supplementary Table 6) highlight those counties with emergency service accessibility most affected by flooding for their 7-minute and 5-minute timeframes respectively. Three counties in the south and southeast of England are expected to have the most significant service area reduction for their population, including

Hampshire, Kent and Essex. A 30-year surface water flood event will reduce Essex Fire & Rescue Service 5-minute population coverage from 78% to 53%, and Ambulance Service from 87% to 49%. Large surface water flooding (1000-year) appears to be more disruptive than fluvial/coastal flooding with similar magnitude, due to its widespread nature, a finding echoed in Coles *et al.* (2017) and Green *et al.* (2017).

Vulnerable Facility Coverage

We identify the facilities with vulnerable people that emergency services might not be able to reach within regulatory timeframes under baseline and flooding scenarios. Figure 4 shows the care homes outside of the Ambulance Service 7-minute and 15-minute coverage under a 30-year, 100-year and 1000-year surface water flood event. Ambulance Service accessibility to all vulnerable facilities within all compliance timeframes (7-minute, 15-minute, 18-minute and 40-minute) under both surface water and coastal/fluvial flood scenarios are summarised in Supplementary Table 3. Equivalent summary statistics for Fire & Rescue Service are shown in Supplementary Table 4.

Results suggest that, with the increase of flood magnitude, there is a growing number of vulnerable facilities not covered by the emergency services. For example, national coverage of care homes within the Ambulance 7-minute timeframe under baseline conditions is 86%, but reduces to 70%, 58% and 29% during 30-, 100- and 1000-year surface water flood events, respectively. Similar declines in service coverage were found for other facilities, and for coastal/fluvial flooding, as well as for the Fire & Rescue Service (Supplementary Table 4).

Hotspot Analysis

Supplementary Figure 8 shows hotspots of low coverage of vulnerable population facilities by the Ambulance Service within the 7-minute response time under baseline and flood conditions. Perhaps most notable is that flood events cause hotspots of reduced coverage in some of the major urban agglomerations (e.g. London, Birmingham, Liverpool, Newcastle) and that this happens even for low magnitude flood events.

Hotspots under Traffic Congestion

The above results do not consider the impact of route inaccessibility on other road users and the congestion that can follow. Hotspots of vulnerable facilities under combined surface water flooding and congestion scenarios are shown in Supplementary Figure 9, compared with situations under no-flood conditions. Although traffic congestion varies spatially, the scenarios are still plausible given the widespread nature of surface water flooding and cascading impacts of floods on transport networks. In “worst-case” scenarios, traffic congestions caused by extreme flooding induced by large weather events (e.g. 1000-year flood events) can render the transport network of a city to standstill. Sensitivity testing shows that the hotspot pattern is more sensitive to traffic speed reductions under no-flood conditions and low to medium magnitude (30-year and 100-year) flooding than to more severe (e.g., 1000-year) floods.

Validation

A unique mobilisation and incident response dataset associated with a large surface water flood event on UK European Union referendum polling day (23 June 2016) in Greater London was obtained from London Fire & Rescue Service (LFRS). This extreme surface water flood event (second largest daily total on record) stretched the operation of the Fire & Rescue Service. Figure 5 shows the timing, response time and the nature of delay for each incident attended by the Fire & Rescue Service between 22nd and 24th of June 2016, along with the hourly rainfall recorded at seven rain gauges in the Greater London area.

In total, 1002 incidents were attended by LFRS on 23 June 2016, of which 450 (45%) were flood-related. This represents a three-fold increase in the total number of incidents compared with the 22 June 2016. In total, 1337 dispatches were made, of which over 59% of the journeys took more than 6 minutes (LFRS's internal target timeframe), compared with 33% on the previous day. Records for 23 June show that 10% and 9% of the responses were 'held-up' by weather and traffic conditions respectively.

We modelled the event at 5-meter resolution for the entire city, using distributed rainfall derived from the Met Office 1 km Radar observation and a high-resolution LiDAR dataset. Modelled flood footprints were compared to the recorded flood-related incident points and a good agreement was achieved (see Supplementary Information S6). Flooded roads over 30 cm were used as barriers in the network analysis and the 6-minute (London Fire & Rescue Service internal target for responding to incidents) service areas from Fire & Rescue stations were derived. The modelled 6-minute service area agrees well with the actual response time recorded on a binary basis (i.e. whether an incident was attended within 6-minutes or not). More details of the validation are provided in Supplementary Information S6. The analysis provides further insight as to how floods affect the operation of Fire & Rescue Service in terms of their ability to reach incidents within target time frame. Figure 6 shows the areas (light blue) modelled as unreachable within 6 minutes and the response time for each individual incident (bars). The modelled response time for individual incidents has a moderate correlation with the recorded response time. For example, 52% of the incidents that fall within the modelled 6-minute accessible areas were attended by LFRS in 6 minutes. And, 69% of the incident points which are estimated to be unreachable within 6 minutes were attended outside of 6 minutes. The moderate correlation is associated with the assumption that traffic speed remains optimal during flooding and there are no other interacting factors. However, further analysis of the mobilisation dataset (Supplementary Information S6; Supplementary Figures 1 and 2) revealed the complex interaction between surge demand for emergency rescue, adverse weather and traffic conditions, and limited resources available at individual stations.

Discussion

Infrastructure networks are often dependent on transport systems for continued operation, such as ensuring access to fuel, personnel and emergency response (Dawson *et al.* 2018). Research reported herein is the first study that evaluated the interdependency of emergency services on the transport network at the national scale, in a systematic way using authoritative datasets, under the systems framework for national assessment of climate risks to infrastructure (Dawson *et al.* 2018). The national perspective reveals just how stressed the emergency services are in England in meeting their response timeframes even without flooding and the places (hotspots) that require attention under various flooding scenarios. The fact that these challenges are so geographically variable is a major finding and suggests improvements in resilience must be geographically targeted. This information is needed to support strategic planning for emergency service planning and to improve overall resilience to flooding under evolving climate conditions.

Even under the baseline conditions, areal coverage of both Ambulance and Fire & Rescue Services is modest at 37% (Figure 2) and 59% (Supplementary Table 2) for their respective 7-minute and 8-minute key timeframe targets. Government policies over past decades have led to the centralisation of Accident and Emergency Departments, resulting in increased journey times between emergency facilities and incidents (Williams *et al.*, 1996). Notably, a large proportion of rural areas are not covered by the Ambulance 7-minute service. The low rural areal coverage under the current Ambulance Service arrangement is of concern as, despite the lower population densities compared to urban areas, many emergency calls arise from rural areas (Turner *et al.*, 2017). Research also shows that road traffic mortality rates are higher in rural areas (Jones and Bentham, 1995; Bentham, 1986; Williams *et al.*, 1991) and positively correlated with time waiting for ambulance arrival (Brown *et al.*, 1979) and distance from hospitals (Nicholl, *et al.* 2007; Byrne et al. 2019). On the other hand, for the Fire & Rescue Service, the government's push to decentralise the service to cover more peri-urban/rural areas may alleviate the poor spatial coverage of such locations. However, such changes may at the same time reduce the accessibility to vulnerable populations in urban areas, especially in cities where the surge capacity of fire & rescue service is limited.

Our analysis reveals important inequalities between population groups in terms of Ambulance Service response time provision in England. Regardless of the response timeframe, flood type or severity, the elderly always had least cover. Furthermore, under both coastal/fluvial and surface water flood scenarios, flooding reduces the spatial coverage of all population sub-groups dramatically, but disproportionately for the elderly population. The same result emerges from our analysis of Fire & Rescue Service coverage (Supplementary Information, Supplementary Table 2). Comparable analysis was undertaken for different ethnic groups and households with various levels of deprivation, as defined by the 2011 census data. Results are presented in Supplementary Information S9. In terms of ethnicity, white populations were found to have least spatial coverage and greatest reduction in Ambulance service accessibility within 7-minute and 15-minute under all scenarios (including baseline) (Supplementary Figure 12), compared with ethnic minorities (mixed, Asian and black). We also found that households with more dimensions of deprivation (as defined by the 2011 census data) tend to be less affected by flood impacts on emergency accessibility (Supplementary Figure 13). These patterns can be explained by urban/rural population proportions of each population group (Supplementary Tables 8 and 9). Our analysis of the urban/rural demographic distribution shows that greater proportions of deprived households and ethnic minorities live in city/town centres (as defined by the UK Office for National Statistics in 2015), whilst greater proportions of elderly and white population group tend to live in rural areas. These findings highlight the importance of addressing geographies of (in)equality in emergency planning.

Future studies could consider population vulnerability in the context of environmental injustice (Cutter, 2006) and encompass more granularity in defining vulnerable populations (Iowa Department of Public Health, 2009), by including factors such as: physical, mental, emotional, or cognitive status; ethnicity (Maantay and Maroko, 2009); culture and religion; language; or socio-economic status (Walker and Burningham, 2009). Severe hurricanes in the US have already exposed significant gaps in emergency preparedness, and highlighted social, physical, and economic inequities among population sub-groups (Nick *et al.*, 2009). For example, Hurricane Katrina (2005) disproportionately killed black, elderly males (Brunkard *et al.*, 2008; Sharkey, 2007), whereas Hurricane Irma (2017) claimed eight lives in a Florida nursing home that was left without power for days (http://www.bbc.co.uk/news/world-us-canada-41258307).

Whilst direct impacts of flooding on vulnerable facilities may be evaluated relatively easily by overlaying hazard maps with facility locations, wider cascading impacts on emergency service provision are poorly understood. Our analysis contributes to this understanding. Hotspot analysis of vulnerable facilities revealed that many facilities, where elderly, children and people with very bad health concentrate, fall outside emergency service areas during flood events. This is a serious issue because flood events render vulnerable populations more exposed in a double sense – flooding does not just mean that vulnerable people need help (e.g. evacuation) but it is much harder for emergency responders to gain access to those affected in good time. Identifying service vulnerability hotspots ahead of major events where emergency services are already under strain helps to prioritise resources.

Extreme flooding is of major concern to emergency responders. However, we also revealed that even relatively low-magnitude coastal/fluvial (<30-year) and surface water (30-year) flood events can lead to dramatic reductions in the spatial coverage of emergency services, reducing the already limited areal coverage of Ambulance Service from 37% to 21% and 20% under coastal/fluvial and surface water flood scenarios respectively. Similarly, small (<30-year) to medium (30-100 year) coastal/fluvial events reduce the spatial coverage of the overall population and sub-groups more dramatically than larger events (>100-year).

Notably, whilst areal and population coverage under coastal/fluvial and surface water flood scenarios of various severities exhibit similar patterns, they are distinctively different for the most extreme high-end scenario (1000-year+). There is little change in areal and population coverage between a 1 in 100 to 1000 year and greater than 1000-year coastal/fluvial event for Ambulance Service (Figure 2). However, a 1 in 1000-year surface water flood event results in the least coverage, both areally (7%) and overall population (27%), more than halving the coverage of a 1 in 100-year surface water event in all categories. This is an important finding, especially for cities, which are arguably more prepared for coastal/fluvial flooding than surface water flooding arising from heavy downpours, despite the recognition that surface water flooding is the “biggest flood risk of all” in the UK (https://www.gov.uk/government/news/surface-water-the-biggest-flood-risk-of-all).

Detailed investigation (Supplementary Information, S6) of the mobilisation and incident response dataset associated with an extreme surface water flood event in Greater London also generates further insights into: (i) the interaction between flooding & traffic (Figure 5; Supplementary Figure 1), (ii) the ‘surge demand’ for emergency rescue during flooding, and (iii) the needs for ‘surge capacity’ in response to ‘surge demand’ within LFRS (see Supplementary Figure 2). The interaction between flooding and traffic is well known (Pregnolato *et al.* 2017a, b) and this dataset provides further evidence from emergency responders’ perspectives. The most important revelation is the need for ‘surge capacity’ within Fire & Rescue Service, and perhaps more efficient use of existing resources (Supplementary Figure 2), to deal with the spatially and temporally distributed ‘surge demand’ during flooding under difficult weather and traffic conditions. Surge in demand has also been reported for Ambulance Service in extreme weather conditions. A study undertaken for London Ambulance Service found rising demand for ambulance service when temperature drops below 2°C or rises above 20°C (Mahmood *et al.*, 2017). This agrees well with the call for ‘surge capacity’ within medical care facilities during extreme weather conditions including flooding (Banks *et al.*, 2007; Hess *et al.*, 2009). Whilst there is clear evidence of correlation between extreme temperature, call-out volumes and Ambulance Service response time, further quantitative analysis is needed to evaluate to what extent flooding is related to increased demand for Ambulance Service. Such demand should also be investigated in conjunction with the implication for Fire & Rescue Service as increasingly both category 1 responders are responding together to emergency 999 and 112 calls in England (Home Office, 2017).

Recommendations for Adaptation Policy

Emergency service provision is an essential part of the critical infrastructure underpinning the well-being of society. Developing reliable, sustainable and resilient emergency services, whilst recognising the need for affordability, equality and inclusivity, contributes to several of the targets laid out in the United Nations Sustainable Development Goals (e.g. Target 1.4; Target 9.1; Target 11.a; Target 11.2; Target 11.5).

This study provides the first detailed risk assessment of potential impacts of different flood types on emergency response services in England, focusing on vulnerable populations. Knowledge of the patterns of vulnerability hotspots allows all levels of government to identify opportunities for strengthening the resilience of emergency services to flooding. At the national level, vulnerability mapping and ranking tables can be used by authorities (e.g. UK National Health Service; Home Office) to inform strategic planning, and to optimise resource allocation, especially in anticipation of widespread multi-basin flood events (De Luca *et al.*, 2017). Under such extreme conditions, cross-administrative regional response is needed, because local resources are often strained (e.g. Figures 5 and 6; Supplementary Figures 1 and 2). Our mapping and network analysis could be applied under different scenarios to reveal the impact of station closures, movements or additions to service coverage.

At city-region scales, where individual emergency service organisations operate, our risk information can be used to: (i) raise awareness of existing vulnerability, (ii) drive more robust contingency planning, and (iii) design more tangible measures for improved accessibility to vulnerable populations. An example of a local/regional scale adaptation (e.g. Supplementary Figures 11c and 11b respectively) would be to increase pumping capacity for local roads that are known to be susceptible to flooding (e.g. circles in Supplementary Figure 11c), or to position emergency vehicles ahead of major events. Furthermore, whilst it is rare for Fire & Rescue Service to have standby vehicles, they are routinely placed in strategic locations by the England Ambulance Service (National Audit Office, 2017) to meet response times for life-threatening incidents. We note that optimisation of emergency provision for “normal times” is not necessarily going to lead to optimisation for more difficult times because floods have a particular spatial structure and its impact on the road network has a different spatial structure. As shown by our analyses, the superposition of these two spatial structures leads to non-linear reductions in response times. Therefore, further geospatial analysis should be undertaken to identify the optimal sites for standby vehicles, for specified flood types and severity.

Whilst the management and operational structure of emergency responders in other countries might be different from the centralised emergency services in England, the methods demonstrated herein can be readily adapted to other regions where data exist on road networks, flood mapping, and for exposed people. Unfortunately, many of the regions that are most vulnerable to flood hazards (such as rapidly developing cities in Africa, south and Southeast Asia) are also amongst the most data and resource scarce. Nonetheless, a risk assessment approach that integrates network-flood-vulnerability methods for emergency service has the potential to support more efficient distribution of resources, in this case the number and location of emergency service stations, improving the well-being of the population in general and most vulnerable groups in particular.

Future implications of the findings from this research are presented in S10 of the Supplementary Information, including the needs to: (i) incorporate climate change to consider future risks, (ii) undertake economic evaluation of flood impact on emergency response service provision; and (iii) consider non-technological solutions in adapting to flood impacts on emergency service provision to vulnerable populations.

Methods

Our accessibility mapping involves a network-based geospatial analysis (Coles *et al.*, 2017; Green *et al.*, 2017) which derives areas that can be reached by individual emergency service nodes within a certain timeframe (Supplementary Information, S1). We map accessibility corresponding to the various timeframe targets for the Ambulance Service and Fire & Rescue Service in England. For the Ambulance Service, we consider spatial accessibility within 7-, 15-, 18- and 40-minute response times. The 7- and 15-minute targets are, respectively, the average and 90th percentile of the time required for the Ambulance Service to reach life-threatening incidents ('Category 1'; such as cardiac arrest and serious allergic reactions). The average and 90th percentiles are 18- and 40-minutes respectively for Category 2 calls (emergency calls such as those associated with burns, epilepsy and strokes). For the Fire & Rescue Service, the corresponding upper limits recommended by the Home Office for various categories of incidents are 5-, 8-, 10- and 20-minutes (Home Office, 1985) (Supplementary Information, S2). However, local Fire & Rescue services in England often have their internal response timeframe target and in London it is 6 minutes.

The assessment was undertaken for: (i) baseline (no-flood) conditions; and (ii) flood conditions with prescribed AEPs, for coastal, river (fluvial) and extreme rainfall related (surface water) floods. The Risks of Flooding from Rivers and Sea (RoFRS) dataset (Environment Agency, 2016) provides the chance of flooding by rivers and the sea, corresponding to an AEP greater than 3.3% (High; <30 year), between 3.3% and 1% (Medium; 30- to 100-year), between 1% and 0.1% (Low; 100- to 1000-year), and less than 0.1% (Very Low; >1000 year). Extreme rainfall related flood scenarios are based on the Environment Agency's Risks of Flooding from Surface Water (RoFSW) dataset (Environment Agency, 2013), delineating three potential flood zones (AEPs: 3.3%, 1% and 0.1%, respectively). Further details of the datasets and their processing are provided in the Supplementary Information (S3). These data sets were used to introduce restrictions into the transport network, from which the accessibility could be recalculated (Supplementary Information, S4).

Finally, the spatial distributions of potentially vulnerable populations (the elderly, young children, people with very bad health, households with deprivation, and ethnic groups) were obtained from two datasets: (i) UK 2011 Census (Office for National Statistics, 2011); and (ii) key facilities where these populations concentrate (Ordnance Survey) (Supplementary Information, S5). Using this information, hotspots of relatively low emergency service coverage were then identified for the chosen populations and facilities for the baseline and flood condition scenarios, using the quartic kernel function described by Silverman (1986). Sensitivity of the hotspot patterns to congestion was evaluated using three traffic scenarios, by 'stress-testing' (Brown and Wilby, 2012) through reducing road traffic speeds by 20%, 50% and 80%.

We note the key assumptions involved in accessibility mapping. The method we use is designed to provide a first-order analysis of where emergency responders can reach following the legislated road speeds and under traffic congestion scenarios. Whilst areas that can be covered by emergency responders can be accurately modelled with the navigation-grade transport network that we use, other factors such as availability of resources (e.g. crew and vehicles), trip-specific traffic details (e.g. use of hard-shoulder), or interactions between traffic and weather are not considered in our national-scale modelling. However, such details could be captured using methods such as Agent-Based Modelling, which can incorporate the behaviours of individual agents (Haer *et al.* 2019), the dynamic environmental processes and the interactions between them. Such analysis could reveal further insights into the emergency response vulnerability for different population groups. Second, the use of national flood risk maps does not indicate simultaneous occurrence of flooding, hence results should be interpreted as local/regional manifestation of flood impacts, rather than their simultaneous occurrence. However, we also recognise that widespread multi-basin flooding does occur (De Luca *et al.*, 2017) during which cross-boundary operations are often involved.

Data Availability

The transport network of roads in England were obtained from the UK Ordnance Survey MasterMap® Integrated Transport Network™ (https://digimap.edina.ac.uk/). Locations of emergency service stations were collated from various sources including UK Ordnance Survey, Ambulance trusts, Fire & Rescue Services and open sources. Whilst station locations were quality-checked to ensure their accuracy, there might be inconsistencies as they came from different sources. Data were used under licenses for the current study. Certain datasets are however available from the lead and corresponding author upon reasonable request and with permission of the parties that provided the data. Locations of vulnerable facilities were extracted from the UK Ordnance Survey datasets (https://digimap.edina.ac.uk/) under license. Fluvial/coastal and surface water flood risks maps were provided by the UK Environment Agency (https://data.gov.uk/publisher/environment-agency). Vulnerable population groups were derived from the 2011 England & Wales Census, available from the Office for National Statistics. Major city and town boundaries are defined by the Office for National Statistics in 2015.

Competing Interests

The authors declare no competing interests.

Author Contributions

DY coordinated this work and led to the first drafting of the manuscript. DY, JY and RLW designed the initial method. JC, JHA, SNL and NL contributed to the further development of the methods. DY, JY and JGC. performed the data processing and analysis. DY, JY, RLW, SNL, JC, JHA, and NL interpreted the results and wrote the final manuscript. All authors contributed to the analysis and interpretation of results and drafting of the manuscript.

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References

Adger, W.N. 2006. Vulnerability. *Global Environmental Change,* 16: 268-281.

Arent, D.J., Tol, R.S.J., Faust, E., Hella, J.P., Kumar, S., Strzepek, K.M., Tóth, F.L. and Yan, D. 2014. Key economic sectors and services. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.

Adaptation Sub-Committee. 2014. *Managing Risks to Well-being and the Economy.* UK Committee on Climate Change.

Banks, L.L., Shah, M.B. and Richards, M.E. 2007: Effective healthcare system response to consecutive Florida hurricanes. *American Journal of Disaster Medicine*, 2(6): 285-295.

Bentham, G., 1986. Proximity to hospital and mortality from motor vehicle traffic accidents. *Social Science & Medicine,* 23: 1021–1026.

Brown, D.B. 1979. Proxy measures in accident countermeasure evaluation: a study of emergency medical services. *Journal of Safety Research,* 11: 37-41.

Brown, C. and Wilby, R.L. 2012. An alternate approach to assessing climate risks, Eos, 93(41): 401-402.

Brunkard, J., Namulanda, G. and Ratard, R., 2008. Hurricane Katrina deaths, Louisiana, 2005. *Disaster Medicine and Public Health Preparedness*, 2(4): 215-223.

Byrne, J.P., Mann N.C., Dai M., Mason, S.A., Karanicolas, P., Rizoli, S. and Nathens, A.B. 2019. Association Between Emergency Medical Service Response Time and Motor Vehicle Crash Mortality in the United States. *JAMA Surgery*, 154(4):286-293.

Coles, D., Yu, D., Wilby, R.L., Green, D. and Herring, Z. 2017. Beyond 'flood hotspots': Modelling emergency service accessibility during flooding in York, UK, *Journal of Hydrology*, 546: 419-436.

Cutter, S.L. 2006. *Hazards, vulnerability and environmental Justice*, Earthscan, London, UK, 418 pp.

Dawson R.J., Thompson D., Johns D., Wood R., Darch G., Chapman L., Hughes P.N., Watson G.V.R., Paulson K., Bell S., Gosling S.N., Powrie W., Hall J.W. 2018. A systems framework for national assessment of climate risks to infrastructure. Philosophical Transactions of the Royal Society A 2018, 376(2121), 20170298.

De Luca, P., Hillier, J., Wilby, R.L., Quinn, N.W., Harrigan, S. (2017) Extreme multi-basin flooding linked with extra-tropical cyclones. *Environmental Research Letters*, 12(114009)

Green, D., Yu, D., Pattison, I., Wilby, R., Bosher, L., Patel, R., Thompson, P., Trowell, K., Draycon, J., Halse, M., Yang, L. and Ryley, T. 2017. City-scale accessibility of emergency responders operating during flood events. *Natural Hazards and Earth System Sciences*, 17: 1-16.

Haer, T., Wouter Botzen, W.J. and Aerts, C.J.H. 2019. Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach. Environmental Research Letters 14(2019) 044022.

Her Majesty's Government. 2016*. National Flood Resilience Review*. London.

Hess, J.J., Heilpern, K.L., Davis, T.E. and Frumkin, H. 2009: Climate change and emergency medicine: impacts and opportunities. *Academic Emergency Medicine*, 16(8): 782-794.

Home Office. 1985. *Report of the joint committee on standards of fire cover by Central Fire Brigades Advisory Councils for England and Wales and Scotland*. London: Home Office.

Home Office. 2017. Fire and Rescue Incident Statistics: England, April 2016 to March 2017. Statistical Bulletin 13/17.

Jones, A.P. and Bentham, G. 1995. Emergency medical service accessibility and outcome from road traffic accidents. Public Health, 109: 169-177.

Iowa Department of Public Health. 2009. Emergency planning for people with disability. Available from: URL: https://idph.iowa.gov/disability-injury-violence-prevention/disability-health/preparedness

Kendon, E.J., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C. and Senior, C.A. 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, 4: 570-576.

Lesnikowski, A., Ford, J., Biesbroek R., Berrang-Ford, L. and Heymann, S.J. 2015. National-level progress on adaptation. *Nature Climate Change*, 6: 261-265.

Maantay, J. and Maroko, A. 2009. Mapping urban risk: flood hazards, race & environmental justice in New York City. *Applied Geography*, 29:111-124.

Mahmood, M.A., Thornes, J.E., Pope, F.D., Fisher, P.A. and Vardoulakis S. 2017. Impact of Air Temperature on London Ambulance call-out incidents and response times. Climate, 5 (61). https://doi.org/10.3390/cli5030061

Mysiak, J. Surminski, S., Thieken, A., Mechler, R. and Aerts, J.C.J.H. 2016. Brief Communication: Sendai Framework for Disaster Risk Reduction – success or warning sign for Paris? *Natural Hazards and Earth System Science,* 16: 2189-2193.

National Audit Office. 2017. *NHS Ambulance Services*. HC 972 Session 2016-17.

Ngo, E.B. 2001. When disasters and age collide: reviewing vulnerability of the elderly. *Natural Disaster Review*, 2(2): 80-89.

Nicholl, J., West, J., Goodacre, S. and Turner, J. 2007. The relationship between distance to hospital and patient mortality in emergencies: an observational study. *Emergency Medicine Journal*, 24(9): 609-609.

Nick, G.A., Savoia, E., Elqura, L., Crowther, S., Cohen, B., Leary, M., Wright, T., Auerbach, J. and Koh, H.K. 2009. Emergency Preparedness for Vulnerable Populations: People with Special Health-care Needs. *Public Health Reports*, 124(2): 338–343.

Pregnolato, M., Ford, A., Glenis, V., Wilkinson, S., Dawson, R.J. 2017a. Potential impact of climate change on flooding disruptions to urban transport networks. Journal of Infrastructure System. 23(4), 04017015.

Pregnolato, M., Ford, A., Wilkinson, S.M., Dawson, R.J. 2017b. The impact of flooding on road transport: a depth-disruption function. Transportation Research Part D 55: 67–81.

Sharkey, P. 2007. Survival and death in New Orleans - An empirical look at the human impact of Katrina. *Journal of Black Studies*, 37: 482-501.

Silverman, B.W. 1986. Density Estimation for Statistics and Data Analysis. New York: Chapman and Hall.

Turner, J. Jacques, R., Crum, A., Coster, J., Stone, T. and Nicholl, J. 2017. *Ambulance Response Programme: evaluation of phase 1 and phase 2, final report*.

U.S. Department for Transportation. 2014. *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2*. Report No.: FHWA-HEP-14-033.

Walker, G. and Burningham, K. 2011. Flood risk, vulnerability and environmental justice: Evidence and evaluation of inequality in a UK context. Critical Social Policy, 32(2):216-240.

Walker, M., Whittle, R., Medd, W., Burningham, K., Moran Ellis, J. and Tapsell, S. 2010. Children and Young People 'After the Rain Has Gone' – Learning Lessons for Flood Recovery and Resilience, final project report for 'Children, Flood and Urban Resilience: Understanding Children and Young People's Experience and Agency in the Flood Recovery Process'. Lancaster: Lancaster University. [www.lec.lancs.ac.uk/cswm/hcfp]

Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., Mappin, B., Dalrymple, U., Rozier, J., Lucas, T.C.D., Howes, R.E., Tusting, L.S., Kang, S.Y., Cameron, E., Bisanzio, D., Battle, K.E., Bhatt S. and Gething, P.W. 2018. A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature*, 553: 333–336.

Williams, F.L.R., Lloyd, O.L.I. and Dunbar, J.A. 1991. Deaths from road traffic accidents in Scotland: 1979–1988. Does it matter where you live? *Public Health,* 105: 319–326.

Williams, B.T., Nicholl, J., and Brazier, J.E. 1996. Health Care Needs Assessment: Accident and Emergency Departments In (eds) Stevens A. and Raftery J. *Health Care Needs Assessment 2nd Series*, Radcliffe Medical Press, Frome.

Figure Captions

Figure 1: Accessibility by Fire & Rescue stations in England (inset) and South West England (main figure) within 5-, 8-, and 10-minute during a local 1 in 100-year surface water flood event. The maps do not imply simultaneous occurrence of flooding. Contains OS data © Crown Copyright [and database right] (2018).

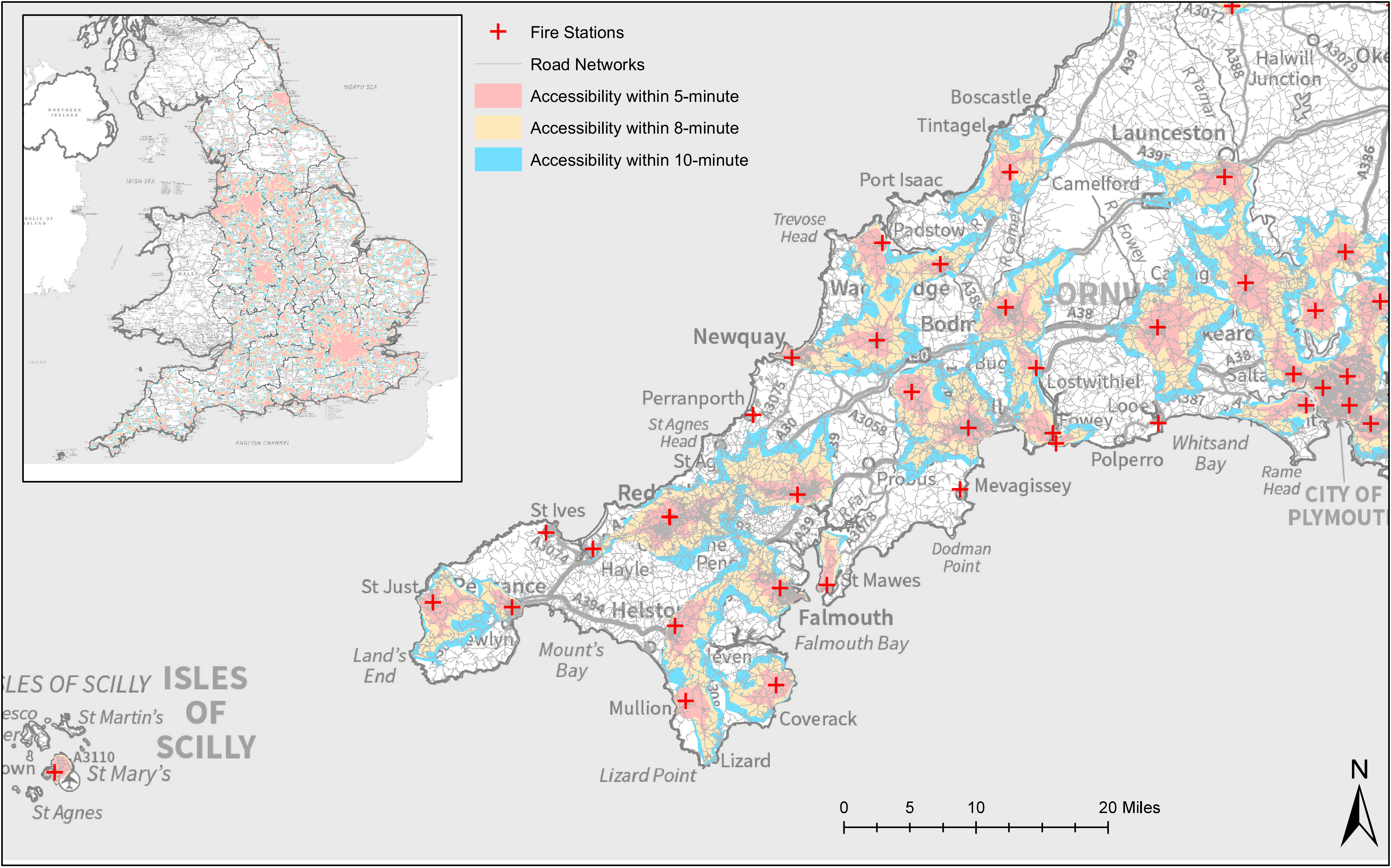
Figure 2: Ambulance Service spatial accessibility: coverage expressed as percentages of total area, total population, population over 75, population under 5, and population with Very Bad Health (VBH) in England, for specified return periods of local coastal/fluvial/surface water flood events, and mandatory 7-minute targets for life-threatening incidents categories. (a) River and coastal flooding; (b) Surface water flooding.

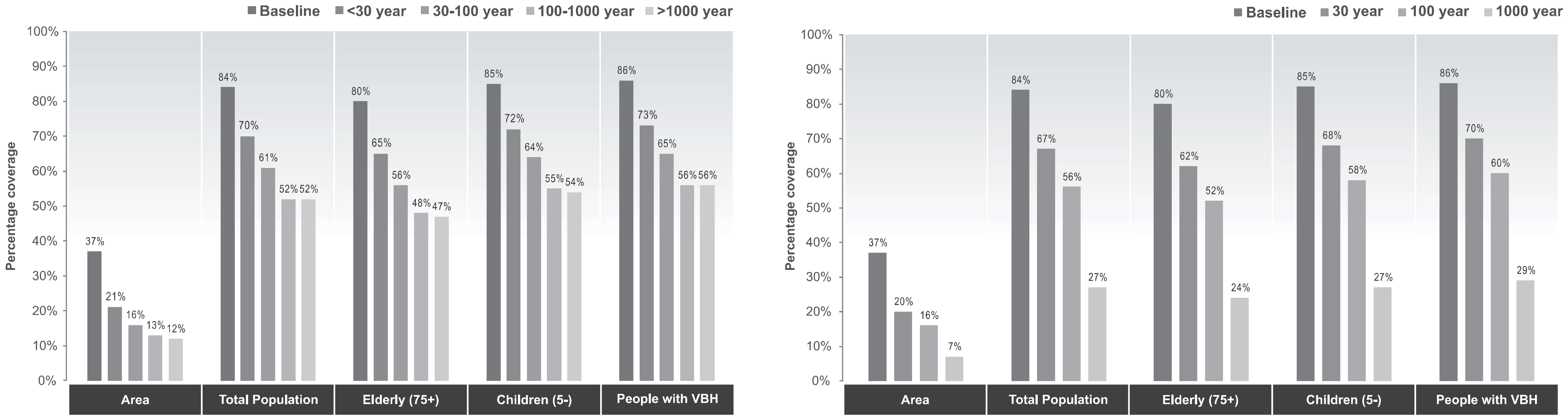
Figure 3: Scatter plots of Ambulance Service baseline coverage *versus* coverage for coastal/fluvial floods (RoFRS) of various magnitudes: (a) total population; (b) elderly (>75 year); (c) children (<5 year); and (d) people with Very Bad Health. Counties with population coverage of less than 60% in the baseline and counties with the most dramatic reduction of population coverage from baseline are annotated on the graphs.

Figure 4: Care homes in England that fall outside (red pluses) of the Ambulance 7-minute and 15-minute service area (blue areas): (a) and (d) 1 in 30 year surface water flood event; (b) and (e) 1 in 100 year surface water flood event; (c) and (f) 1 in 1000 year surface water flood event. The maps do not imply simultaneous occurrence of flooding. Color scheme (5-class PiYG diverging color scheme) adopts Brewer, Cynthia A., 200x. http://www.ColorBrewer.org. The color scheme is colour-blind friendly. Contains OS data © Crown Copyright [and database right] (2018).

Figure 5: Timing, response time and delay mode for each incident attended by the London Fire & Rescue Service on 22nd to 24th June 2016. Circles represent individual incidents attended by London Fire & Rescue Service. Individual lines are the hourly rainfall total in millimetres at gauging stations within the Greater London area. The red line parallel to the *x* axis represents the 6-minute internal response timeframe target of London Fire & Rescue Service to emergency incidents.

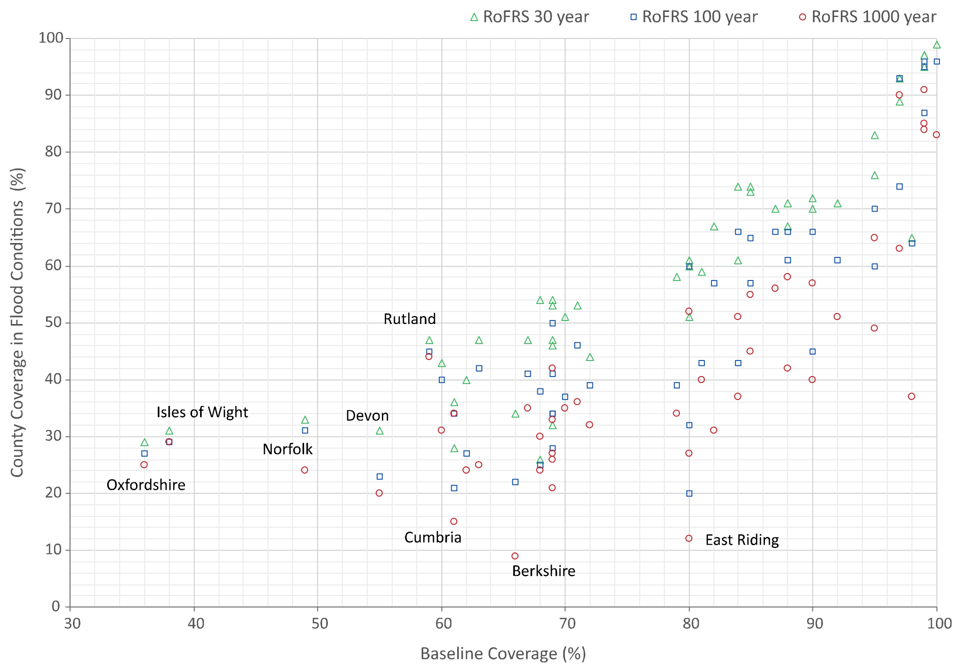
Figure 6: Modelled 6-minute service area (white areas) for London Fire & Rescue Service on the 23rd of June 2016. Blue areas are classified as unreachable within 6 minutes due to flooded roads. Size of the bar indicates the response time in minutes. The base of the bar pinpoints the recorded location of incidents (within 50-meter accuracy).


Fire Stations
Road Networks
Accessibility within 5-minute
Accessibility within 8-minute
Accessibility within 10-minute
NORTH SEA
IRISH SEA
ENGLISH CHANNEL
NORTHERN IRELAND
WALES
Boscastle
Tintagel
Launceston
Halwill Junction
Port Isaac
Camelford
Trevose Head
Padstow
R Camel
R Fowey
R Tamar
Newquay
Bodmin
Perranporth
St Agnes Head
Lostwithiel
Looe
Fowey
Polperro
Whitsand Bay
Rame Head
CITY OF PLYMOUTH
Mevagissey
Probus
Dodman Point
St Ives
Hayle
St Mawes
Falmouth
Falmouth Bay
St Just
Helston
Land's End
Mount's Bay
Mullion
Coverack
Lizard
Lizard Point
ISLES OF SCILLY
St Martin's
St Mary's
St Agnes
A30
A38
A39
A388
A386
A3072
A3079
A3058
A3075
A3078
A394
A3074
A3110
A387
0
5
10
20 Miles
N

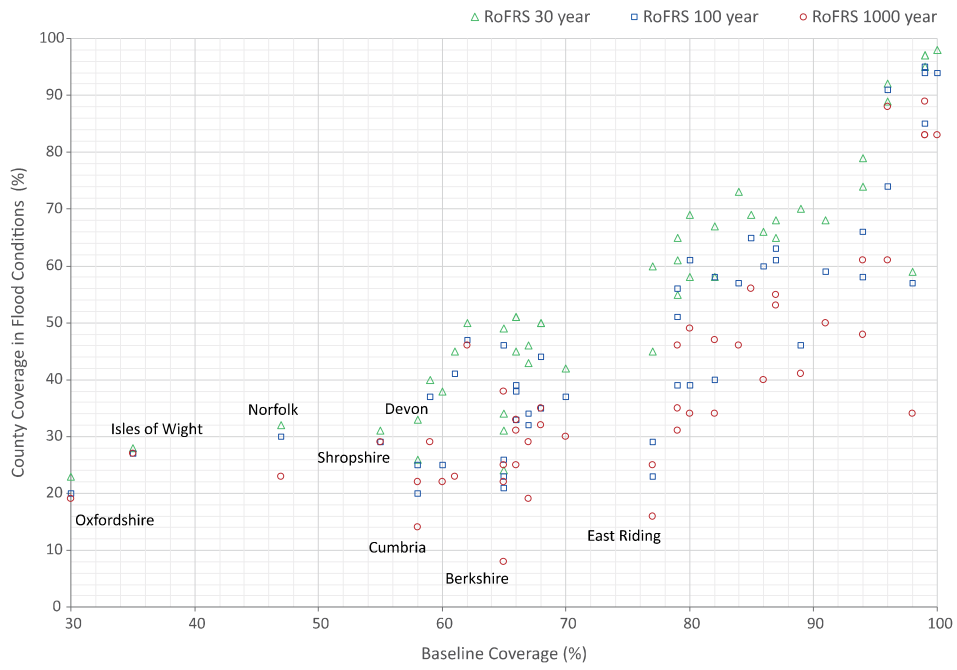

Baseline
<30 year
30-100 year
100-1000 year
>1000 year
Percentage coverage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Area
37%
21%
16%
13%
12%
Total Population
84%
70%
61%
52%
52%
Elderly (75+)
80%
65%
56%
48%
47%
Children (5-)
85%
72%
64%
55%
54%
People with VBH
86%
73%
65%
56%
56%
Baseline
30 year
100 year
1000 year
Percentage coverage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Area
37%
20%
16%
7%
Total Population
84%
67%
56%
27%
Elderly (75+)
80%
62%
52%
24%
Children (5-)
85%
68%
58%
27%
People with VBH
86%
70%
60%
29%

(a)

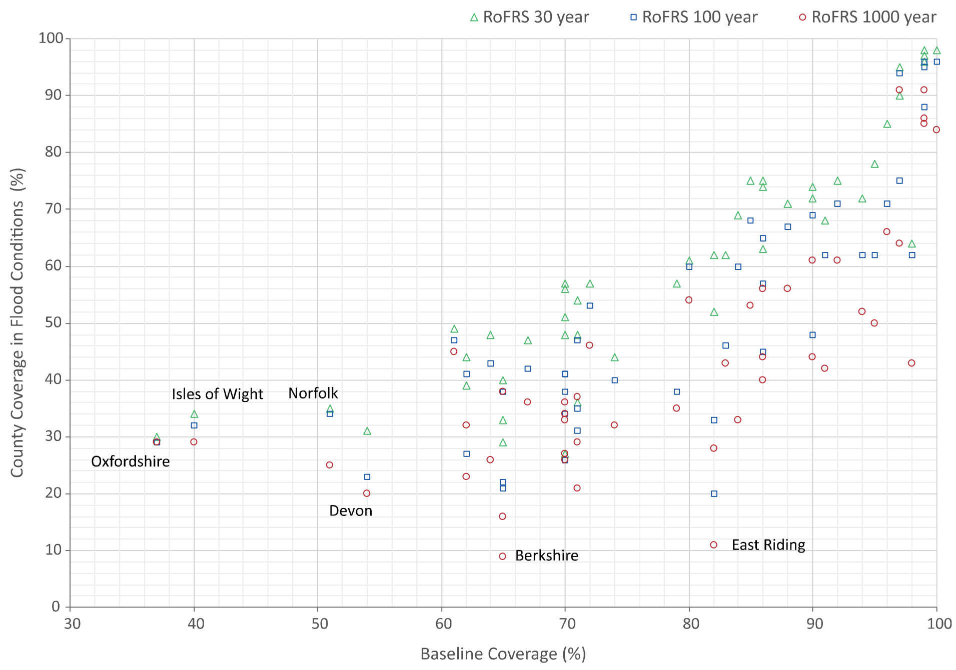
(b)


△ RoFRS 30 year
□ RoFRS 100 year
○ RoFRS 1000 year
County Coverage in Flood Conditions (%)
0
10
20
30
40
50
60
70
80
90
100
Baseline Coverage (%)
30
40
50
60
70
80
90
100
Isles of Wight
Oxfordshire
Norfolk
Devon
Rutland
Cumbria
Berkshire
East Riding

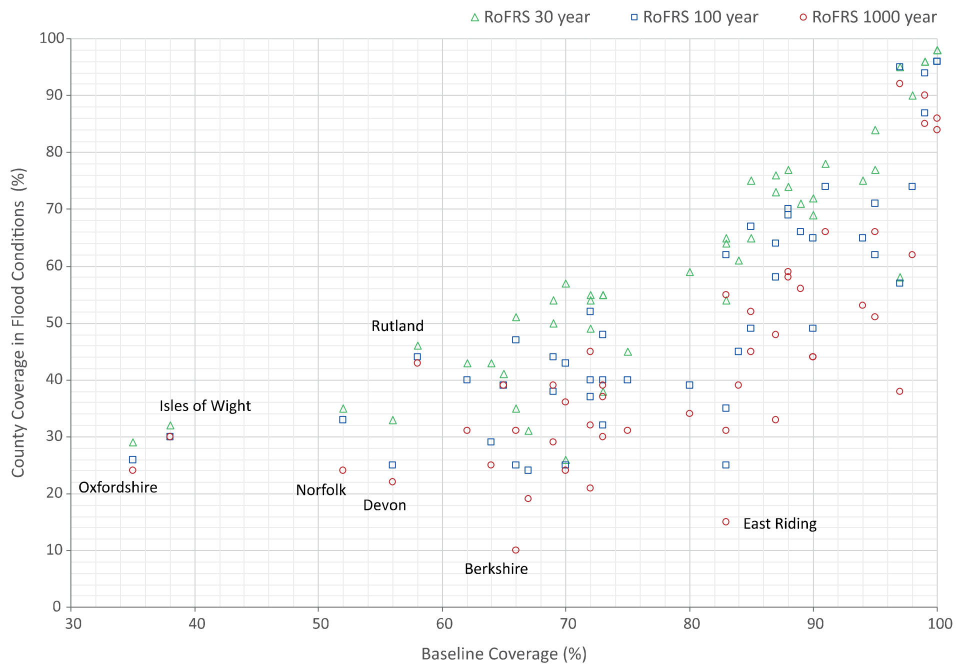
(a)


△ RoFRS 30 year
□ RoFRS 100 year
○ RoFRS 1000 year
County Coverage in Flood Conditions (%)
0
10
20
30
40
50
60
70
80
90
100
Baseline Coverage (%)
30
40
50
60
70
80
90
100
Isles of Wight
Oxfordshire
Norfolk
Devon
Shropshire
Cumbria
Berkshire
East Riding

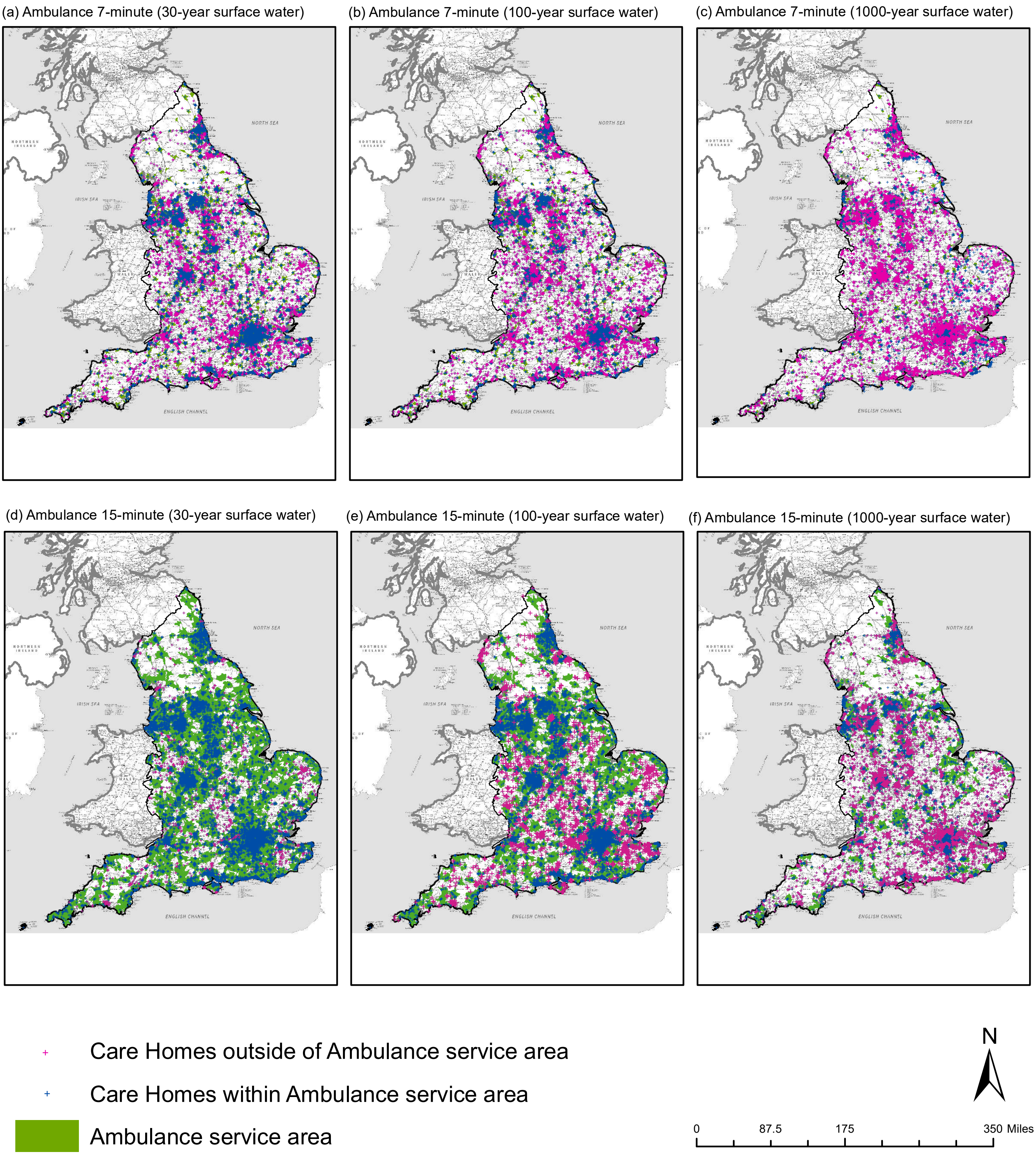
(b)


△ RoFRS 30 year
□ RoFRS 100 year
○ RoFRS 1000 year
County Coverage in Flood Conditions (%)
0
10
20
30
40
50
60
70
80
90
100
Baseline Coverage (%)
30
40
50
60
70
80
90
100
Isles of Wight
Norfolk
Oxfordshire
Devon
Berkshire
East Riding

(c)


△ RoFRS 30 year
□ RoFRS 100 year
○ RoFRS 1000 year
County Coverage in Flood Conditions (%)
0
10
20
30
40
50
60
70
80
90
100
Baseline Coverage (%)
30
40
50
60
70
80
90
100
Rutland
Isles of Wight
Oxfordshire
Norfolk
Devon
Berkshire
East Riding

(d)



(a) Ambulance 7-minute (30-year surface water)

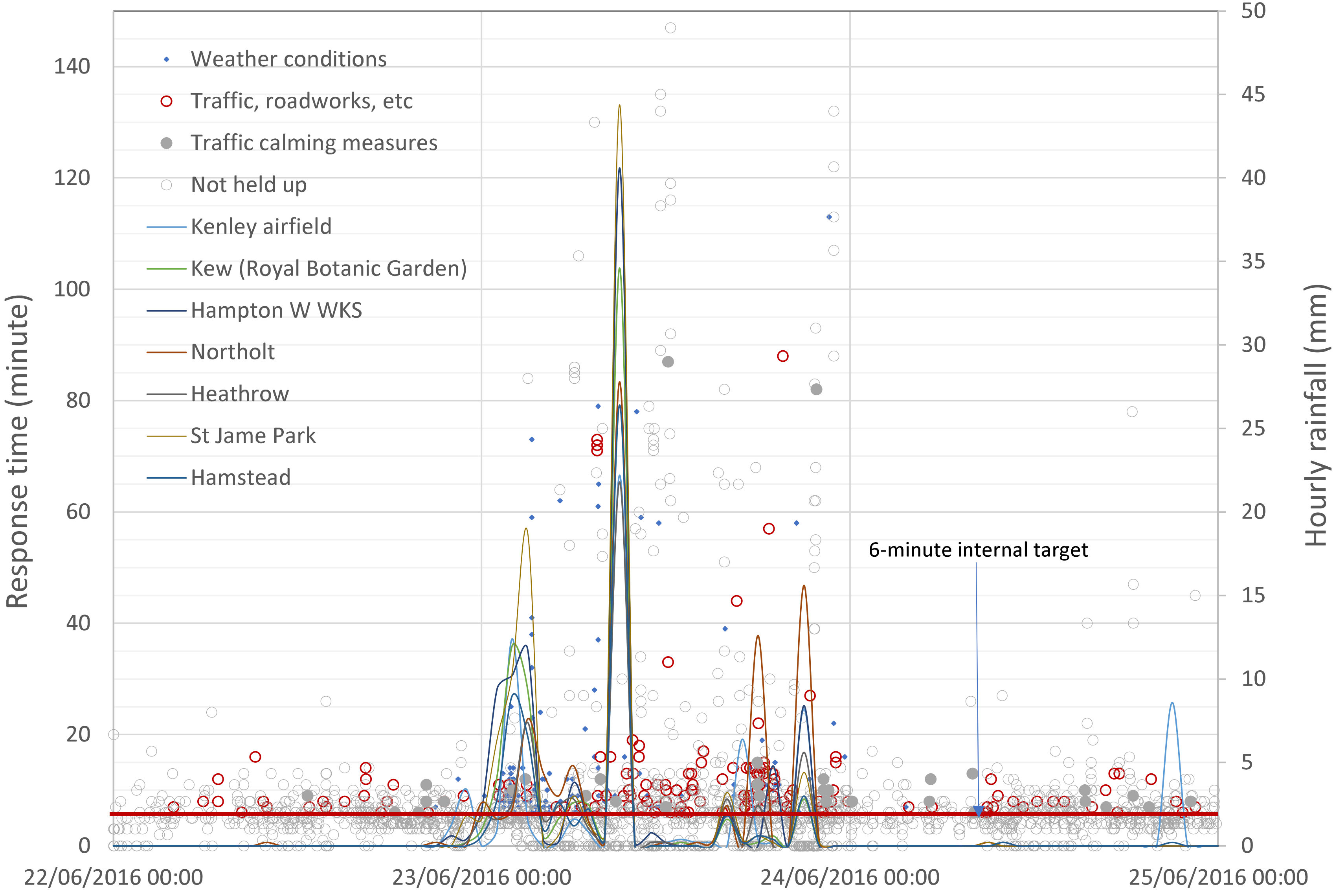
(b) Ambulance 7-minute (100-year surface water)

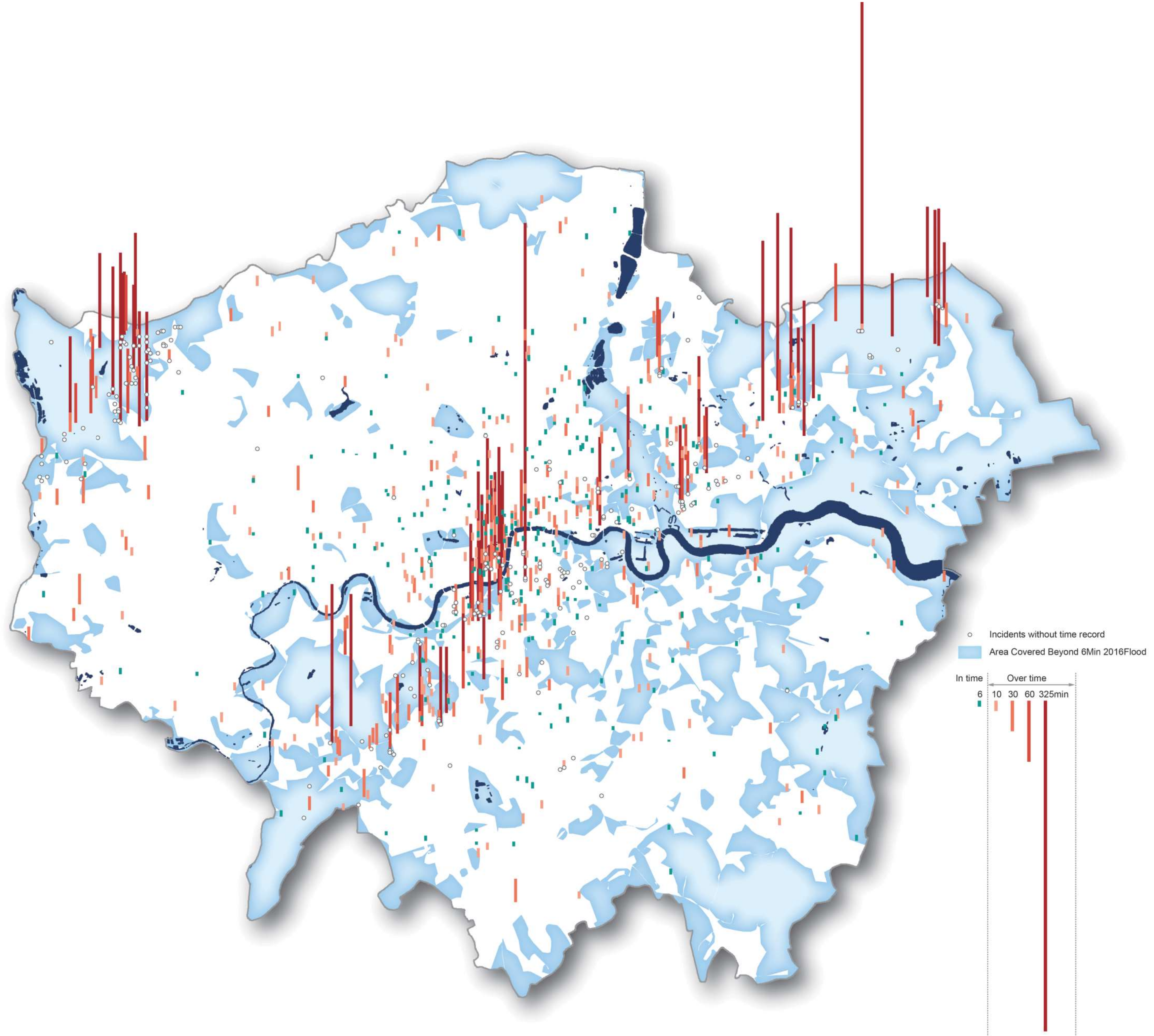
(c) Ambulance 7-minute (1000-year surface water)

(d) Ambulance 15-minute (30-year surface water)

(e) Ambulance 15-minute (100-year surface water)

(f) Ambulance 15-minute (1000-year surface water)


Weather conditions
Traffic, roadworks, etc
Traffic calming measures
Not held up
Kenley airfield
Kew (Royal Botanic Garden)
Hampton W WKS
Northolt
Heathrow
St Jame Park
Hamstead
6-minute internal target
Response time (minute)
0
20
40
60
80
100
120
140
Hourly rainfall (mm)
0
5
10
15
20
25
30
35
40
45
50
22/06/2016 00:00
23/06/2016 00:00
24/06/2016 00:00
25/06/2016 00:00


Incidents without time record
Area Covered Beyond 6Min 2016Flood
In time
Over time
6
10
30
60
325min