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Research papers

Beyond 'flood hotspots': Modelling emergency service accessibility during flooding in York, UK

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ABSTRACT

This paper describes the development of a method that couples flood modelling with network analysis to evaluate the accessibility of city districts by emergency responders during flood events. We integrate numerical modelling of flood inundation with geographical analysis of service areas for the Ambulance Service and the Fire & Rescue Service. The method was demonstrated for two flood events in the City of York, UK to assess the vulnerability of care homes and sheltered accommodation. We determine the feasibility of emergency services gaining access within the statutory 8- and 10-min targets for high-priority, life-threatening incidents 75% of the time, during flood episodes. A hydrodynamic flood inundation model (FloodMap) simulates the 2014 pluvial and 2015 fluvial flood events. Predicted floods (with depth >25 cm and areas >100 m^2) were overlain on the road network to identify sites with potentially restricted access. Accessibility of the city to emergency responders during flooding was quantified and mapped using; (i) spatial coverage from individual emergency nodes within the legislated timeframes, and; (ii) response times from individual emergency service nodes to vulnerable care homes and sheltered accommodation under flood and non-flood conditions. Results show that, during the 2015 fluvial flood, the area covered by two of the three Fire & Rescue Service stations reduced by 14% and 39% respectively, while the remaining station needed to increase its coverage by 39%. This amounts to an overall reduction of 6% and 20% for modelled and observed floods respectively. During the 2014 surface water flood, 7 out of 22 care homes (32%) and 15 out of 43 sheltered accommodation nodes (35%) had modelled response times above the 8-min threshold from any Ambulance station. Overall, modelled surface water flooding has a larger spatial footprint than fluvial flood events. Hence, accessibility of emergency services may be impacted differently depending on flood mechanism. Moreover, we expect emergency services to face greater challenges under a changing climate with a growing, more vulnerable population. The methodology developed in this study could be applied to other cities, as well as for scenario-based evaluation of emergency preparedness to support strategic decision making, and in real-time forecasting to guide operational decisions where heavy rainfall lead-time and spatial resolution are sufficient.

1. Introduction

1.1. An integrated approach to flood emergency response management

The 'Making Space for Water' (DEFRA, 2004) strategy document marked a shift to a more integrated approach to flood management in England and Wales (Hall et al., 2003). The report also highlighted the need to manage all types of flooding, including sewer, surface water and groundwater flooding alongside traditional coastal and riverine flooding (Johnson and Priest, 2008). Ambulance and Fire & Rescue Services need to be able to respond to and operate during flood events. Accordingly, the UK Civil Contingencies Act 2004 established the framework for civil protection, including the Local Resilience Forum (LRF), the main group focusing on multi-agency emergency response (DEFRA, 2013). LRFs are made up of Category 1 organisations, (such as Local Authorities, the Environment Agency, emergency services and National Health Service trusts), and Category 2 organisations (including utility and transport companies). Recurrent flood episodes in the UK reiterate the need for cooperation between these organisations in the way that they share, coordinate and execute their management responsibilities

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– all key factors in determining the success of emergency response (Brown and Damery, 2002).

Emergency services play a crucial role during the flood response process, as they participate in joint command-control structures and are central to rescue and relief efforts (Frost, 2002). Because of the risks posed by flooding, these organisations are encouraged to collectively produce a Multi-Agency Flood Plan (DEFRA, 2014), which can be a valuable tool for flood planners and responders. Jha et al. (2012) highlight the importance of creating an emergency flood plan for coordinating response to a flood event. However, road closures, electrical substation failures, and/or telephone exchanges being cut-off can cause problems. Therefore, contingency plans need to be formulated for these eventualities in order to keep vital services operating, such as identifying alternative sources of electricity for key facilities (such as hospitals) (Jha et al., 2012). The *National Flood Resilience Review* (HMG, 2016) exposes the extent to which significant numbers of critical assets are still vulnerable to flooding in England and Wales. In particular, it highlights that the loss of infrastructure services can have significant impacts on people's health and wellbeing.

Lumbroso et al. (2011) found that flood emergency plans may define the roles and responsibilities of different organisations, but lack detailed information on evacuations, and impacts of floods on critical infrastructure, including the road network. A review of the flood emergency plan used in Cumbria during the 2009 flooding found that emergency responders particularly value tools that help them evaluate the vulnerability of critical infrastructure (such as roads, electricity substations and care homes) during the response phase of a flood emergency (Lumbroso and Vinet, 2012). Furthermore, McCarthy et al. (2007) found that models of breach locations and inundation extent were considered useful by emergency responders in the Thamesmead area of London when planning for evacuations or deciding where to allocate resources. Although tools used to determine the extent of flooding (e.g. flood hazard maps) are often well integrated into flood emergency plans in the UK (98% of flood managers said that they used fluvial flood hazard maps to inform emergency plans), other instruments, such as those for assessing the accessibility of inundated roads and evacuation routes, are seldom used (Lumbroso and Vinet, 2012).

Flood emergency plans also need to consider the needs of vulnerable groups, such as the elderly or disabled, as they may need special assistance during flood events (Sene, 2008). Large proportions of the elderly population live in either care homes (where continuous support is provided) or sheltered accommodation (which allows residents more independence while still having the security of a warden) (Shelter England, 2016). However, members of the public have argued that local authorities are good at identifying vulnerable groups when they are located together in care homes or hospitals, but are less able to locate vulnerable individuals in the community (Houston et al., 2011).

1.2. Legislated response times

Emergency responders are often legislated to meet defined response times. For example, UK legislation requires that emergency responders comply with strict timeframes when reacting to incidents. Category 1 responders such as the Ambulance Service and the Fire & Rescue Service are required to reach 75% of 'Red 1' (high-priority, life-threatening incidents) in less than 8 and 10 min respectively from the time when the initial call was received. This includes blue-light incidents such as life-threatening and traumatic injury, cardiac arrest, road collisions, and individuals trapped by floodwaters. In 2015, the BBC reported that the East Midlands Ambulance Service (EMAS) had failed to meet targets to reach the highest priority calls in 8 min for a fifth year running. Rising demand combined with inefficient call handling and dispatch system are often cited as the reasons for missing this target. However, response times can also be affected by flood episodes which may limit the ability of emergency responders to navigate through a disrupted road network. The impact of flooding on road networks is well known and is expected to get worse in a changing climate with more intense rainfall. For example, in Portland, USA under one climate change scenario, road closures due to flooding could increase time spent travelling by 10% (Chang et al., 2010). The impact of an increased number of flooding episodes, due to climate change, on road networks has also been modelled by Suarez et al. (2005) for the Boston Metropolitan area, USA. Their results show that delays and trip-time losses could increase by 80% and 82% respectively, between 2000 and 2100 (Suarez et al., 2005).

1.3. Identification of vulnerable roads and areas

Meeting legislative timeframes for high-priority incidents set by governments requires not only identifying roads immediately at risk of flooding, but also the wider cascading impacts of road closures. Research has focused on the former to evaluate road vulnerability and identify 'strategic' roads. For example, Koetse and Rietveld (2009) suggested that identifying the most vulnerable locations to flooding in a regional road network, as well as those routes that are critical for the operation of the network and accessing facilities such as hospitals, is a crucial part of developing an adaptation strategy. The capacity of the road network to cope with natural hazards such as flooding can be examined using resilience methods, where the redundancy of road links is studied, using the structure of the network and the number of alternative paths when one route is disrupted (Lhomme et al., 2013). Naulin et al. (2013) used a simple rainfall-runoff model to identify roads vulnerable to flooding at the regional scale, validated against observed inundation, focusing on vulnerability rating in ungauged locations. In addition, it is important to note that certain road networks in a city have greater importance in terms of maintaining access between different locations. Recently, studies have established a hierarchy of road network connections to model the impact of loss of important linkages (Albano et al., 2014; Balijepalli and Oppong, 2014). For instance, Albano et al. (2014) found using this method for Ginosa, Italy, that those roads close to health facilities, linking main parts of the town, or with no alternatives were given a high importance in terms of the operation of the network. Using this approach meant that decision makers could identify flood hotspots on the road network which may require prioritisation for risk reduction measures (Albano et al., 2014).

Whilst flood hotspots in a road network may be readily identified, whether a flooded road "hotspot" will translate into wider impacts what will affect emergency response requires further investigation as impacts are often not at the immediate vicinity of a flooded road but can manifest in a much wider context. Research on the wider impacts of road closure due to flooding and its implications for emergency responders' strategic planning and operation has been limited. A few studies have been undertaken for evacuation modelling during flooding. For example, Dawson et al. (2011) developed a multi-agent based model to guide evacuation planning during storm surge flood events, focusing on estimating the vulnerability of individuals to flooding under different conditions (e.g. storm surge, defence breach, flood warning times and evacuation strategies). Yang et al. (2015) developed a model for evacuation planning by coupling routing algorithms with numerical modelling outputs (flood extent). Moreover, a recent study by Andersson and Stålhult (2014) undertook network analysis to determine the shortest routes from hospitals to various administrative regions in the Manila city, Philippines, and the effect that floods of various magnitude had on these routes. Simi-