Assessing the need for infrastructure adaptation by simulating impacts of extreme weather events on urban transport infrastructure

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Summary

Cities face risks from climate change, placing increased pressure on infrastructure extremes. A methodology to assess the impacts of extreme weather events on urban networks has been developed, using a catastrophe modelling approach to risk assessment by overlaying spatial data, applying hazard thresholds, and testing potential adaptations. Utilising future climate projections, downscaled using stochastic weather generators, future urban temperature and flooding extremes are simulated. These are coupled with spatial urban transport network models and, applying thresholds, disruption to the networks can be simulated. Results for heat and surface water flooding events, and the impacts on the travelling public, are demonstrated.

KEYWORDS: climate change, infrastructure, network, flooding, heat, transport, impact

1. Introduction

The IPCC 5th Assessment Working Group 2 (IPCC, 2014) report on climate impacts highlights the risks faced in urban areas by future climate change, but also that the complex nature of urban areas and their interconnected systems means they cannot be considered in absolute terms but as "system of systems" (Lhomme et al., 2011). In particular, infrastructure in cities will be placed under more pressure in the future due to the changes in climate extremes (e.g. rainfall and temperature) and the concurrent increase in demand from population growth and urbanisation (Hallegatte and Corfee-Morlot, 2011).With the frequency of extreme weather events expected to increase, causing severe damage to buildings and infrastructures (Dawson, 2007), addressing robustness of the urban environment under multiple hazards is pivotal. The Tyndall Centre's Urban Integrated Assessment Framework (UIAF) was developed (Hall et al, 2010) to allow the assessment of the urban impacts of climate change coincident with other changes which may be seen in cities.

The work presented in this paper highlights a rapid assessment methodology using the UIAF for understanding potential future impacts on the users of urban transport networks from extreme weather events. This begins with climate downscaling using the UKCP Weather Generator and, in the case of extreme rainfall, simulation of surface water flooding using the CityCat model. The spatial footprints of resulting climate hazards are then overlaid on the urban transport networks and thresholds applied to understand where impacts will be felt. These impacts can then be assessed in terms of increased travel time for the users of the transport infrastructure and the total cost of disruption calculated. This methodology is demonstrated in this paper for both extreme heat and extreme rainfall events, on public transport and road networks in the UK.

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2. Method

2.1. Hazard modelling

The initial step of the risk-based approach is to understand the hazards to which the system may be exposed. An Urban Weather Generator (UWG) has been produced to supplement the UKCP09 outputs and provide hourly time series of weather variables, such as rainfall or maximum temperature, for future climate scenarios at 5km resolution. The UWG uses a stochastic rainfall model coupled to change factors using probabilistic projections from UKCP09 (Jones et al., 2009). Recent advances in the UWG give an improved reproduction of extreme temperatures, spatial correlations in weather (Kilsby et al., 2011), and urban heat island effects (McCarthy et al., 2012).

The outputs from the UWG are used to assess the spatial and temporal variation of hazards in the urban area. A thresholding approach is applied with impacts assessed when the climate inputs exceed a certain level of severity. For extreme heat events, temperature thresholds are defined above which it is expected disruption will begin to be felt on transport networks. For extreme rainfall events, a further intermediate step is needed to translate heavy rain into flood extents using City Catchment Analysis Tool (CityCAT) developed by Newcastle University (Glenis et al., 2013), the thresholding being applied to the resultant water depths, an example output shown in Figure 1.

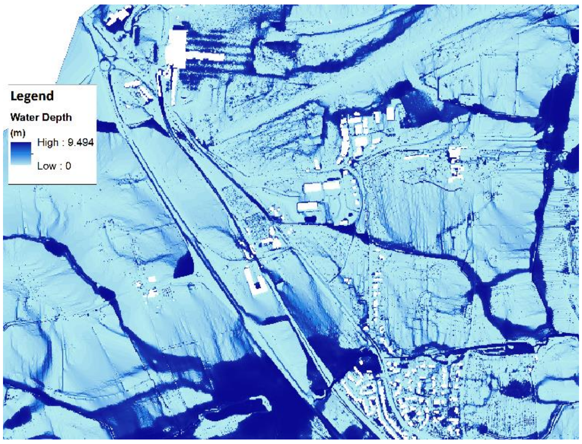

Figure 1 An example output from CityCat showing the depth of water (hazard map) across an urban area during an extreme rainfall event at 1m resolution (2 hours of duration, 200 ys return period).

To calculate the disruptive effect of flooding on transport networks, a function that relates water depth to safe driving car speed has been developed from combining data from experimental reports (Morris et al., 2011), safety literature (Great Britain Department for Transport, 1999), analysis of videos of cars driving through floodwater and expert judgement.

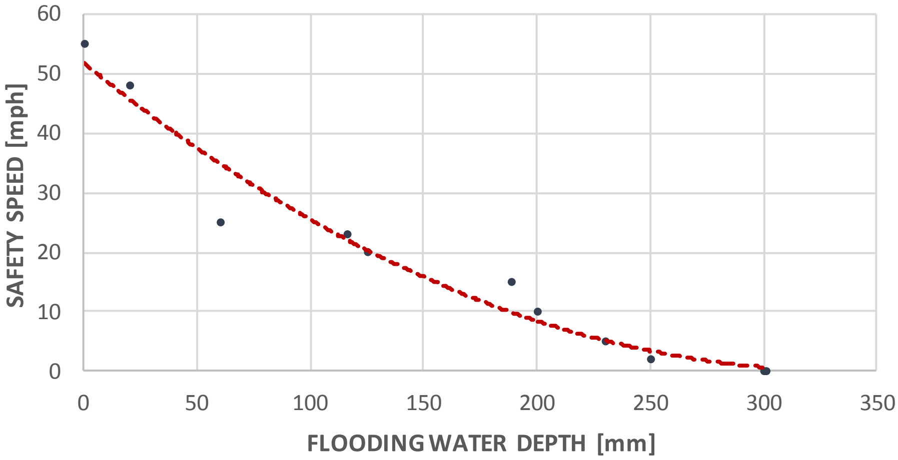

Figure 2 Representation of the safety driving speed as a function of the flooding water depth.

Heat impacts are considered on the railway network. Dobney et al., (2009, 2010) showed that disruption to railways in London and the South East can occur when temperature exceeds 27°C, based on analysis historic rail buckling events in the Network Rail Alteration database and the corresponding observed temperature. The frequency with which 27°C is exceeded in UWG outputs for a given climate scenario is assessed. Figure 3 shows the probability of the annual number of days where the maximum temperature in one or more grid cell in the study area exceeds the 27°C threshold for a range of time-periods and climate scenarios.

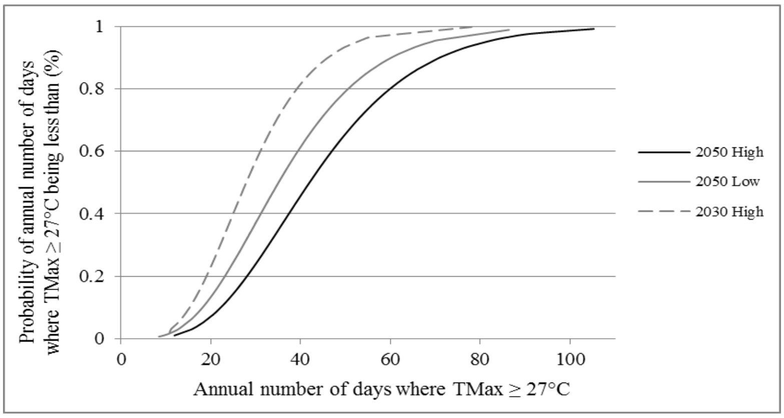

Figure 3 Probability of the annual number of days where TMax exceeds 27°C for one or more grid cells in the study area, for the 2030s and 2050s under low and high emission scenarios

To analyse the impact of these events on the transport network, further temperature thresholds are related to speed restrictions imposed on railway lines (see Table 2). Single days in the UWG outputs are identified at least one grid cell exceeds one of these thresholds and then the maximum daily temperatures for each of these events can be mapped spatially across the study area on the 5km grid. Figure 4 shows the number of times each grid cell in the London study area exceeds the 27°C temperature threshold.

Table 2 Temperature thresholds where speed restrictions are imposed.

Threshold	**Speed restriction**
<27°C	None
Poor Rail Track ≥ 27°C < 28°C	30mph
Poor Rail Track ≥ 28°C	20mph

Moderate Rail Track ≥ 33°C <35°C	60mph
Moderate Rail Track ≥ 35°C	20mph
Good Rail Track ≥ 36°C	90mph
Good Rail Track ≥ 42.6°C	60mph

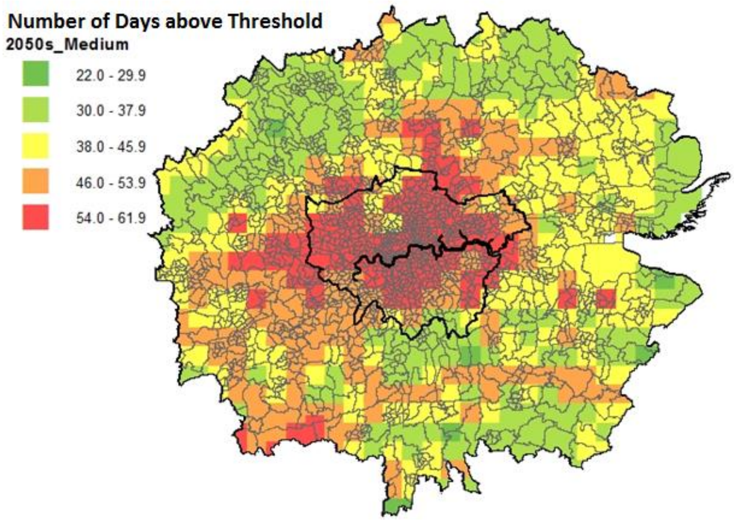

Figure 4 Number of days in a given 100-year simulation from the UWG for Greater London where the maximum daily temperature exceeds the 27°C threshold.

2.2. Exposure modelling

As the study is focused disruption to commuter journeys, a simple model of network trips was developed using ArcGIS. The model a Frank-Wolf-style trip assignment algorithm (Dafermos and Sparrow, 1968) to load journey-to-work (JTW) observations from the 2001 UK census onto network representations. Networks were constructed from publicly-available data sources (e.g. Ordnance Survey ITN and Meridian data, UK NAPTAN data for public transport stops) supplemented with speed and capacity information. These extra elements allow the calculation of shortest routes in terms of time between origin and destination locations for the JTW observations. Using this model, the appraisal of both the relative importance of network segments (in relation to their levels of use) and the number of users considered in the disrupted network could be achieved.

2.3. Risk Modelling

Spatial footprints of hazards, either from heat or flooding, are overlaid on transportation networks in GIS to calculate of disruption, Thus, the spatial footprint of the hazard (i.e. a 5km grid cell in which the defined temperature threshold has been exceeded, or a 1m grid cell in water depth has exceeded the a given value from Figure 2) is overlaid on the transport network, the travel speeds on the disrupted network segments adjusted, and new travel times between sets of origins and destinations calculated. By comparing the perturbed travel times with travel times before disruption, the impact on commuting journeys can be estimated, and since the number of journeys using that route is known from the JTW table, the total impact in terms of Person-Minutes can be computed.

3. Results

For flooding, analysis has been conducted on the Newcastle road network based on the comparison between the pre-event and post-event travel time maps (see Figure 5). In the pre-event map, the free-flow car speeds are assumed, whilst in the post-event map travel speeds are adjusted according to the water depth-speed curve and new travel times generated. By comparing pre- and post-event maps, delays caused by flooding to commuter routes can be estimated in terms of delay minutes and economic metrics, based on the generalised cost of travel. Adaptation options can then be assessed, through adjustments of land use and building characteristics in CityCat, and comparison between scenarios determines the cost-effectiveness of the solution considered.

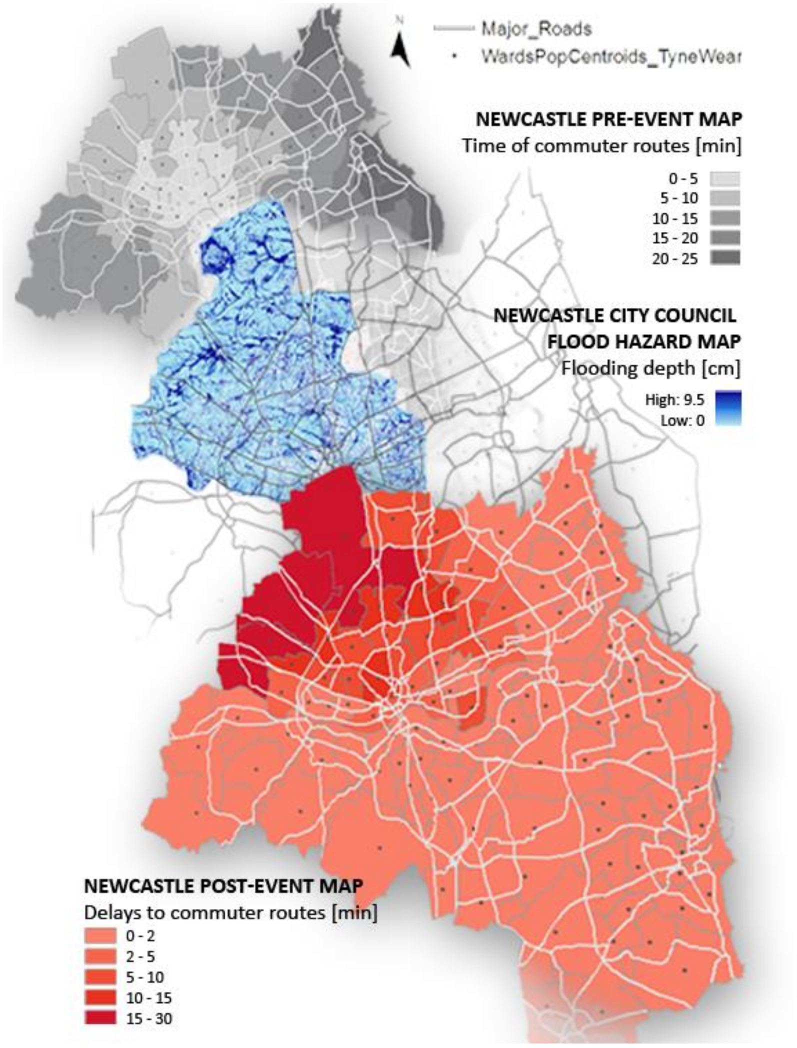

Figure 5 The results maps from the analysis in Tyne and Wear

For heat disruption, 18 daily events in Greater London were produced by sampling across a range weather generator simulations. For each of these events, a map of daily maximum temperature was produced and overlaid on the railway network as described above, and the impact on the railway network calculated in terms of speed restrictions and thus increased travel times. Figure 6 shows the relationship between the magnitude of each sampled event and the total person delay in minutes which results from the disruption to the network. In this example, it is assumed that all track in the simulation is of Poor quality (see Table 2). In order to represent simple adaptation to future temperature changes, similar simulations were also run with assumptions that all track was Moderate or Good.

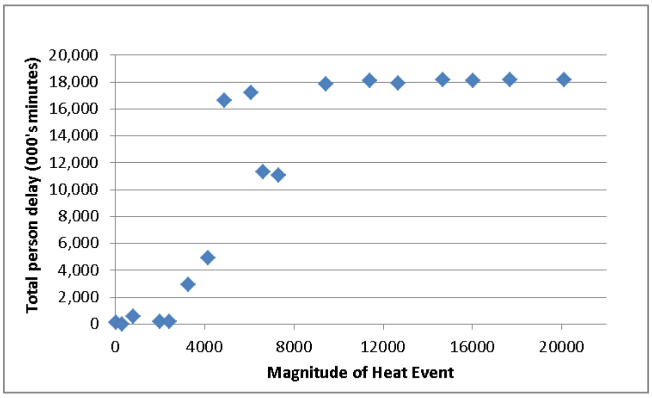

Figure 6: Total delays for each of the 18 events of different magnitudes

4. Conclusion

This paper has presented a methodology to investigate the impacts of extreme weather events on urban environment, in particular infrastructure networks, through a combination of climate simulations and spatial representations. By overlaying spatial data on hazard thresholds and transport networks, disruptions to commuting journeys are evaluated. This approach can be applied to the present conditions as well as future uncertain scenarios, allowing the examination of the impacts alongside socio-economic and climate changes.

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7. Biography

Alistair Ford is a research associate in the Centre for Earth Systems Engineering Research and School of Civil Engineering and Geoscinces at Newcastle University. His work involves developing models of climate impacts on urban areas, assessing future climate change and socio-economic change concurrently. He was worked on the Tyndall Centre Cities programme, the EPSRC ARCADIA project, and is currently working on the EC Framework 7 RAMSES project.

After a Master Degree in Building-Engineering Architecture at the University of Pavia (Italy) and at Tongji University of Shanghai (China), Maria Pregnolato started her PhD at Newcastle University (UK). Her research consists of advancing multi-hazard modelling and decision-support study to shape the management of risk and associated uncertainties of urban systems.

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