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Mapping urban infrastructure interdependencies and fuzzy risks

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Abstract

In this study, we considered the relationships between different types of CI and services to simulate possible cascading effects during extreme hazard conditions brought on by climate change and how to analyse impacts with limited data resources. An area in central Bristol, UK, was used as the case study to investigate the interdependencies among select assets and services. A wide range of plausible scenarios caused by pipe bursts in the area were simulated using the CADDIES 2D modelling framework, to identify the hotspots with high risk. The impact on CI, including water supply, electricity, wastewater, solid waste, transportation, telecommunication, and emergency services were assessed by the HAZUR tool. The analysis demonstrated that with limited data resources the dynamics of the interdependencies between CI networks can be highlighted and a basis of risk quantification can be established. The same procedure can be repeated to evaluate the impact of other types of hazards, or the compound hazard scenarios to provide a holistic assessment. Therefore, urban planners and managers can further explore options of interventions for setting up strategies to strengthen city resilience.

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Keywords: critical infrasttructure (CI); cascading effects; multisectorial approach; interconnectivity; flood resilience.

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1. Introduction

Urbanisation, population growth and increasing reliance upon secure and dependable services such as water, energy and telecommunications has put pressure on urban Critical Infrastructure (CI) networks and associated services. However, with technological advancement comes increasing interdependency, with almost all networks experiencing some degree of reliance upon other CI and the failure of a single element of the urban network can quickly cascade, impact other CI or escalate to other systems, potentially paralysing the entire network for an extended period.

The functioning of modern cities relies on the services of many CI networks such as the energy grid, water supply, transportation, telecommunication, etc. These CIs are interconnected and cannot operate in isolation to deliver their services to end users. A failure in one CI network could quickly propagate across the network and affect other CI services. Such cascading effects can be investigated at a 'systems of systems' level instead of individual system to determine how the interdependencies among different CIs influence the services to the whole community [1].

Within the water supply network, for example, a burst main may not only limit water supply service to a region, but also cause localised flooding, this flooding could damage a substation supplying electricity to a railway or road traffic signals and bring the transportation network to a halt. Another example is an extreme storm surge that may lead to coastal flooding inundating a wastewater network pumping station, subsequently causing sewer flooding and Combined Sewer Overflows (CSO). Both examples of flooding could likely disrupt road networks, potentially isolating the area and preventing emergency services from reaching vulnerable communities in good time. Once the interdependencies are identified, the risk of various hazard scenarios can be properly evaluated to help decision makers set up adaptation strategies for enhancing urban resilience against hazards.

The RESCCUE (RESilience to cope with Climate Change in Urban arEas) project aims to develop a multi-sectorial approach, focusing on water to improve the resilience of urban services for the future climate. Within RESCCUE, a comprehensive flood resilience assessment framework is developed considering the impacts on natural, physical, economic, social and institutional dimensions to quantify the effectiveness of adaptation measures. This framework involves all urban services and functions potentially affected by flooding e.g. transport, the other water systems, energy supply, solid waste, etc.

In the winter 2016/17, Thames Water experienced three major mains burst events in one week and attended to 1,000 pipe burst repairs within another week [2], [3], hundreds of residents were evacuated during the accidents and main roads were closed for several days. Thames Water reviewed the causes of eight high profile events but concluded that there were no common causes for all the events [4]. However, better risk management practice and improved predictive analysis was cited as a key recommendation for preventing future accidents.

In this paper, we demonstrate the concept of CI interdependency through the evaluation of burst water mains scenario in Bristol, UK. This relatively simple case study tests the approach of analyzing impacts with limited data and the results show the feasibility of the methodology can be implemented for more complex scenarios.

2. Methodology

Due to the sensitive nature and/or absence of data relating to the spatial location of the water distribution systems network we're making inferences about the supply network and likely burst points along the network. The burst points along the network are in relative proximity to each other and a flood model is run for each scenario. Due to the assumptions made both in terms of network layout and burst point locations, the resulting flood maps are speculative and as such a fuzzy based approach was used to define the risks of CI being impacted by burst water mains in this study.

2.1. Case study

In order to demonstrate the links between water, health and energy networks, a small area in the center of Bristol was chosen. This area houses Bristol Temple Meads (Bristol's central train station), the Bristol Royal Infirmary (one of Bristol's major hospitals) and emergency services as well as being a high density residential and business district.

As the exact location of the water distribution network in this area is unknown, we assumed that the pipe network follows the road network. Failure or 'bursting' points were set at 100 m linear intervals along the pipe network.

2.2. Flood simulation

A flood model simulating a pipe burst event at each of these locations was run separately using the CADDIES 2D. The CADDIES 2D model thus generates a maximum flood depth inundation map for each simulated burst location. This model was chosen due to its computationally simplified Cellular Automata approach that allows for multiple simulations to be carried out in relatively short time frames in comparison to more computationally demanding models [5].

2.3. Identifying high risk areas

Fig. 1 shows the flow process of how maximum flood depths from each model are used to derive the final fuzzy risk occurrence map. The fuzzy risk occurrence map is then combined with the maximum depth maps to create a risk matrix view (Fig. 2) of the risk of impacts to an infrastructure, where we combine the level of impact (associated with maximum depth value) with the likelihood of impact (derived from fuzzy occurrence map). To achieve this the occurrence likelihood raster map that was generated is reclassified to a range of 0 – 3 that corresponds to a zero membership (value of 0) or high membership of a cell being flooded (value of 3). An additional overall maximum depth raster map is also created by combining all the maximum depth maps from each simulation (from 1 to *N*) and only taking the maximum recorded depth in each cell. These depths are then also reclassified with ranges from 0 – 3 based on the perceived severity of impact water depth in that cell could cause. The sum of these two raster maps thus creates a risk score map corresponding to both the flood class membership and perceived severity of the flood impact.

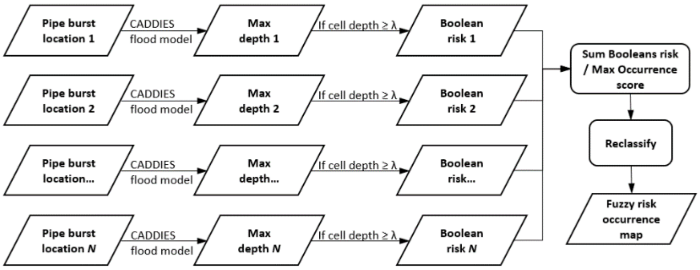
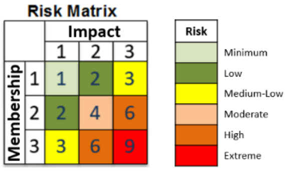


Fig. 1. Creating fuzzy flood risk map from pipe burst events

Previous research has been done in translating water depth data into monetary damage via spatial analysis of water depth data and its proximity to buildings with different land use characteristic [6]; a modified version of this approach was used where the risk map data is substituted in place of water depth data. Spatially analysing the risk output data with respect to its proximity to critical infrastructures, allows for risk scores can to be applied to each infrastructure.


Risk Matrix

		Impact		
		1	2	3
Membership	1	1	2	3
	2	2	4	6
	3	3	6	9

Risk	
	Minimum
	Low
	Medium-Low
	Moderate
	High
	Extreme

Fig. 2. Simple 3 x 3 Risk Matrix where risk = likelihood x impact

Fig. 3 shows the layout of the sections of pipe, with 21 simulated burst locations and a number of CIs including electrical substations, emergency services, hospitals and the railway.

When investigating the possible impacts of flooding within the area, three classes of risks were analysed:

- Direct risk of flood water on infrastructures;
- Indirect risk to infrastructure/service due to potential loss of power; and

- Indirect risk to infrastructure/service due to diminished road access.

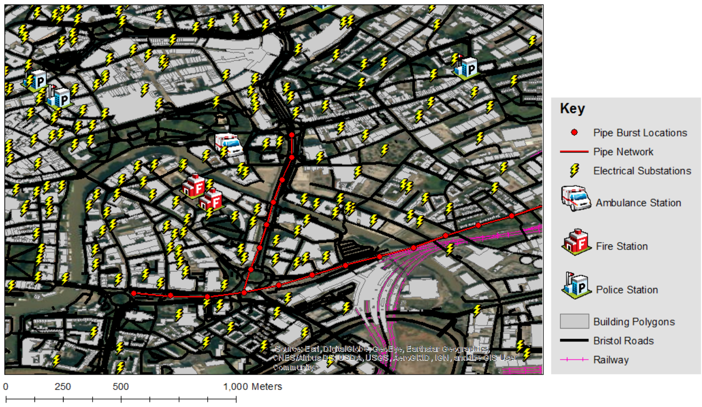


Fig. 3. Study area around Bristol Temple Meads indicating key critical infrastructure locations and theoretical pipe network

The direct risk level to an infrastructure is determined by analysing the values of the fuzzy risk map that are within range (2 m buffer) of building polygons. The indirect risk to infrastructure due to power loss is determined by analysing the risk levels in proximity to electrical substations potentially supplying power to those buildings. Due to the absence of data in relation to which substations provide power to which buildings, it was assumed that electricity supply to buildings comes from the nearest substation. In this approach, we assume that there is a high likelihood that an infrastructure that lies within a substation's service area is supplied energy from that substation. To define the area that is receiving power from an electrical substation we generate Voronoi (otherwise known as Thiessen) polygons [7] and assume power is provided to the buildings that lie within these zones. The final indirect risk to an infrastructure relates to the perceived level of access to roads. If flood water presents on the road (or railway) and the depth is above a threshold depth, then the road (or railway) was assumed to be either blocked or at a reduced capacity.

Within the scope of this paper the primary focus was on the impacts of a pipe burst upon the emergency services within the study area.

3. Results & Discussion

For pipe failure scenarios, we assumed that the pipe network was part of a trunk main with a diameter of 800 mm and a flow rate of 300 L·s^{-1} with a burst duration of 2 hours. As there are 21 burst pipe locations (shown in Fig. 3), the CADDIES 2D was run multiple times to generate 21 possible maximum depth flood extents. Utilising the approach depicted in Fig. 1 and setting a threshold depth of 0.1 m, a fuzzy occurrence map was generated (Fig. 4A).

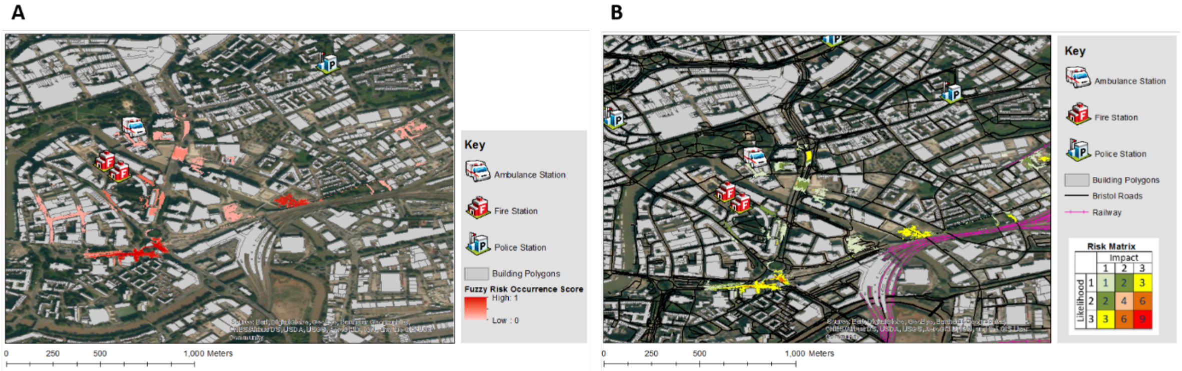


Fig. 4. (A) Fuzzy occurrence map due to pipe burst scenarios, (B) Derived fuzzy flood impact risk map

For this study of 21 simulations (pipe burst locations) were carried out. During the simulations the maximum percentage of times certain cells were flooded with a depth equal or greater than 0.1m was 33% which corresponds (in this instance) to the highest level of membership of a cell being in a flooded state. The maximum recorded water depth in a cell during all the simulations was 3.6m. To convert this information into a fuzzy impact risk matric as defined in Fig. 2 we need to reclassify memberships and depth/impacts into values ranging from 0 – 3. The derived risk matrix is thus calculated via reclassifying the data from the fuzzy occurrence outputs and the impact level derived from maximum depth (**Error! Reference source not found.**). This reclassification of data generates a fuzzy risk raster map that is depicted in Fig. 4B where the level (value) of risk is colour coded with respect to the Risk Matrix view. The distribution of risks reveal that the emergency service locations are at risk, as well as the railway track near the main train station. Significant risks to some commercial buildings in the south of the region are also identified though these were not investigated within the scope of this paper where the focus is on the emergency service sector.

Table 1. Reclassification of data to generate risk matrix

Fuzzy Risk Occurrence Score Range (%)	Reclassified Flood Membership Level	Depth Range	Reclassified Flood Impact Level
0 – 0.0476	0	0.0 – 0.1	0
0.0476 – 0.095	1	0.1 – 0.5	1
0.095 – 0.190	2	0.5 – 1.0	2
0.190 – 1.00	3	> 1.0	3

3.1. Direct risk to buildings

The estimation of risk posed to infrastructure is determined via examining the overlap of the risk matrix data with the footprint of the infrastructure data (plus a buffer zone around the infrastructure data). In the case of the emergency service buildings, this analysis reveals that that both the ambulance station and the fire stations are at risk of direct damage due to flooding from the simulated bust pipe scenarios. Fig. 5 shows that the overall level of risk in this instance is greater to the fire station than that of the ambulance station.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 5. Risk of buildings being impacted

3.2. Indirect risk - Power loss

As the substations are represented by point datasets a 10m circular buffer zone is applied around each of the substations and a value of the impact risk was derived again via analysing the overlap of risk matrix data with these substation buffer zones. The service areas of each of the affected substations is thus linked with the previously derived Vornoni polygons, that were then used to identify the zones an risk levels to infrastructures that were likely to experience some degree power disruption (Fig. 6). In Fig. 6 only one of the two fire station buildings are affected (highlighted by the red square) due to the other part of the building lying within a different electrical substation zone. Visual analysis shows that several substations within the immediate vicinity of the ambulance station could be potentially taken offline. This visual analysis of risk indicates (based on the assumptions made for which substations provide power to which buildings), that the ambulance station is at greater risk of power disruption.

Fig. 6. Indirect risk due to power loss

3.3. Indirect risk - Road access

The final analysis shows that the resulting water from the simulated pipe bursts could potentially disrupt road access in the vicinity of both the emergency services in question (Fig. 7). The major road network to the east of these stations is also at risk, potentially reducing access to the south-eastern part of the city.

Fig. 7. Indirect risk due to road access

3.4. Stakeholder engagement

The fuzzy-based approach serves primarily as a means of beginning to quantify impact (reduction of failure of a service) risks provided by an infrastructure. It is envisioned that these results could potentially be used as a means for engaging with stakeholders to encourage the release and sharing of high quality data to improve the understanding of the interdependencies between infrastructures and the inherent risks that come with these. For stakeholder engagement the information derived from a fuzzy-based analysis can be fed into tools for use in managing the resilience of a city whereby the impacts (both direct and indirect) of certain events can be visualised along with the prospect of highlighting potential cascading effects. For example, in the HAZUR®[†] software we can define the services and spatial data highlighted earlier in this paper along with their associated interdependencies e.g. which substations are likely to provide power to which buildings and the main roads that are in proximity of those buildings which are needed for the services to function adequately. Once the interdependencies have been defined we can (based on simulation results) define an event and its impacts through the HAZUR® interface via the "WHAT IF" screen. Fig 8 shows how this data can be ustilised in such a tool with selection of screen grabs taken from the HAZUR® interface.

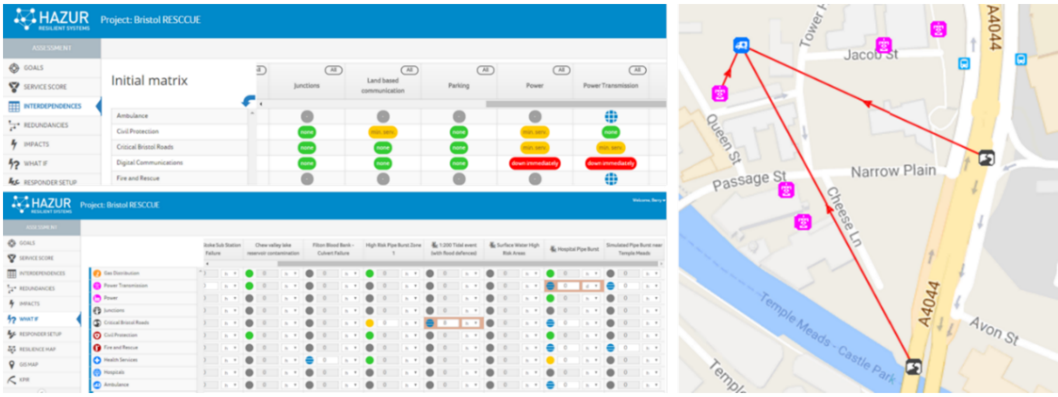


Fig 8. INTERDEPENDENCIES, WHAT IF, and GIS MAP data view partial screen grabs taken from the HAZUR tool

The HAZUR® tool facilitates the collection of data about services, infrastructures, interdependencies and impacts from multiple users to build up a comprehensive perspective of the workings and resilience of a city and highlighted the potential consequences of given impacts. By having all these interdependency links in place this tool can potentially highlight indirect and cascading effects of disasters (such as a pipe burst) which may not be immediately obvious to stakeholders. By analysing this information the users of the HAZUR® tool can evaluate the resilience of their city to certain impact driven events and if needed take appropriate action to improve the level of resilience in anticipation of such events

4. Summary and Conclusions

This study has investigated the possibility of building up a picture of small section of a city with limited data to assess the level of risk to selected CIs would fair against a potential pipe burst event.

Due to the very nature of CIs data there may be limitations on the availability of high quality data to carry out detailed analyses. In the absence of such data, obtaining a fuzzy-based perspective on the risks associated with services within a city is a promising approach as first order approximations can be made, high risk areas identified and situations analysed in greater detail as and when more data becomes available.

[†] http://opticits.com/

The results of this study have shown that even with limited data sources a fuzzy based analyses with logical assumptions made can begin to create a picture of the level of risks present to CIs within a city. Utilising this fuzzy based approach in conjunction with city resilience managing software could provide a baseline for stakeholder engagement whereby the model can be later refined as and when more detailed data/information becomes available.

This framework applied in conjunction with the HAZUR® software could allow city managers to understand potential cascading effects resulting from an event such as flooding. Improved visualisation and understanding of the related risks to CIs enables the development of tailored prevention, mitigation and response plans and measures, making this approach an invaluable mapping exercise for decision makers interested in the resilience of urban CIs.

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