About flood risk in the City of York

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***Abstract*—The City of York is particularly susceptible to flooding due to its location in the confluence of the River Ouse and River Foss. This report covers the implications of flooding in the financial and societal point of view, noting how global climate change can enhance its consequences. Also, an hydrodynamic simulation of the City of York has been performed in order to analyse the effects of a 500 m^3/s discharge in the North Street-Skeldergate area.**

I. INTRODUCTION

YORK has always been a very active area historically due to its location. York is placed in the Vale of York, a region of prolific arable land bounded by the Yorkshire Wolds, the North York Moors and the Pennines, and established at the juncture of the Rivers Ouse and Foss.
In the Roman era, the land around its rivers was miry, making the location simple to protect. Also, the city became a major trading centre in the 13th century due to its closeness to the Great North Road, accelerating the development and expansion of the city boundaries. By the late 19th century, York was built up as a major railway centre, bringing a noticeable number of workers to the city and serving to its enlargement.

River Ouse drains the Yorkshire Dales catchment and the eastern slopes of Pennines, and is formed mainly by the rivers Ure, Nidd, Swale and Foss. When heavy rains occur, the water collected by the Ouse runs rapidly from the higher ground north of York and rushes down its tributaries towards the city, making it especially prone to inundation.

York has an extensive historical flood record, dating back to 1263 A.D. The most severely damaging floods of the recent era occurred in 1947, 1978, 1982, 2000, 2012 and 2015[1]. Since then, defences have been constructed to manage periodic flooding. However, systematic flooding after their construction has increased the attention to the flood defence systems used in the City of York, where, accordingly to the Environment Agency[1], there are more than 6000 properties at risk of flooding.

The location of the City of York, in combination with modern city development, which tends to be built on hard surfaces deteriorating the draining capacity of the soil, and the negative perspectives of climate change, which according to Defra river peak flows could increase up to 20% over the next 50 years[2], make the protection of York against floods a major challenge for the present and future.

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II. ECONOMIC CONSEQUENCES

THE Roman roots and Viking past of York build its streets with an unique spirit of ancient history. York keeps intact some of its medieval features such as The Shambles, the Walls, the York Minster or the Merchant Adventurers' Hall. Due to the diversity of cultural activities the City of York offers, it has an strong focus on tourism and receives around 7 million visitors annually, supporting roughly 20000 jobs and contributing £500 million to the local economy[3].

According to the Environment Agency, it is difficult to evaluate the impacts of floods on tourism because these are likely to be transferred to other impact categories. However, the Environment Agency estimated at national scale flood damages on tourism of roughly £20 million between 2015 and 2016[4].

Floods can have disastrous consequences on the local businesses. Within the City of York there are roads prone to flooding which locate small retail businesses, and flood effects may result in damage to premises, equipment, loss of stock and business disruptions. The Environment Agency calculated at national scale damages to business properties worth up to £500 million between 2015 and 2016[4].

After 1978 flood, a defence building strategy was initiated. Leeman Road and Lower Ebor Street were the first areas to be protected since these were badly flooded in 1978. Flood walls were built in combination with flood banks and sewerage system improvements. In 1982, at a cost of £1.25 million, the flood banks in Clifton Ings were raised to increase the water storage in response to the 1982 floods which caused £1.2 million worth of damage to 134 properties in Lower Bootham and other areas of the city[5]. Also, the Foss Barrier was built to maintain an optimum level of water in the River Foss by pumping water into the Ouse. The total cost of the barrier was £3.34 million[6]. Since then, the Environment Agency has been responsible for the flood walls, gates and embankments built during the following years.

The stage height recorded at North Street in York on 28 December 2015 was the second highest level ever recorded (10.20m AOD), resulting in the worst flooding seen in York since 1982 in terms of impact on the city. At least 627 properties were flooded (453 residential and 174 commercial), including the BT exchange building, which resulted in the loss of phone network to approximately 50000 customers[7]. In response to this, additional £45 million were destined to the Environment Agency and £17 million to upgrade and improve the Foss Barrier to better protect 2000 properties in

York[5]. Some of the last investments include £200000 a year spent on maintaining the River Foss and the Foss Barrier over the past 5 years, £5.2 million in the flood alleviation scheme and £500000 in Property Level Resilience Grants to help residents[5]. This, in combination with the budget spent in previous years sum up a total of approximately £100 million in flood defence systems since 1978.

III. Environmental implications

Global climate change is one of the humanity's greatest challenges. Man-made greenhouse gas emissions, largely associated with the burning of fossil fuels, are considered the major contributory cause to global climate change. The Intergovernmental Panel on Climate Change notices that a warmer climate is likely to increase the frequency of heavy precipitation, and this would contribute to increases in local flooding[8]. Figure 1 shows the evolution of the global flood exposure for the 20C 1% flood, or above, in millions, for 11 different scenarios, predicting 27 million people with the 2°C increase, 62 milion with the 4°C increase and 93 million with the 6°C increase[9].

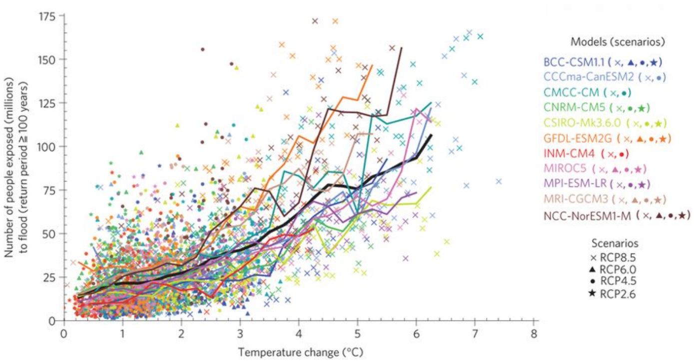

Fig. (1) Global flood exposure for the 20C 1% flood, or above, in millions against global temperature change. Historical simulations (thick black line) and the future simulations for each scenario (coloured lines). Shading denotes the ± 1 s.d.[9].

Defra has taken a safety approach to increased flood risk due to climate change. Table 1 shows the recommended national precautionary sensitivity ranges for peak rainfall intensities and peak river flows[1]. These ranges may provide an appropriate precautionary response to the uncertainty about climate change impacts on rainfall intensities or river flows, and should be taken into account for future flood defence constructions or flood risk scenarios. These estimates are that peak river flows in the UK could be 20% higher by 2025, which could have severe consequences in a country where tenth percent of the population lives on floodplains[2].

Flood risks in York can be increased due to climate change by two mechanisms: more intense rainfall will increase peak river flows and soil will tend to be wetter, worsening its draining properties. Figure 2 shows the increase in the annual

Parameter	1990 to 2025	2025 to 2055	2055 to 2085	2085 to 2115
Peak rainfall intensity	+5%	+10%	+20%	+30%
Peak river flow	+10%	+20%		

TABLE (I) Recommended national precautionary sensitivity ranges for peak rainfall intensities and peak river flows[1].

maximum levels at the 'Viking' river level recorder[5]. The steady increase in the annual maximum of the River Ouse, in combination with the Defra's safety approach and the evolution of the global flood exposure, make necessary a long-term strategy to mitigate the effects of climate change and reduce the risk of future floods.

The Environment Agency has already started a plan of action which takes into account the consequences of climate change[5]. The plan has a focus on:

- Upgrade new and existing developments to reduce the future flood risks.
- Enhance flood forecasting tools to issue more accurate flood warnings.
- Improve the upstream flood management techniques to soften the flow water into the city.

Traditionally, the hydrological models used for flood frequency estimations are rainfall-runoff models, requiring inputs such as catchment-average rainfall and potential evaporation, with their linked uncertainties[10]. Taking in consideration global climate change requires estimates of climate variables such as air temperature or precipitation, which are not exempt of uncertainty. These variables include assumptions in the population growth, energy demand or greenhouse gasses emissions[11]. In conclusion, global climate change is a potential game changer that could remodel the way risk-based strategies against floods are performed.

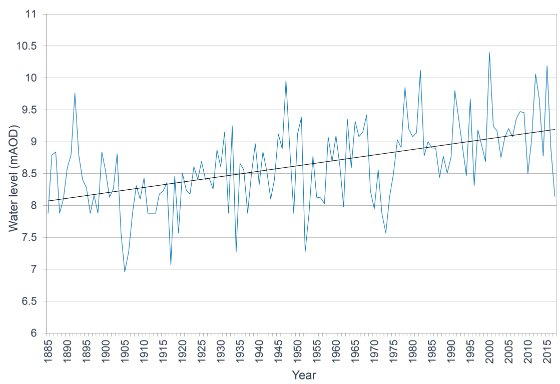

Fig. (2) Increase in the annual maximum levels at the Viking river level recorder in central York[5].

IV. Impacts on society

Despite substantial investments done to prevent and manage floods, they still are one of the most devastating natural hazards. Their unpredictable behavior and sudden onset can result in loss of lives and long-term health effects.

Table 2 summarizes some negative flood impacts on society. The most immediate and apparent impact of floods is direct damage caused after physical contact with flood waters, injuring people or even causing death. Intangible impacts are harder to quantify, as they only become apparent after some length of time[12], normally appearing when emergency situations are already settled and reconstruction work is ongoing.

	Tangible	Intangible
Direct	Physical impact of floodwaters causing damage to: - Infrastructure - Houses	Phyisical impact of floodwaters causing: - Casualties - Injuries
Indirect	Impacts outside of the flood zone: - Disruptions	Societal impacts outside of the flood zone: - Social life destruction - Long-term health effects

TABLE (II) Typology of negative flood impacts and examples[13].

The number of casualties a flood can cause depends on its severity and population vulnerability characteristics. Flash floods tend to have a higher mortality rate than fluvial floods. Figure 3 shows a geographical analysis of global flood fatalities from 1980 to 2015 according to EM-DAT[14]. The highest number of fatalities occurred in Asia (67%), followed by America (22%). These distribution of fatalities differs from economic flood losses, where Europe suffers most of them. This has been associated with the improved disaster management and early warning capacity of the industrialized countries constituting Europe[15].

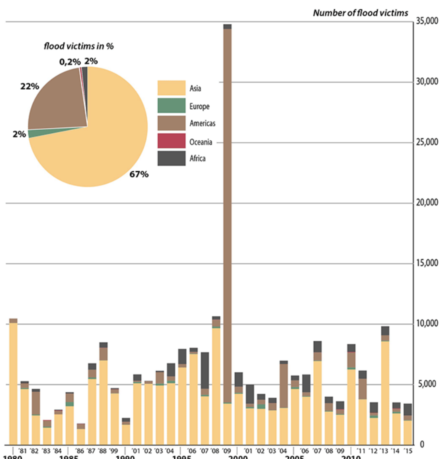

Fig. (3) Geographical analysis of global flood fatalities from 1980 to 2015[14].

Scientific knowledge is reduced on indirect intangible impacts compared to more apparent direct costs[16]. Floods can spread diseases by contaminating water or food and causing diarrhea, cholera, hepatitis or other viral sicknesses[17]. In general, health impacts of flooding vary between low and high-income countries: developed countries tend to have high standards of water quality or hygiene and health care is usually efficient[12].

The most common mental disorders reported to increase after flooding are anxiety and depression. These mental illnesses are often described in the context of pos-traumatic stress disorder (PTSD)[18]. However, robust findings on mental impacts of flooding are rare[12], making necessary to undertake more research on health impacts after flooding.

V. Engineering solutions

RECENT improvements in computational power have enabled the possibility to develop studies and perform simulations on complex systems and environments. Also, the amount of data available from diagnostic and monitoring networks increases over time. The combination of both has opened a broad framework of possibilities to analyse and evaluate different modeling techniques without precedents.

UK disposes of a substantial forecast monitoring system, which helps to gather large amounts of data regarding river levels, discharges or rainfalls[19]. Also, EDINA at the University of Edinburgh operates Digimap, an online map and data delivery service, which includes Ordnance Survey, historical, geological, LiDAR and marine maps and spatial data[20]. Combining forecast information and the data from Digimap it is possible to build weather prediction models or study the effects of heavy rainfalls on cities using different approaches.

In this section, an hydrodynamic simulation of the City of York has been performed using digital elevation models from Digimap and ANUGA, an open source software for the simulation of the shallow water equations, developed by Geoscience Australia and Mathematical Sciences Institute at the Australian National University[21]. The scenario simulated replicated a discharge of 500 m^3/s in the River Ouse, and the area studied corresponds to North Street and Skeldergate, considered a flood Zone 3 and prone to rapid inundation. Since it is widely accepted that is not possible to prevent all flooding, these analyses can help to study how to mitigate and reduce the impacts of flooding.

A. *Rapid Inundation Zones*

The River Ouse responds to heavy rainfall in a relatively slow way, taking between 1 and 1.5 days to reach the City of York from the upper catchment based on upstream conditions. Rapid inundation zones are areas where the combination of water depth and velocity could lead to potential damages or even loss of lives. These zones can be identified by carrying out hydrodynamic analysis within the city, and studying how the flooding evolves over time.

Table 3 illustrates the potential danger to people in a Rapid Inundation Zone during defence breach scenarios[1]. It provides a simplified guide to classify groups of people that should be considered in potential risk scenarios. White colour indicates no danger for any group, yellow colour represents cases where children and the elderly could be in danger, orange colour includes the general public and red colour includes emergency services.

Velocity (m/s)	Depth of flooding (m)										
	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.80	1.00	1.50	2.00	2.50
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TABLE (III) Relationship between flood depth,velocity and danger to people. Red indicates danger for all, orange is danger for most, yellow danger for some and white no danger[1].

The conclusions of the Flood Risk to People project show that flood depths below 0.25m and velocities below 0.5m/s are usually considered low hazard. When planning secure access and exit ways, the combinations of depth and velocity on these should be in the white boxes of the diagram. The risk increases as flood depth or velocity increase. Also, to produce the above table, a debris factor has been taken into account in the calculations.

However, these classifications should be contemplated as subjective, and are mostly appropriate to identify the least risk areas within the area studied in order to set a successive approach to assign land for development. Mostly, this recommends that within the first few hundred meters of the defence, development should be avoided, because there is a risk to all people exposed to floodwater. The secure distance relies on the head of water above the floodplain. Furthermore, the velocities in this zone will be generally high and subsequently there is a direct risk of damage to people and/or properties.

B. *Digital Elevation Model*

Digital elevation models (DEM) are 3D computer graphic representations of a terrain's surface. Some of the uses DEM have are to create relief maps, perform geography analyses or hydrology modeling. These models are constructed using LiDAR data, which is captured by firing rapid laser pulses at the ground surface from an aircraft. After comparing the laser energy reflected back from the ground with the initial energy, it is possible to measure heights on the surface and build high detailed terrain models. Figure 4 shows a Digital Terrain Model (DTM) of the city centre of York. All the LiDAR data used in this report has been collected from Digimap[20] with a resolution of 1 m, and it is available under the Open Government Licence.

The area chosen for the scope of this report is North Street-Skeldergate and surroundings. According to the Environment Agency, it corresponds to a flood Zone 3, which has high probability of flooding. Also, it is an area in high risk of rapid inundation, being within 500 m of existing flood defences and representing a threat to human life[1]. Figure 5 illustrates the

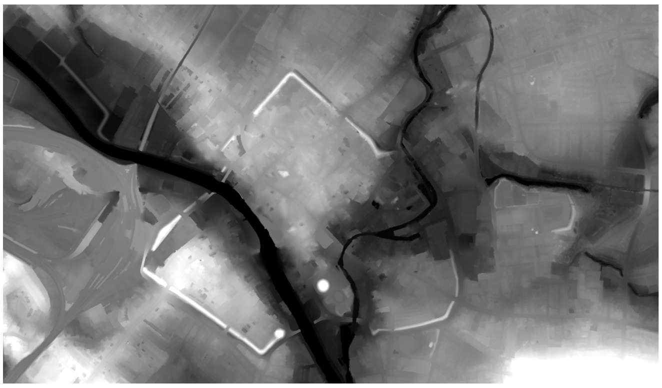


Fig. (4) Digital Terrain Model of the city centre of York from Digimap[20].

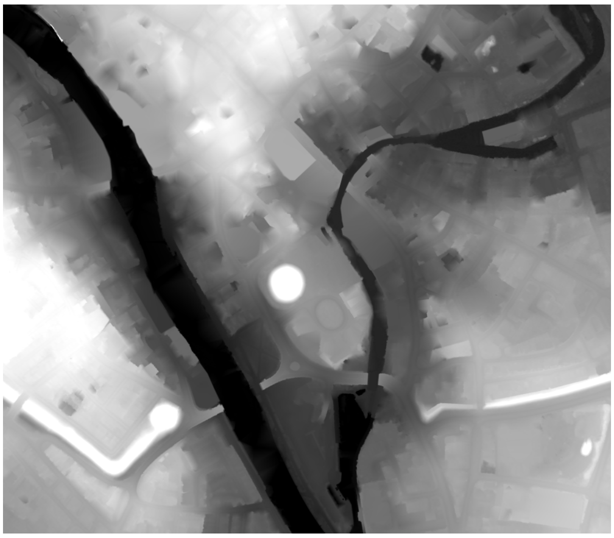


Fig. (5) Digital Terrain Model of the North Street-Skeldergate area within the City of York from Digimap[20].

Digital Terrain Model used of the North Street-Skeldergate area.

C. *Hydrodynamic Modeling*

ANUGA is a free and open source software, written mainly in Python, capable of modeling the impact of hydrological disasters such as dam breaks or floods by solving the Shallow Water Wave Equation discretised to unstructured triangular meshes using a finite-volumes numerical method[21]. It is developed by the Australian National University and Geoscience Australia.

Figure 6 shows the Digital Terrain Model of the city centre of York processed and converted into a finite element grid. The base resolution used for most of the mesh is 500 m^2. The grid resolution has been increased to 50 m^2 along the river and in the North Street-Skeldergate roads to better estimate the effects of floods in these areas. Figure 7 shows the finite element grid combined with the Digital Terrain Model, showing elevation values for each triangle.

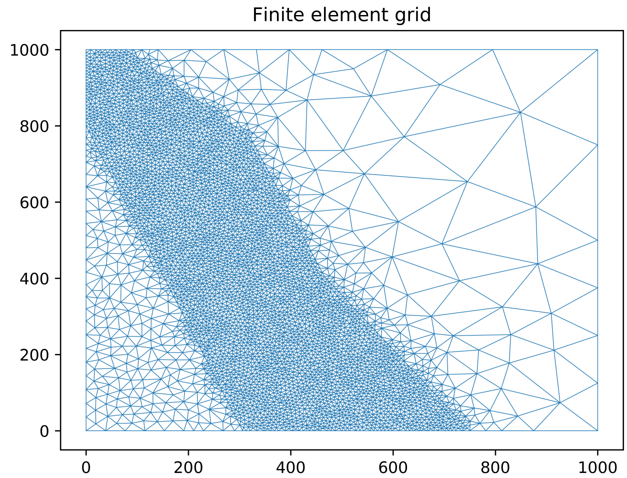


Fig. (6) Digital Terrain Model of the city centre of York processed and converted into a finite element grid.

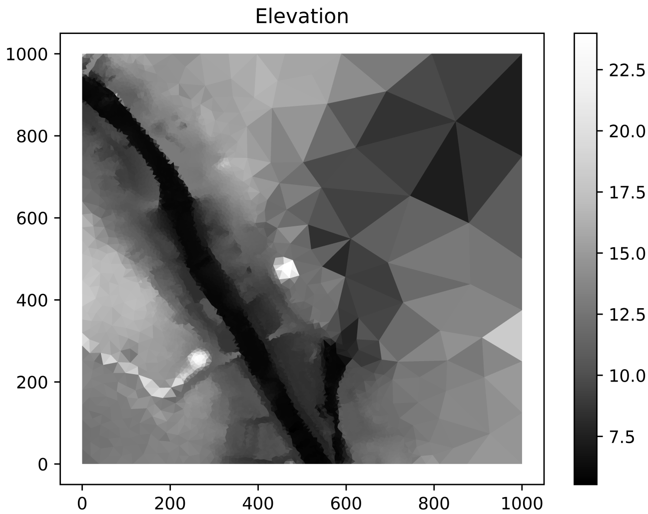
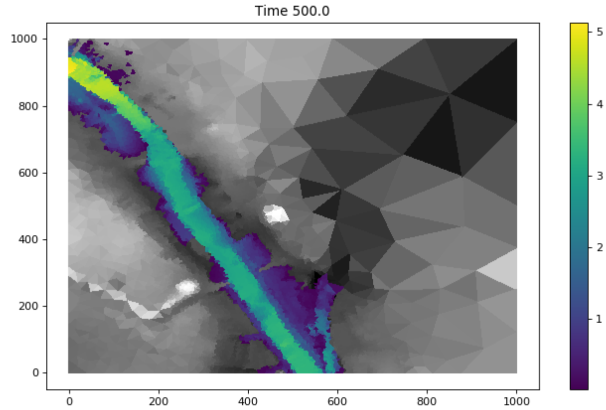


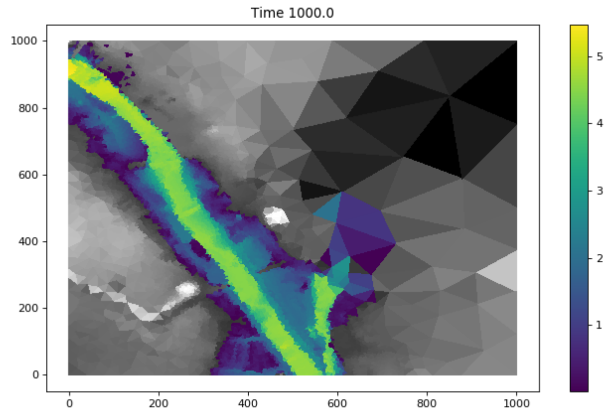
Fig. (7) Finite element grid combined with the Digital Terrain Model.

The analysis was performed simulating a discharge of Q=500 m^3/s on the River Ouse, with a duration of 2000 seconds. Figures 8, 9 and 10 shows the evolution of the flood after 500, 1000 and 2000 seconds respectively. The flood depth is given in metres. Note how after 10 minutes approximately the area gets flooded under more than 1 metre of water. Also, it is possible to visualise the contribution River Ouse does to River Foss, with the consequent flooding of its surroundings. The Foss Barrier was built to avoid this effect.

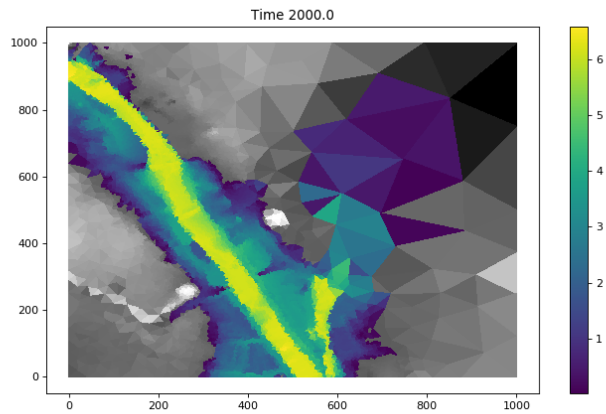
These simulations can give an estimation about how flood would develop in certain areas and agree with the Environment Agency calculations. Future development in the Nort Street-Skeldergate area should be constrained, as it is classified as high-risk, rapid inundation zone, with significant flood depth exceeding 0.6 metres.



(a) Flood depth after 500 seconds.



(b) Flood depth after 1000 seconds.



(c) Flood depth after 2000 seconds.

Fig. (8) Evolution of the flood after 500, 1000 and 2000 seconds.

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