Cite as: Smith, A. D., Goff, C. A. and Panzeri, M. (2014). Enhancements in reservoir flood risk mapping: example application for Ulley. In A. Pepper (Ed.), Maintaining the Safety of our Dams and Reservoirs (pp. 295-306). ICE Publishing, London (ISBN: 9780727760340)

Enhancements in reservoir flood risk mapping: example application for Ulley

A D SMITH, University of Southampton, UK.
C A GOFF, HR Wallingford, UK.
M PANZERI, HR Wallingford, UK.

SYNOPSIS. In July 2007, at Ulley Reservoir, South Yorkshire, a catastrophic dam failure was narrowly avoided due to emergency preventative actions. During the event, a number of homes were evacuated and roads were closed for precautionary measures. Within very close proximity of the reservoir lies the town of Rotherham, the busy M1 motorway and a trunk freight railway line. The incident highlights the need for detailed flood risk and hazard modelling to improve management of the risk and better incident planning.

Hazards and population vary in both time and space, but when traditionally modelling flood risk, the population are invariably located within the residential housing stock. This paper innovatively combines flood inundation and spatio-temporal population modelling for better estimates of the population potentially at risk. This is demonstrated though application to Ulley for the most probable worst case failure scenario should the preventative measures not have been undertaken and the dam have failed.

This paper proposes an enhanced flood risk assessment in three stages: (i) probabilistic modelling of a failure scenario using embankment breach models; (ii) hydrodynamic inundation modelling for assessment of flood water spreading, depths and velocities; (iii) spatio-temporal population modelling to assess the risk to the population likely to be present. The combination with spatio-temporal population outputs aims to demonstrate the enhancements achievable in reservoir flood risk mapping when vulnerable populations are concerned.

INTRODUCTION

The number of people potentially at risk during rapid onset flood events, such as dam failures, varies at a range of temporal scales. Traditionally decadal censuses alone are linked to residential housing datasets and therefore consider a static 'night-time' residential population estimate.

Additional approaches are required to assess the impact on people. For example, the same flood occurring in an urban centre during a weekday afternoon may have a greater effect on the temporarily present population (e.g. workforce, children concentrated at school sites) than in the evening. Dam failure events can occur with little warning and rapid onset times. This may result in devastating catastrophes in downstream areas (He *et al.* 2008). The risk from such events remains high in locations with significant potential for severe losses. In these events human susceptibility and key infrastructural assets heighten vulnerability and the risk posed from sudden dam failures.

This paper aims to demonstrate one example of an enhanced method to assess the impact of a rapid onset dam breach event in the United Kingdom (UK). The approach adopted concerns the combination of numerical modelling of an embankment scenario, resultant flood inundation extent and exposure to any population likely to be present at the time of event. It is acknowledged that flood hazard and population vary in both time and space at a range of scales (Aubrecht *et al.* 2012). The example application provided combines flood spreading and dam breach models developed at HR Wallingford with the 'SurfaceBuilder24/7' spatio-temporal modelling tool to estimate gridded population densities at a range of times. This is demonstrated on an evaluation of a scenario for the failure at Ulley Reservoir in South Yorkshire, a nineteenth century clay-earth embankment dam that is believed to have been close to failure during severe UK-wide flooding of June 2007.

BACKGROUND

Ulley reservoir is located three miles south-east of Rotherham and five miles east of Sheffield, Yorkshire, UK. It is presently a country park, owned by Rotherham Metropolitan Borough Council (MBC). Construction of the earth embankment dam was completed in 1873. The supply of drinking water from Ulley ceased in 1986 when it was taken over by MBC as a recreational facility. During exceptional widespread flooding experienced in the UK during summer 2007 the dam was destabilized. Although the modern spillway coped admirably with the high overflows, the older masonry spillway along the left mitre of the embankment suffered from out of bank flows and deterioration of the channel. This in turn led to a large erosion hole developing in the downstream face of the embankment, putting the stability of the entire dam at risk.

Historical context

This region surrounding Ulley is not immune from unprecedented, catastrophic dam failures. The collapse of Dale Dike Dam in 1864 (13 miles east of Ulley) caused the Great Sheffield Flood, resulting in considerable downstream destruction and 244 fatalities. The dam collapsed under severe storm conditions while being filled for the first time. The breach resulted in the discharge of c. 3 million m^3 of water (Amey 1974) into the narrow catchment below. The embankment was of the same earth/clay construction type as Ulley, which was to be constructed less than ten years later.

Increasing industrialisation and population growth within the Yorkshire region during the nineteenth century increased the demand for an adequate and clean water supply. This was driven by the increase in the cotton and steel industries and concerns over healthcare and access to safe drinking water. Poor health and intermittent water supply caused by shortages prompted the construction of the reservoir at Ulley to alleviate these concerns. The dam was constructed by Messrs, Lawson and Mausergh of Westminster between 1871 and 1874. It consists of an earth embankment and puddle clay core.

<u>Ulley June 2007</u>

On 25 June a slow moving depression bought prolonged heavy rainfall to northern and central England, with more than 90 mm of rain falling in 18 hours (Environment Agency 2007b; Met Office 2011). In 2007 June was the wettest for England and Wales since 1860 (Marsh and Hannaford 2007). Intense slow moving frontal rainfall on the 25 June fell on saturated ground with some rivers already exceeding capacity and reservoir levels high. It is estimated that the rainfall levels that led to this event had an annual probability of occurrence of 1% (Warren and Stewart 2008).

Flooding on the River Don at Sheffield nearby was also at its worst extent since the 1864 collapse of Dale Dike dam (Environment Agency 2007a). The prolonged rainfall had already caused widespread flooding in this region. A potential collapse of the Ulley embankment would have been exacerbated by significant volumes of standing flood water already immediately downstream due to the excessive rainfall.

Spillway failure

The mechanics of the events leading to the risk of destabilization at Ulley have been well documented (e.g. Hinks *et al.* 2008; Mason and Hinks 2009, 2008) and are therefore not reproduced in detail for this paper.. Despite a larger concrete spillway constructed in 1943, flood water reverted to the original masonry stepped spillway in the left mitre of the main earth embankment. The hydraulic pressure of the channel flow exceeded the retaining wall threshold causing it to collapse and facilitating the erosion of the dam embankment material (Warren and Stewart 2008). During the flood, peak flow on the failed spillway was estimated at 6.1 ms^{-1} (Horrocks 2010). Rotherham MBC was advised to take immediate emergency action to prevent major flooding downstream (Environment Agency 2007b).

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Population at risk and response

Approximately 1000 people were evacuated in downstream areas of the dam from the villages of Catcliffe, Whiston and Treeton. The M1 motorway was closed northbound between junctions 32 and 34, and southbound between junctions 34 and 36 (Sturcke *et al.* 2007) for 40 hours at an estimated cost of £2.3 million (Environment Agency 2007b). In addition to the population exposure there was also a substantial risk to critical infrastructure and assets. This included a high pressure gas main, high voltage electricity pylons, a regional substation, telecommunication towers, highways, water treatment works and the M1 motorway.

Emergency work to stabilise the dam and reduce water levels continued before the motorway was reopened. The initial remedial action resulted in packing the scour hole with 2,500 tonnes of coarse limestone and pumping water from the reservoir to the newer spillway channel to lower the reservoir level. Repair of the dam cost £3.8 million and resulted in the construction of improved scour pipe capacity and a new reinforced concrete spillway in the centre of the dam. The new scour pipe has twice the capacity of the previous one and can drain 40,000 m^3 day^{-1}, enough to lower the reservoir water level by 1 metre (Horrocks 2010).

MODELLING METHOD AND DATA

The modelling method consists of three main components which are discussed in turn; embankment breach, hydraulic flood spreading, and spatio-temporal population modelling. Two modelling tools developed by HR Wallingford were used for breach analysis and checking; the EMBREA (EMbankment BREch Assessment) complex model and AREBA (A Rapid Embankment Breach Assessment) simplified model. These models were used to simulate the failure mechanism of the dam and derive the resultant outflow hydrograph. Initial slope stability analysis suggests that the supporting embankment material is liable to slipping following erosion of the toe material and exposure of the core. The process was initiated during the 2007 flood event but was fortunately prevented from worsening following emergency remedial work. Should the breach have continued, preliminary core stability calculations suggest that the core would have failed under these conditions. After block failure of part of the core due to the initial slip of supporting embankment material, breach flow causes further removal of embankment material supporting the core. With increasing exposure of the core, stresses in the core increase and subsequently give rise to two further block failures indicated by the 2nd and 3rd peak in the breach hydrograph (Figure 2a). Due to the block failures, the head driving the flow suddenly increases leading to high breach flows.

The extent of a potential inundation following a breach at Ulley was modelled using the open source TELEMAC-2D hydraulic model. The breach hydrograph was used for the reservoir discharge parameter. A 2 metre LiDAR digital elevation model (DEM) (Environment Agency 2013) was used to generate a mesh for the model input. Depths for the existing downstream flood extent were estimated from aerial photographs taken during the emergency response and evaluated using Ordnance Survey spot heights. This was accounted for in the modelled scenario to simulate realistic conditions should a breach have occurred within the already inundated catchment. Culverts through notable barriers downstream such as the railway and motorway embankments were accounted for in the DEM. The modelled outputs for the spreading for a breach event concerning water depth and velocity at a 15 metre resolution were analysed using a Geographic Information System (GIS).

Finally, spatio-temporal population modelling was undertaken for an 8 x 10 km study area centred on Ulley and Rotherham using the 'SurfaceBuilder24/7' tool (Martin 2011). This employs a variable kernel density estimation technique with a distance decay function. This facilitates the spatial redistribution of population datasets in space and time based on centroid locations and ancillary datasets. A population centroid is a georeferenced point with an associated population count. The model utilises 'origin' centroids taken from the UK census and georeferenced residential postcode locations. The model redistributes population from these to 'destination' centroids (such as schools and places of work) based on their location and site capacities informed by administrative datasets (e.g. school census, census workplace data). The proportion of the available capacity occupied at a destination centroid varies by time of day and is governed by a site specific time profile. A destination example would be location and number of pupils on the roll at a school (informed by the school census) who are present during school hours on a term-time weekday. The school aged population is then drawn from the surrounding origin centroids within the school's catchment area to fulfil the destination's expected capacity. Mid year population estimates for 2007 were used as the baseline residential population for the creation of the data library for this paper.

A background mask is also utilised to constrain population allocation to habitable locations (e.g. excluding water bodies) and to represent the road transport network. The population on the road network also varies by time of day and is informed by the distribution of vehicle count data and capacities from the Department for Transport's (DfT) National Transport Model. The modelled population output is in the form of a rasterised regular grid at 100 m resolution, based on the current resolution of available input data. The output is disaggregated and adjusted for a 15 m resolution to match the output from TELEMAC-2D. The gridded results are analysed at the output resolution comparing water depths, velocity and population for each cell. This has been used to calculate a hazard rating and fatality estimate for each cell based on the method outlined by Penning-Rowsell *et al.* (2005).

RESULTS

Water depth and velocity results derived from TELEMAC-2D for the post-breach inundation extent for Ulley Reservoir are shown in Figure 1. The output extent recognises the antecedent flood conditions. The greatest depths occur in river channels, while increased velocity occurs from the initial breach and through culverts.

An example reservoir breach hydrograph used in the model identifies three distinct peaks (Figure 2a) representing initial overtopping followed by downstream undercutting and core failure.

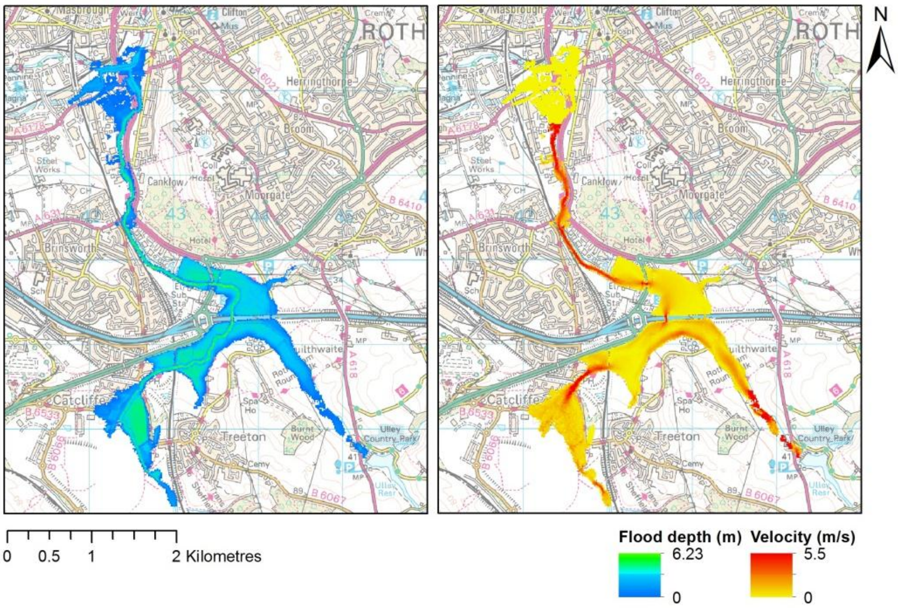

Figure 1 Flood inundation results for water depth (left) and velocity (right)

A velocity time-series was taken at the motorway embankment immediately downstream from the reservoir (Figure 2b) with a profile closely aligned to the initial hydrograph. Figure 2c represents another location on the motorway embankment at its lowest elevation (at the R. Rother culvert) and a time-series for water depth normalised to height above ordnance datum (AOD).

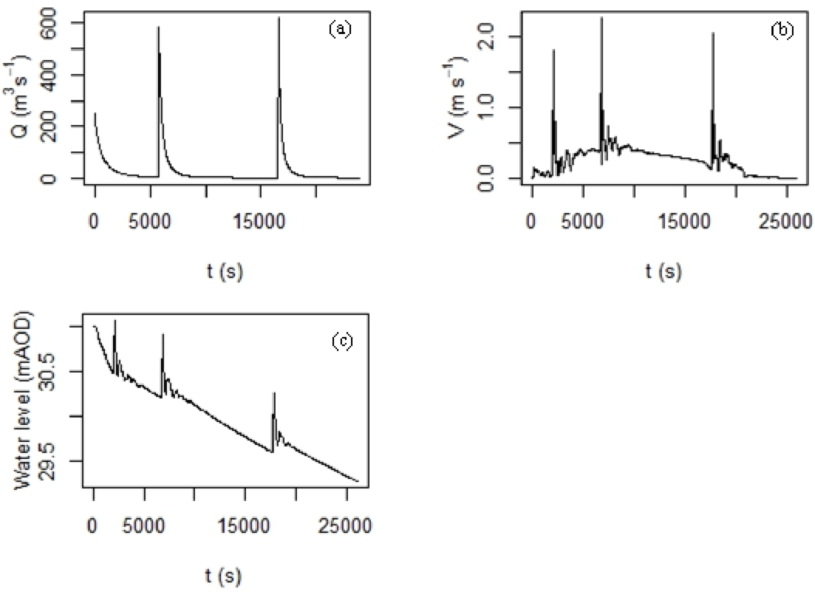

Figure 2(a) AREBA reservoir breach discharge hydrograph, (b) velocity profile at motorway embankment, (c) flood level at motorway embankment.

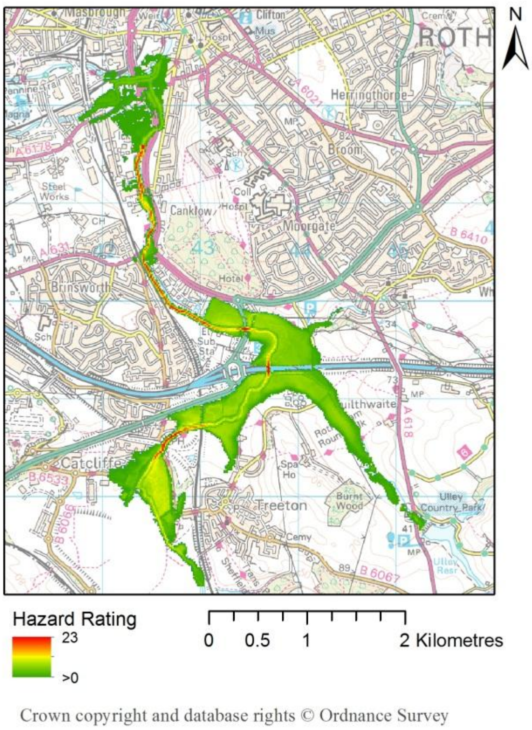

Figure 3 Hazard rating per cell for an Ulley flood scenario

The hazard rating (Figure 3) primarily identifies the locations of greatest depth and velocity. The highest rating occurs within the original channels. The population exposed also varies by time of day. Figure 4 displays the estimated population for three different times of day (00:00, 08:30 and 12:00), for a represented weekday.

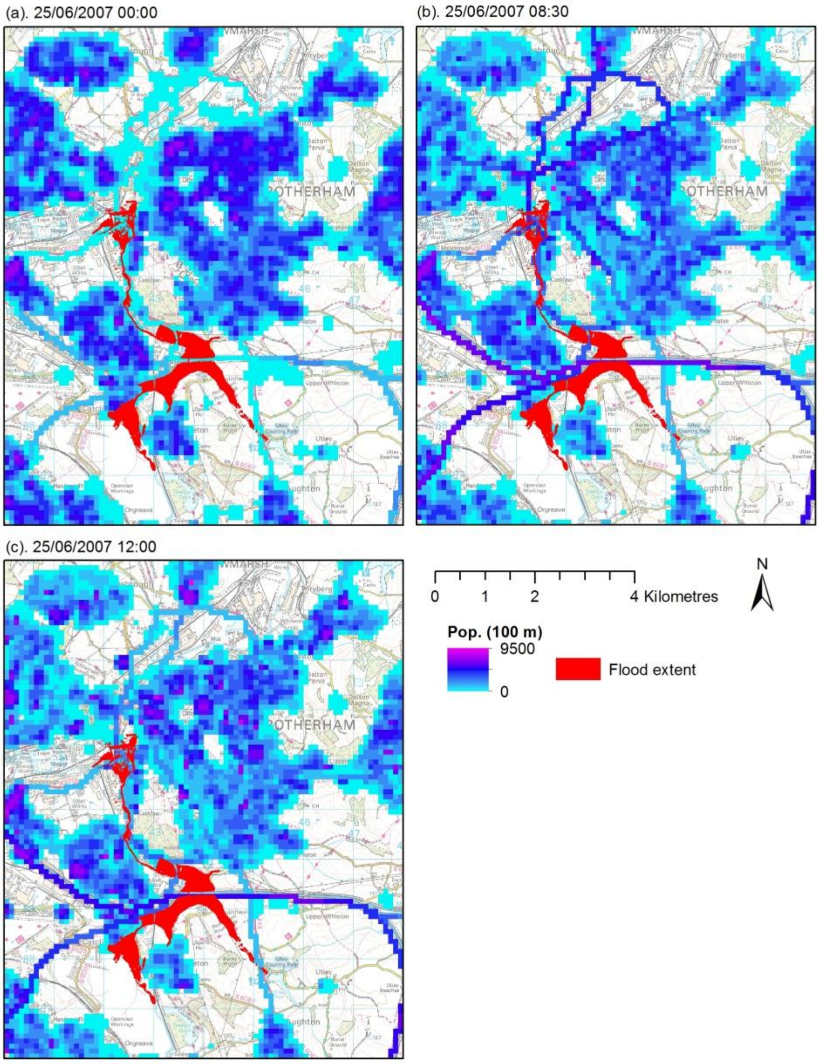

Figure 4 Gridded (100 m) spatio-temporal population estimate for the Ulley region.

DISCUSSION

There are an exponential number of possible permutations for the temporal variation in the population modelled outputs (e.g. time of day, day of week, season) when combined with scenarios for flood extent, parameters and time step. Therefore, this paper only attempts to demonstrate a few of the possibilities while striving to demonstrate the enhancements in reservoir flood risk to people when considering spatio-temporal population data.

The comparison of the potential water depths adjacent to the motorway and the lowest elevation of the motorway surface (31.7 m) according to the LiDAR data suggest that the motorway embankment may not have been overtopped. However this is based on the assumption that the culverts (or road underpasses acting as temporary culverts) are unobstructed. Nevertheless, the level of the maximum water depth for the scenario modelled indicates that the water level could have come within 0.70 m of overtopping the carriageway. The depth time-series at the embankment also indicates that the breach events could add up to a metre to pre-existing flood water levels. This is consistent with the same estimation made by Mason and Hinks (2009).

The TELEMAC-2D simulations show that the leading edge of a breach flood wave could reach the motorway embankment in less than 30 minutes. If destabilisation of the embankment at Ulley had continued unchecked or rapidly deteriorated then the model simulations, and historic events, indicate there would have been no time for an effective warning. Flow velocities are highest immediately downstream, but rapidly dissipate when entering the existing standing water. The channelization effect of the culverts creates localised intensification in velocity (Figure 1).

A velocity time-series was taken adjacent to the southern edge of the motorway embankment closest to the reservoir (Figure 2b). Although flood flows have slowed significantly at this point velocities around 2 m s^{-1} are still estimated. This is within the velocity threshold for masonry and concrete significant for the onset of structural damage (Priest *et al.* 2007). Therefore it is possible that the integrity of the motorway structure could be comprised, particularly at the locations of culverts and bridges. In turn the flood hazard rating (Figure 3) adjacent to the motorway embankment ranges from 1-1.5, high enough in places to pose a significant hazard with a danger to most people (Priest *et al.* 2007). It is possible that the resultant risk to the saturated earth motorway embankment (due to preceding flooding conditions) could have been unacceptably high.

Table 1 Population exposure

Time	**Flood extent**	**Study area**
00:00	633	118,937
08:30	2,155	127,714
12:00	1,608	121,995

Spatio-temporal population estimations (Figure 4) highlight the variability throughout the weekday of the incident had the onset occurred at different times. Table 1 gives the population estimates for the study area contained within Figure 4.

On the representative weekday in questions there is a large notable shift of population to the potential flood extent at 08:30 and 12:00 compared to the 00:00 'night-time' population. The peak at 08:30 is attributed to commuter flows on the road transport network. The section of motorway (M1) passing through the flood extent has an average annual daily flow of 116,000 vehicles with occupancy typically ranging from 1 to 13 (DfT 2013, 2005). The 12:00 representation (Figure 4c) illustrates the localised concentration of the temporally present population at 'day-time' destination locations.

A hazard rating was calculated (Figure 3) based on the method proposed by Penning-Rowsell *et al.* (2005). This was used to estimate the number of fatalities based on the area and people vulnerability. The initial result suggests that there could have been up to 137 fatalities within Catcliffe, the downstream village that was evacuated, had the event occurred with no warning and action taken. Further analysis is required assess how this fluctuates with cyclical population change. The very nature of modelling an unknown variable make this value difficult to validate and therefore it is provisional. However, this would account for 14% of the population actually evacuated had they remained behind.

The number of possible variations within a flood scenario has already been noted. This paper does not attempt to provide a single definitive answer nor to even identify all possible combinations. It attempts to demonstrate one possible scenario based on an embankment failure at Ulley reservoir and provide an enhancement to considering risk to people in flood mapping. There are a number of uncertainties and external factors to consider.

CONCLUSION

This paper highlights the potential advantages with integrating spatio-temporal population estimations with established flood modelling techniques. The population component does not attempt to predict individual moments in human behaviour but rather represents predictable trends based on range of available datasets. Results suggest that the closure of the motorway and evacuation of residents was necessary and proportionate, and would have undoubtedly prevented fatalities had the dam failed. The possible impact of a failure at Ulley has been analysed and subsequent remedial work on the dam's embankment justified, within this context in potentially preventing a future catastrophic flood. Modelled assessment for a typical weekday shows that the worst time for this dam to fail is likely to have been during the morning peak commute under standard conditions. When considering worst case, but possible, failure scenario the money spent by the relevant authorities to reduce future flood risk potentially could have prevented in excess of 100 fatalities.

ACKNOWLEDGMENTS
The authors are grateful for the data and technical information kindly provided by Rotherham Metropolitan Borough Council and the Environment Agency. Funded as part of the EPSRC Impact Acceleration Account through the University of Southampton.

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