Cost Effective Hydraulic Modelling to enable Resilient Urban Regeneration within Reservoir Inundation Areas

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ABSTRACT

Within Northern Ireland (NI), planning policy severely restricts development within the predicted inundation area of dams that are not considered to have responsible reservoir manager status. This paper aims to present a cost-effective method to allow these brownfield sites to be regenerated by applying appropriate flood resilience measures at hydraulic modelling stage. DfI Rivers, who are the flood defence and drainage authority for NI, are in possession of detailed hydraulic modelling of dam failures, but they will only release limited information from those models due to national security reasons. To develop a site within an inundation area, a developer would therefore have to create their own hydraulic model from the reservoir to their site and then demonstrate the above restrictions regarding risk to life and third-party land can be overcome. With reservoirs often being several miles from the site and the bathymetry of the reservoir being unknown, most small-scale developers cannot afford the substantial surveying costs for the land between the reservoir and their site, as well as acquiring details for the dam and reservoir itself, in order to build an appropriate hydraulic model. In order to address the growing number of brownfield sites that cannot be regenerated because of the above restrictions, the author has developed an Infoworks ICM hydraulic model method that uses basic reservoir measurements and free Digital Terrain Model (DTM) data to mimic DfI Rivers' predicted inundation area from the reservoir to the site in question and then applies parameters to the hydraulic model based on DEFRAs "Hazard to People Classification using Hazard Rating" to determine flood risk to various people groups using the developed site, including vulnerable people, the general public and the emergency services.

1 INTRODUCTION

Proposed regeneration of brownfield sites in NI often encounters planning issues whenever the dams and reservoirs that sit above the towns and cities within which the regeneration is being proposed are not considered to be in an appropriate state of repair. The majority of these proposed regeneration schemes are relatively small in nature and so the developer does not have adequate funds to fully hydraulically model potential reservoir failures from reservoirs potentially miles from their sites in order to propose mitigation measures that would allow the proposal to proceed beyond planning stage. This paper will present a case study that made use of cost-effective hydraulic modelling that used basic reservoir measurements and free topographical survey information between the reservoir and the site and then proposed reconfiguration of the topography of the site itself in order to address future reservoir flood risk to people using the regenerated site without increasing risk to third party land beyond the site.

2 RESERVOIR MODELLING IN THE UK

2.1 Historical context for reservoir modelling

There has been no loss of life from reservoir failure in the UK since reservoir safety legislation was introduced in 1930. Nevertheless, a risk was identified that should the potential collapse of a reservoir be considered imminent, the emergency services would not have easily accessible information on which areas to evacuate first. In 2007, Sir Michael Pitt therefore recommended creating national flood maps for reservoir failure to enable Local Resilience Forums to assess risks and plan for contingency, warning and evacuation. The Reservoir Inundation Mapping (RIM) Specification, now known as Reservoir Flood Mapping (RFM) Specification, was first established in 2009 (EA, 2009) and used to produce a total of 2,232 reservoir flood maps in England and Wales.

Dam breach flooding happens when a dam impounding a reservoir breaches, causing water stored in the reservoir to be released through the breach and flooding areas downstream of the dam. The dam breach scenario simulated on the reservoir flood maps is a "credible worst case" scenario that represents a generic dam failure that could be adopted across the country. The procedure for the development of the flood maps included the prediction of the dam breach outflow hydrograph and routing of the hydrograph downstream of the reservoir, where the approach for the modelled breach scenario for an impounding reservoir assumed that the reservoir water level has risen to dam crest level plus 0.5, leading to overtopping over the entire height of the dam. These breach assumptions were intended to produce a single, simplified dam breach hydrograph that reflected a credible worst-case scenario for a hypothetical dam breach. In addition to the above addition to crest level, the calculation method of the outflow hydrographs used for the flood mapping for earthfill embankments identifies that a factor of safety of 1.5 is applied to the peak discharge (according to Froehlich (1995)). Therefore, the modelling of an impounding reservoir generally assumes a crest level plus 0.5m, that the full extent of the dam structure itself effectively disappears, causing flooding that occurs along the full length of the reservoir rather than at an isolated breach location, and that a safety factor of 1.5 is applied to the discharge flow.

The topography downstream of the reservoirs is presented in the hydraulic model by a digital terrain model (DTM), constructed using either LiDAR or IFSAR data. Flood plain features such as road and railway embankments are represented in the hydraulic model, but buildings, bridges and culverts are not represented. Finally, a Manning's friction *n* value of 0.10 is set globally for the reservoir flood modelling.

2.2 Flood Risk to People Methodology

In order to quantify risk to life from various forms of flooding, such as from rivers, estuaries and the sea, the Risks to People Methodology was created as a multi-criteria assessment based on the concepts of flood hazard, area vulnerability and people vulnerability. As such, the methodology does not consider a specific threshold for tolerable risk such as flood hazard, but instead combines the hazard with both area and people vulnerabilities to determine risk. Phase 1 of the above methodology then used the above criteria to calculate whether the annual risk of fatality from a potential flood source was deemed 'acceptable' if it was less than a 'tolerable' value (HR Wallingford, 2005a).

Phase 1 methodology is outlined by the following equation, applied to a particular flood risk:

$$Ninj = NZ \times HR \times AAV \times PV \qquad (1)$$

Where Ninj = number of injuries

NZ = population at risk of flooding
HR = Hazard Rating, a function of flood depth and velocity and debris factor
AV = Area Vulnerability, a function of effectiveness of flood warning, speed of onset of flooding and nature of area (including types of buildings)
PV = People vulnerability, a function of presence of people who are very old and/or infirm/disabled/long term sick

2.3 Flood Hazard (HR)

There is a broad consensus that the degree of hazard that floodwaters present to people (and to vehicles and property) is a function of both velocity and depth. In addition, other factors may affect the stability of people during flooding, where a debris factor is included in the flood hazard equation. The equation for Flood Hazard HR is as follows:

$$HR = d(v + 0.5) + DF \tag{2}$$

Where HR = flood hazard rating
d = depth of flooding (m)
v = velocity of floodwaters (m/s)
DF = debris factor (+0, 0.5 or 1 depending on the probability that debris will lead to a significantly greater hazard)

The supplementary note on flood hazard ratings and thresholds by Surendran et al. (2008) was produced to reconcile the above information with planning policy in England and Wales, which requires that people should be appropriately safe around new development. This document emphasised that rather than concentrating on Phase 1 of the Risks to People methodology, which also allows consideration of factors such as the population at risk of flooding and the Area Vulnerability factor, Flood Risk Assessment (FRA) reports that are produced as part of a planning application for an individual site should take a simplified approach by concentrating on the flood hazard rating (HR) and the people vulnerability (PV).

2.4 Planning Policy in NI for Development in Proximity to Reservoirs

Policy FLD 5 of PPS 15 (DOE, 2014) states that new development in NI will only permitted within the potential flood inundation area of a controlled reservoir (i.e. reservoirs with an individual or combined capacity greater than 10,000 cubic metres above the natural level of any part of the surrounding land) if the applicant can demonstrate that the condition, management and maintenance regime of the reservoir is appropriate to provide sufficient assurance regarding reservoir safety, so as to enable the development to proceed. Where a reservoir has been conferred ‘Responsible reservoir management status’ the above criteria is assumed to have been met. However, where this status has not been conferred, DFI (2020) have stated that the Flood Risk to People Methodology proposed by HR Wallingford (2005a) & HR Wallingford (2005b) should be used in conjunction with Surendran et al.’s (2008) simplified approach of considering flood hazard ratings for various people groups when applying Policy FLD 5 of PPS 15 to proposed development that lies within the predicted inundation path of a controlled reservoir.

DfI Rivers, who are the NI government body responsible for flood defence, watercourse maintenance and managing river and sea defences, are in possession of reservoir inundation mapping for all the controlled reservoirs across NI. However, they will only release limited information from those models due to national security reasons. Instead, DfI Rivers will advise the Planning Authority when an FRA would be required to assess the Flood Hazard Rating (HR) for an individual planning application that lies within the predicted inundation area of a controlled reservoir that is not in possession of Responsible reservoir management status. However, the majority of proposed regeneration schemes are relatively small in nature and so the developer does not have adequate funds to fully hydraulically model potential reservoir failures from reservoirs potentially miles from their sites in order to propose mitigation measures that would allow the proposal to proceed beyond planning stage. The author therefore developed cost-effective hydraulic modelling that uses basic reservoir measurements and free topographical survey information between the reservoir and the site and then proposes reconfiguration of the topography of the site itself in order to address future reservoir flood risk to people using the regenerated site without increasing risk to third party land beyond the site. The remainder of this paper will present a case study of this approach.

3 CASE STUDY OF COST-EFFECTIVE HYDRAULIC RESERVOIR MODELLING

3.1 Dam breach hydrograph calculation

EA (2016) presents guidance on dam breach modelling, including the determination of a dam breach hydrograph which can be calculated based on the dimensions and nature of the embankment structure and the impounded waters. The peak discharge from the reservoir and the time to peak discharge are calculated using the Froehlich (1995) equation (Equation 3) and the Brown and Gosden (2004) equation (Equation 4). Finally, the time of end discharge can be calculated based on the consideration that the volume under the hydrograph represents the volume of water within the reservoir above the adjacent ground level.

$$Q_P = FOS\ [0.607(V_W^{0.295} \times H_W^{1.24})] \tag{3}$$

where Q_P = Peak discharge (m3/s)
FOS = Factor of safety: 1.5
V_W = Volume of reservoir above adjacent ground levels (m^3)
H_W = Dam height (m)

$$T_P = 120\ H_W \tag{4}$$

Where T_P = Time to peak discharge (s)
H_W = Dam height (m)

Therefore, by recording basis measurements for both the dam height and adjacent ground level and then calculating the footprint area of the reservoir using available mapping, it is possible to estimate both a peak discharge and hydrograph shape for the design flow from the failed reservoir. In NI, free DTM data is available at 10m resolution across the country, with some areas of the country also providing free 1m LiDAR information. Based on the best information that can be freely sourced, a ground model is therefore created using Infoworks ICM (Integrated Catchment Modelling) software. A 2D line source can be created along the boundary of the reservoir and the design flow hydrograph applied to order to create the appropriate inundation area for the failed reservoir. Figure 1 presents the case study's inundation area 6 minutes and 18 minutes after the commencement of the flood event.

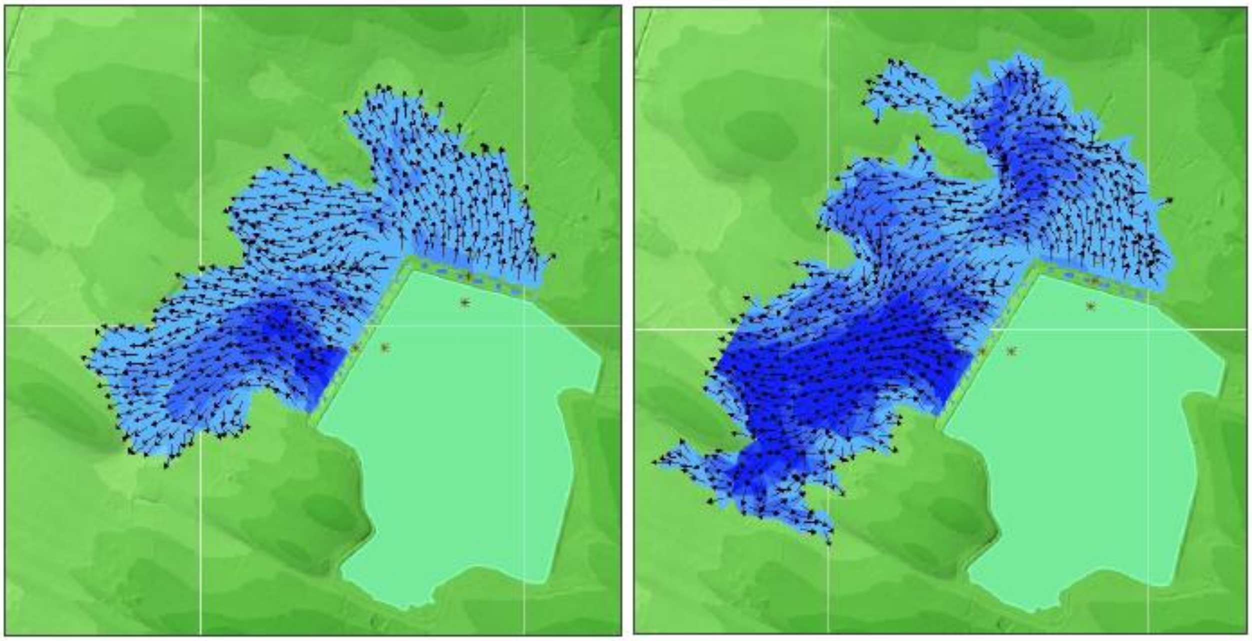

Figure 1: Time series of inundation area from failed reservoir

Figure 2 presents the maximum flood extent and depths from the hydraulic model, as focused on the proposed site (red line). Inundation is predicted across the majority of the site, with the main route and therefore deeper flooding (darker bands of blue hatching) predicted immediately south of the site.

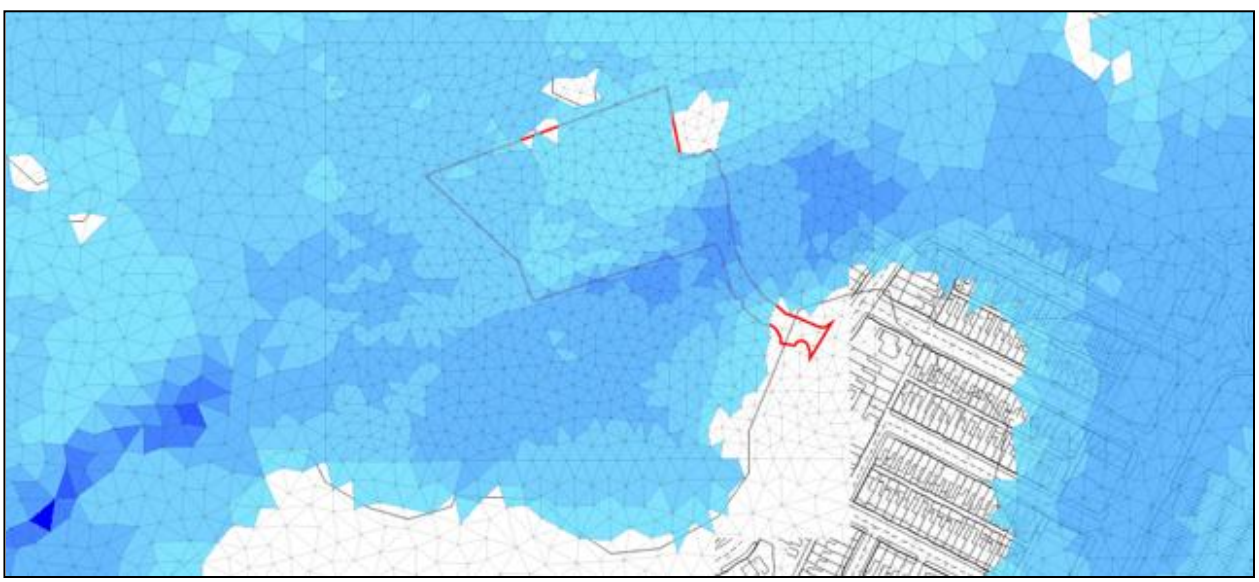

Figure 2: Maximum flood extents and depths at the site

A 'theme' is then applied to the results of the Infoworks ICM hydraulic model that is defined by both the predicted depth and velocity and each individual element within the hydraulic model mesh, as based on the parameters set out by Surendran et al. (2008). Figure 3 presents the predicted flood 'hazard to people' results, which reflect the parameters used by Defra/EA. These results show that the red banding, categorised as 'Danger to all – includes the emergency services' extends along the western and southern sides of the site. Orange banding, categorised as dangerous to the general public, extends across the majority of the western half of the site, while yellow (danger for some – includes children, the elderly and the infirm) and blue hatching (very low hazard) extends across the remainder of the eastern half of the site. The planning application proposed constructing 18 dwellings within the eastern part of the site (red rectangles), but 3 of the 18 dwellings were located within areas of land that were considered either dangerous to the general public or to the emergency services and therefore the planning application in its present state was not deemed viable.

Figure 3: Hazard to people (HR) results

A trial-and-error process was therefore undertaken to reprofile the site by applying various 'mesh level zones' to the footprint of the site within the hydraulic model. The goal of the trial and error process was to allow reservoir inundation to continue passing through the site, so as not to increase flood risk beyond the site. However, by some minor reprofiling of the site, it was possible to reduce the orange and red hatched areas in the eastern part of the site and so allow all 18 dwellings to fall into the low hazard rating categories. Figure 4 presents a 3D image of the reprofiled site, with vehicle access provided from the south to a slightly elevated residential area. Figure 5 presents the hazard to people (HR) results for the reprofiled residential development, where flooding continues to pass through the residential area at a low risk combination of depth and velocity without increasing the predicted hazard rating beyond the site.

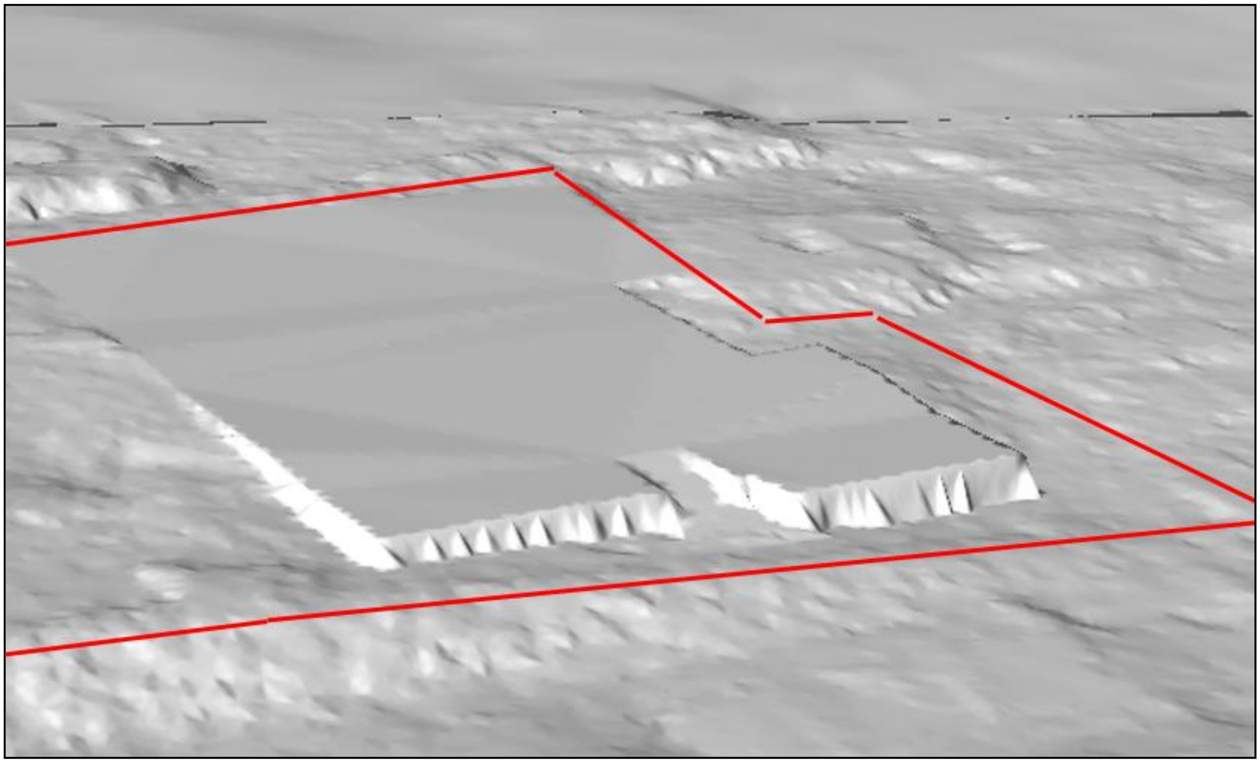

Figure 4: 3D image of reprofiled site

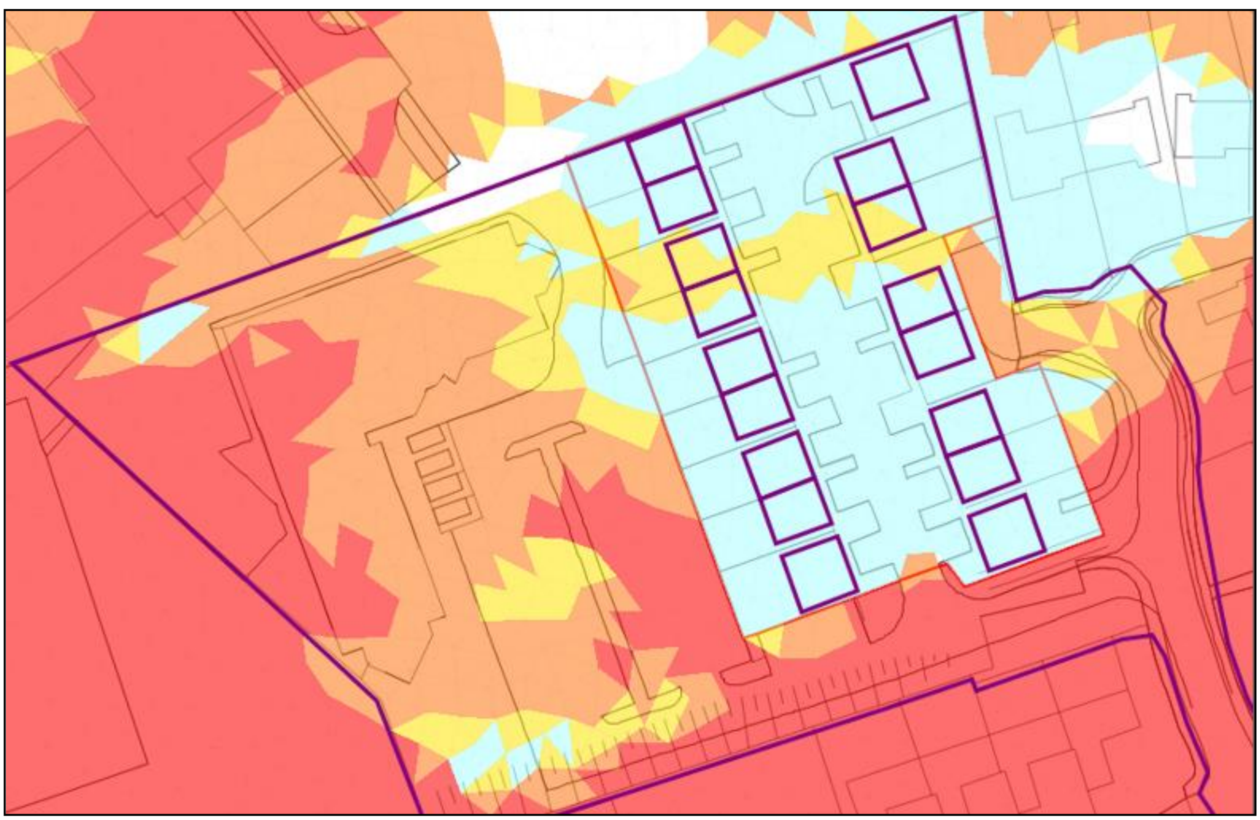

Figure 5: Hazard to people (HR) results for reprofiled site

4 CONCLUSION

Planning policy in NI is restricting development within the predicted inundation area of dams that are not considered to have responsible reservoir manager status. With the drainage authority for NI only allowed to release limited information on potential reservoir inundation areas for national security reasons, developers of small sites cannot afford to have detailed hydraulic models constructed from reservoirs that could be several miles from their site. This paper has therefore presented a case study to demonstrate how an Infoworks ICM hydraulic model can be constructed using basic reservoir measurements and free Digital Terrain Model (DTM) data to mimic DfI Rivers' predicted inundation area from the reservoir to the site in question. DEFRAs "Hazard to People Classification using Hazard Rating" method can then be examined within the hydraulic model and where feasible, the site can be topographically reconfigured within the hydraulic model to maximise the area of land that is considered to have an acceptable hazard rating for future development, while ensuring that flood risk is not increased to adjacent third-party land.

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