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A review of the applicability of the EA reservoir flood mapping specification for reservoir risk assessments

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SYNOPSIS In 2021, the Environment Agency (EA) published new reservoir flood maps of all the statutory reservoirs in England. These maps are intended to be used for a range of purposes related to flood risk and planning. In parallel, the EA also undertook to assess the Average Societal Life Loss (ASLL) associated with a breach for each reservoir, although this information has not been made publicly available.

The new reservoir flood maps (and ASLL figures) developed by the EA were assessed following the guidance provided in the EA's Reservoir Flood Mapping (RFM) Specification (EA, 2019). This was a nationwide exercise and therefore some broad assumptions had to be adopted so the methodology could be applied to all the reservoirs.

This paper presents a review of the EA's RFM Specification and associated technical papers to understand where there is the potential for conservatism in the assumptions made when developing EA Breach hydrographs and ASLL figures. This will equip reservoir undertakers with an understanding of the applicability of the data for use in assessing the societal risk posed by a reservoir.

INTRODUCTION

EA RFM Specification Background

Reservoir flood maps are used to inform people about areas at risk of flooding in the event of a dam or reservoir failure and sudden uncontrolled escape of water. In 2007, Sir Michael Pitt 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 established in 2009 (EA, 2009) and used to produce a total of 2,232 reservoirs flood maps in England and Wales.

In 2021, the Environment Agency (EA) published new reservoir flood maps for all the statutory reservoirs in England. These updated maps were produced following the methodology of an updated RFM Specification that had been published in 2016 and revised in 2019. The new specification superseded the 2009 RIM Specification. The review process was informed by an improved understanding of flood risk, incorporating advancements in modelling, analysis, and legislative considerations.

Managing Risks for Dams and Reservoirs

The principal changes in the RFM Specification (EA, 2019) included:

- Change in the terminology of the dam failure scenario from “credible upper case” to “reasonable worst case” for consistency with wider fields.
- Introduction of a new “dry day” scenario which represents a dam failure when the reservoir level is at top water level and there is no associated river flooding.
- For the “wet day” scenario (already present in the 2009 RIM Specification), explicit modelling with and without dam failure to assess the incremental effect of a dam break over and above the river flooding.
- More realistic representation of the flooding downstream by using 1 in 1000 chance per year (0.001% Annual Exceedance Probability) fluvial flood event to represent the “wet day” scenario.
- The calculation of peak flow during a breach in an embankment uses the Xu and Zhang (2009) formulation rather than Froehlich (1995), and time to peak uses Froehlich (2008) rather than simple multiplier on height.
- Revision of the water levels and volume at time of breach for the “wet day”.

The detailed flood maps were produced for emergency planning and are key components of the on-site emergency plans that have recently been prepared to meet 2021 Flood Plan Ministerial Direction.

As part of the 2021 reservoir flood mapping exercise, the EA also calculated the Average Societal Life Loss (ASLL) and damages for all scenarios (dry day, wet day, fluvial only) associated with the worst breach location for each reservoir.

Applicability of the EA RFM to reservoir risk assessment

The Guide to Risk Assessment for Reservoir Safety Management (RARS) (EA, 2013) states that the societal risk posed by the presence of a reservoir can be classed as “Tolerable”, “ALARP (as low as reasonably practicable)” or “Unacceptable”. Two components inform the tolerability of the risk posed by a reservoir: the probability of dam failure and the consequences of failure. The consequences of failure are quantified in terms of the ASLL. A typical F-N chart which is a graphical representation of the level of societal risk generated by some activity is shown in Figure 1.

If a reservoir falls within the “Unacceptable” zone, the undertaker will likely need to take measures to reduce the risk and/or consequences of reservoir failure. If a reservoir falls within the ALARP zone, as a minimum, the undertaker will likely be required to perform a proportionality assessment between the cost of risk reduction measures and the expected reduction in risks.

For Tier 2 and Tier 3 (quantitative) risk assessments, RARS states that existing dam break maps can be used where available and of an appropriate standard. The EA reservoir flood maps are readily available for statutory reservoirs in England so prove a convenient source of data on the consequences of dam failure for undertakers. Furthermore, although not publicly available, reservoir undertakers have access to the consequence metrics for the worst-case breach scenario at each reservoir, which includes the ASLL. This gives undertakers a value for the consequences of failure, which can be input directly into an F-N chart, without the need for further time consuming, costly analyses.

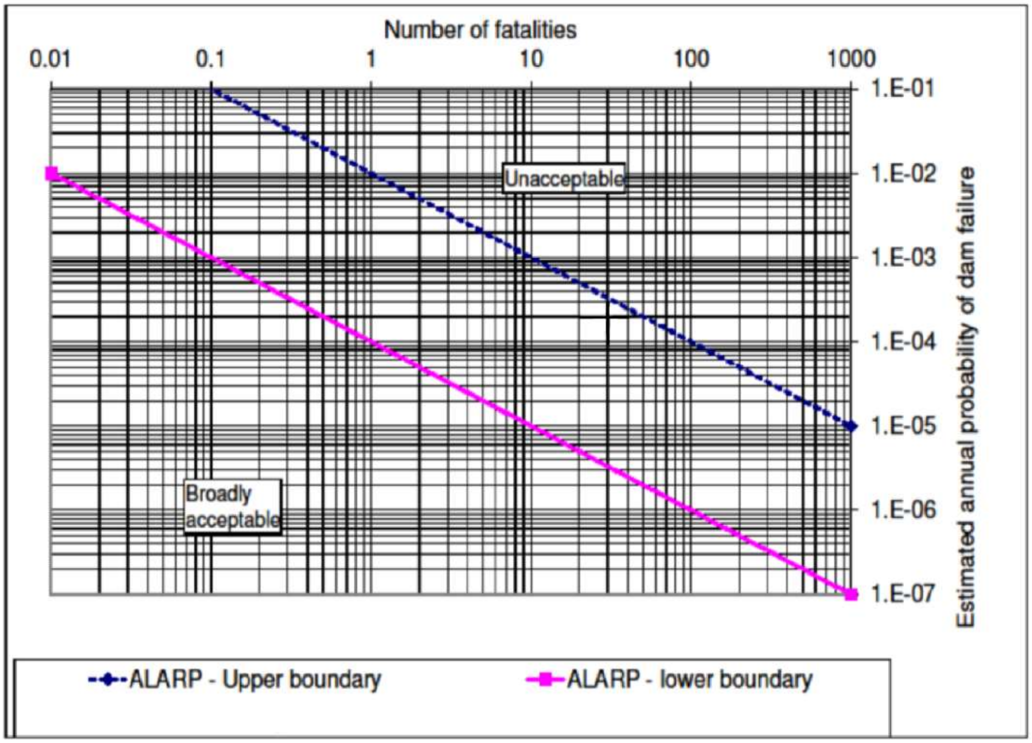

Figure 1. F-N Chart with ALARP limits (taken from RARS (EA, 2013))

However, and as shown later in this paper, the RFM methodology adopts some conservative assumptions which could result in higher ASLL figures and consequently also a higher risk profile for the reservoir. This could ultimately lead the undertaker to carry out works to reduce the probability of dam failure. Therefore, the EA's ASLL values should be used with caution if being applied to the assessment of the societal risk posed by a reservoir.

This paper discusses the conservatisms in the EA RFM Specification methodology for creating reservoir flood maps and calculating the fatality rate, both of which inform the ASLL. The review highlights the assumptions that can impact the accuracy of the breach modelling and ASLL values. This could be useful to reservoir owners if, following an initial assessment of societal risk using the EA's ASLL value, the reservoir falls within the "Unacceptable" zone, but relatively close to the ALARP zone. Review of the site-specific data against the EA adopted values could provide an indication of whether a more detailed analysis may lead to a lower ASLL value.

REVIEW OF THE EA RESERVOIR FLOOD MAPS

The RFM Specification is a national specification that applies to all reservoirs in England and therefore the assumptions and values used are not bespoke to individual reservoirs.

The methodology proposes deriving the dam breach hydrograph outside of the hydraulic model using the empirical equation for peak flow proposed by Xu and Zhang (2009), and the equation for time to failure proposed by Froehlich (2008), both shown in Table 1.

Table 1. Xu and Zhang (2009) and Froehlich (2008) equations to calculate peak outflow and failure time respectively.

Equation	**Coefficients**
Peak Outflow Rate (Qxz) $$\frac{Q_{xz}}{\sqrt{gV_w^{\frac{5}{3}}}} = 0.133(\frac{V_w^{\frac{1}{3}}}{H_w})^{-1.276}e^{C4}$$	$C_4=b_4+b_5$ $b_4=-0.788$ and -1.232 for overtopping and seepage erosion/piping $b_5=-0.089$, -0.498, and -1.433 for high, medium and low dam erodibility
Failure time or time of breach formation (T_f) $$T_f = 63.36\sqrt{\frac{V_w}{gH_d^2}}$$	

The parameters that shape the hydrograph; peak flow (Q_p), time to peak flow (T_p) and time to end of hydrograph (T_e), are subsequently derived from the ratio between peak flow (Q_{xz}), failure time (T_f) and the escapable reservoir volume (V_w), as presented in Table 2.

Table 2. Hydrograph parameter (Source: RFM Specification 2019)

$Q_{xz}T_f/V_w$	**Q_p**	**T_p**	**T_e**
< 2	$Q_p=Q_{xz}$	$T_P = T_f/2$	$T_e = 2V_w/Q_{xz}$
> 2 and <5	$Q_p=Q_{xz}$	$T_p = V_w/Q_{xz}$	$T_e = 2V_w/Q_{xz}$
> 5	$Q_p = 5V_w/T_f$	$T_P = T_f/5$	$T_e = 2T_f/5$

The peak flow equation presented in RFM Specification assumes high erodibility dams, whereas the original Xu and Zhang equation (Table 1), allows for three levels of erodibility: high, medium and low, through the inclusion of a coefficient (b_5).

As well as the erodibility of the dam (b_5), the Xu and Zhang equation also takes into account the type of the dam failure through a coefficient (b_4), the escapable reservoir volume at the time of failure (V_w) and the height of water above the breach bottom (H_w), while the Froehlich equation also considers the height of the dam (H_d).

The various parameters of the breach hydrograph are discussed in the following sub-sections.

Embankment erodibility

The new reservoir flood maps were developed under the assumption of a reservoir with a high erodibility dam, due to lack of readily available data to determine the actual erodibility of the dam as outlined in the RFM Specification. Should this assumption be changed to medium erodibility, then the peak outfall rate would decrease by 30%, and the failure time would increase by 40%, when compared to the results considering high erodibility. This change would significantly affect the calculation of the breach hydrographs, as illustrated in Figure 2.

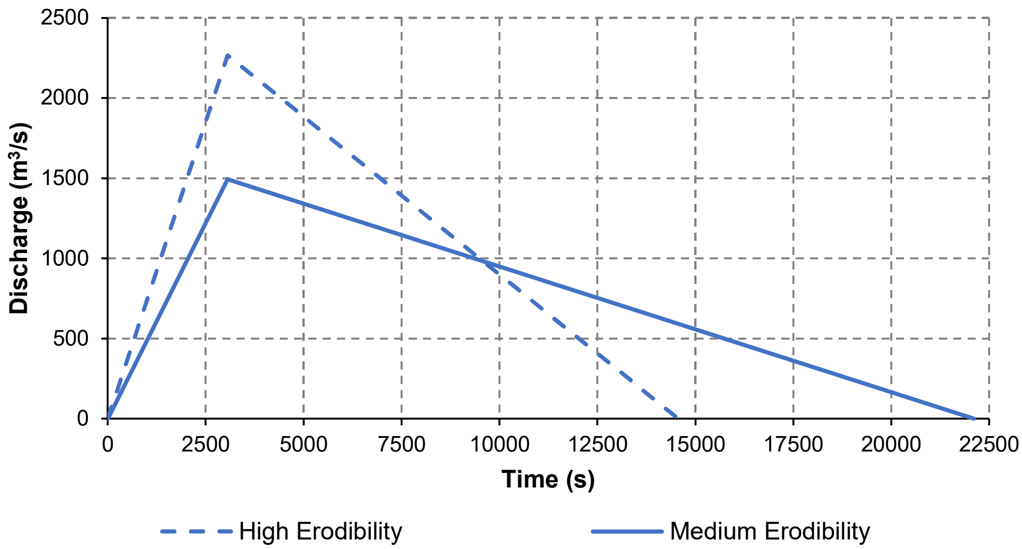

Figure 2. Example of breach hydrograph comparison between high and medium dam erodibility keeping all other parameters consistent.

The erodibility of an embankment can be reviewed against the erosion categories proposed in Briaud (2008) and reproduced in Figure 3.

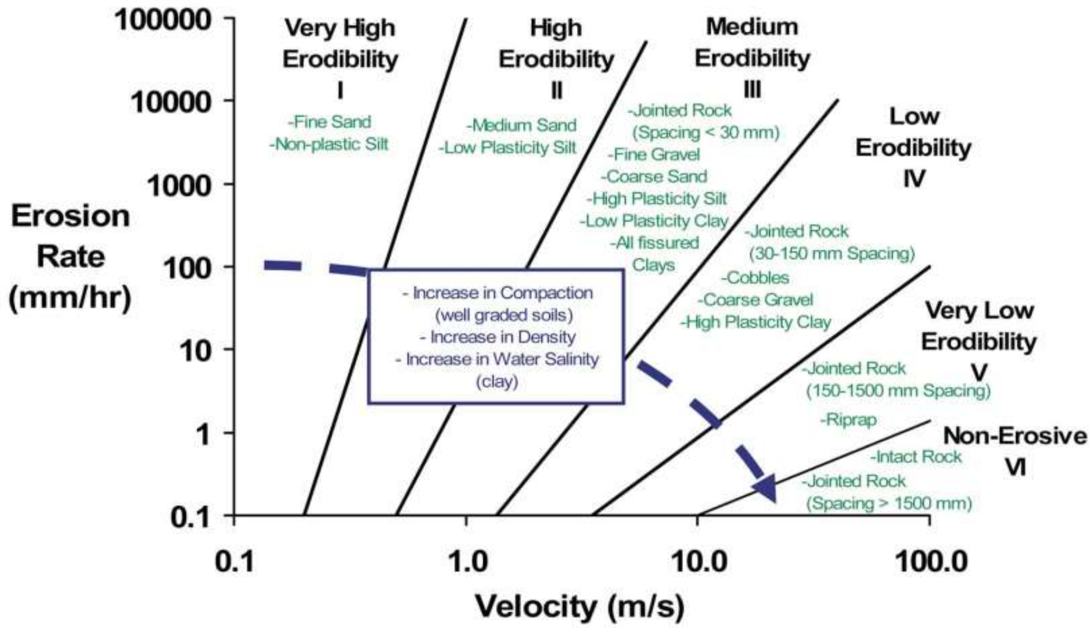

Figure 3. Erosion categories for soils and rocks (Source: Briaud, 2008).

The particle size distribution and Atterberg limits of the embankment materials of a couple of reservoirs located in the south of England, where historical ground information was available, were reviewed. The review showed that these embankments were mostly formed by medium erodibility materials, with the presence of some low erodibility materials (high plasticity clays in the core). For these embankments, the high erodibility assumption was found to be conservative.

Small embankment dams and a minority of larger embankment dams have a homogenous impermeable embankment typically formed by clay, which would fit in the medium erodibility category. In larger embankment dams, the core is supported by earthfill shoulders. The nature of the shoulders' materials and therefore their erodibility can vary significantly.

Geometrical parameters

The height of the breach (H_b), which is related to the height of the dam at the location of the breach (H_d), varies along the length of the embankment. In addition, depending on the relationship between the lowest level within the reservoir and the downstream ground level at the breach location, the escapable volume (Vw) will also vary.

The worst breach location of impounding reservoirs is often at the highest section of the embankment, however, for non-impounding reservoirs formed by perimeter embankments, the worst breach location will not be so obvious.

The 2021 EA reservoir flood maps of non-impounding reservoirs considered different possible locations for the breach, conservatively assuming the same worst parameters (dam height and escapable volume) for each location being studied. This approach can be refined by reviewing the available topographic data at each breach location to determine the height of the embankment and to reassess the escapable volume considering the downstream ground levels. In many cases, these reservoirs were built with materials from the reservoir area and the bottom of the reservoir is below the surrounding ground levels, which means that the escapable volume might be smaller than the total volume stored in the reservoir.

BREACH SCENARIOS

The new reservoir flood maps were produced for the "dry day" scenario and the "wet day" scenario. The "wet day" scenario corresponds to an overflow failure, whilst the "dry day" scenario accounts for other possible failure modes, such as internal erosion. The type of failure mode is accounted for in the peak outflow equation by the b_4 coefficient (Table 1).

When using the reservoir flood maps to determine the risk profile of the reservoir, it is important to use the ASLL value from the scenario associated with the failure mode that dictates the probability of failure of the reservoir. For instance, the probability of failure of a non-impounding reservoir is generally dictated by internal erosion and therefore the ASLL figures for the dry day scenario should be used.

FATALITY RATE

The outputs of the breach inundation mapping (flow depth and velocity) are used to calculate the individual fatality rate for each receptor (property) using the "no warning" relationship originally developed in the *Interim guide to Quantitative Risk Assessment for UK Reservoirs* (Brown and Gosden, 2004) based on DSO-99-06 (USBR, 1999). The sum product of the fatality rate and maximum occupancy at each receptor then provides a value of the ASLL.

Reclamation's Consequence Estimating Methodology (RCEM) (USBR, 2015) replaced DSO-99-06 in 2015. The RCEM 2015 fatality rates are based on case history data which was expanded from DSO-99-06. This expansion of case history data helped to strengthen the empirical relationships from which the fatality rate estimates are derived.

RCEM 2015 upper and lower limits of the suggested range for the fatality rate for little or no warning are plotted in Figure 4 together with case history data and the relationship proposed in the RFM Specification. RCEM 2015 quantifies the flood intensity in terms of maximum DV (depth multiplied by velocity), while DSO-99-06 used discharge/flooded width.

For DV values greater than 1, the RFM proposed relationship between DV and fatality rate fits reasonably well with the upper limit curve of the RCEM suggested range for fatality rate values. However, there is almost no data for DV values smaller than 1 to support the alignment of the lower leg of the RFM relationship.

The Interim guide (Brown & Gosden, 2004) mentions that the population at risk may be taken as the population in the areas where both DV is greater than 0.5m²/s and the depth above external ground is greater than 0.5m.

The alignment of the lower leg is particularly important for non-impounding reservoirs where the reservoir breach floods highly populated areas with flat topography. We have tested the sensitivity of the results in one of these reservoirs where more than 90% of the properties were in areas with DV smaller than 1. It was found that by increasing the no risk threshold from 0.1 m²/s to 0.5m²/s, the ASLL reduced by 40%.

The assessment of the fatality rate in areas with DV smaller than 1m²/s (or with fatality rates smaller than 1%) is one aspect of the RFM methodology that would benefit from further research. FD2701 (Defra, 2020) suggests that data from fluvial events with fatalities could be used. Limited Llynmouth data (only two points) were included in the original chart prepared for the Interim Guide.

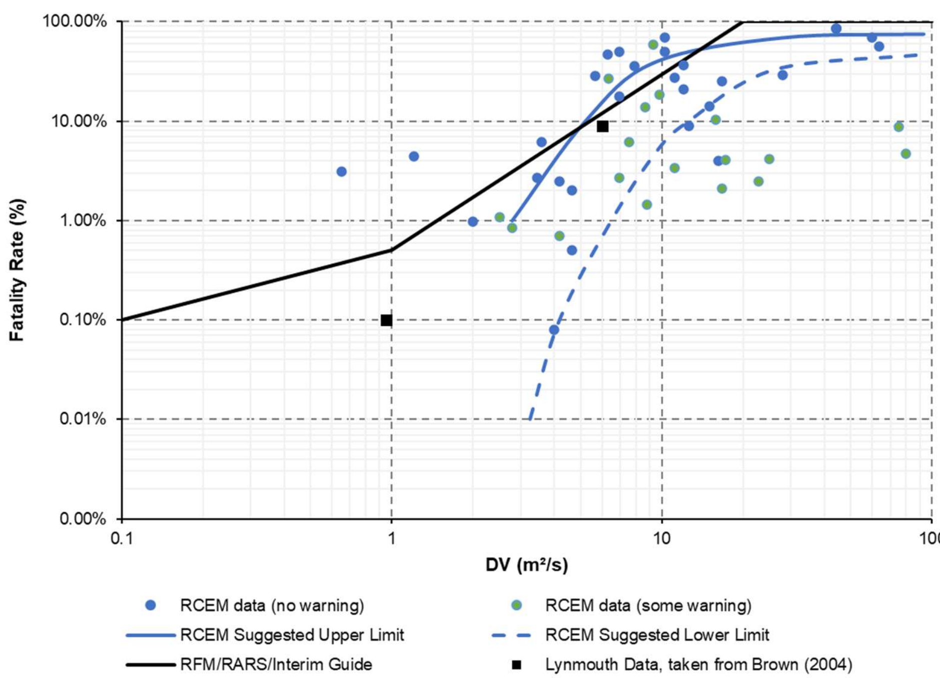

Figure 4. Fatality Rate vs DV

CONCLUSIONS

The new EA reservoir flood maps represent a significant improvement over the previous reservoir inundation maps. However, due to the lack of detailed information readily available for all reservoirs in England, certain potentially conservative assumptions regarding embankment erodibility and geometric characteristics had to be adopted for this mapping exercise to be feasible on a national scale. ASLL values calculated as part of this exercise were naturally influenced by these conservatisms.

The EA ASLL values are available to reservoir undertakers and can prove a convenient source of consequence data for reservoir risk assessments, particularly for those undertakers with limited resources to carry out detailed analyses. However, use of these values can result in the reservoir having a higher risk profile, which could lead to undertakers carrying out costly works to reduce the probability of dam failure.

This paper has outlined some of the key conservatisms with the EA RFM Specification methodology, highlighting the need for the available ASLL values to be used with caution if being applied to the assessment of the societal risk posed by a reservoir. Furthermore, with an understanding of these conservatisms, if the reservoir risk profile sits relatively close to ALARP boundary lines, the undertaker can review the site-specific data (embankment erodibility and geometrical parameters) against the data used to develop the EA reservoir flood maps, to obtain an initial indication as to whether a more detailed analysis could move the reservoir to a lower risk zone.

Outputs from the breach inundation mapping are used to calculate the fatality rate at each receptor, which is in turn used to calculate the ASLL across the inundated area. Calculation of the fatality rate considers a relationship with discharge/flood width, based on empirical equations presented in DS-99-06 (USBR, 1999). A review of more recent publications and guidance has indicated that the RFM methodology would benefit from further research into this relationship for low discharge/flood width values (<$1m^2/s$) as there is no empirical data in the USBR guides to support the alignment of the lower leg of the proposed RFM fatality rate graph. The refinement of this relationship would be particularly important for non-impounding reservoirs where the breach could flood highly populated areas with flat topography, resulting in a high ASLL value due to a large number of receptors with very low (<1%) fatality rates.

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