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Review of the Existing Risk Methodology

FD2701 – Objective 3

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Applying a Risk-based Approach and Improving the Evidence Base Related to Small Raised Reservoirs

Review of the Existing Risk Methodology

Objective 3 report - FD2701

Produced: March 2020

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Executive Summary

The Scope of this report is to address Stage 2 of the research project entitled "Contract for Applying a Risk-based Approach and Improving the Evidence Base Related to Small Raised Reservoirs".

Stage 2 was originally intended to focus mainly on improving the methodology for risk designation which would take into account the probability of failure. However, as, by the time the project commenced, similar work has already been undertaken in Scotland, the scope was amended slightly. The amended scope included a review of the work undertaken in Scotland together with research into other areas where changes to legislation could be beneficial. Four separate tasks were therefore identified as follows:

- Task 1 – Review of the recent SEPA / Aecom Research (Aecom, 2016);
- Task 2 – Review risk designation thresholds and categories;
- Task 3 – Review criteria for the definition of a large raised reservoir;
- Task 4 – Consider the case for further deregulation of certain types of reservoir.

The research was, in part, informed by the ongoing Reservoir Flood Mapping (Environment Agency, 2016) project.

The research was largely complete at the time of the Toddbrook Reservoir incident on 1st August 2019. It is possible that recommendations following investigations into the incident may shed new light on some of the findings of this research.

The scope and findings of each task are summarised in the following sections.

Task 1 – Review of the recent SEPA / Aecom Research (Aecom, 2016)

The basis of this task was a review of the report entitled "Probability Matrix for the Risk Designation of Controlled Reservoirs under the Reservoirs (Scotland) Act 2011: Probability Matrix Development, Final Report", (AECOM, 2016) with a view to assessing its applicability to England.

The overall conclusion is that it is not possible to meaningfully quantify the likelihood of failure of dams on the basis of information available in the public record. Notwithstanding this finding, there remains an option to incorporate likelihood of failure into the risk designation process if the process is informed by site specific risk assessments.

Task 2 – Review risk designation thresholds and categories

The objective of this task was to review whether the current interpretation of the boundary between "high-risk" and "not high-risk" is appropriate and to also consider the merits of introducing a three tier risk designation structure.

The findings of the research into the "high-risk" threshold were that the reservoirs industry is broadly in line with other high hazard industries and that the adopted interpretation of "endangerment of life" is appropriate. The research findings are supported by the findings of first tier tribunals.

Notwithstanding the interpretation of the legislation, it is noted that the cost of regulating some lower consequence reservoirs is potentially disproportionate to the value of the benefits secured. However, it is proposed that such considerations should not be used as a basis changing the designation of "high-risk". The reason for this is that it could result in some re-designated “not high-risk” reservoirs presenting a risk to life for individuals which is greater than the broadly acceptable limits suggested by the Health and Safety Executive (HSE).

The review of the merits of introducing a three tier risk designation structure concluded that there could be benefit in bringing in a three-tier risk designation structure if there is a future requirement to increase the rigour of the dam safety regulation on higher consequence reservoirs which are currently designated “high-risk”. Such recommendations might come out of investigations into the Toddbrook incident. If such a change were to be made, the boundary between “medium-risk” and high-risk” could be informed by ASLL with the boundary set by consideration of the proportionality of costs and benefits. “Medium-risk” and “high-risk” would be subsets of the existing “high-risk”, while the existing “not high-risk” would become “low-risk”. Regulatory requirements for “medium-risk” reservoirs would remain unchanged.

Task 3 – Review criteria for the definition of a large raised reservoir

The objective of this task was to review whether the current practice of regulating reservoirs on the basis of stored volume is the best way of identifying the most critical reservoirs.

The research identified that there is a stronger correlation between ASLL and dam height than between ASLL and reservoir volume. As such, if the Act were being rewritten, it would be preferable for the threshold for regulation to be based on height rather than volume. This would mean that, for a given number of regulated reservoirs, the average ASLL would be higher.

However, the reality is that legislation based on volume is in place, and it is anticipated that there would be reluctance to bring in a change which could result in some “high-risk” reservoirs being deregulated.

The recommendation of this research is therefore that the current 25,000 m^3 volume threshold should be retained, but that, if there is a wish to regulate reservoirs smaller than 25,000 m^3, these reservoirs should be selected on the basis of height. Further research would however be required to develop height criteria, and to determine the number of Small Raised Reservoirs (SRRs) falling under the proposed criteria.

Task 4 – Consider the case for further deregulation

The objective of this task was to identify whether there are certain types of reservoir which could be deregulated, or designated “not high-risk” on the basis of usage, construction type or maintenance, in accordance with Section 2C of the Reservoirs Act 1975.

The research identified that the only potential candidates for deregulation, or default “not high risk” designation, are reinforced concrete service reservoirs constructed after 1976. Such reservoirs are nearly all likely to be owned by water companies. Consultation with a number of water companies did not identify any clear appetite for deregulation. Analysis of failure modes identified that, whilst these structures are more robust than other types of dam, they are still vulnerable to over-spilling through over-pumping, pipe bursts, subsidence and structural deterioration. It was noted that although structural deficiencies may be picked up through water quality monitoring it would be in appropriate to rely on water quality monitoring to ensure the safety of the structures. On balance, it was concluded that there are insufficient grounds for the deregulation of service reservoirs.

1 Introduction

This report is the final deliverable for Aim 3 (Stage 2) of the Defra research project entitled *Applying a Risk-based Approach and Improving the Evidence Base Related to Small Raised Reservoirs* (FD2701).

1.1 Terms of reference

Stage 2 of the research project was originally intended to focus mainly on improving the methodology for risk designation which would take into account the probability of failure.

The aim (Aim 3) as stated in the Terms of Reference (ToR) was:

> *"To review the existing risk methodology, including consideration of any refinements such as the consideration of probability and exemptions of certain reservoir types to provide information to make decisions on potential changes to regulation."*

However, as, by the time the project commenced, similar work has already been undertaken in Scotland (Aecom, 2016), the scope was amended slightly. The amended scope included a review of the work undertaken in Scotland together with research into other areas where changes to legislation could be beneficial. Four separate tasks were therefore identified as follows:

- Task 1 – Review of the recent SEPA / Aecom Research (Aecom, 2016);
- Task 2 – Review risk designation thresholds and categories;
- Task 3 – Review criteria for the definition of a large raised reservoir;
- Task 4 – Consider the case for further deregulation of certain types of reservoir;

Tasks 1 to 4 are covered under sections 3 to 6 respectively.

Tasks 2, 3 and 4 were informed by data made available from the Reservoir Flood Mapping Project. Details of the analysis of this data is provided in section 2.

1.2 Project Background

Since the 1980s reservoir safety in Great Britain (England, Scotland and Wales) has been legislated by the Reservoirs Act 1975 which placed legal duties on those owning or operating (Undertakers) reservoirs of more than 25,000 m^3 storage capacity above natural ground, i.e. Large Raised Reservoirs (LRRs). In 2013, the 1975 Act was amended for reservoirs located in England and Wales by Schedule 4 of the Flood and Water Management Act 2010 (FWMA 2010).

In Scotland there is separate legislation. The Reservoirs (Scotland) Act 2011 is referred to hereafter as the "Scottish Act". Regulations made subsequent to, and with direct relevance to, the Scottish Act are referred to hereafter as the "Scottish Regulations".

In Wales the main difference to England is that the volumetric threshold is 10,000 m^3 whereas in England it is still 25,000 m^3. Prior to the FWMA 2010 the value was 25,000 m^3 in both England and Wales. The difference between the legislation in England and Wales is prescribed through regulations.

This research is for England only therefore the Reservoirs Act 1975, as amended by subsequent legislation, is referred to as the “English Act” in this report in order to differentiate from differing Welsh and Scottish legislation. Regulations with direct relevance to the English Act are referred to hereafter as the “English Regulations”.

1.3 Purpose of this report

The purpose of this report is to provide evidence to inform decisions on potential changes to interpretation of existing legislation and potential amendments to primary and secondary legislation.

1.4 Key Terminology

1.4.1 Introduction

This section sets out some key terminology which is adopted throughout the rest of the report.

1.4.2 Probability and Likelihood

For probability or likelihood of failure the recent SEPA research (Scottish Environment Protection Agency, 2015) uses the term Overall Likelihood of Failure (OLOF) to differentiate from the likelihood of failure related to specific failure modes: Flooding Likelihood of Failure (FLOF) / Internal Likelihood of Failure (ILOF) / Stability Likelihood of Failure (SLOF). Probability, likelihood and OLOF are synonymous and are used interchangeably in this report to suit the context. Where the term “risk assessment” is used this is assuming the meaning as per the guide to Risk Assessment for Reservoir Safety management (RARS) guidance (Environment Agency, 2013a) which incorporates both likelihood and consequence of failure. It should be noted that “risk assessment” is different to the current process of “risk designation” which is based, only, on the consequence of failure. If future methods of risk designation are to incorporate likelihood of failure it is assumed that this would be using a risk assessment process, which may be simple or complex; qualitative or quantitative; and automated or bespoke. In some instances, for the avoidance of doubt, the term “consequence designation” is used to refer to a risk designation which does not incorporate probability of failure.

It is worth stating at this point that the probability of dam failure is inherently stochastic process based on a range of physical process, which are complex to quantify broadly. Technological developments that improve our understanding and monitoring of these physical processes have the potential to reduce some of this uncertainty.

1.4.3 Average Societal Loss of Life (ASLL)

Average Societal Loss of Life (ASLL) (Environment Agency, 2016), previously known as Likely Loss of Life (LLOL) (Environment Agency, 2009), is the summation of the peak Fatality Rate multiplied by the Maximum Population at Risk (MPAR) at each individual property and is usually expressed for one reservoir as the maximum of all tested breach locations. Fatality Rate is a function of depth and velocity. A detailed specification for ASLL is available (Environment Agency, 2016).

ASLL is, statistically, the expected number of lives lost in the unlikely event of a catastrophic breach. Since it is a statistical concept, it can be non-integer. For example, if there were two reservoirs in different valleys, each with an ASLL of 0.5, and if they both underwent a catastrophic breach at the same time the total expected loss of life would be one person in total. It should, however, be noted that this does not take into account the number of people that could be seriously injured.

1.4.4 Hazard

Hazard is referred to across a number of disciplines in different publications. In this report, unless stated otherwise, hazard is as defined in the Reservoir Flood Mapping Specification (Environment Agency, 2016) and is a function of water depth and velocity. Hazard is discussed in some detail in section 4.5.2.1.

1.4.5 Risk designation

The Reservoirs Act 1975 makes provision for reservoirs to be designated “high-risk”. There is no prescribed designation for the reservoirs which are not designated “high-risk”. However, as an expedient for this report we have adopted the term “not high-risk” which can be treated as the designation of reservoir which are not designated “high-risk”.

2 Reservoir Flood Mapping Project

2.1.1 Introduction

A key input to Tasks 2, 3 and 4 of this research has been the ongoing Reservoir Flood Mapping (RFM) Project. The RFM Project is a national scale flood modelling study of the impact of dam failure for all large raised reservoirs in England. This project is being managed by the Environment Agency and is due to be completed in December 2020. At the time of writing this report, nearly 650 reservoirs have been modelled and the results of these analyses was made available for this research. Table 1 lists the main deliverables produced for each modelled reservoir.

2.1.2 Previous studies

The Reservoir Flood Mapping (RFM) Project will supersede the previous Reservoir Inundation Mapping (RIM) Project undertaken in 2009.

The RFM mapping includes some significant changes compared to the RIM mapping which include the following:

- Consideration of wet and dry day dam break scenarios;
- More representative estimates of peak reservoir levels in overtopping scenarios;
- More representative estimates of peak discharge based on more recent research;
- Inclusion of estimation of Hazard Rating based on the research report FD2321 *Flood Risks to People Methodology* (Defra, 2008).

2.1.3 RFM Deliverables

The data which is generated by the RFM project is set out in **Table 1**.

Table 1: RFM Project Output

Deliverable	Description
Summary Sheet	An Excel spreadsheet that details the key information that was used to model the dam failure. Includes summaries of the consequence metrics that were recorded, such as ASLL, MPAR and Flood Damages.
Flood Depth Map	A raster data based map that shows maximum depth of flooding downstream following dam failure.
Flood Extent Map	A vector data based map that shows the maximum extent of flooding downstream following dam failure.

Deliverable	Description
Flood Hazard Map	A raster data based map that shows hazard downstream following dam failure.
Flood Impact Map	A vector data based map that shows the maximum extent of flooding downstream following dam failure. Also shows the properties that have been impacted by the dam failure. These properties have been categorised into completely destroyed, partially destroyed and flood damage only based on the flood depths and velocities recorded at that location.
Flood Velocity Map	A raster data based map that shows maximum velocities downstream following dam failure.

Source: Adapted from RFM Specification (Environment Agency, 2016)

Both summary sheet data and the GIS data used to produce the maps, such as maximum hazard and maximum flow per unit width, were requested. Unfortunately, due to the partially completed status of the RFM project, the GIS data could not be made available for the purposes of this research. The summary sheets were made available and their use is discussed in the subsequent sections

2.1.4 Data Processing

647 summary sheets were received for use in this study. Scripting tools were developed to extract the required data from each summary sheet spreadsheet file into a new summary spreadsheet containing data for each reservoir. There were variations in the format of the summary sheets based on their version number, and therefore it was not possible to create a single script that works with all versions. To enable automated extraction a single script was created for the latest version. This allowed for the extraction of data for 608 reservoirs in total. Data for the remaining 39 reservoirs was not included as the additional time that would be required to extract the data was not considered commensurate to the corresponding change in sample size which would increase from 29% to 31% of the population. Table 2 lists the data that was extracted from the summary sheets for use in this study.

Table 2: RFM Summary Sheet Data Used

Summary Sheet Field	Description
Reservoir ID	A unique ID given to each reservoir
Category	Non-Impounding (excluding Service), Impounding and Service
Freeboard	The distance (height) between the top of the dam and the top water level of the reservoir
Max escapable volume	Escapable reservoir volume at top water level. Equivalent to Capacity in the public register of large raised reservoirs and to “capacity of reservoir between lowest natural ground level of any land adjoining the reservoir and top water level’ in the Prescribed Form of Record

Summary Sheet Field	Description
Breach ID	Multiple breaches were modelled for each dam. Each was given a unique ID between 1 and 5. The dam failure consequences are recorded for the breach with the highest consequences
Water depth at breach	Freeboard subtracted from the maximum height of dam. Maximum height of dam is taken from the lowest natural ground at the downstream toe to the top of the dam, wall or embankment. This is equivalent to the 'Maximum Height' in the Public Register and Prescribed Form of Record.
Max escapable volume at breach	The maximum volume that would be released due to the failure of the dam. This is different to the maximum escapable volume, which is the registered volume of the large raised reservoir. If the failure of a reservoir dam causes an adjacent reservoir to fail, this will be included in the maximum escapable volume at breach, but not in the maximum escapable volume.
Distance downstream of dam	The distance in kilometres from the dam breach to the centre of the nearest cluster of properties
Peak discharge	The peak discharge of the dam breach hydrograph. It is a function of dam height and reservoir volume, based on the dam breach equations for each dam type.
Maximum Population at Risk (MPAR)	Sum of the Maximum Occupancy (based on property type) for all affected properties
Average Societal Life Loss (ASLL)	Sum of the product of the Fatality Rate (based on depth and velocity) and the Maximum Occupancy (based on property type) over all affected properties. Formerly known as Likely Loss of Life (LLOL).
Property Damages	Sum of cost of direct damage over all affected properties, applying simple unit costs depending on level of damage: flooding only ($V<2$ m/s or $DV<3$ m^2/s), partially destroyed ($V>2$ m/s and $3\ m^2/s < DV < 7\ m^2/s$) or totally destroyed ($V>2$ m/s and $DV>7\ m^2/s$)

Source: (Environment Agency, 2016)

2.1.5 Limitations of data and methodology

2.1.5.1 Dry day and Wet day scenarios

The RFM study calculates dam failure consequence for a 'dry day' and 'wet day' scenario. In the dry day scenario, the reservoir is full to the top water level when there is an uncontrolled release of water. In the wet day scenario, the reservoir water level is derived to be consistent with a Probable Maximum Precipitation (PMP) event over the catchment, with the spillway being blocked. In addition to this, a routing model incorporates river flooding corresponding to a 1 in 1000 Year flood event due to runoff from the catchment downstream of the dam. This research only considers the 'dry day' scenario to maintain consistency with the analysis undertaken in the Objective 2 report (Mott MacDonald, 2018b).

2.1.5.2 Difference between registered and modelled dam height and reservoir volume

This research uses the registered reservoir volume and dam height (including freeboard) to relate dam characteristics to dam failure consequences. This differs slightly from the RFM methodology which uses height to top water level in the 'dry day' scenario. The purpose of using the registered reservoir volume and dam height is so that any conclusions are derived in terms of the registered reservoir volume and dam height, and no further consideration of freeboard is required while interpreting the results.

2.1.6 Kernel Density and Box Plots

Kernel Density and Box Plots have been used in the presentation of data.

Kernel density plots are smoothed out versions of histograms. They are created by drawing probability distribution curves at each data point, and then summing the curves together to obtain the final density estimate. The width of the individual curves dictates how frequently peaks occur in the combined curve, and can be optimized for a given sample size and variance.

Box plots (also known as box and whisker plots) are used to show the spread of distribution. They typically show the median and interquartile range (25th percentile and 75th percentile). In this study, the whiskers have been used to show the 5th and 95th percentiles.

Both types of plots have been used in the subsequent sections to visualise the data being analysed.

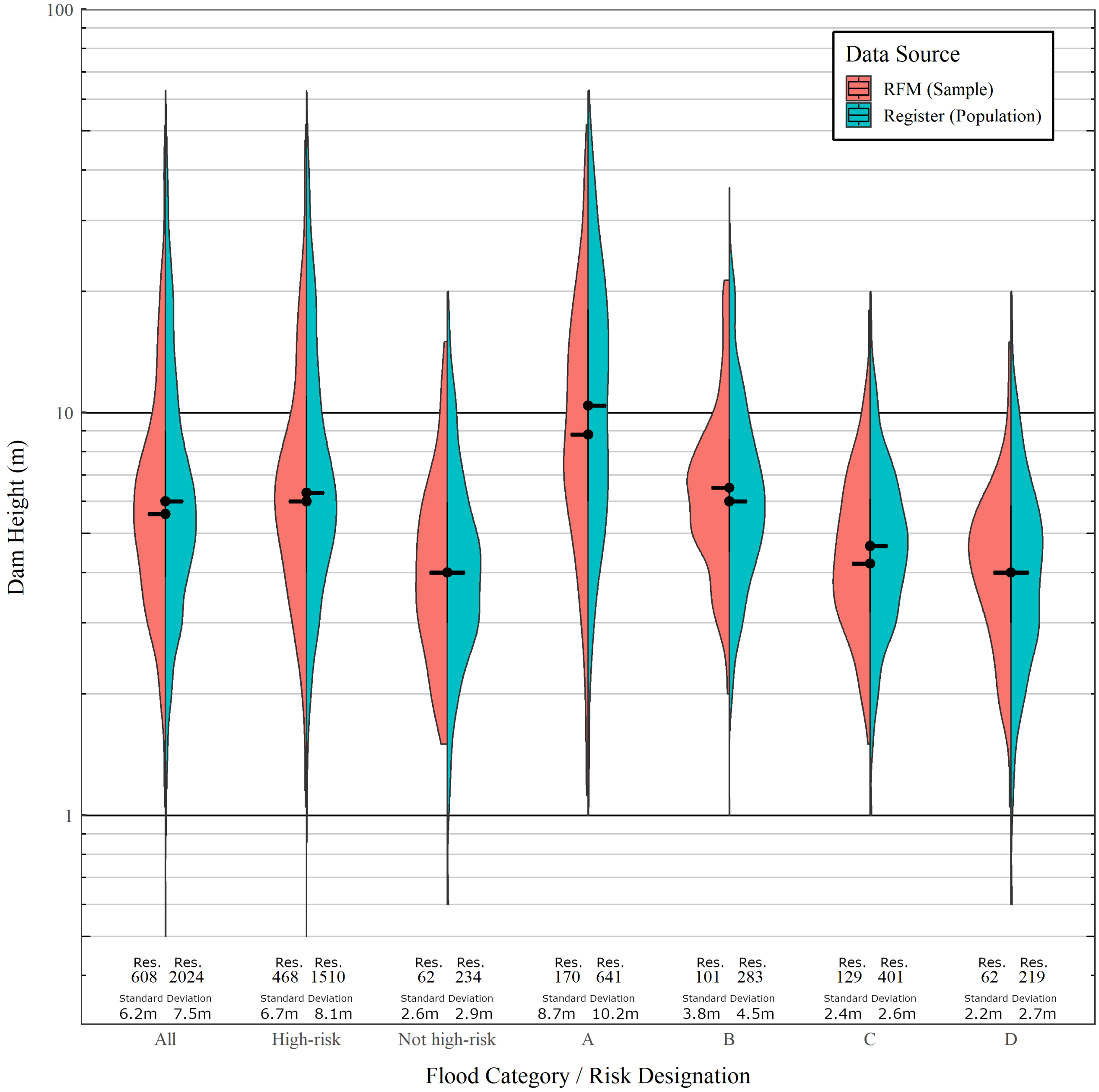
2.1.7 Representativeness of sample

As noted in section 2.1.1, the RFM study is still in progress and the sample of reservoirs analysed in this study is a subset of the broader population of reservoirs in England. Furthermore, the order in which the models were completed was not chosen randomly, and prioritisation was based on the separate objectives of the RFM project, for example, ensuring a balanced workload to all consultants. Therefore, there is a risk that the sample of reservoirs is not representative of the whole population.

To check the representativeness of the sample, the difference in the height and volume distributions between the sample and population were compared by visual analysis of kernel density plots and comparison of median values. The population characteristics were informed by the public register maintained by the Environment Agency. Figure 1 compares dam height, while Figure 2 compares reservoir volume.

The numbers below each density plot indicate the number of reservoirs in that part of the sample or population and the standard deviation in each group. In general, the sample appears to represent the population reasonably well. The greatest difference in median values is within category A reservoirs, where the median differs by 1 m and 150,000 m^3. Given the significant spread of volumes within category A reservoirs, this sample is still considered sufficiently representative of the population. The difference in standard deviation of volumes between the sample and population is largest for category B and “not high-risk” reservoirs. This can be attributed to the fact that some of the larger reservoirs within these populations are not in the RFM sample.

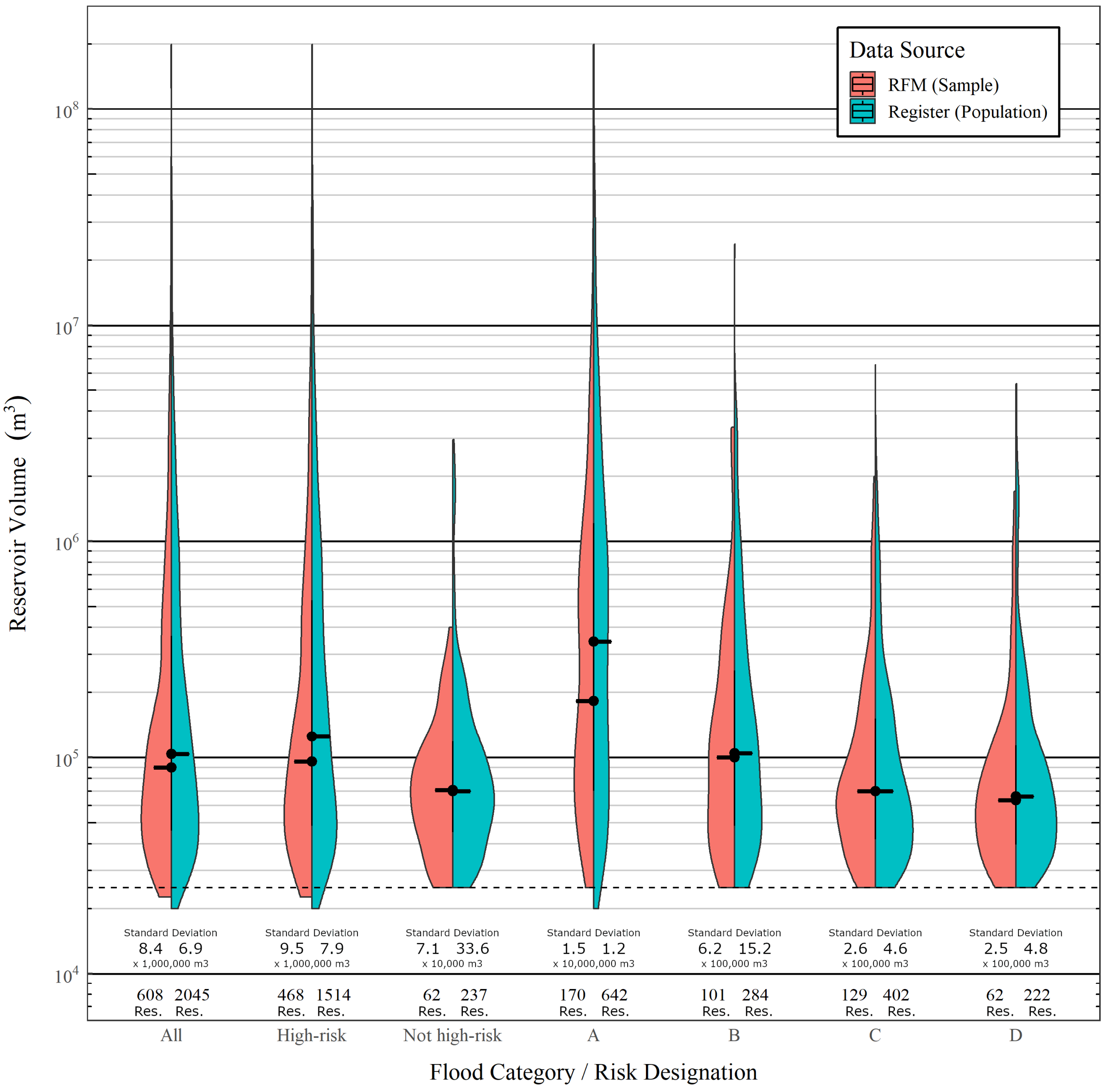
Figure 1: Variation in Dam Height between Risk Designations / Flood Categories



Notes: Centreline = Median, Total number of reservoirs is less than 2065 because of missing dam height data in public register

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Figure 2: Reservoir Volume across Risk Designations / Flood Categories



Notes: Centreline = Median, Total number of reservoirs is less than 2065 because of incorrect or missing reservoir volume data in public register

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

2.1.8 Distribution of ASLL in flood categories/ risk designations

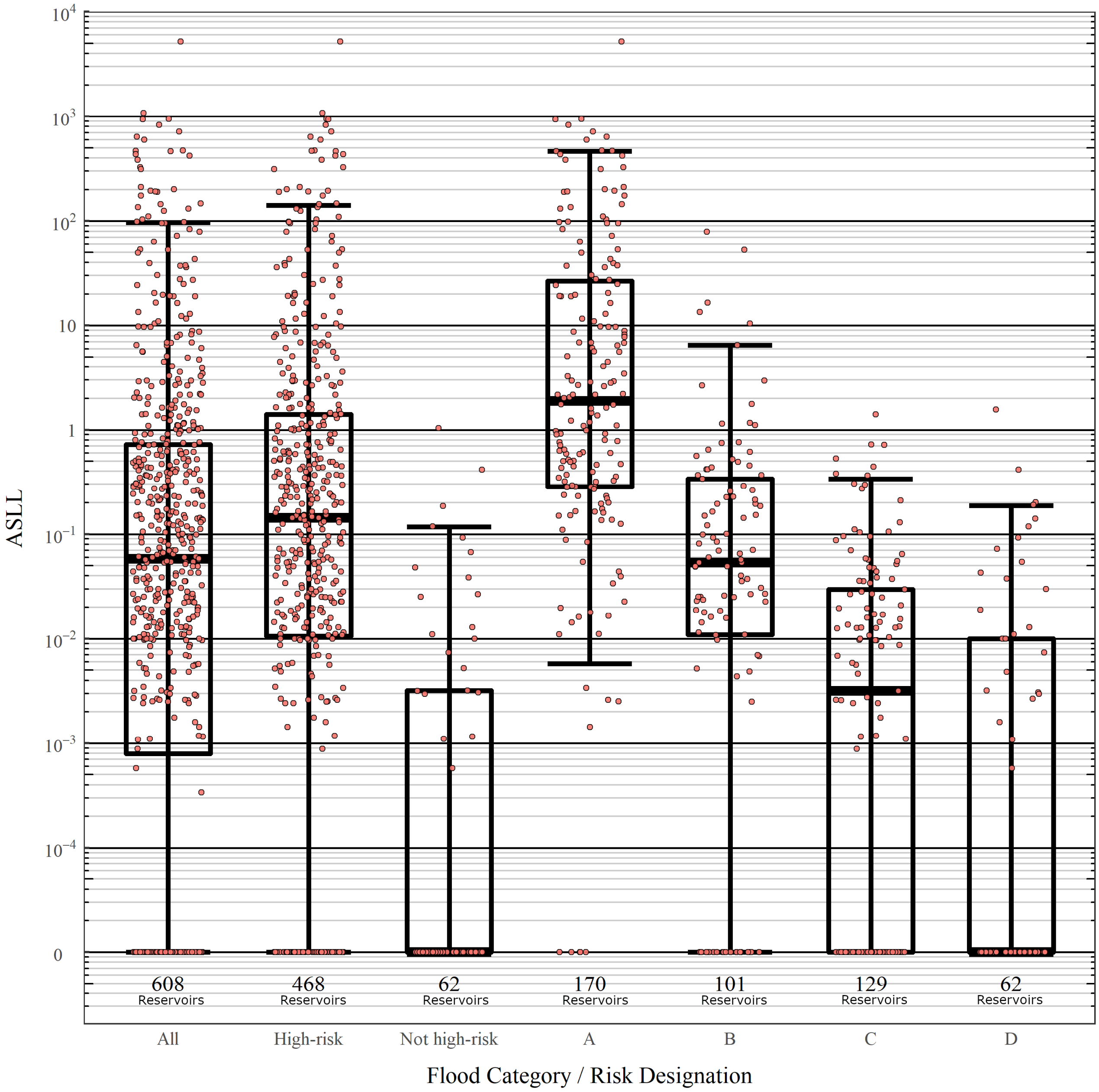
This sub-section presents the ASLL values for the RFM reservoirs against the following consequence categories:

- Risk designation
  - "High-risk"

  - "Not high-risk"
- Flood category (A, B, C, D) in accordance with FRS guidance (Institution of Civil Engineers, 2015)

This analysis of ASLL by consequence class provides context for the subsequent analysis of ASLL in the rest of the report. This is considered to be of value because while under this study ASLL is a singular automated output parameter, consequence categories are determined drawing on expert judgement often following a site visit and review of a range of information. This graphical comparison is considered to be useful background information which may inform future research.

Figure 3: Distribution of ASLL for RFM reservoirs in each flood category and against risk designation



Notes: Centreline = Median, Box = 25%ile and 75%ile, Whiskers = 5%ile and 95%ile, 10^{-5} nominally added to all ASLL values to show zero values on log scale

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

The box plot in Figure 3 shows the distribution of ASLL for reservoirs within each flood category and risk designation. The smallest non-zero ASLL value is 3.29 x 10^{-4}. To capture zero values on a log scale, 10^{-5} was nominally added to all ASLL values. The red dots indicate the recorded ASLL values within each group. Each box represents the interquartile range (25% to 75%) with the median shown as a horizontal line. The whiskers show the 5th and 95th percentile ASLL values for that group. This information is also summarised in Table 3.

Table 3: ASLL values in each reservoir group

Value	All	"Not high-risk"	"High-risk"	A	B	C	D
Maximum	5193	1.0	5193	5193	78.8	1.4	1.6
95th %ile	97.2	0.1	141.5	465.4	6.5	0.3	0.2
75th %ile	0.7	3.2 x 10^{-3}	1.4	26.7	0.3	3.0 x 10^{-2}	1.0 x 10^{-2}
Median	5.7 x 10^{-2}	0.0	0.1	1.9	5.3 x 10^{-2}	3.2 x 10^{-3}	0.0
25th %ile	7.2 x 10^{-4}	0.0	1.0 x 10^{-2}	2.8 x 10^{-1}	1.1 x 10^{-2}	0.0	0.0
5th %ile	0.0	0.0	0.0	6.8 x 10^{-3}	0.0	0.0	0.0
Minimum	0.0	0.0	0.0	0.00	0.0	0.0	0.0

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

The largest ASLL values of all reservoirs in the RFM sample is 5,193. However, from inspection of Figure 3 above this appears to be an extreme value, with ASLL values being typically between zero and 1,000. The median ASLL value for all reservoirs is 0.0573. The median ASLL for "high-risk" reservoirs is higher, at 0.143. For "not high-risk" reservoirs, 95% of the reservoirs have ASLL less than 0.1. 45% of "high-risk" reservoirs also fall within the zero to 0.1 ASLL range indicating a significant degree of overlap.

The variation in ASLL between the flood categories is as expected, with higher ASLL values for flood categories A and B and lower ASLL values for C and D. There are category A reservoirs with zero ASLL, but these are less common. Median ASLL for category A reservoirs is at about two, reducing with each category down to zero for category D reservoirs. Most reservoirs with ASLL above one are category A.

2.1.9 Low RFM consequence reservoirs

During the analysis, it was observed that there were dams with zero ASLL values that had "high-risk" designations. This study aims to use ASLL as a measure of consequence of dam failure, therefore it would be of interest to review in detail these reservoirs with "high-risk" designation.

Out of the 608 reservoirs in the RFM sample, the 150 reservoirs with zero ASLL values were analysed. It was observed that nearly half of these reservoirs also had non-zero values for flood damages. The flood maps indicate that there could be large scale flooding of properties due to dam failure, albeit at sufficiently low flow per unit metre to calculate a zero value of loss of life. However, the extent of low depth flooding was significant enough to cause non-zero property flood damage values. Therefore, this subset of reservoirs with low dam failure consequences has been reviewed in more detail in order to examine the reservoirs with the lowest RFM summary sheet consequence result: zero ASLL and zero flood damages.

In the sample there are 57 reservoirs with both zero ASLL and zero monetary flood damages. Out of these, 23 were "high-risk" and 23 were "not high-risk". The remaining 11 have not yet been designated. The hazard maps of the 23 "high-risk" reservoirs were analysed to understand the reasons for their low failure consequences.

Table 4: Reservoirs with Relatively Low RFM Consequence and "High-risk" Designation

Reservoir	Risk Designation	ASLL	Flood Damages (£)	Comments on dam failure consequences from RFM hazard maps	Flood Category
1	“High-risk”	0	0	Public park with historic building just downstream of dam.	A
2	“High-risk”	0	0	Dam crest is on an A road.	A
3	“High-risk”	0	0	There are some properties just downstream of the dam, but dry day 2016 modelling indicates they are safe from flooding. Extreme hazard values (>2) under bridge on A-road.	A
4	“High-risk”	0	0	B-road on the dam crest.	B
5	“High-risk”	0	0	Road on downstream side of the dam.	B
6	“High-risk”	0	0	A-road and golf course on downstream side of dam.	B
7	“High-risk”	0	0	Unidentified buildings on the downstream side of dam.	B
8	“High-risk”	0	0	Consists of multiple reservoirs next to each other. Adjoining reservoirs have higher failure consequences.	B
9	“High-risk”	0	0	Extreme hazard (> 2) in downstream pools. Possible “high-risk” designation because of cascade failure risk or use of downstream pools.	C
10	“High-risk”	0	0	No identifiable receptors	C
11	“High-risk”	0	0	No identifiable receptors	C
12	“High-risk”	0	0	Landowner property immediately downstream of dam. Buildings are not inundated in 2016 modelling, but are very close to being flooded, which may have been represented differently under the previous modelling which informed the risk designation.	C
13	“High-risk”	0	0	Significant hazard (> 1.25) values in downstream nature reserve.	C
14	“High-risk”	0	0	Road on dam crest, in addition to extreme hazard values (> 2) recorded on footpaths.	C
15	“High-risk”	0	0	No identifiable receptors	C
16	“High-risk”	0	0	Significant hazard (> 1.25) in downstream pools. Possible “high-risk” because of cascade failure risk.	C
17	“High-risk”	0	0	Outhouse building with significant hazard (> 1.25).	C
18	“High-risk”	0	0	Road on dam crest.	D
19	“High-risk”	0	0	Significant hazard (> 1.25) in downstream pools. Possibly “high-risk” due to risk of cascade failure.	D
20	“High-risk”	0	0	There is an A-road just downstream of the dam. Modelling shows no flood inundation on the road, but “high-risk” designation could be related to the risk to the road embankment.	D
21	“High-risk”	0	0	No identifiable receptors	None

Reservoir	Risk Designation	ASLL	Flood Damages (£)	Comments on dam failure consequences from RFM hazard maps	Flood Category
22	"High-risk"	0	0	Lakes, footpaths and a car park on the downstream side of dam with significant hazard (> 1.25).	None
23	"High-risk"	0	0	Nature reserve and historic site on downstream side of dam with significant hazard (> 1.25).	None

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

The analysis of relating low consequence / "high-risk" reservoirs shows that even for the lowest possible consequence results based on the RFM summary sheets (which do not include flood hazard) the probability of a "high-risk" designation is approximately 50%. One possibility for that this is because the previous iteration of the RFM project, the RIM project (Environment Agency, 2009) was known to be more conservative, and it was expected that overall the flooding extents would go down. However, without directly comparing the old and new maps, it would not be possible to ascertain if that is the case for each reservoir. Another possibility is that the hazard map review exercise summarised in Table 4 has correctly identified the flood receptors at risk that resulted in the high-risk designation. These receptors do not form part of the ASLL calculation and therefore there are some limitations in the use of ASLL as a precise measure of endangerment to human life. To overcome these limitations in using ASLL alone as a measure of dam failure consequence, the following recommendations are made for any future studies:

- Using peak hazard: Peak hazard has a more direct relationship with the risk designation process, and would therefore provide more insight into the relationship between dam characteristics, dam failure consequences, and the risk designations that are being investigated in this study;
- Increase the type of flood receptors analysed: As demonstrated in Table 4, there are a number of receptors that it would be beneficial to include in the analysis of dam failure consequences, such as major roads and outbuildings. These can be extracted from OS MasterMap and used to measure any occurrences of high hazard values as a result of dam failure.

2.1.10 Summary

This section introduced the RFM data that has been used in this study and showed some representative dam failure consequence values (ASLL) for dams of different risk designation / flood category. The limitations of using the RFM data for this study were discussed, and recommendations were made on how to overcome some of these limitations.

The RFM data is used for analysis in the following sections:

- Task 2: As a potential threshold between high-risk and medium-risk reservoirs
- Task 3: To correlate dam characteristics (such as height and volume) to dam failure consequence (ASLL)
- Task 4: To compare the dam failure consequences (ASLL) between types of reservoirs (service and non-service)

3 Task 1: Review of Aecom Research (Aecom, 2016)

3.1 Task Description

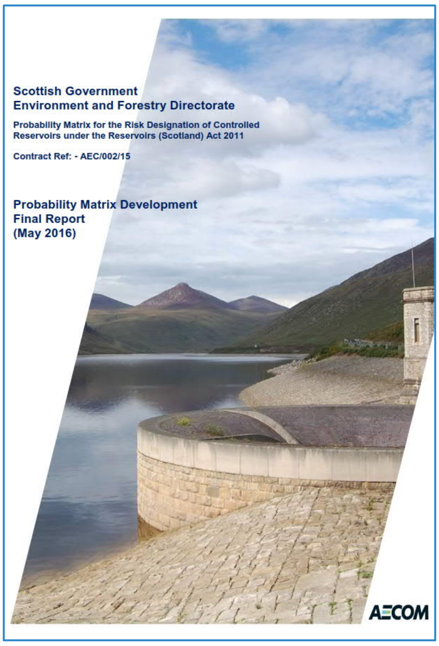
Research was commissioned by the Scottish Government and undertaken by Aecom entitled:

“Probability Matrix for the Risk Designation of Controlled Reservoirs under the Reservoirs (Scotland) Act 2011: Probability Matrix Development, Final Report”

The research, completed in May 2016, produced a simple methodology for estimating approximate probability of failure of a dam based on information already available in SEPA’s register of large raised reservoirs. This procedure was trialled to produce a new risk designation based on both consequence and probability for a portfolio of Scottish Water dams.

In most cases the model resulted in a reduction of overall risk designation during the trial, which in the case of high consequence reservoirs was considered likely to be unacceptable. Therefore, for high consequence reservoirs a safeguard was proposed which was necessarily conservative given the limited available data.

Figure 4: Aecom Research



Scottish Government
Environment and Forestry Directorate
Probability Matrix for the Risk Designation of Controlled Reservoirs under the Reservoirs (Scotland) Act 2011
Contract Ref: - AEC/002/15

Probability Matrix Development
Final Report
(May 2016)

AECOM

Source: (Aecom, 2016)

Under this task we have reviewed the SEPA / Aecom research and commented on the applicability to England. In particular we have:

- reviewed the work undertaken;
- commented on applicability to England;
- explored reservoir characteristics which have previously been proposed for use in risk assessment and comment on applicability to future changes to legislation, for example maintenance or conditions which can vary over time;
- fed conclusions into other tasks under this Aim.

3.2 Review of the work undertaken

3.2.1 Introduction to the research

Research was commissioned by the Scottish Government and undertaken by Aecom entitled:

“Probability Matrix for the Risk Designation of Controlled Reservoirs under the Reservoirs (Scotland) Act 2011: Probability Matrix Development, Final Report” (May 2016).

Any reference in this report to “the Aecom Report” is a reference to the report cited above.

The research, completed in May 2016, produced a simple methodology for estimating probability of failure of a dam based on information already available in Scottish Environment Protection Agency (SEPA) register of large raised reservoirs. This procedure was trialled to produce a new risk designation based on both consequence and probability for a portfolio of Scottish Water dams.

The initial outputs of this review were captured in the Interim Progress Report. These findings were fed into the other tasks (task numbers 2, 3 and 4).

The aim of the research project in Scotland was to propose a model enabling SEPA, using the limited information already obtained through the registration process, to readily incorporate the likelihood of failure with the existing consequence-based designation to arrive at an overall risk designation matrix in line with the three levels ("high", "medium" and "low") stated in the Scottish Act.

The proposed method was based on adopting and simplifying the principles in the RARS guide (Environment Agency, 2013a) to combine qualitative descriptors of consequence and likelihood of failure to arrive at one of the three statutory risk designations. It incorporates the likelihood of failure based on intrinsic condition determined by marrying historical failure rates against certain dam characteristics. It does not take account of current or future change in condition.

3.2.2 Determination of Overall Likelihood of Failure (OLOF)

Table 4-1 of the research report (Aecom, 2016) gives *"factors available and adopted for the assessments."* The starting point for these "inputs" was based on the need to utilise existing data available in the Scottish register of statutory reservoirs. These are summarised by the current writers as follows:

- Construction year;
- Consequence designation (high / medium / low);
- Dam type (concrete / earthfill);
- Dam height.

A qualitative assessment of overall likelihood of failure (OLOF) is determined and taken as the greatest of the:

- Internal likelihood of failure (ILOF);
- Flooding likelihood of failure (FLOF);
- Stability likelihood of failure (SLOF).

Each of these characteristics is categorised as Extreme, Very High, Moderate, Low or Very Low.

FLOF and SLOF can be combined to give external likelihood of failure (ELOF) but this does not change the method or the results.

For both concrete and embankment dams ILOF would ideally be based on a range of site-specific factors governing both the intrinsic and current condition. In the absence of site-specific data all pre-1935 dams were assigned a moderate ILOF and all post-1935 dams were assigned a low ILOF.

For embankment dams FLOF would ideally be based on flood category for a very high-level assessment. In the absence of the available data flood category was substituted for consequence designation with:

- High consequence mapping to medium FLOF;
- Medium consequence mapping to high FLOF; and
- Low consequence mapping to very high FLOF.

For concrete dams FLOF was not considered to be related to a significant failure mode and was not used, although flooding was incorporated into the determination of SLOF for concrete dams as discussed below.

For embankment dams, SLOF was to be determined based on dam height (H), crest width (C) and embankment slope relative to modern design practice for that specific material. Since the material type was unknown, it appears that the model assumes a modern design slope and then the SLOF is either “moderate” or “low” with the cut-off at C/H = 0.5. Crest width (C) was also unknown and was therefore selected based on construction year with a crest of 5 m assumed for pre-1800 dams; 3 m for dam from 1800 to 1935; and 4 m for dams constructed post-1935. Sensitivity analysis was undertaken to test the assumptions.

For concrete dams SLOF was to be based on a combination of vulnerability to stability failure and flood category as per Table 4.11 in RARS (Environment Agency, 2013a). Flood category was substituted for consequence designation and vulnerability to stability failure was based on year of construction with post-1935 dams representing *“neutral”* vulnerability and pre-1935 dams representing *“unlikely”* vulnerability. For all high consequence dams these combinations can only map to “low” SLOF.

Appendix B to the research report (Aecom, 2016) gives an extract from the model and demonstrates how these inputs can determine an updated risk designation. Based on the results in the appendix and the results for OLOF presented in Figure 6-3 of the Aecom report (Aecom, 2016) it appears that the critical failure mechanism is typically:

- FLOF for embankments – determined based on consequence designation;
- ILOF for concrete dams – determined based on year of construction.

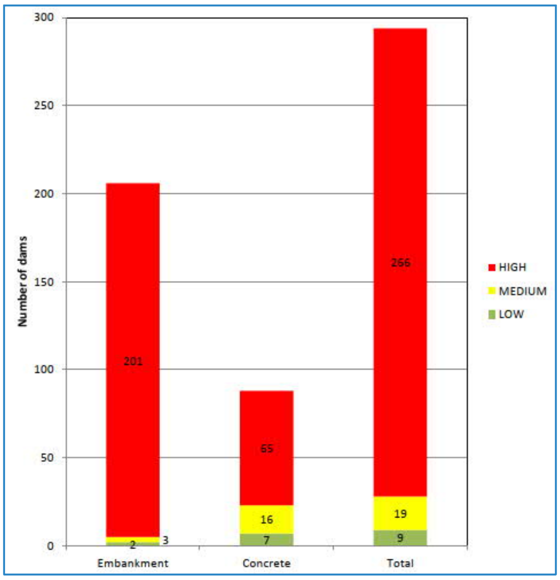
Dam height was used to determine SLOF, which was not the critical failure mode for any of the 52 dams considered in Appendix B and therefore it appears that in effect dam height is rarely used, if at all.

The results for OLOF are shown in Figure 6 below, copied from the Aecom report (Aecom, 2016).

201 embankment dams out of 206 (98%) have high consequence designation. 195 embankment dams out of 206 (95%) map directly across to “moderate” OLOF. Therefore, while FLOF does not always determine OLOF for embankment dams, it does typically.

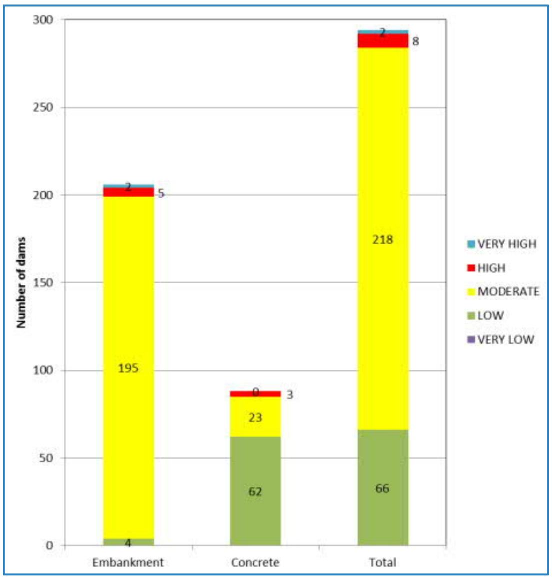
For concrete dams ILOF typically determines OLOF in the model. ILOF is determined by construction date with the cut-off between “low” and “moderate” being post- and pre-1930s respectively, and represents, inter alia, internal erosion of the foundation leading to sliding. As such, 85 out of 88 concrete dams (97%) are mapped across to a “low” or “moderate” OLOF.

Figure 5: Current risk designation (consequence)



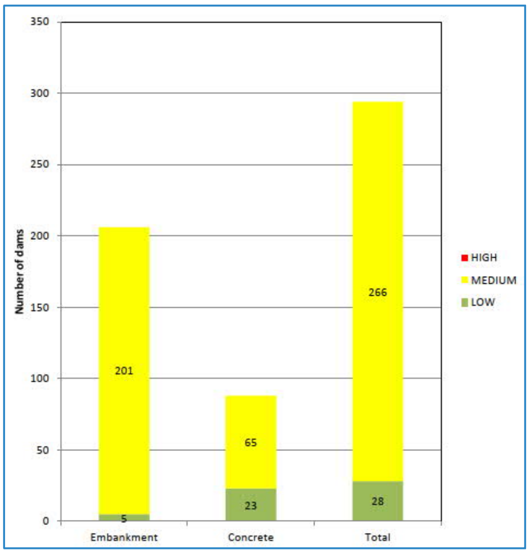
Source: Scottish Water dams (Aecom, 2016)

Figure 6: Overall Likelihood of Failure (OLOF)



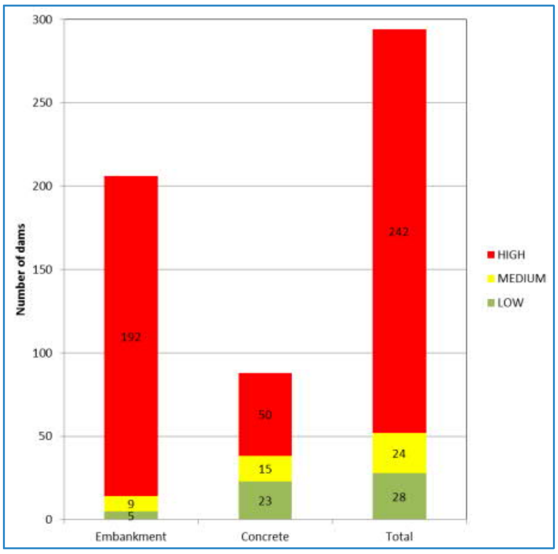
Source: Scottish Water dams (Aecom, 2016)

Figure 7: Modelled risk designation (pre-safeguard)



Source: Scottish Water dams (Aecom, 2016)

Figure 8: Modelled risk designation (post-safeguard)



Source: Scottish Water dams (Aecom, 2016)

3.2.3 Combining likelihood with consequence to develop a risk matrix

Once a qualitative estimation of OLOF has been established this is combined with consequence in a matrix to determine an updated risk designation. The “tolerability of risk” chart from RARS (Environment Agency, 2013a) was used as a starting point, copied below in Table 5.

Table 5: Tolerability of Risk

Likelihood of downstream flooding	Potential magnitude of consequences (ASLL)				
	Level 0	Level 1	Level 2	Level 3	Level 4
Extreme	ALARP	ALARP	ALARP	Unacceptable	Unacceptable
Very high	Tolerable	ALARP	ALARP	ALARP	Unacceptable
High	Tolerable	Tolerable	ALARP	ALARP	ALARP
Moderate	Tolerable	Tolerable	Tolerable	ALARP	ALARP
Low	Tolerable	Tolerable	Tolerable	Tolerable	ALARP
Very Low	Tolerable	Tolerable	Tolerable	Tolerable	Tolerable

Source: Table 5-1 (Aecom, 2016) and Table 6-1 (Environment Agency, 2013a)

The likelihood in already mapped directly onto the OLOF categories. Consequence (level 0 to 4) now needed to be mapped onto consequence designations (low, medium, high). Based on the guidance on consequence levels in table 5.1 of the RARS guide (Environment Agency, 2013a):

- Levels 2-4 were mapped onto high consequence designation;
- Level 1 was mapped onto medium consequence designation; and
- Level 0 was mapped onto low consequence designation.

This gives the updated risk matrix below in Table 6.

Table 6: Combined Risk Matrix (pre-safeguard)

	SEPA consequences designation		
OLOF	Low	Medium	High
Extreme	Medium	Medium	High
Very high	Low	Medium	High
High	Low	Low	Medium
Medium	Low	Low	Medium
Low	Low	Low	Medium
Very Low	Low	Low	Low

Source: (Aecom, 2016)

3.2.4 Results

The results from the assessment of OLOF were then combined with the existing consequence designation to give an overall updated risk designation. The result was:

- 0% of reservoir “high” risk;
- 90% of reservoirs “medium” risk;
- 10% of reservoirs “low” risk.

Since more than 90% of the dams are medium consequence it was considered inappropriate that none of these would be subject to the full regulatory requirements of the reservoir safety legislation and as such a “safeguard” was proposed. This is discussed in section 3.2.5 below.

3.2.5 Safeguard

In most cases the model resulted in a reduction of overall risk designation during the trial, which in the case of reservoirs with a risk to life, was considered to be unacceptable. Therefore, a safeguard was put in place giving all reservoirs with *"risk to life"* (all of which are high consequence) a "high" overall risk designation, irrespective of OLOF.

Table 4-1 of the Aecom report lists the *"factors available and adopted for research".* The *"risk to life"* status is not included in that table and it is not required by law to be held on the Scottish register, yet it is used (Appendix B to the Aecom report) as a proposed safeguard. This would involve access to data not on the Scottish register of statutory reservoirs, but available to SEPA separately as part of their risk designation process. However, this would impose a requirement on SEPA beyond the original brief that the risk assessment would run directly off the registration database.

A further consideration is that the likely loss of life and other information on potential consequences of failure is sensitive in terms of national security, and this may compromise its use in applications where undertakers challenging a risk designation, who do not have security clearance, request to see this data.

The safeguard was cited as a topic for further research and another suggestion, made by the Aecom report, was that an alternative safeguard could be a combination of dam height and volume. This suggestion effectively links with the work under Task 3 (report section 5) which considers alternative definitions for reservoirs, in particular based on height and volume.

3.2.6 Critique of the model

Repeating the exercise undertaken by the Aecom for a different stock of dams would be unlikely to yield significantly different results. The model was tested by comparison with an initial QRA study carried out by Aecom on the full stock of Scottish Water dams which form about 50% of the statutory reservoirs in Scotland providing a good test for this process.

While the approach to risk assessment outlined in the RARS guide (Environment Agency, 2013a) is necessarily involved in order to arrive at a realistic estimate of likelihood of failure, this process has shown that the risk assessment under this model is based almost entirely on:

- Dam type (binary: concrete or embankment);
- Construction year (binary: pre-1930s or post-1930s); and
- Consequence designation (low / medium / high).

The idea of using consequence to calculate FLOF is clear; flood design guidance for freeboard and spillway capacity are set out in Table 2.1 of Floods and Reservoir Safety (Institution of Civil Engineers, 2015) for regulated reservoirs of different flood categories (A, B, C and D). Higher consequence dams have a higher flood category which in turn means they should have a lower probability of failure from flooding. Indeed, this is the basis of the approach for calculation of FLOF in RARS (Environment Agency, 2013a). Nevertheless, the use of consequence designation on its own would appear to be somewhat circular; effectively a low consequence dam would be considered to have high FLOF because low consequence dams are designed for lower return period flood event. The existing designation is based on consequence and the aim for any new approach would be to have it based on consequence and OLOF. However, where consequence is used to calculate OLOF as described above, no new data is used to arrive at the new designation. This essentially means that the new designation process would still be consequence-based for almost all embankment dams. This is logical for regulated reservoirs that have had flood assessments but not for reservoirs which have never been regulated in the past.

The perceived requirement to safeguard using consequence to ensure that all reservoirs with a risk to life become “high-risk” shows the industry reluctance to follow a risk-based approach which truly embraces likelihood of failure. For the 52 examples given in Appendix B to the Aecom Report (Aecom, 2016) every reservoir with risk to life remained “high-risk”. For the same sample every reservoir without risk to life was de-risked by one category, which is from high to medium or medium to low.

The OLOF for concrete dams has been determined based almost entirely on construction date, with the cut-off between medium and low OLOF being at around 1930. OLOF is then mapped to risk designation using the matrix below in Table 7. The table is taken from the Aecom report with the black box added by the authors of this report. It can be seen that within the black box OLOF can be low, medium or high and the outcome for risk designation is unchanged because all three rows are identical in the matrix. The example (52 reservoirs) in Appendix B to the Aecom report shows that, for that sample, OLOF is always “low”, “medium”, or “high”. For OLOF within that range:

- high consequence always maps to medium risk; and
- medium or low consequence always maps to low risk.

As such the process has not been able to differentiate meaningfully between different likelihoods of failure.

Table 7: Consequence - OLOF Matrix

	SEPA consequences designation		
OLOF	Low	Medium	High
Extreme	Medium	Medium	High
Very high	Low	Medium	High
High	Low	Low	Medium
Medium	Low	Low	Medium
Low	Low	Low	Medium
Very Low	Low	Low	Low

Source: Table by Aecom (Aecom, 2016); black box by Mott MacDonald

The model is based on data which is already available in the SEPA register of statutory reservoirs. This was a given requirement to ensure the process is low cost and easily applicable to the existing register. Unfortunately, there is no differentiation between the high consequence reservoirs as a result of the application of OLOF to the risk designation process. It appears as though every high consequence reservoir (Figure 5) became a medium risk reservoir prior to the “safeguard” being applied (Figure 7). The benefits of a simple approach are clear. However, the simplicity has meant that, effectively, there is insufficient information available in the register of statutory reservoirs to be able to differentiate, in a meaningful way, between the OLOF at different reservoirs in this respect.

3.3 Applicability to England

3.3.1 Input Data

In Scotland there are three levels of risk designation (low, medium and high) whereas in England and Wales there is one; “high-risk” (everything else is “not high-risk”). In England, Wales and Scotland the risk designation is currently based on consequence alone (Scottish Environment Protection Agency, 2015). In England and Scotland the risk designation is required by law to be held in the register of statutory reservoirs held by the Environment Agency (EA) in England and by SEPA in Scotland.

Although not required to be by law, it is understood that the flood category is held in a database by the EA. Flood category is defined in Floods and Reservoir Safety guidance (Institution of Civil Engineers, 2015) as A, B, C or D. Flood category is a different and more detailed reflection of consequence than consequence designation, especially in England where there are only two levels of consequence designation compared with four levels of flood category. Not all reservoirs have a flood category but it would be straightforward in this instance to defer back to consequence designation.

The input data used to determine almost all of the OLOF results are also available in England:

- ✓ Flood category – understood to be held by the EA when available, although not a statutory requirement and therefore potentially less likely to be up-to-date compared with the statutory register
- ✓ Year of construction – held by the EA as a statutory requirement when available in the statutory documentation
- ✓ The materials used to construct the reservoir – held by the EA by law when available in statutory documents, although potentially difficult to rely on especially if there are composite structures

3.3.2 Reliance on Consequence Category

Embankment dams form about 80% of dams in Britain (British Research Establishment, 1999). Bearing this in mind and considering the comments in section 3.2.6 above, the process is heavily dependent on the consequence designation. It has already been noted that FLOF is determined by consequence, OLOF typically makes no difference to the risk designation, and the safeguard is also determined by consequence. As discussed earlier, with risk designation already determined by the consequence designation this approach is somewhat circular and does not add much new information.

3.3.3 Safeguard

In Scotland, the current criteria for “high-risk” and the criteria for “risk to life” are not always the same, whereas in England the criteria for “high-risk” and for risk to life (*“human life could be endangered”*) are identical. That, coupled with the fact that England has a binary system of consequence designation means that the safeguard system proposed would be ineffective in England because it would result in the number of “high-risk” reservoirs being unchanged.

3.3.4 Likely variation in OLOF

Whilst an assessment of probability of failure could potentially generate outcomes varying from low risk to very high-risk this is unlikely to happen in practice. In reality any proposed regulating regime should be ensuring that no dam have an intolerable probability of failure and that most dams are moderate or low probability of failure. The exceptions to this would be Category C and D dams which may have a high (or very high) FLOF, but are arguably less relevant as they are of relatively low consequence.

3.3.5 Summary of Applicability to England

The model as proposed in the Aecom study would not be applicable in England.

Furthermore, this study has demonstrated that there is unlikely to be sufficient information available in the register of statutory reservoirs in England to provide any meaningful distinction in likelihood of failure for English reservoirs.

Other options are discussed briefly in section 3.4.

3.4 Alternative option for assessing overall likelihood of failure (OLOF)

The estimation of likelihood of failure can be extremely simple, automated and based on readily available information, or at the other end of the scale can be bespoke and detailed by carrying out a full Tier 3 quantitative risk assessment based on the guidance in RARS (Environment Agency, 2013a). Aecom necessarily presented a model at the simple, automated end of the scale. The main drawback of more complex bespoke risk assessments is the cost of undertaking the study. Such bespoke risk assessments are sometimes referred to in the literature as “safety cases”. It is noted that in the nuclear industry the formal risk assessment, known as the Periodic Safety Review (PSR), is required to be updated at least once every 10 years for all reactors. International practice for dams is covered under section 5.2; the majority of countries considered in this research (refer to Figure 13 for countries considered) do not attempt to quantify the probability of failure for the purpose of defining whether reservoirs are regulated or not (Halcrow, 2008).

The dam safety case is a concept which is supported by a growing body of research including papers by Brown, Claydon and Gosden (Brown A. J., 2008) and, particularly for high consequence dams, Brown and Hewitt (Brown A. a., 2016). It is also now standard practice in some developed countries such as Australia which for high consequence dams requires a comprehensive safety review every ten to 20 years (ANCOLD Guidelines on dam safety management, 2003)

Consideration could be given to the practicality of, and appetite for, the option for Undertakers to undertake their own bespoke risk assessments (including likelihood of failure) by changing the legislation to remove the requirement for the inspections and/or supervision where appropriate through full (or partial) deregulation where probability of failure is deemed to be acceptable. It is recognised that most Undertakers would be unable to produce the risk assessments entirely in-house and would need assistance from external consultancies; it is likely that such a risk assessment would require the supervision of a Qualified Civil Engineer (QCE). This proposal entails a number of constraints, principally:

- **Cost.** It can be assumed that the average cost of inspection and supervision is about £1k per year and the cost of a bespoke risk assessment would be £50k, much depending on the level of information available/required on the physical characteristics of the dam structures. In this case it can be seen that the reservoir would need to be deregulated for more than 50 years before the bespoke risk assessment would be economically justified. Therefore, this approach appears unlikely to be attractive to Undertakers. Costs presented here are high level estimates based on experience and are highly sensitive to the level of detail required in any risk assessment. The costs exclude those incurred by an Undertaker to carry into effect any statutory safety works and maintenance measures as recommended by a statutory inspection. The latter costs are justifiably excluded on the basis that if a reservoir was considered to be “not high-risk” on the basis of the probability of failure it would be unlikely that there would be any outstanding statutory measures given that statutory measures are related to reservoir safety;
- **Deterioration over time.** It is unlikely to be acceptable that a reservoir is effectively deregulated indefinitely, in case the condition should deteriorate in the future. Therefore, the risk assessment could only be valid for a finite period of time.

One way to resolve the issue of deterioration over time could be to require the supervision of the deregulated reservoirs by a Supervising Engineer, who would have the power (under existing legislation) to call for an inspection by an All Reservoirs Panel Engineer (ARPE) should they consider such an inspection to be required - in some ways this would be similar to the system in place in Scotland. However most of the inspection / supervision costs under the Reservoirs Act 1975 are for the annual visits and reports by Supervising Engineers, not for the relatively infrequent inspections by ARPEs, therefore this solution would be relatively costly.

If there were an industry appetite for bespoke risk assessments, the processes and implementation would need full consideration. Although outside the scope of this research, as a starting point, it might be assumed that:

- Assessments would be undertaken by a QCE under the Reservoirs Act 1975 (possibly as part of an inspection under section 10 if a phased implementation over ten years was accepted);
- Assessments would need to be accepted by the Enforcement Authority;
- A standard methodology would need to be developed possibly based on existing guidance such as RARS (Environment Agency, 2013a).

3.5 Task 1 Summary

The Aecom project was worthwhile and robustly checked against a large sample (approximately 50% of Scottish reservoirs). It is unlikely that a further research project would come up with a radically different approach that could be applied at a strategic level at a national scale.

The overall conclusion is that, in Scotland, it is not possible to meaningfully quantify the likelihood of failure of dams on the basis of information available in the public record and it is recognised that there are many factors that can change the probability of failure over time which might be difficult to monitor through regulatory controls.

The same finding would also apply dams in England and Wales. This effectively rules out any straightforward method, based on data already available, of incorporating the probability of failure into assessment of risk designation. Furthermore, the proposed safeguarding process which was found to be necessary in Scotland would be unworkable in England.

Notwithstanding the above, an option for further consideration in future research is:

- To change the definition of “high-risk” to incorporate probability as well as consequence; and
- For Undertakers to provide their own detailed risk assessment, incorporating both probability and consequence of failure, to reassess the initial consequence-only designation. This was explored in more detail under sub-section 3.4 above.

4 Task 2: Review risk designation thresholds and categories

4.1 Introduction

The objective of this task is to review the threshold for “high-risk” designation, taking into consideration other high hazard industries and coastal and fluvial flood defences (levees).

The driver for this research is that prior to implementation of the risk designation process, it was predicted that 55% of reservoirs would be designated as “not high-risk” whereas following implementation only 12% were actually designated as “not high-risk”.

The research will consider whether the currently adopted threshold for “high-risk” designation is appropriate. Separate consideration will be given to whether there would be merit in introducing a three-tier risk designation system.

4.2 Historical British Dam Failures Causing Loss of Life (in the context of Task 2)

In addition to this sub-section (4.2) there is another sub-section on dam fatalities in the context of Task 3 (5.4).

The purpose of this sub-section is to provide background information on reservoir safety prior to the introduction of statutory legislation for reservoirs.

The primary source of information on dam failures in Britain is *Lessons from incidents at dams and reservoirs* (CIRIA, 2014b). Since that reference was published (and indeed since 1925) there has been no loss of life from dam failures in Britain.

The record of loss of life from dam incidents in England is summarised in Table 8 below.

Table 8: English Dam Failures that caused loss of life

Failure Date	Dam	Deaths
1799	Tunnel End	1
1810	Diggle Moss (Black Moss)	6
1841	Brent (Welsh Harp)	2
1848	Bold Venture (Darwen)	12
1852	Bilberry	81
1864	Dale Dyke	244
1870	Rishton	3
	TOTAL	**349**

Notes: Eigiau and Coedty are in Wales therefore not included here
Source: (CIRIA, 2014b)

The population of regulated dams in England prior to 1930 has a historical total number of reservoir-years of 97,724 (Environment Agency, 2019) with 349 lives lost (CIRIA, 2014b). The number of reservoir-years estimated is based on the data in the public register going back to 1086. This indicates a fatality rate based on historical evidence for England of about 1 / 280 per reservoir per year. The Reservoir (Safety Provisions) Act 1930 came into force 89 years ago with no loss of life since. Therefore, this safety record appears intuitively to be strong but is statistically limited by the period of data available since the legislation came into force. To establish an indication of the current level of reservoir safety in England for statistical purposes, it can be assumed that one life was lost over the last 89 years which would indicate a statistical fatality rate of less than 1 / 100,000 per reservoir per year. Based on comparison with historical data from the 89 year preceding 1930 and following the RARS guidance (Environment Agency, 2013a), the legislation would appear to have improved reservoir safety at the typical dam from an unacceptably high-risk to a broadly acceptable risk. These findings are tabulated in Table 9. It is worth stating that it could be argued that it would have been sufficient to reduce risk to within the ALARP zone, and then examine whether the cost of further extension of regulation would be proportionate in cost to the benefits.

Table 9: Overview of statistical dam safety in England based on historical data

Time period	No. of fatalities	No. of reservoir-yrs	Reservoir-yrs for one life	Typical Individual Risk Status**	Typical Societal Risk Status	Typical Overall Risk Status
1841 - 1930	342	25,891	76	UNACCEPTABLE	UNACCEPTABLE	**UNACCEPTABLE**
1930 - 2019	0*	177,766	>117,766	BROADLY ACCEPTABLE	BROADLY ACCEPTABLE	**BROADLY ACCEPTABLE**

Notes: *taken as one for statistical analysis

**assumed but not certain; statistically also depends on the number of people who were at risk and did not lose their lives

Source: Public Register (Environment Agency, 2019) and RARS (Environment Agency, 2013a)

The historical data indicates that the level of regulation since 1930 has improved dam safety in England and it provides useful background information prior to consideration of risk designation. It is noted that the evidence is limited by the time periods available for analysis.

4.3 Review of requirements of Reservoirs Act 1975

Under the English Act all reservoirs with an escapable volume greater than 25,000 m^3 are regulated. These reservoirs are designated as “high-risk” or are otherwise considered “not high-risk” depending on whether an uncontrolled release of water could endanger life. “Not high-risk” reservoirs remain statutory reservoirs on the public register and will be subject to periodic risk review but do not have any standing requirements for inspections. Such a review would be carried out under the provision of section 2D of the English Act, and would be informed by the six yearly reviews of flood hazard maps required by the Flood Risk Regulations 2009.

New reservoirs with an escapable volume greater than 25,000 m^3 are designated as “high-risk” or otherwise following issue of the Final Certificate.

The basis of the risk designation process is the wording contained in the English Act. The relevant section is section 2C(1) which states:

> *The appropriate agency may designate a reservoir as a high-risk reservoir if-*
>
> a) *The appropriate agency think that, in the event of an uncontrolled release of water from the reservoir, human life could be endangered, and*
> b) *The reservoir does not satisfy the conditions (if any) specified in regulations made by the Minister*

This wording appears outwardly to be promoting a risk based approach, but the reality is that it is solely hazard based because there is a presumption of an “uncontrolled release of water”. In effect this is prescribing a probability of failure of one. As such, the risk of endangerment has to be evaluated against a breach outflow with no consideration of the probability of occurrence of a breach.

The English Act is not prescriptive on how reservoirs should be designed or maintained, but within the industry there are various guides which are accepted as best practice and followed, unless there is good reason to do otherwise.

"High-risk" reservoirs are subject to periodic inspections which will review the intrinsic and current condition of the dam structure(s) and may reference:

- Guidance and standards such as:
  - Floods and Reservoir Safety (Institution of Civil Engineers, 2015)
  - Guide to drawdown capacity for reservoir safety and emergency planning (Environment Agency, 2017a)
  - An engineering guide to seismic risk to dams in the United Kingdom (BRE, 1991)
  - An Application Note to *An engineering guide to seismic risk to dams in the United Kingdom* (Institution of Civil Engineers, 1998)
  - EN 1990 – consequence classes and reliability classes
  - EN 1997 – geotechnical design
- a risk-based approach as defined in RARS (Environment Agency, 2013a) which takes consequence and probability into account

Lower hazard structures are subject to less stringent standards. For example, a regulated reservoir with a maximum population at risk (MPAR) of more than 10 persons is required, subject to risk assessment where applicable, to safely pass the Probable Maximum Flood, whereas if the MPAR is between 1 and 10 the equivalent requirement is to safely pass the lower magnitude 10,000-year flood. Similar variations in standards exist for seismicity and drawdown requirements.

On this basis, even if there were no risk designation system in place, the lower risk reservoirs typically only require works if those works are deemed proportionate on a reservoir-specific basis. The key requirement across all "high-risk" reservoirs is that for regular inspection and supervision, which is standard practice for high hazard civil engineering structures.

4.4 Review of other industries in UK and comparison with dams and reservoirs

4.4.1 Introduction

This sub-section (4.4) assesses the threshold for "high-risk" designation against HSE guidance and practices in other industries. The industries considered are:

- Flood Risk Management
  - Coastal
  - Fluvial
- Nuclear
- Rail
- Chemical

Flood risk management and nuclear industries are considered in more detail with a relatively brief overview of rail and chemical industries.

4.4.2 HSE Guidance

The Health and Safety Executive (HSE) set out their approach to risk management for the safety of people in England in *Reducing Risks Protecting People (R2P2)* (HSE, 2001). A theme throughout that document, and in general throughout subsequent risk management guidance, is the assumption that people are more accepting of risk when there is a tangible benefit connected to it.

The guidance recognises that the level of risk may vary from a "Broadly acceptable" region through a "Tolerable" region into an "Unacceptable" region. The boundary between unacceptable and tolerable for individuals for *"members of the public who have a risk imposed on them in the wider interests of society"* is judged to be 1 in 10,000 per annum, while the limit proposed for the boundary between tolerable and broadly acceptable is 1 in 1,000,000 per annum.

In the context of individual risks, the guide notes:

> *"However, these limits rarely bite. As we have already pointed out, hazards that give rise to such levels of individual risks also give rise to societal concerns and the latter often play a far greater role in deciding whether a risk is acceptable or not. Secondly these limits were derived for activities most difficult to control and reflect agreement reached at international level. In practice most industries in the UK do much better than that."*

Whilst this may be applicable for industries as a whole, it should be noted that dams often present situations where individual risks are more likely to dominate than societal risks. An example would be a dam with few flood receptors (such as a property, other infrastructure or vehicles) within the flood extent.

With regards to the risks for society as a whole, the guidance states that "*the risk of an accident causing the death of 50 people or more in a single event should be regarded as intolerable if the frequency is estimated to be more than 1 in 5,000 per annum*." Although this is expressed as a single point, the UK guidance on risk assessment for reservoir safety management (Defra, 2013) extrapolates it linearly in log-log space to 1 in 100 or 1,000 in 100,000.

The definition of "tolerable" is risks that are typical of the risks that people are prepared to tolerate in order to secure benefits, in the expectation that:

- *The nature and level of the risks are properly assessed and the results used properly to determine and control measures. The assessment of the risks needs to be based on the best available scientific evidence and, where evidence is lacking on the best available scientific advice.*
- *The residual risks are not unduly high and kept as low as reasonably practical (the ALARP principle).*
- *The risks are periodically reviewed to ensure they still meet the ALARP criteria, for example, by ascertaining whether further or new control measures need to be introduced to take into account changes over time, such as knowledge about the risk or the availability of new techniques for reducing or eliminating risks.*

It is useful to consider where this zone sits within the "high-risk" / "not high-risk" designations. A reservoir not designated as "high-risk" will remain on the register of reservoirs, but will not be subject to any inspections by reservoir professionals. As such it would appear incompatible for a "not high-risk" reservoir to fall into the tolerable zone; ideally, a "not high-risk" reservoir would need to fall into the "broadly acceptable" zone with a commensurate annual risk of death for an individual of, at worst, 1 in 1,000,000.

4.4.3 Flood Risk Management (Flood defences)

4.4.3.1 General

For coastal and fluvial flood risk management there is no statutory legislation which is directly comparable to the English Act. Therefore, there is no equivalent regulatory authority and no equivalent risk designation process.

4.4.3.2 Consideration of local benefits

In the case of fluvial and coastal defences the structure is there to protect people and property from flooding. This is also a key difference between flood defences and reservoirs, which are used for commercial or private use and this should be taken into consideration when comparing the levels of risk.

4.4.3.3 Standards and Risk Management

It is important to differentiate between an exceedance event where a flood defence no longer prevents flooding and a complete failure of the flood defence structure resulting in a sudden and uncontrolled release of water. In this document only the latter is referred to as a "failure". For example, consider the following hypothetical failure progression:

A 2 m-high raised river bank is designed to provide a 1/100 Annual Exceedance Probability (AEP) standard of protection (SOP). During the 1/1,000 AEP event the river bank overflows and fails due to external erosion of the downstream face leading to complete failure. A large volume of water exits the breach location and the breach flow causes damage and loss of life in a village affecting 10 households.

The embankment is likely to only have been checked against failure for the 1/100 AEP event. A flood storage dam capable of impounding an equal height and volume of water, which is designed to prevent flooding to a population of equal size and with similar breach consequences, would be a Category A reservoir designed not to fail during the Probable Maximum Flood (PMF). The PMF can be taken as having an AEP of about 1/400,000 (Environment Agency, 2013a). In this situation, considering only one failure mode for the purposes of this example, there appears to be a factor of 4,000 between the design criteria for the two structures. It could be argued that this consideration should be partly covered through a designer risk assessment and/or through the economic analysis (e.g. by applying a statistical loss of life every year associated with failure of the embankment) but this is seldom done during the development of business cases for flood risk management schemes. While this provides an indicative numerical comparison between the two scenarios, it should be noted that the use of the PMF as design standard for Category A dams is not founded on risk-informed methodology, but rather it is about ensuring that designed structures have an insignificant probability of failure where a failure could endanger many lives. Another difference to note between these events is that natural floods are actively forecast and monitored by the Met Office and the Environment Agency using telemetry systems. Therefore, if high rainfall or tides are expected to overtop flood defences, severe flood warnings would be issued, and properties would be evacuated.

Box 9.3 of the ILH (CIRIA, 2013) provides an example method for determining risk categories for levees and explains how such risk categories could be used to determine design standards.

The example process uses flood duration, levee height, population at risk and potential for damage to determine the subsequent level of investigative and design effort. For the United Kingdom and Ireland the guide on the *Application of Eurocode 7 to the design of flood embankments* (CIRIA, 2014a) brings together the relationship between ILH risk categories (CIRIA, 2013), consequence classes (EN 1990), reliability classes (EN 1990) and geotechnical categories (EN 1997). In Germany a similar process is used to determine the geotechnical category of the levee under Eurocode 7, which in turn is used to determine the extent and cost of investigation.

Inspections of flood defence assets, according to guidance (Environment Agency, 2014), are carried out, at least once every six months to five years by Environment Agency operations staff dependent on the outcome of a 9-box-grid risk assessment. For example, high probability and high consequence requires an inspection every six months whereas low probability and low consequence requires an inspection every five years.

4.4.3.4 Comparison of level of historical risk

Table 1 from *"A step change in reservoir safety management"* (Brown A. J., 2008) brings together a comparison of likelihood and consequence from some major floods in the United Kingdom. This has been augmented (by the current authors) in Table 10 and repeated (without edit) graphically in Figure 9.

Table 10 and Figure 9 show that, in England, over the last century fluvial and coastal flooding have been the cause of loss of life of more than 360 people, whereas there is no recorded loss of life from a dam failure in England for almost 150 years (CIRIA, 2014b). The probability of occurrence of the loss of life, shown in Figure 9, is higher than would be acceptable for a reservoir following the procedure in RARS (Environment Agency, 2013a).

It must be emphasised that the deaths from the fluvial and coastal flooding (excluding dam failures), referred to above and listed below, are from natural events and are not known to be due to the failure of a man-made structure. The main source of the risk is typically the rainfall or storm surge event, not the flood defence and it is considered that the risk would be there even if the structure was not. In terms of coastal defences during a tidal surge, the sea level on the seaward side would be very similar whether or not the coastal defence was in place and as such the coastal defence is not artificially increasing the hydraulic head significantly at the source of the hazard (in this case the sea). Nevertheless, a sudden breach of a coastal defence could cause more rapid flooding than a natural tidal flood rise at properties close to a defence. Raised fluvial levees are somewhat different in that the river levels in parts of England are held above natural ground level during wetter times of the year. In this case the hydraulic head of the hazard source (river) is artificially raised introducing an additional hazard compared with coastal flood defences.

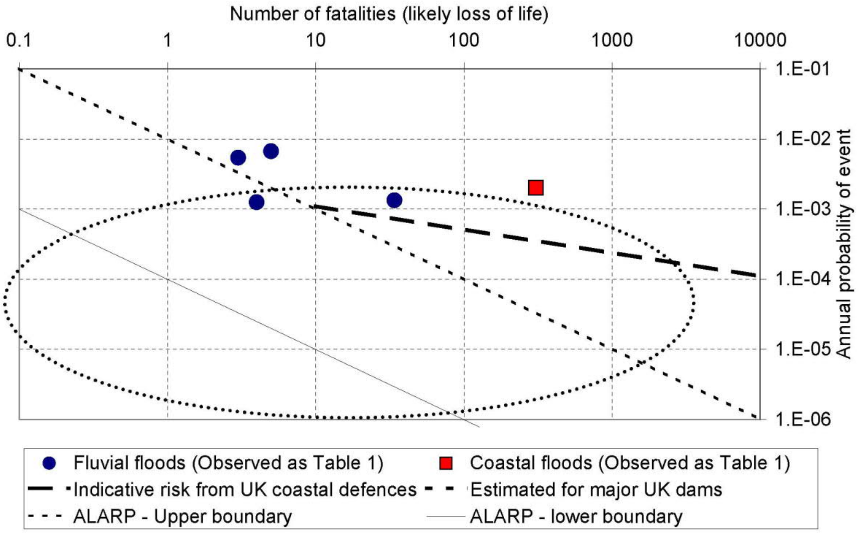
Table 10: Loss of life in some major floods affecting England

Year	Source of flooding	Location	Annual chance	Number of properties flooded	Loss of life
2007	Fluvial	Widespread	Commonly 4 times average monthly rainfall	48,000	13
2005	Fluvial	Carlisle	1 in 185	1,800	3
2000	Fluvial	Widespread	Commonly 1 in 15	9,000	0
1998	Fluvial	Widespread	1 in 150 to 1 in 50	Not available	5
1953	Coastal	East Coast	1 in 500	24,000	307
1952	Fluvial	Lynmouth	1 in 750	165	34

Year	Source of flooding	Location	Annual chance	Number of properties flooded	Loss of life
1912	Fluvial	Norwich	1 in 800	1200	4
1870	Dam failure	Rishton	Not available	Not available	3
1864	Dam failure	Dale Dyke	Not available	Not available	250
1852	Dam failure	Bilberry	Not available	Not available	81
1848	Dam failure	Bold Venture (Darwen)	Not available	Not available	12
1841	Dam failure	Brent (Welsh Harp)	Not available	Not available	2
1810	Dam failure	Diggle Moss (Black Moss)	Not available	Not available	6
1799	Dam failure	Tunnel End	Not available	Not available	1

Source: (Brown A. J., 2008) and (CIRIA, 2014b)

Figure 9: Comparison of risk from various forms of flooding



Source: (Brown A. J., 2008)

4.4.3.5 Ongoing Levee Research

There is ongoing research on levees and dams through the International Commission on Large Dams (ICOLD) Technical Committee (TC) on Levees. A synopsis and presentation were given by Jonathan Simm of HR Wallingford at the Institution of Civil Engineers on 25 February 2019 providing an update on the project. Dr Jonathan Simm was also the technical lead for the International Levee Handbook (CIRIA, 2013). A draft copy of the research is planned to be released for discussion in April 2020.

4.4.3.6 Summary of Flood Risk Management

Although it appears that the standards for levees are simply less onerous than for dams (all other things being equal) it is unlikely that the risks from levees outweigh the reduction in risk that they bring about. Although historical loss of life from flooding is significant, it is considered that far more lives could have been lost had the flood defences not been in place. The same cannot be said for most dam incidents. With the exception of flood storage reservoirs, which make up 13% of “high-risk” reservoirs in England (Environment Agency, 2019), dams do not directly provide a net reduction in flood risk. There are very few normally-impounded reservoirs in the United Kingdom that provide a formalised flood protection function in addition to their primary function such as water supply or hydroelectric power.

4.4.4 Nuclear

4.4.4.1 General

The nuclear industry is often used as a comparison to other industries for safety standards perhaps because nuclear technology is contentious to many (OECD, 2010). This may be because the worst-case consequences are relatively high (although the probability and overall risks appear to be relatively low – see Table 11). The perception of risk for high consequence low probability activities tends to be disproportionately high (Zielinski, 2019) and the corresponding tolerance for it is disproportionately low. Some dams in England also have high consequence and low probability of catastrophic failure but perhaps the relative familiarity of reservoirs, for example as a public amenity and a habitat for wildlife, makes dams and reservoirs less contentious.

4.4.4.2 Regulatory Authority

From a public safety point of view the nuclear industry is regulated by the Office for Nuclear Regulation (ONR), a statutory public corporation under government control. The environmental regulator is the Environment Agency in England. All nuclear power plants are regulated by the ONR, in addition to some other sites, for example nuclear waste sites. Military sites are regulated separately but with almost identical standards. All sites have stringent requirements for audits, inspections and risk assessments.

4.4.4.3 Risk designation equivalence

There is no equivalent of the “high-risk” / “not high-risk” threshold; all reactor sites are regulated in the same way, irrespective of hazard.

4.4.4.4 Standards and Risk Management

Low hazard sites have a lower level of requirements. This is similar to the reservoir industry in the United Kingdom, for example under the system of flood categories under FRS4 (Institution of Civil Engineers, 2015), low hazard dams have lower requirements for spillway capacity.

Nuclear Licence Condition 28 states that examination, maintenance, inspections and testing need to be systematic and regular. This is broadly comparable to the duties of the Undertaker (English Act section 11) and Supervising Engineer (English Act section 12).

All sites require a Periodic Safety Review (PSR), similar to a risk assessment, which is to be updated every 10 years. The PSR is mainly standards-based but probabilistic PSRs are also recognised. As Low as Reasonably Achievable (ALARA) or As Low As Reasonably Practicable (ALARP) tests must be satisfied and proportionality may be taken into account.

In overview, the standards would appear commensurate with reservoirs standards, given that:

- For new-build sites the maximum credible scenarios are considered for natural events such as floods and earthquakes;
- The design basis event for flooding is the 10,000-year flood (plus allowance for climate change, plus additional defences inside the site such as sealing doors);

- Tolerable risk to life from radiological exposure is in accordance with R2P2 (HSE, 2001) (ONR, 2014).

4.4.4.5 Decommissioning

Nuclear power stations typically have a design life of around 60 years before decommissioning, whereas the average age of dams in England is over 100 years old, with the oldest dam over 900 years old (Environment Agency, 2019). If it were assumed that safety standards for new-build dams and new-build nuclear power plants are equally onerous, then inherently dams have a higher risk associated with their higher average age. This is partly due to deterioration over time but mainly due to changes in standards and construction methods over time.

4.4.4.6 Comparison of level of historical risk

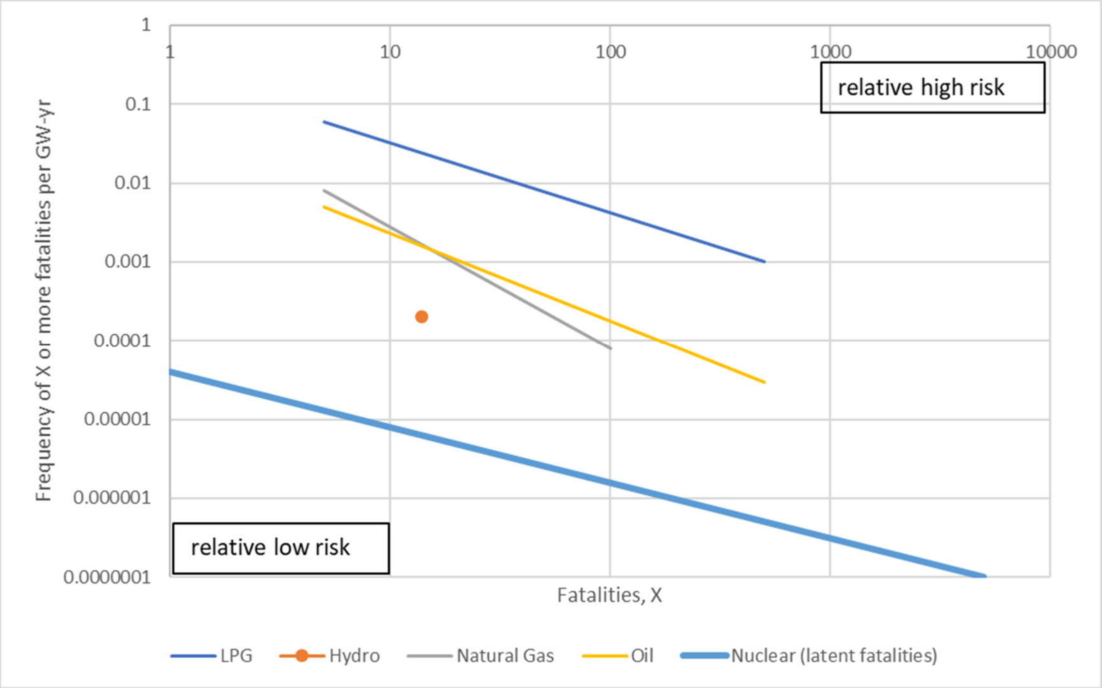
The Nuclear Energy Agency (NEA), part of the Organisation for Economic Co-operation and Development (OECD), issued *Comparing Nuclear Accident Risks with Those from other Energy Sources* in 2010 (OECD, 2010). Table 11 illustrates the relative level of historical risk in the various energy sectors from 1969 to 2000. The energy sectors in Table 11 are ordered from relative-high to relative-low fatalities per gigawatt-year for OECD countries. The figures in the table only provide data for immediate fatalities. Broad estimates for latent fatalities in OECD countries is included in Figure 10. Even when latent fatalities are included in the comparison the nuclear industry appears to be safer than the hydro industry. Although the hydro industry in the OECD can be considered linked to dam safety in England, it should be noted that there are very few significant hydropower installations in England, and therefore is likely not to be representative.

Table 11: Summary of Severe (≥5 fatalities) accidents that occurred in the energy sector from 1969 to 2000

Energy Sector	OECD Fatalities (lives)	OECD Fatalities (lives/GW-yr)	Non-OECD Fatalities (lives)	Non-OECD Fatalities (lives/GW-yr)
Liquified Petroleum Gas	1,905	1.957	2,016	14.896
Coal	2,259	0.157	18,017	0.597
Oil	3,713	0.132	16,505	0.897
Natural Gas	1,043	0.085	1,000	0.111
Hydro	14	0.003	29,924	10.285
Nuclear	0	-	31*	0.048
TOTAL	8,934		67,493	

Source: Based on data from table 2 from Nuclear Energy Agency document (OECD, 2010) *immediate fatalities only

Figure 10: Comparison between frequency-consequence curves in the energy sector based on severe accidents in OECD countries from 1969 to 2000



Source: Adapted from figure 10 from the Nuclear Energy Agency report (OECD, 2010). Original figure contains more detailed data for both OECD and non-OECD countries; data shown here at a high level for illustrative purposes only.

To give an indication of the worst-case consequence historically in the nuclear industry internationally, the death toll from Chernobyl is estimated to be 10,000 to 30,000 lives (OECD, 2010). There is some evidence that loss of life for singular dam incidents can be broadly comparable. It is stated (CIRIA, 2014b) for Banqiao in China that *"it has been reported that tens of thousands died in this disaster that involved the failure of a number of dams".* Data available from the Reservoir Flood Mapping project (Environment Agency, 2019) indicates that consequences of the same order of magnitude would be possible in England in the unlikely event of a breach. From a sample of 608 reservoirs considered from the Reservoir Flood Mapping study (Environment Agency, 2019) out of 2,065 in the public register (Environment Agency, 2019) the maximum ASLL is approximately 5,000.

It is noted that in 1957 the Windscale fire caused a release of radioactivity which may have claimed, the order of, 100 lives due to cancers caused directly by the incident (The Guardian, 2019). If considering the period of time since government regulation was brought into place, with the introduction of the Reservoirs (Safety Provisions) Act 1930 came into force and if including latent fatalities in the nuclear industry, the Windscale incident would indicate that more lives have been lost in England in the nuclear industry (about 100) compared to the reservoirs industry (zero) for that timeframe.

4.4.4.7 Summary of Nuclear Industry

Based on the research undertaken for this project there is no clear evidence that the reservoir industry is significantly more or less risk averse than the nuclear industry. Both industries apply similar standards-based approaches in addition to applying a risk-based approach. Both industries require regular inspection of major infrastructure.

The nuclear industry goes further in that all reactors require full regulation so there is no equivalence to the “not high-risk” reservoir group (and indeed there is no equivalence to the volumetric threshold of 25,000 m^3, but this is more relevant to Task 3). It is possible that even if there were an equivalent “not high-risk” category, none of the reactors would fall into it if following a risk-to-life test. It could be argued in this case that the two systems are comparable in principle, however in practice every reactor is given a “high-risk” designation.

4.4.5 Rail

4.4.5.1 Mainline railways

For new civil works projects to alter or build mainline railways a project is designated as significant or non-significant. Significant projects require the engagement of an independent Assessment Body. Significance of the change is based on the following (RSSB, 2017):

- Failure consequence
- Novelty
- Complexity
- Ability to monitor and intervene
- Reversibility of the change
- Significance of the change considering other recent non-significant changes

One of the key tests is whether the project affects safety.

From a mainline railway perspective, there are no differences in safety regulations, across Europe because the European Union has harmonised regulation for safety and this applies to the United Kingdom as well (Commission Implementing Regulation (EU) – 402/2013).

Mainline railways are typically inspected on foot every 1-2 weeks (ORR, 2008).

4.4.5.2 Private Railways

Private railways (such as Longleat Safari Park Railway) do not need to follow mainline railway regulations. Nevertheless, the regulator, the Office of Rail and Road (ORR), are involved in authorisation of any private railway safety management system when the railway is used to carry members of the public.

4.4.5.3 Summary of Rail

There is no direct comparison which is applicable to risk designation of reservoirs. Although “significance” of projects is linked to safety, it is also linked to a number of other factors and is not linked to statutory periodical inspections by independent engineers.

4.4.6 Chemical Establishments

4.4.6.1 General Findings

The chemical industry is subject to the Control of Major Accident Hazards Regulations (HSE, 2015) which is enforced by the Environment Agency and the HSE. The regulations have three levels based on trigger thresholds for quantities of named dangerous substances:

- below lower tier threshold – regulations do not apply;
- above upper tier threshold – full regulations apply.
- above lower tier threshold and below upper tier threshold – lower tier regulations apply only;

No information has been found on how these quantities were determined, and the potential loss of life associated with each.

The main additional requirements of higher tier establishments include the requirement for a safety case and an emergency plan. The safety case must take account of a risk assessment (probability and consequence).

This system is comparable to the volumetric threshold of 25,000 m^3 for regulated reservoirs (this threshold is covered under Task 3).

There is no known equivalent of a “high-risk” designation in the chemical industry; chemical establishments are not designated directly based on risk.

4.4.6.2 Summary of Chemical Establishments

There is no known equivalent of a “high-risk” designation; chemical establishments are not designated directly based on risk. It is not possible to draw any conclusions, for the reservoirs industry, from these findings of the chemical industry.

4.4.7 ALARP Principle

As set out in section 4.4.2 the ALARP (As Low As Reasonably Practicable) principle is fundamental to managing risks which fall in the tolerable zone. The approach should be adopted by all industries and this is confirmed by Treasury Guidance as described in Section 4.5.3.

However, there is no evidence of ALARP currently being used as the basis for regulation per se in other industries, and such there is no benchmark or comparison relevant to reservoir safety regulation. This concept is discussed further in section 4.5.3.

4.4.8 Summary of review of other industries

It is difficult to draw direct comparisons between the industries due to the systemic differences. The chemical industry has a lower threshold for regulation similar to the volumetric threshold used to define a regulated reservoir whereas nuclear and rail industries regulate all infrastructure of a certain type to the same level. None of the industries considered have an equivalent risk designation system. It appears that, similar to the reservoirs industry, most industries carry out periodical inspections, safety reports or risk assessments.

Based on the research under this project related to other industries it is considered that the reservoirs industry is not an outlier and that the current system is commensurate with other high hazard industries.

4.5 Review of the application of the risk designation process

4.5.1 Introduction

The criterion for risk designation is set out in the English Act as:

> *“in the event of an uncontrolled release of water from the reservoir, human life could be endangered”*

This is not a prescriptive statement as there is no clear definition of endanger. Commonly used synonyms for endanger are imperil, jeopardise, compromise and threaten. The phrase is open to interpretation between the limits of where a dam breach would have no impact and where a dam breach would cause significant loss of life.

4.5.2 Existing research

Guidance on tolerable risk to life is presented in:

- Reducing Risks, Protecting People (R2P2), HSE, 2001 (see section 4.4.2)

Primary pieces or research into the impact of flowing water on populations are:

- FD2321 – Flood Risks to People, Defra/EA 2006, and supplement dated May 2008
- DSO-99-06 – A Procedure for Estimating Loss of Life Caused by Dam Failure, US Dept of the Interior Sept 1999.
- Downstream Hazard Classification Guidelines, USBR, 1988

Relevant secondary research which makes use of the above documents include:

- Interim Guide to Quantitative Risk Assessment for UK Reservoirs, KBR Defra, 2004
- Guide to Risk Management for reservoirs safety management (RARS), Defra, 2013
- Observations on the boundary between high and lower risk reservoirs, Brown, Gosden and Gotch, 2012
- Risk Designation Guidance, Environment Agency, 2013

Key aspects from these documents are set out below.

4.5.2.1 FD2321 (Defra, 2008)

This document sets out a methodology for calculating a Hazard Rating based on depth, velocity and a debris factor as:

$$\boldsymbol{H = D(V + 0.5) + D_f}$$

Where:

- H is hazard rating;
- D is flood depth (m);
- V is velocity (m/s);
- D_f is the debris factor, which is taken as 0.5 for D ≤ 0.25 and 1.0 for D > 0.25.

The limits are described qualitatively with respect to level of risk in the table below, adopted from the supplementary note to FD2320/TR2 and FD2321/TR1 (Defra, 2008).

Table 12: Hazard Classification

Flood Hazard Rating (Hazard)	Hazard to People Classification
< 0.75	Very low hazard – Caution
0.75 to 1.25	Danger for some – includes children, the elderly and the infirm
1.25 to 2.0	Danger for most – includes the general public
> 2.0	Danger for all – includes the emergency services

Source: Supplementary note to FD2320/TR2 and FD2321/TR1 (Defra, 2008)

The equation and limits were given by Surendran et al. (Defra, 2008) and were adopted as part of both the Reservoir Inundation Mapping Specification (Environment Agency, 2009) and the Reservoir Flood Mapping Specification (Environment Agency, 2016). The 2009 mapping was used to inform the risk designation process. The new mapping has not, to date, been used for this purpose, however there is an intention to use it on newly registered reservoirs or older reservoirs that have not been assessed.

The equation defines a limit for depth for the boundary between very low hazard and danger for some, at zero velocity, as about 0.3 m.

Hazard rating does not relate directly to DV (see section 4.5.2.4), but the relationship between D & V is essentially hyperbolic (i.e. D is proportional to 1/V for a given Hazard Rating (HR)) with a cut-off on depth at low velocities. This is sensible as there is clearly, in all categories, a depth at which there is danger even if the velocity is zero. The limit to “Danger for some” is around 0.1 m^2/s for depth of 0.25 m and velocity of 0.5 m/s.

Section 6.2.4 of the guide includes the following wording in relation to a worked example of the calculation of fatalities:

> *“It would be expected that in zones with a relatively high hazard rating (which is a function of depth, velocity and debris), there would be an increased probability of fatalities. It has been assumed that a factor of twice the hazard rating is appropriate, expressed as a percentage.”*

Implicitly this is stating that:

Fatality rate (%) = 2 x Hazard Rating

No substantiation of this relationship is provided. It would appear just to be an expedient to calculate fatalities on the basis of Hazard Rating. However, on this basis the fatality rates as shown in Table 13 can be calculated.

Table 13: Calculation of Fatality Rates based on Hazard Rating

Hazard rating	Hazard classification	Fatality rate from FD2321 (%)
<0.75	Very low hazard – Caution	<1.5
0.75 to 1.25	Danger for some – includes children, the elderly and the infirm	1.5 to 2.5
1.25 to 2.0	Danger for most – includes the general public	2.5 to 4.0
>2.0	Danger for all – includes the emergency services	>4.0

Source: FD2321 (Defra, 2008)

It is interesting to note that, on this basis, the fatality rate associated with “very low hazard” is up to 1.5%. This seems quite high for “very low hazard” based on the guidance given in R2P2 (HSE, 2001).

It may reasonably be assumed that the guide is referring to the impact of flood waters on open spaces (hence the inclusion of a debris factor).

4.5.2.2 Downstream Hazard Classification Guidelines (USBR, 1988)

This publication includes curves of depth against velocity for High, Judgement and Low danger zones for:

- Permanent residences
- Mobile homes
- Passenger vehicles
- Adults
- Children

In terms of considering endangerment it would appear most appropriate to consider children, this being the category with the lowest tolerance. The description of the three zones as applied to children are:

- High Danger Zone – Almost any size child is in danger from flood waters
- Judgement Zone – Danger level is based upon engineering judgement
- Low Danger Zone – Almost any size child (excluding infants) is not seriously threatened by flood water

The boundary of the low danger zone for children is as shown in Table 14.

Table 14: Boundary of low danger zone for children

Depth (m)	Velocity (m/s)	Depth x Velocity (m^2/s)
0	n/a	0
0.1	0.84	0.08
0.2	0.55	0.11
0.3	0.32	0.09
0.4	0.19	0.07
>0.5	0.00	0.00

Source: (USBR, 1988)

It can be noted that, away from the extremes of zero depth and maximum depth, the threshold of flow intensity (DxV) is around 0.1 m^2/s. This is broadly in agreement with FD2321. The equivalent value proposed for adults is about 0.25 m^2/s.

4.5.2.3 DSO-99-06 (USBR, 1999)

This document sets out a method for calculating fatality rates based on observations of dam failures in the US and elsewhere.

The severity of floods is categorised as follows:

- Low severity – when no buildings are washed off their foundation
- Medium severity – when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on
- High severity – when the flood sweeps the area clean and nothing remains

Table 5 of DSO-99-06 includes data of historic failures including flow intensity, fatality rate and distance from the dam.

Recommended fatality rates are a shown in Table 15.

Table 15: Recommended fatality rates (fraction)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate	
			Suggested	Suggested Range
High	no warning	Not applicable	0.75	0.30 to 1.00
	15 to 60	Vague	Use the value shown above and apply to the number of people who remain in the dam failure floodplain after warnings are issued.	
		Precise		
	More than 60	Vague		

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate	
		Precise	No guidance is provided on how many people will remain in the floodplain.	
Medium	No warning	Not applicable	0.15	0.03 to 0.35
	15 to 60	Vague	0.04	0.01 to 0.08
		Precise	0.02	0.005 to 0.04
	More than 60	Vague	0.03	0.005 to 0.06
		Precise	0.01	0.002 to 0.02
Low	No warning	Not applicable	0.01	0.0 to 0.02
	15 to 60	Vague	0.007	0.0 to 0.015
		Precise	0.002	0.0 to 0.004
	More than 60	Vague	0.0003	0.0 to 0.0006
		Precise	0.0002	0.0 to 0.0004

Source: DSO-99-06 (USBR, 1999)

It is noted that the suggested fatality rates, assuming no warning, are:

- High severity 75% (Range 30 to 100%)
- Medium severity 15% (Range 3 to 35%)
- Low severity 1% (Range 0 to 2%)

The report states that the upper limit of lower severity should be where Depth x Velocity (DV) is greater than 4.6 m^2/s (50 ft^2/s). Implicitly this suggests that the fatality rate for an intensity of less than 4.6 m^2/s would be between 0 and 2%.

This research is based on actual data of dam failures. Although not stated, it is presumed that the fatalities would be a combination of events occurring in the open and events occurring in damaged / collapsed buildings.

4.5.2.4 Risk Assessment for Reservoir Safety Management (RARS)

RARS was published in 2013. It is primarily a guide to quantitative risk assessment.

RARS includes a figure (Figure 9.1) which shows a relationship between flow intensity (Discharge/flooded width) and likely loss of life, which has been taken from Figure 9.1 of the Interim guide to risk assessment (2004), which stated that the graph is "*based on Reclamation paper DSO-99-06 Table 5*" as described above. This table in DSO-99-06 includes both discharge divided by flooded width and fatality rate, with these points plotted on Figure 9.1 of the Interim Guide (although the DSO Table 5 data points were omitted on the version in RARS).

Separate relationships are shown for "warning" and "no warning". The relationship for "no warning" comprises straight lines in loglog space between the points shown in Table 16, these lines being based on a visual best fit to the data in Table 5 of DSO-99-06. These lines are reasonably consistent with other published relationships, summarised in Section 3.4 and Figure 3.1 of the earlier research report (KBR, 2002).

Table 16: Fatality rates (no warning)

Discharge / flooded width (m^2/s)	Fatality rate (%)
0.1	0.1

Discharge / flooded width (m^2/s)	Fatality rate (%)
1	0.5
20	100

Source: RARS (Environment Agency, 2013a)

A key point to note is that there is only one data point in DSO-99-06 for fatality rates below around 1% (Table 5 for some warning), although in principle, this should be available from fluvial events with fatalities in UK, with the data for Lynmouth included on Figure 9.1 in the Interim Guide. The lower leg of the RARS curve would appear to be an expedient to provide a continuous function for use in QRA.

While DV may be a useful measure of flow intensity, and hence impact on population, it must be appreciated that it is a hyperbolic function where depth will tend to infinity as velocity decreases. Clearly there needs to be an upper limit on depth for zero velocity. This supports the use of overall discharge divided by flooded width as used in RARS and DSO-99-06, rather than point velocity and depth as used in FD2320/TR2 and FD2321/TR1.

In the context of buildings, RARS (reproducing work done by Binnie & Partners in 1991) states the following: "*For conventional UK property it may be assumed that when the product of depth and velocity (VD) is less than 2 m^2/s, damage is limited to inundation damage, while when it exceeds 7 m^2/s the building is destroyed…*"

4.5.2.5 Interim Guide to Risk Assessment for UK Reservoirs

This document is largely superseded by RARS. There is however some information in this document which is not repeated elsewhere. Pertinent items to note are:

Suggested limits for severity of damage to buildings are shown in Table 17.

Table 17: Limits for severity of damage to buildings

Severity of damage	V -average velocity, D- point depth
Inundated only	V < 2 m/s or DV < 3 m^2/s
Partial structural damage	V > 2 m/s and 3 m^2/s < DV < 7 m^2/s
Destroyed	V > 2 m/s and DV > 7 m^2/s

Source: Interim Guide (Defra, 2004)

Stated limits for population at risk, i.e. where there is a tangible risk to life, are where both:

- the product of depth and velocity is greater than 0.5 m^2/s

AND

- the depth above external ground level is greater than 0.5 m

4.5.2.6 Observations on the boundary between high and lower risk reservoirs (Brown, Gosden and Gotch, 2012)

This paper suggests definitions for the boundary between "high-risk" and "not high-risk".

It recognises the statement in R2P2 that the annual risk of death due to a dam failure to an individual in the inundation area downstream of the dam, at the tolerable / intolerable boundary, should be less than 1 in 10,000, and considers that individual risk, rather than societal risk, is likely to be the key factor in risk determination. The paper makes the assumption that a currently unregulated reservoir has an annual probability of failure of 1 in 100 (i.e. 10 times greater than an existing Category C / D reservoir), and downstream properties have an occupancy rate of 80%. On this basis it proposes a maximum acceptable fatality rate of 1.25% on the basis that the risk to an individual should be *"tolerable".* Based on Figure 9.1 of RARS, this in turn suggests a maximum acceptable flow intensity at an individual property of about 1 m^2/s.

This appears to be unconservative as previous discussion has concluded that the boundary between "high-risk" and "not high-risk" should coincide with the tolerable / broadly acceptable boundary rather than the tolerable / unacceptable boundary (see Section 4.4.2).

The assumption of a probability of failure of 1 in 100 appears pessimistic based on records of failures of SRRs (Mott MacDonald, 2018b), but it must be appreciated that the assumption of a lower probability would push the acceptable (in terms of proportionality) fatality rate even higher (see section 4.5.3).

The paper also includes a modified version of Figure 9.1 of RARS which includes curves based on FD2321. The curves have been generated assuming v=d (velocity = depth) and debris factors of 0.5 and 0.0 (see section 4.5.2.1). On the basis of these relationships the maximum acceptable flow intensity for a fatality rate of 1.25% at an individual property would be about 0.1 m^2/s (i.e. an order of magnitude less than proposed by RARS).

4.5.2.7 Risk Designation Guidance, Environment Agency (2013)

This document was produced by the Environment Agency to inform the risk designation process. The basic principle of the guidance is that human life could be endangered if:

- Likely loss of life is greater than 1.0
- Flow intensity at an individual property is greater than 3 m^2/s
- Likely loss of life is between 0.8 and 1.0 and there is significant population at risk downstream

These criteria were, however, intended to be used to identify reservoirs which are clearly "high-risk" rather than to identify those which are "not high-risk". Other reservoirs, with the exception of Category D reservoirs which did not meet the above criteria, were to be provisionally designated as "high-risk" unless "*there is clear evidence that human life could not be endangered*". This led to a circular argument as there is no definition of what is meant by endangered.

It should also be noted that the guidance does not set out or reference a methodology for calculating likely loss of life.

Detail of how this guidance was applied is covered under Objective 1 (Mott MacDonald, 2018a). In essence, the definition of endangerment has generally been informed by the Hazard Rating approach detailed in FD2321. An acceptable Hazard Rating being taken as 0.75 (very low hazard).

The process was informed by the latest Section 10 Inspection Report and the Reservoir Inundation Map (RIM).

4.5.3 Consideration of proportionality of costs and benefits (ALARP approach)

4.5.3.1 Introduction

The previous section has looked at the strict application of existing legislation. It is however also important to consider proportionality of costs and benefits in accordance with treasury guidelines. In this context the question is whether the costs of regulating a high-risk reservoir are proportional to the benefits realised in terms of lives saved. The objective is to determine the value of ASLL at which the costs of regulation are disproportionate to the benefits realised.

Key documents which set out Treasury Guidance are:

- "The Orange Book, Management of Risk – Principles and Concepts", 2019
- "Managing Risks to the Public Appraisal Guidance", 2005
- "The Green Book, Central Government Guidance on Appraisal and Evaluation", 2018

4.5.3.2 Reduction in probability of failure

It has been suggested that the current annual probability of failure of unregulated SRRs is of the order of 1 in 5,000 (Mott MacDonald, 2018b). This is however based on very limited data and it is likely that some failures of SRRs will have gone unreported. Separate analysis (Brown A. e., 2012) shows the distribution of probability of failure for a sample of 250 LLRs varying from 1 in 100 to 1 in 1,000,000. For the purpose of this analysis it will be assumed that the probability of failure of an unregulated reservoir can vary from 1 in 100 to 1 in 5,000. It will be assumed that the impact of regulation is to reduce the probability of failure by one order of magnitude. These assumptions are in line with guidance from RARS (Environment Agency, 2013a).

4.5.3.3 Cost of regulating a high-risk reservoir

Analysis of SRRs (Mott MacDonald, 2018b) identifies the recurring annual cost of regulating an SRR as £12,200. This value can also be assumed to be appropriate, although possibly an underestimate, for smaller, lower hazard LRRs. In round numbers it may be taken as £10,000. For the sensitivity study an upper limit will be assumed to be £25,000 based on separate research (Environment Agency, 2018c). These values do not take account of initial capital costs, but the effect of this is not likely to be significant and it is conservative to assume lower costs.

4.5.3.4 Value of saving a life

Analysis of SRRs (Mott MacDonald, 2018b) identifies the Value to Prevent a Fatality as approximately £2,000,000 and suggests a proportion factor of 10 for comparing costs and benefits. As such the value of a life lost should be taken as £20,000,000.

4.5.3.5 ASLL for proportionality between cost and benefits

Using the above information, it is possible to estimate the ASLL at which the cost of regulation would become disproportionate based on the following formula:

Value of Life Lost x ASLL x Reduction in Probability of Failure = Annual cost

The results are presented in Table 18 and show that, for the values assumed, the ASLL at which regulation would become disproportionate can vary from 0.06 to 7.

Table 18: Determination of ASLL for Proportionality Factor of 10

Probability of failure pre regulation	Probability of failure post regulation	Annual cost of regulation	ASLL for Proportionality Factor of 10
1 in 100	1 in 1,000	10,000	0.06
1 in 1,000	1 in 10,000	10,000	0.56
1 in 5,000	1 in 50,000	10,000	2.8
1 in 100	1 in 1,000	25,000	0.14

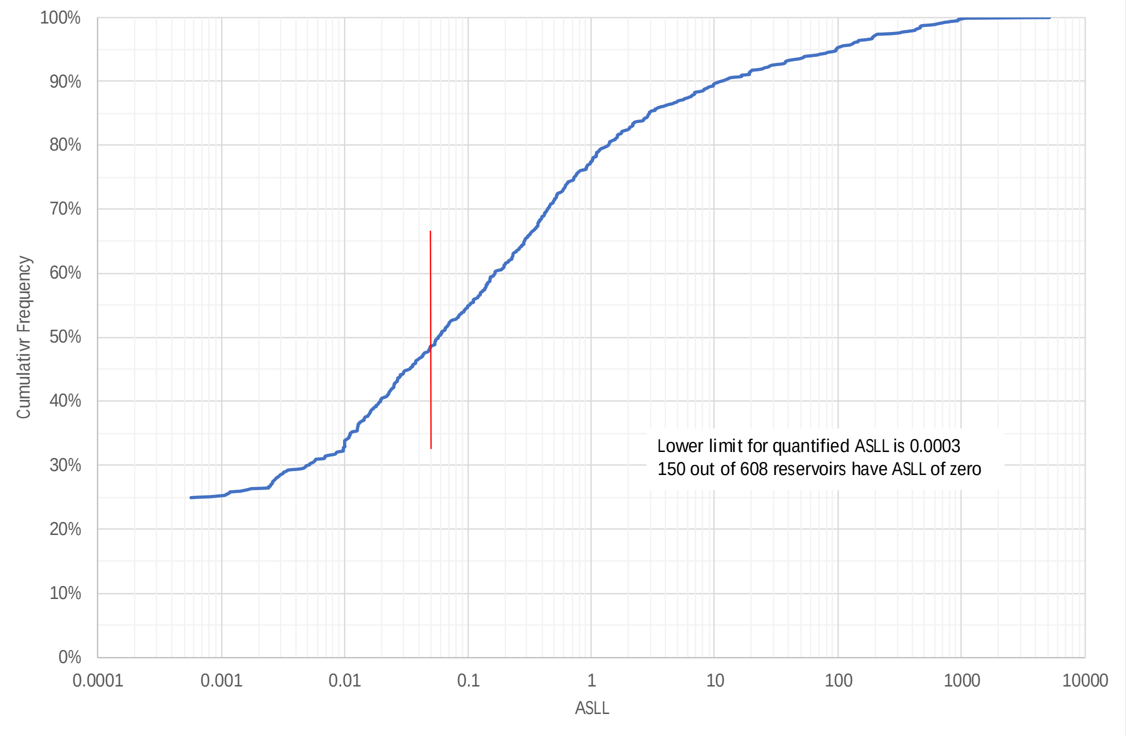
Probability of failure pre regulation	Probability of failure post regulation	Annual cost of regulation	ASLL for Proportionality Factor of 10
1 in 1,000	1 in 10,000	25,000	1.4
1 in 5,000	1 in 50,000	25,000	7

Source: Mott MacDonald (2019)

Risk designation on this basis would need to be very robust so it is therefore considered appropriate only to consider the lower bound value of 0.06 which embraces the highest conceivable probability of failure.

Figure 11 shows how ASLL varies across the population of high-risk reservoirs described in section 2.1.8. It must however be appreciated that these ASLL calculations take account only of population in buildings, and do not therefore include transient populations associated with roads and other infrastructure. As such they may be an underestimate.

Figure 11: Cumulative frequncy of ASLL based on RFM data



Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Adopting a threshold of 0.06 would imply that 50% of the population of reservoirs would be designated not high risk. This would be a significant change from the current situation where 11% of reservoirs are designated not high risk. The results therefore suggest that the cost of regulation of some high-risk reservoirs may currently be disproportionate to the value of the benefits secured. At the upper end of the scenarios analysed, an ASLL of 7 would imply that 88% of the population of reservoirs would be designated not high risk.

However, a further point to consider is whether this approach should be applied to reservoirs which are in the “tolerable” or “broadly acceptable zone”. This issue was discussed in Section

4.4.2 where it was concluded that for a reservoir to be designated not high risk it should be in the broadly acceptable zone with a commensurate risk to individuals of less than 1 in 1,000,000.

Application of the ASLL = 0.06 criteria would correspond, for example, to the situation where the fatality rate at a single property with 2 residents would be 0.03. Assuming a probability of failure of 1 in 100, this would imply a risk to an individual life of 1 in 3,300 which is well outside the "broadly acceptable zone" and could not be accepted unless the cost of regulation is grossly disproportionate to the reduction in risk achieved through regulation. Turned the other way, this means that the ASLL of 0.06 could only be applied to populations at risk of more than 600 if the risk to individuals is to be less than 1 in 1,000000. This would in practice apply to only a very small number of reservoirs.

The approach does not therefore appear to be particularly applicable if the recommendations of R2P2 for limits of broadly acceptable risk are to be respected.

Notwithstanding the above, it must be appreciated that proportionality of costs and benefits can be considered when evaluating whether or not to undertake remedial works on reservoirs. As such the annual cost of regulating a reservoir, which includes the cost of remedial works, is tempered by proportionality.

4.5.4 Findings of First Tier Tribunals

The risk designation process included provision for appeal following final designation. To date, there have been four First Tier Tribunals, all four of which have found in favour of the Environment Agency and their risk designation procedure.

A summary of the decisions is provided in the Objective 1 Final Report (Mott Macdonald, 2018).

Some key statements by the judges, as extracted from their rulings are:

> *"I find the evidence indicates human life at the single dwelling could be endangered. I also consider that, on the state of the current evidence, it is not possible to discount as entirely fanciful the risk to life in respect of the two residential buildings…"*
>
> *"….shallow flooding of a farmhouse and buildings is contemplated (by that report). In such a scenario, it is not fanciful to envisage a child, on the ground floor of the residence, being endangered or, indeed, other persons, regardless of age, as a result of the interaction between water and the electricity supply of the farmhouse and buildings"*
>
> *"whilst I have some doubt as to whether flooding of footpaths, apparently at some distance from the reservoir, would, in the circumstances, satisfy the test in section 2C(1)(a), it is plain that a number of residential buildings could be affected by an uncontrolled release of water from Dene Lake. I also agree that flooding of vehicular roads involves risks of a different order to those involving footpaths"*

This process provides unambiguous confirmation that, in the opinion of the judiciary, the approach to high-risk designation adopted by the Environment Agency is in accordance with the requirements of the English Act. However it must be noted that this process has not indicated that the 'not high-risk' designation is always appropriate.

4.5.5 Possible revision of the English Act

A possible limitation of the current wording of the Act is that, except as covered by Section 2C(1)(b), it does not recognise that the annual probability of failure of a dam will be less than one. This comes about because of the wording "*in the event of an uncontrolled release*…" which is effectively purely consequence based. In reality it is considered that the annual probability of failure of English dams, even in the worst cases of non-statutory reservoirs, will be significantly less than one and probably more likely in the range of 1 in 100 to 1 in 5,000 (see section 4.5.3.2). Accordingly, the risk of death from the flood impact resulting from an uncontrolled release would reduce by a factor of 100 to 5,000 if probability of failure was to be taken into account. Assuming a value of 1 in 1,000 for probability of failure, the boundary between unacceptable & tolerable and tolerable & broadly acceptable for fatality rate would reduce from 1 in 10,000 and 1 in 1,000,000 to 1 in 10 and 1 in 1,000 respectively. This could conceivably allow the threshold of intensity for “not high-risk” designation to be raised from 0.1 m^2/s to 1.0 m^2/s which would have a significant effect on the number of reservoirs designated “high-risk”.

There could therefore be merit in changing the wording of the Act such that there was room, most likely at a very conservative level, for consideration of probability of failure. A possible change to the wording could be as follows:

> *“The appropriate agency may designate a reservoir as a high-risk reservoir if-“*
>
> > Existing
> >
> > *“The appropriate agency think that, in the event of an uncontrolled release of water from the reservoir, human life could be endangered”*
> >
> > Proposed
> >
> > *“The appropriate agency think that there is an intolerable risk of an uncontrolled release of water from the reservoir endangering human life”*

Clearly the detail and wording of any change would require legal advice but the principles described above are appropriate should there be a wish to move the English Act more in line with a risk-based approach. There would need to be a robust definition of “intolerable” or else some alternative form of words.

There could also be benefit in making provision for a Panel Engineer to be able to re-designate low consequence / “high-risk” reservoirs if the probability of failure was considered to be extremely low. An example of this could be a low height dam with a wide crest, very flat side slopes low erodibility fill, and low ASLL.

4.5.6 Summary

HSE guidance proposes that the boundaries between unacceptable and tolerable, and between tolerable and broadly acceptable of risk of death for an individual are 1 in 10,000 (0.01%) and 1 in 1,000,000 (0.0001%) respectively. It is considered that a reservoir would need to sit in the broadly acceptable zone in order be designated “not high-risk”.

Strict application of the English Act would adopt these values directly, assuming a probability of failure of one, implying in both cases that the fatality rate would effectively be zero as it is not credible to differentiate fatality rates below 0.1% (RARS, 2013). In effect this would mean that for a “not high-risk” determination the impact of the flood wave would have to present a negligible risk to life. A zero fatality rate is most readily interpreted as a Hazard Rating of less than 0.75 in terms of FD2321 (see section 4.5.2.1). Although not directly comparable, this implies a maximum flow intensity of about 0.1 m^2/s. This was the approach followed in the risk designation process, and it may therefore be considered that the process was appropriate.

Consideration of proportionality suggests that that the cost of regulating high-risk reservoir is disproportionate in relation to the benefits secured. Such analysis would suggest that the bar for high-risk designation should be raised, possibly to an ASLL of around 0.06. However, this would be in conflict with HSE guidance for risk to individuals and it is therefore felt that proportionality is not an appropriate tool for risk designation.

The English Act, as currently enacted, is potentially over conservative in that risk designation has to assume a probability of failure of one and is therefore based solely on consequence. The Act could potentially be reworded to allow some consideration of probability of failure in the risk designation process.

4.6 Review of risk designation structure

4.6.1 Overview

Notwithstanding consideration of the threshold for "high-risk" designation, this research is also tasked to investigate options for implementing a three-tier risk designation process.

Possible drivers for such a change are:

- Better alignment with devolved administrations
- Requirements for increased rigour on reservoir safety enforcement on high consequence "high-risk" reservoirs
- Declining number of appointed panel engineers

In the context of the second bullet it is possible that requirements for increased rigour of reservoir safety enforcement might come out of the near failure of Toddbrook Reservoir on 1st August 2019. At present it is too early to speculate on what these might be, but it has to be recognised that although no lives were lost at Toddbrook, it was the most serious incident for over a decade and resulted in the evacuation of over 1,000 people. An investigation and report on the incident has been commissioned by Defra.

The following high-level options for risk designation are considered for England:

1) "medium-risk" as a sub-set of existing "not high-risk" (similar to Scotland); or
2) "medium-risk" as a sub-set of existing "high-risk"
    a) medium/high threshold based on bespoke risk assessment (including probability);
    b) medium/high threshold based on hazard; or
    c) medium/high threshold based on ASLL.

This is a non-exhaustive list; other variations on these options may have potential but have not been considered here. Option 2 would widen the different approaches applied between England and Scotland, Wales and Northern Ireland, while Option 1 would increase the similarity in approach between England and Scotland. These options are further defined in the sub-sections below.

If adopted, proper and thorough definition of any proposed limits would benefit from new risk designation guidance to clarify the new system. There may also need to be a change to the legislation which currently describes a two-tier risk designation system.

4.6.2 Option 1 - "Medium-risk" as a sub-set of existing "not high-risk" (Scotland Model)

Option 1 is identical, in structure, to the model currently adopted in Scotland. In Scotland the threshold for "high-risk" is not defined in legislation but is covered by guidance (Scottish Environment Protection Agency, 2015). Under the *"human health"* indicator in the Scottish guidance the threshold is defined as *"risk to life"*. The risk to life threshold is defined in more detail in section 4.5. *"Risk to life"* in Scotland is assumed to be equivalent to *"human life could be endangered"* in England and Wales.

In England and Wales, reservoirs are designated as "high-risk" or are otherwise undesignated ("not high-risk"). In Scotland they are designated "high-risk", "medium-risk" or "low-risk". In terms of regulation, "high-risk" and "not high-risk" (or "low-risk" in Scotland) attract the same inspection and supervision requirements in each territory. The regulatory difference between the "high-risk" and "medium-risk" status is that, unless called for by the Supervising Engineer, "medium-risk" reservoirs do not require periodical inspection by an All Reservoir Panel Engineer (ARPE), which would otherwise be at a minimum frequency of once every 10 years.

At a high level the designations for this option are described as follows:

- "Low-risk" – lowest consequence part of the existing "not high-risk" population;
- "Medium-risk" – medium consequence part of the existing "not high-risk" population;
- "High-risk" – the entirety of the current "high-risk" population plus the highest consequence part of the existing "not high-risk" population fall under this new "high-risk" designation. *"Risk to life"* automatically triggers "high-risk", but the converse is not true: if a reservoir has no risk to life it could still be "high-risk" based on other factors, for example environmental designations.

An advantage of this option would be the harmonisation of legislation between England & Wales, Scotland, and potentially Northern Ireland in the future.

As there is no equivalence in England & Wales to Scotland's "medium-risk", all reservoirs designated as such in Scotland would be "not high-risk" reservoirs in England & Wales. In England & Wales, "high-risk" is currently assigned based solely on there being a threat to life and it follows that all "high-risk" reservoirs in England & Wales would be designated as such under Scottish legislation. The converse is not true as some reservoirs that are designated as "high-risk" in Scotland may not pose a threat to life, and therefore would be "not high-risk" in England & Wales. Thus, it follows, that for an identical population of reservoirs, the current regulatory burden would be slightly greater in Scotland than in England & Wales and therefore the regulatory burden would be greater under this option.

The current number of reservoirs in each risk category in Scotland is not stated in the recent SEPA research (Aecom, 2016), although details are provided for Scottish Water's stock of dams, which make up about 50% of the regulated dams in Scotland. The current proportions based on consequence alone are given as 90% (266 out of 294) "high-risk"; 6% (19 out of 294) "medium-risk", and 4% (9 out of 294) "low-risk". Taking typical panel engineer costs as £1,300/year for a "high-risk" reservoir (Supervising Engineer + Inspecting Engineer averaged over 10 years) and £1,000/year for "medium-risk" (Supervising Engineer only) and £0/year for "low-risk" results in an annual cost of £1,180 per reservoir or less in England & Wales and for £1,240 per reservoir in Scotland. This suggests the burden in Scotland would be at least 5% greater than in England and Wales for the same stock of reservoirs and possibly up to 10%, as the proportion of "high-risk" reservoirs would be lower if the sole threat to life criteria adopted in England & Wales were applied. The costs assumed here are high level costs based on experience and exclude those incurred by an Undertaker to carry into effect any statutory safety works, monitoring and maintenance measures as recommended by a statutory inspection.

To summarise, under this option, regulatory burden would increase but only for the part of the population of the lowest consequence which is not considered to present a risk to life. It is anticipated that the additional cost of regulation could be better spent on higher hazard reservoirs. Only 12% of reservoirs are currently “not high-risk” (Mott MacDonald, 2019b) and it would not appear to be advantageous to sub-divide that relatively small part of the population further into “low” and “medium” risk. Although bringing Small Raised Reservoirs into regulation would increase this percentage to 35%, it would still be increasing regulation on reservoirs that would not be considered a risk to life. Therefore **Option 1 is not recommended** for further consideration at this point in time.

4.6.3 Option 2 – “Medium-risk” as a sub-set of existing “high-risk”

The driver for introducing medium-risk as a subset of high-risk is that the current high-risk designation covers a very wide range of hazard from ASLL values of close to zero to several thousand.

In practice there is little room to reduce regulation at the bottom end as the only credible change available would be to remove the requirement for ten yearly inspections (as per the Scottish system). This would result in a fairly minimal cost saving which could anyway be lost if the Supervising Engineer were to call for an inspection as per the existing regime.

However, there is possibly a need to reconsider what level of inspection / scrutiny is appropriate on a high hazard high-risk reservoir. At present most Section 10 Inspections cost a similar amount, irrespective of hazard, which does not seem logical. A new “high-risk” category could therefore be introduced to increase the rigour of the inspections on a high hazard high-risk reservoir. This issue is discussed further in a paper entitled “Managing the safety of very high consequence dams – is the UK doing enough” (Brown & Hewitt, 2016) which proposes inter alia the development of a “dam safety case” for high consequence reservoirs. Notwithstanding the above, it does nevertheless have to be recognised that the measures recommended in inspection reports on higher consequence reservoirs are already likely to be more extensive than on lower consequence reservoirs, so the concept is already partly in operation.

Options 2a, 2b and 2c all involve the introduction of a “medium-risk” designation category as a subset of the current “high-risk” category. It should be noted that these options do not promote harmonisation with legislation in Scotland, Wales or Northern Ireland because the proposal is different to the existing systems.

4.6.3.1 Option 2a – “Medium-risk” as a sub-set of existing “high-risk” based on bespoke risk assessment

Bespoke risk assessments are discussed in section 3.4 in the context of deregulation from “high-risk” to “not high-risk”.

A bespoke risk assessment would facilitate a much better understanding of the risk posed by a reservoir in terms of both probability of failure and consequence. However, the cost of a bespoke risk assessment is estimated to be ~£50k which is considerable and could not be justified for maintaining the status quo on “medium-risk” reservoirs. It would therefore be preferable for designation to be made on the basis of existing information.

Option 2a is not recommended.

4.6.3.2 Option 2b – “Medium-risk” as a sub-set of existing “high-risk” based on hazard

Option 2b is a variant of Option 2 whereby the threshold between medium-risk and high-risk is set by maximum hazard at that reservoir.

Section 4.5.2.1 defines the limits for hazard resulting from flooding as described in the supplementary note to FD2320 and FD2321 (Defra, 2008). The lower limit for “danger for some” is 0.75, which is currently used (implicitly) as the lower threshold for a “high-risk” reservoir at a receptor such as a property or a major road. If the current “high-risk” population were split into “medium-risk” and “high-risk” the medium / high threshold could be set with hazard somewhere in the range, based on the limits described in FD2321, of 1.25 to 2.

The risk designation split would then be as follows:

- “Low-risk” would be defined by “very low hazard” (hazard < 0.75)
- “Medium-risk” would be defined by “danger for some” (0.75 ≤ hazard < 1.25 to 2.0)
- “High-risk” would be defined by “danger for most” or “danger for all” (hazard ≥ 1.25 to 2.0)

Unfortunately, it is not possible to provide an estimate for the number of “medium-risk” and “high-risk” reservoirs because the data on maximum hazard is currently unavailable. Following completion of the ongoing RFM project this data may become available in the future.

The main problem with this option is in considering the scenario where there is a large population at risk (PAR) subjected to a hazard between 0.75 and 1.25, corresponding to *“danger for some – includes children, the elderly and the infirm”*. Firstly, a relatively large population at such a level of hazard could give rise to high loss of life, and furthermore it would be the most vulnerable who would be most likely to be among the victims which is likely to be unpalatable. In this sense it is more logical to define the “medium-risk” designation using ASLL, which takes account of the PAR. Fundamentally this is because hazard is not a measure of consequence whereas ASLL is. While hazard may be an appropriate metric at the low consequence end of the scale to check whether there is “human endangerment”, for slightly higher consequence dams it is considered to be important to take account of the Population at Risk (PAR). For this reason, **Option 2b is not recommended** for further consideration at this point in time.

4.6.3.3 Option 2c – “Medium-risk” as a sub-set of existing “high-risk” based on ASLL

For Option 2c the existing “high-risk” reservoirs would effectively be sub-divided into “medium-risk” and “high-risk”. Both “medium-risk” and “high-risk” would then represent risk to life. This threshold for risk to life is defined in more detail in section 4.5.2. “Low-risk” would be identical to the existing “not high-risk” designation. The threshold between “medium-risk” and “high-risk” could potentially be based on ASLL. Data on ASLL is available from the RFM study which is currently underway, and is described in some detail in section 2. It should, however, be appreciated that estimation of ASLL is an inexact science and that the risk designation process could be very open to challenge.

Table 19 and Figure 12 show how the split between “high-risk” and “medium-risk” would vary for ASLL increasing from 0.01 to 10. The results could be expected to be slightly different for the incremental effect of the “wet day” scenario, but the principle would be unchanged.

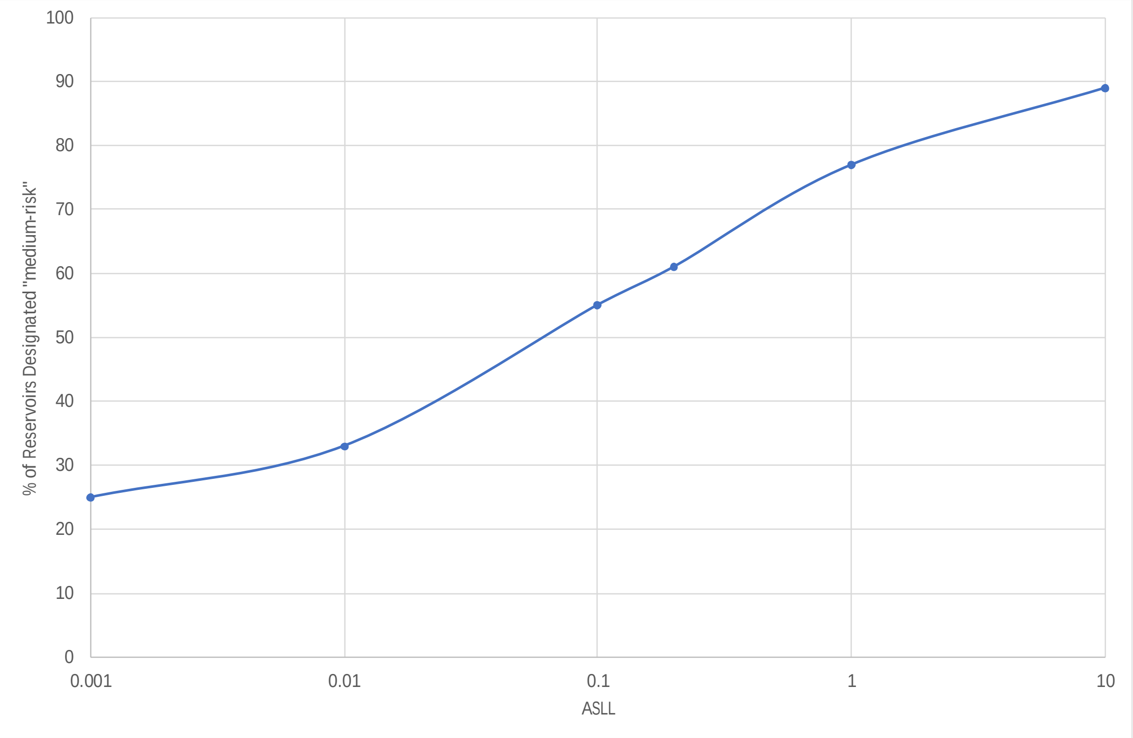
Table 19: Re-designating Relatively Low Consequence "High-risk" Reservoirs to "Medium-risk"

Low Consequence Criteria	No. re-designated from “high-risk” to “medium-risk” in sample under this option	Percentage of “high-risk” reservoirs in the RFM sample re-designated to “medium-risk”	Corresponding no. re-designated in broader population through extrapolation
ASLL = 0	150	25%	451
ASLL = 0.01	199	33%	598
ASLL = 0.1	333	55%	1,001

Low Consequence Criteria	No. re-designated from "high-risk" to "medium-risk" in sample under this option	Percentage of "high-risk" reservoirs in the RFM sample re-designated to "medium-risk"	Corresponding no. re-designated in broader population through extrapolation
ASLL = 0.2	372	61%	1,118
ASLL = 1	470	77%	1,413
ASLL = 10	544	89%	1,636

Notes: RFM Sample Reservoirs = 608, Population Reservoirs = 2065. Reservoirs with no risk designation assumed to be "high-risk" by default.
Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Figure 12: Relationship between ASLL and percentage of reservoirs designated "medium-risk"



Notes: RFM Sample Reservoirs = 608, Population Reservoirs = 2065. Reservoirs with no risk designation assumed to be "high-risk" by default. ASLL of 0 taken to equal 0.001 for plotting on log scale.
Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

It is not currently possible to give clear guidance on where the boundary between "medium-risk" and "high-risk" should sit, but given that the change would be used to increase regulatory burden it is likely that it would only apply to a minority of the current "high-risk" reservoirs. As such an ASLL of 1 is considered to be a reasonable starting point, given that this would embrace mainly higher consequence Category A reservoirs (see Figure 3). Table 19 indicates that, based on the RFM data currently available, this would result in 75% of the current "high-risk" reservoirs falling into the new "medium-risk" category. Adopting this three-tier designation could also limit the total amount of new regulation if SRRs were brought into the registration threshold. Based on the 40 dam breaks modelled under Objective 2 (Mott MacDonald, 2018b) all SRRs would be classified as "medium-risk" if the volumetric threshold is lowered to 10,000 m^3.

Based on the information available, an indicative estimation of the numbers of reservoirs under each risk designation is given in the table below.

Table 20: Indicative estimate of reservoir numbers under Option 2a for threshold of ASLL = 1.0 for Medium / High-risk

Volume, V	Low-risk		Medium-risk		High-risk	
V > 25,000 m^3 (2065 no.)	11%	237	68%	1413	20%	412
10,000 m^3 < V < 25,000 m^3 (1503 no.)	66%	992	34%	511	0%	0
Total (3568 no.)	**34%**	**1229**	**54%**	**1924**	**12%**	**412**

Notes: Percentages may not add up to 100% due to rounding errors
Source: (Environment Agency, 2019) (Mott MacDonald, 2018b)

A further consideration is that selection of the ASLL boundary between "high-risk" and "medium-risk" could be based on proportionality of costs and benefits. Whilst, as described in section 4.5.3, this approach was not considered appropriate for defining the current boundary between "not high-risk" and "high-risk" it could be well suited to defining the new boundary between "medium-risk" and "high-risk" as, in this case, it would not be being used to reduce the regulatory burden on some existing "high-risk" reservoirs.

4.6.4 Summary of review of Risk Designation structure

The conclusion of this element of the research is that there could be benefit in bringing in a three-tier risk designation structure if there is a future requirement to increase the rigour of the dam safety regulation on higher consequence reservoirs which are currently designated "high-risk. With a three-tier structure, existing "not high-risk" reservoirs would become "low-risk" while existing "high-risk" would be split between "medium-risk" and "high-risk". Regulatory requirements would remain unchanged for "low-risk" and "medium-risk" reservoirs while increased rigour would be applied to new "high-risk" reservoirs.

It is proposed that the boundary between "medium-risk" and "high-risk" should be based on ASLL, and possibly be informed by proportionality of costs and benefits.

4.7 Task 2 Summary

High level findings from Task 2 are:

- Prior to the introduction of legislation in 1930 the reservoir safety record in Britain was unacceptable based on the record of fatalities. Since 1925 there have been no fatalities. The reservoir safety record has improved dramatically.
- The findings of the research into the "high-risk" threshold is that the reservoirs industry is broadly in line with other high hazard industries and that the adopted interpretation of "endangerment of life" is appropriate. The research findings are supported by the findings of first tier tribunals.
- The cost of regulating some lower consequence reservoirs is potentially disproportionate to the benefits secured. However, it is not felt that this should be used as a basis for changing the definition of "high-risk" because redefining the boundary between "not high-risk" and "high-risk" on the basis of proportionality could result in some re-designated "not high-risk" reservoirs presenting an unacceptable risk to life for individuals.

- Lower consequence dams are already subject to less stringent standards through existing guidance. In this respect there is already a proportionate approach to the regulation of lower consequence reservoirs.
- The English Act, as currently enacted, is potentially over conservative in that risk designation has to assume a probability of failure of one. The Act could potentially be reworded to allow some consideration of probability of failure.
- Introduction of a three-tier risk designation structure could be beneficial if there is a future requirement to increase the rigour of the dam safety regulation on higher consequence reservoirs which are currently designated "high-risk. Such requirements might come out of recommendations following the investigation of the recent near failure of Toddbrook Reservoir on 1st August 2019. It is proposed that a three tier system would make existing "not high-risk" reservoirs "low risk" and split existing "high-risk" reservoirs between "medium-risk" and "low-risk" based on ASLL or a combination of ASLL and some other metric(s). The boundary could be established based on proportionality of costs and benefits.

5 Task 3: Review criteria for definition of a large raised reservoir

5.1 Introduction

A "Large raised reservoir" is defined in England under Section A1(1) to A1(9) of the English Act. Section A1(3) defines the volume as follows (note the important asterisk):

'A raised structure or area is "large" if it is capable of holding 10,000 cubic metres of water above the natural level of any part of the surrounding land.'*

*In England Regulations 3 and 4 of SI 2013 No. 1590 mean that *'10,000'* is to be read as *'25,000'* until further provisions are made by Ministers. In Scotland the threshold is currently 25,000 m^3 whereas in Wales the threshold has already been reduced to 10,000 m^3.

The purpose of Task 3 is to review the appropriateness of the use of "volume" as the sole criteria for the definition of a reservoir under the English Act. Evidence was gathered by carrying out the following sub-tasks:

- Review of international practice with respect to defining regulated reservoirs;
- Summary of relationship between discharge, height and volume in the breach flow equation;
- Review of the physical characteristics of British dams that have caused loss of life;
- Analysis of "high-risk" and "not high-risk" reservoirs in the public register of English dams;
- Analysis of data produced in the Reservoir Flood Mapping (RFM) study.

This section is concluded with potential alternative criteria for registration of reservoirs in England and the impact these could have on the total number of registered reservoirs.

5.2 International Practice

The International Commission on Large Dams (ICOLD) defines a 'large' dam as *a dam with a height of 15 metres or greater from lowest foundation to crest or a dam between 5 metres and 15 metres impounding more than 3 million cubic metres* (ICOLD, 2019). Similarly, the definition of a large dam given in Geotechnical Engineering of Dams (Fell, MacGregor, Stapledon, & Bell, 2005) is one which "*is more than 15 metres in height (measured from the lowest point in the general foundations to the crest of the dam), or any dam between 10 metres and 15 metres in height which meets one of the following conditions:*

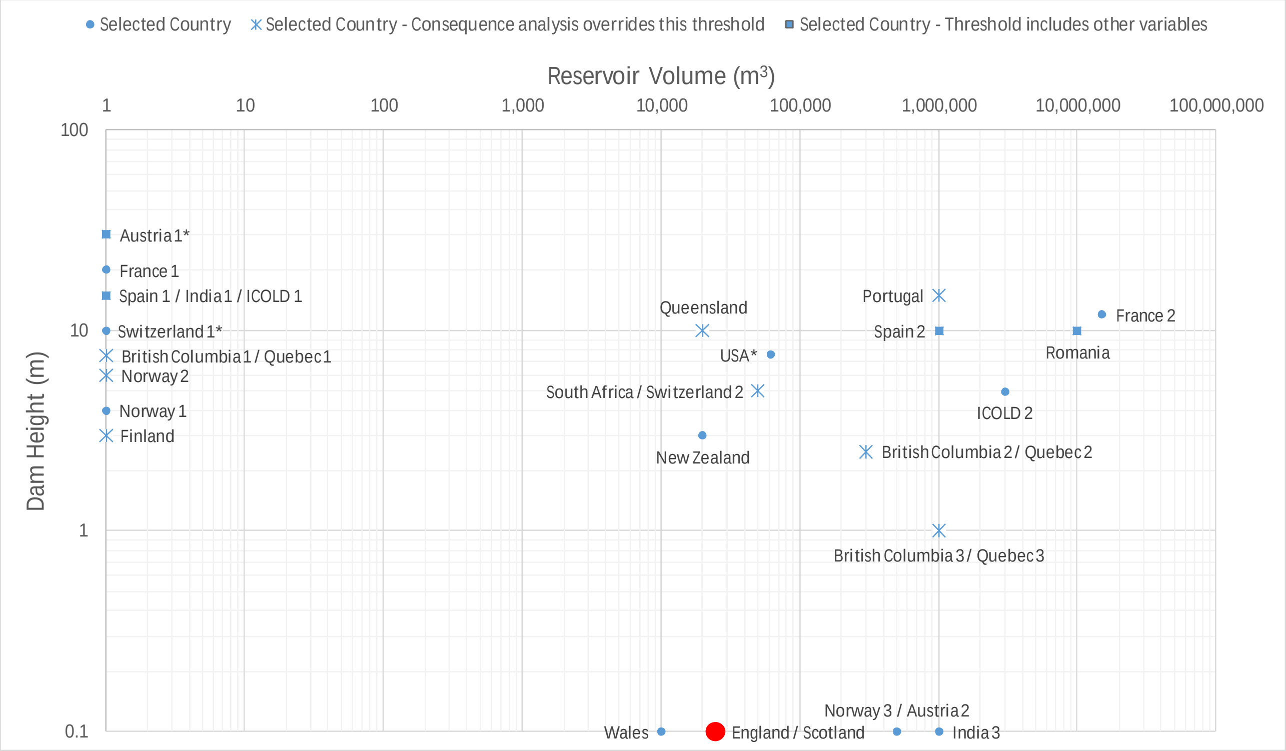
- *The crest is not less than 500 metres;*
- *The capacity of the reservoir formed by the dam is not less than 1,000,000* m^3;
- *The maximum flood discharge dealt with by the dam is not less than 2,000* m^3/s;
- *The dam is of unusual design".*

This shows that there are at least four parameters that can be used to define a large dam:

- Dam height;
- Reservoir volume;
- Crest length;
- Discharge.

Each country has its own thresholds to define large dams and the subsequent regulations that would apply to them. A table describing these thresholds for a select number of countries was provided by the EA to Halcrow as part of a study on a risk-based approach to reservoir safety (Halcrow, 2008). Analysis of this table showed that regulation of dams is based predominately on dam height, reservoir volume or both. In addition to this, some countries use parameters such as crest length, maximum discharge or, in at least one case, proximity to residential properties. To compare the thresholds between countries, they have been plotted in Figure 13. The table describing these thresholds is provided for reference in Appendix A.

Figure 13: Reservoir volume and dam height thresholds for regulated dams in selected countries



Notes: * indicates countries where it is specified that smaller dams are regulated by provincial authorities

Source: Analysis by Mott MacDonald (2019) using data from Reservoirs Act 1975 - Guidance for a new risk-based approach (Halcrow, 2008)

Figure 13 shows reservoir volume in the x-axis and dam height in the y-axis, both on a logarithmic scale. A circle shows the point at which a reservoir larger than that shown will be regulated. Where a square is used, this means that some other dam characteristic is also used, such as crest length or discharge rate. Dam characteristics would have to be to the right or above each of these points to be regulated. Where a cross is shown, this represents where a consequence analysis will be used to override any limits based on dam height or reservoir volume, and therefore a regulated dam could be the left and below as well.

From Figure 13, it can be seen that from the selected countries, the UK is the only country to use volume alone to regulate reservoirs. England and Scotland both regulate any reservoir larger than 25,000 m^3, while Wales reduced the volumetric threshold to 10,000 m^3 in 2016. The countries with the closest volume regulation based on volume alone would be Norway and Austria, which use 500,000 m^3 as one of their thresholds.

A number of countries incorporate consequence analysis to determine regulatory requirements. For example, Norway groups dams into three categories based on the number of dwellings affected by dam failure. The threshold at which regulations apply varies based on the dam category. In Canada there is provision to apply regulations to low capacity dams if they have very high consequences. While the UK has variable standards dependent on consequences (e.g. flood categories, seismicity, drawdown requirements) these are not used to determine whether a reservoir should be regulated or not. Risk designation ("high-risk" or not) is covered separately under Task 2 in section 4.5.

5.3 Dam breach equations

In the area close to the dam the level of potential hazard in the unlikely event of catastrophic failure is governed by peak breach discharge. Further away from the dam the breach volume may have more influence on the consequences. In all cases consequence of failure is a function of peak breach discharge as well as a number of other factors. Therefore, analysis of the dam breach equations gives context to the relationship between height, volume and the consequences of failure.

For a high-erodibility embankment dam, peak discharge as a result of dam failure is given by (Xu & Zhang, 2009):

$$Q = C\left(\frac{V^{0.333}}{H}\right)^{-1.276} \sqrt{gV^{1.667}}$$

Where:

Q = Discharge

C = Constant dependant on failure mode

V = Volume of water

H = Height of water

g = gravitational constant

By simplifying this equation, the following equations can be derived:

$$Q = C\sqrt{g}\,V^{0.409}H^{1.276}$$

The use of both height and volume in the calculation of peak discharge shows that both are important parameters to consider. The higher exponent on height indicates that it has more of an impact than volume on peak discharge during the failure of embankment dams.

Most English dams are embankment dams but for completeness, the breach equation for concrete dams is:

$$Q = cH^{1.5}$$

Where:

L = length of dam

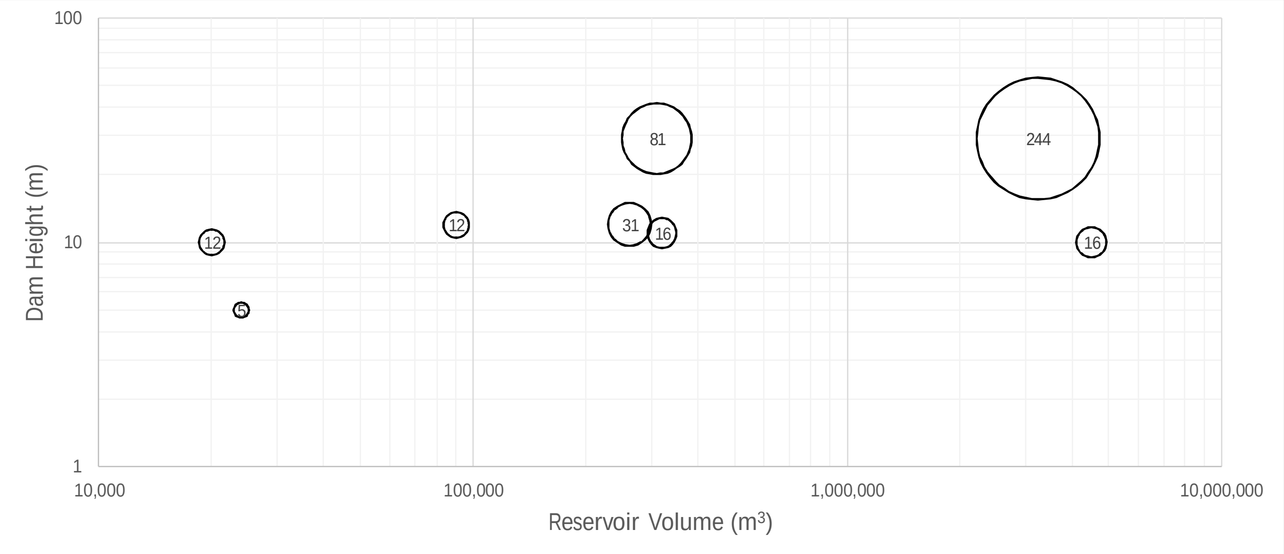
c = f(L)

It can be seen that the concrete dam breach equation does not include volume. This further demonstrates the significance of the height of water as opposed to the volume in terms of the breach flow which is linked to consequence of failure.

5.4 Physical characteristics of British dam failures which caused loss of life

This section compares the height and volume of British dam failures which have caused loss of life to determine which characteristic is more closely correlated to loss of life based on historical data.

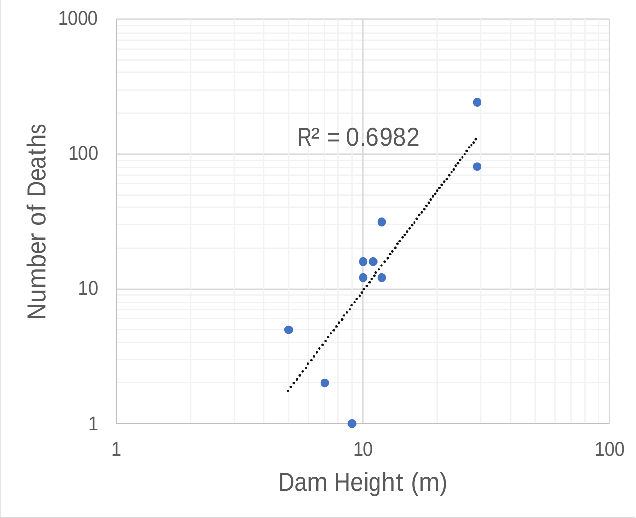
Figure 14: Height and volume of British dam failures that caused loss of life



Source: Analysis by Mott MacDonald (2019) using data from (CIRIA, 2014)

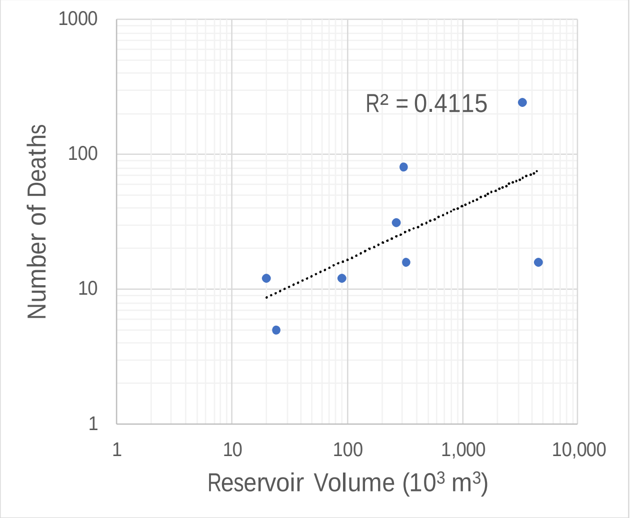
Figure 14 shows dam failures in Britain that have caused loss of life. The lowest volume that caused deaths was 20,000 m^3 when Bold Venture dam in Darwen failed in 1844. It can also be seen from Figure 14 that there can be a large difference in the number of deaths caused by reservoirs with similar volumes, such as with Dale Dyke (244 deaths, 3,240,000 m^3) and Eigiau (16 deaths, 4,500,000 m^3). A final observation can be made that there are five dams that failed which are around 10 m high with a similar number of deaths, but with a wide range of volumes (factor of more than 200 between maximum and minimum volume for those five reservoirs).

Figure 15: Dam height against number of fatalities caused by UK reservoirs



Source: Analysis by Mott MacDonald (2019) using data from (CIRIA, 2014)

Figure 16: Reservoir volume against number of fatalities caused by UK reservoirs



Source: Analysis by Mott MacDonald (2019) using data from (CIRIA, 2014)

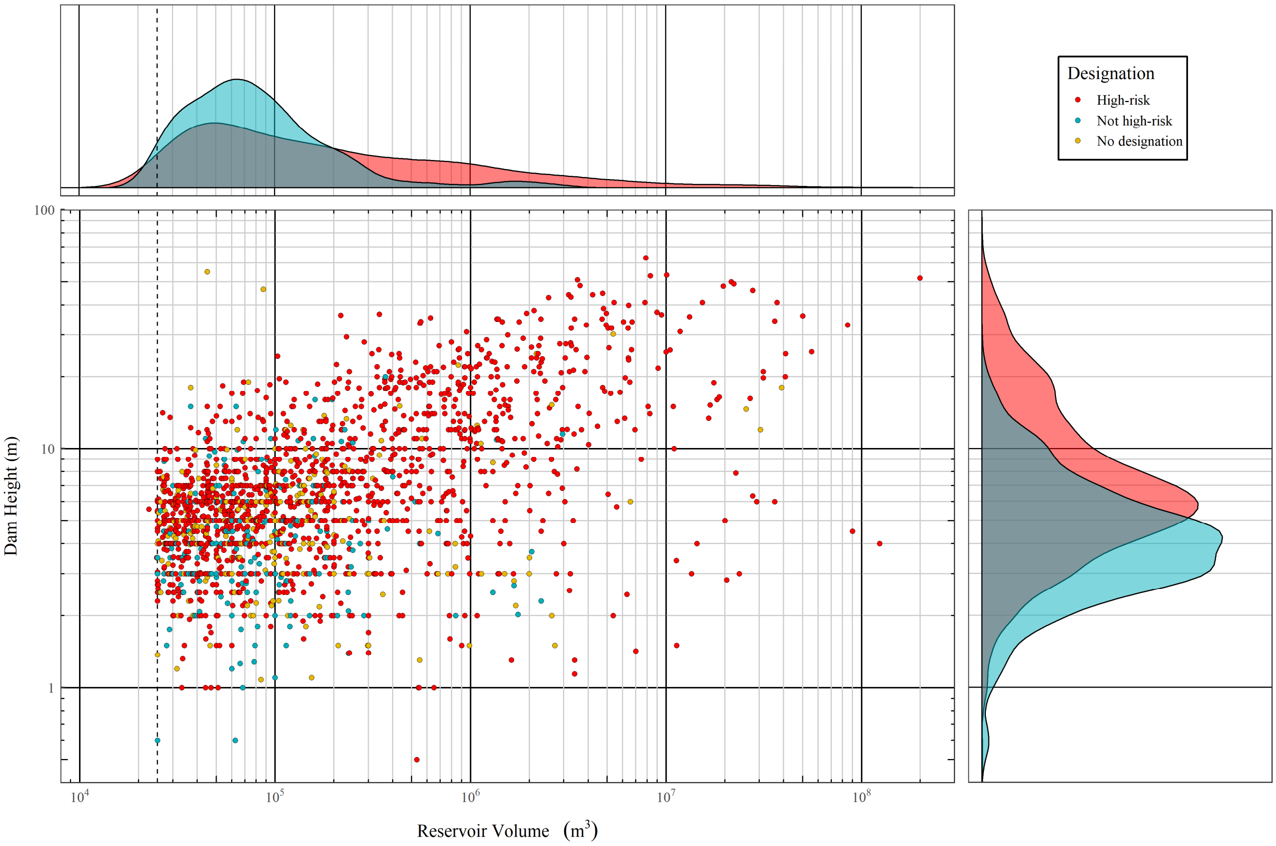
To further demonstrate the correlation between loss of life and dam height and volume, Figure 15 and Figure 16 show regression lines for the number of deaths caused by dam failure plotted against dam height and reservoir volume respectively. Both axes were plotted on a $\log_{10}$ scale to account for the large spread in some of the data, and power trend lines were fitted through the points. The R^2 coefficient can be used to compare the relative spread of data in the two datasets.

It can be seen that, for UK dams with recorded deaths, the correlation of number of deaths with dam height is stronger than the correlation with reservoir volume. It should be noted that the small size of the dataset would make any equations derived unsuitable for use in predicting loss of life as a result of dam failure.

5.5 Analysis of Public Register

The public register of reservoirs in England contains 2,065 unique reservoirs and lists, among other characteristics, the dam height, volume and risk designation of large raised reservoirs in England. This has been used to plot risk designation, height and volume. Some fields in the public register contain blanks, therefore the dataset size used in the analysis is sometimes less than 2,065.

Figure 17: Dam Height and Reservoir Volume of English Large Raised Reservoirs



Notes: Centre = Height-Volume Scatter Plot, Right = Height Density Plot, Top = Volume Density Plot
Source: (Environment Agency, 2019)

Figure 17 (centre) shows a scatter plot of dam height against reservoir volume for reservoirs in the public register in England. There are no clear clusters of “high-risk” or “not high-risk” reservoirs that can be observed; they are interspersed along both axes. By inspection of the density plots (right and top in Figure 17) it can be seen that with increasing height and volume the probability that a dam is “high-risk” increases.

On the right-hand side of Figure 17 there is a density plot that shows the distribution of dam heights for “high-risk” and “not high-risk” reservoirs. If a dam is “not high-risk”, the peak density for height is between 3 m and 5 m. If a dam is “high-risk”, the peak density for height is about 6 m. All dams with height greater than 12 m are “high-risk” (unless they have no designation), however there are “high-risk” dams with height as low as 1 m.

Figure 17 (top) is similarly a density plot for reservoir volume. If a reservoir is “not high-risk”, it is likely to be below 500,000 m^3. The peak density for volume for “not high-risk” reservoirs is 70,000 m^3. “High-risk” reservoirs have a larger and more even spread. The peak density for volume is lower, at 50,000 m^3, however the largest can be as big as 200,000,000 m^3. The shape of the density function lower than 25,000 m^3 cannot be relied upon, as reservoirs of this volume are not required to be registered.

From this it can be derived that any dam larger than 12 m or 500,000 m^3 is very likely to be “high-risk”. There is significant overlap between “high-risk” and “not high-risk” reservoirs at values below this, and it can be concluded that there is no definitive lower threshold for "high-risk" reservoirs based on the available public register data.

5.6 Analysis of Reservoir Flood Mapping (RFM) Project outputs

5.6.1 Introduction

Dam characteristics (dam height, reservoir volume, peak breach discharge) have been reviewed against ASLL values calculated in the RFM study (see Section 2) to draw out underlying relationships. This sub-section presents this analysis.

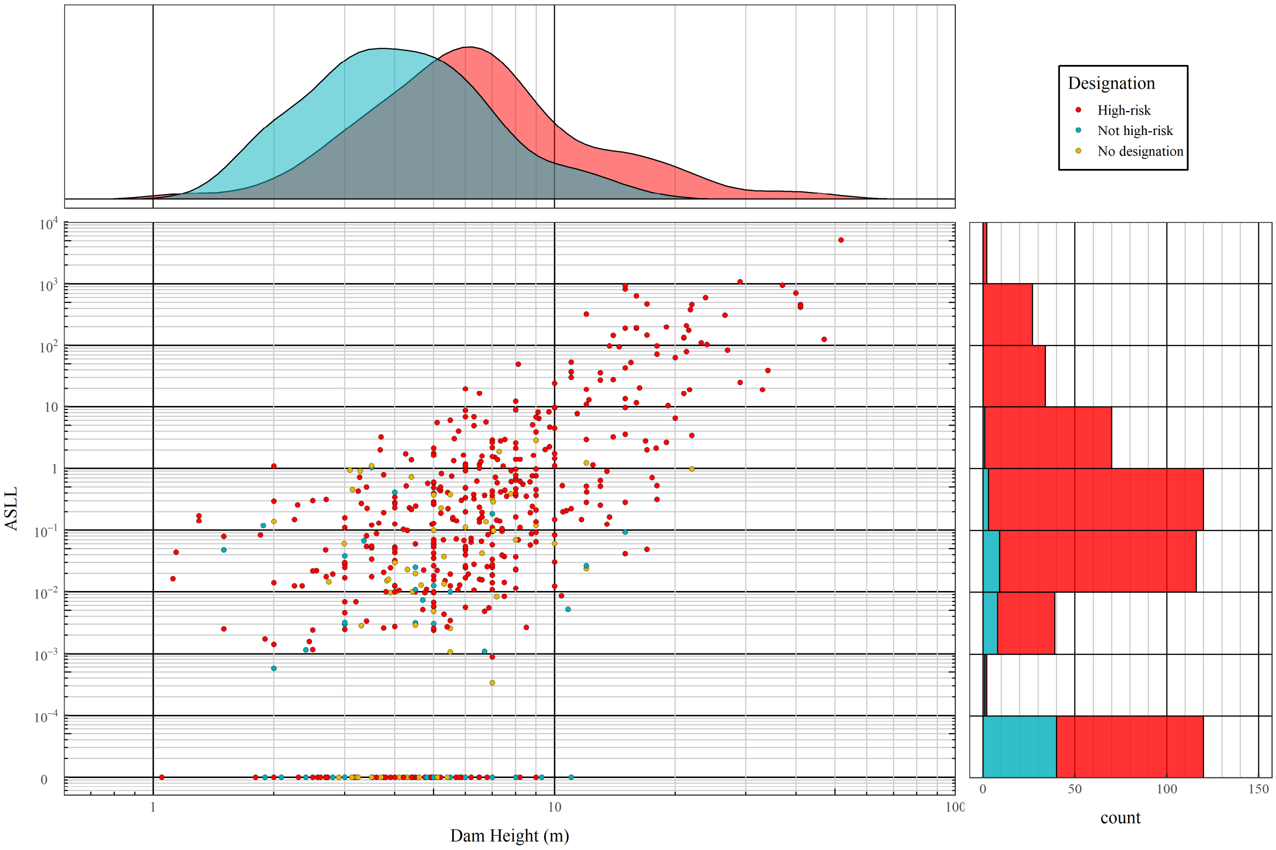
5.6.2 Variation of ASLL with height

This section considers the relationship between dam height and ASLL. Figure 18 (centre) shows a scatter plot with dam height in the x-axis and ASLL in the y-axis, both on logarithmic scales. A positive correlation between dam height and ASLL can be observed, with high dam heights corresponding with high ASLL and vice versa. This plot can be used to identify height thresholds based on ASLL. Below a dam height of 3 m ASLL is almost always less than ASLL of 0.4. The exception to this is a reservoir with a relatively large volume for the dam height which has an ASLL of 1.1 for a dam height of 2 m. For dam height of less than 2 m the ASLL is lower than 0.2 for all sample data. Unfortunately, the sample does not contain any dams with dam height of 1 m or less although the public register contains 15 such dams with a dam height of 1 m or less.

The density graph at the top of Figure 18 shows the distribution of "high-risk" and "not high-risk" dams that form part of the RFM sample for a given dam height. By inspection this is similar to the density plot on the right-hand side of Figure 17, which shows the equivalent plot for the dams in the public register.

Figure 18 (right) shows the count of reservoirs in each ASLL band, increasing in size logarithmically from zero to 10,000. It can be seen that only one third of reservoirs with zero ASLL are "not high-risk".

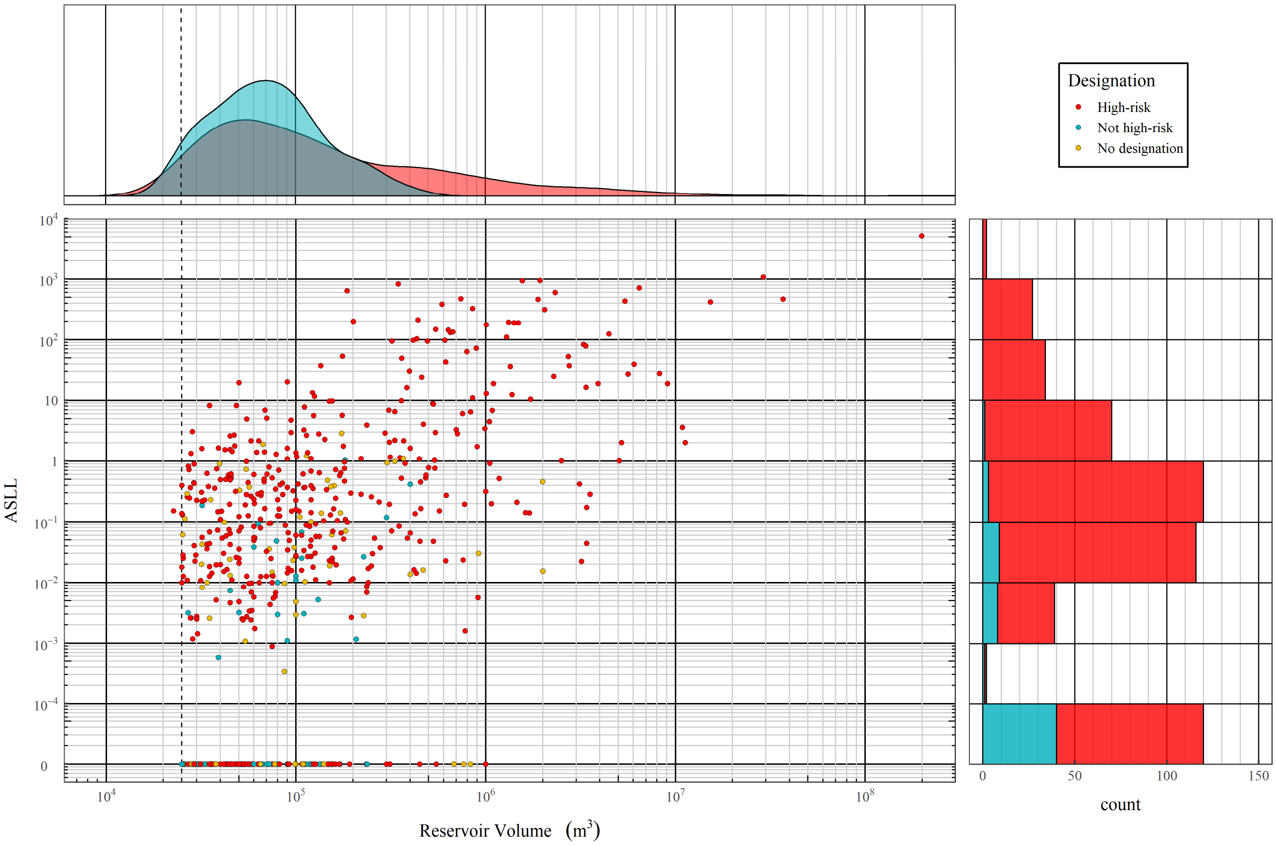
Figure 18: Variation of ASLL with Dam Height



Notes: Centre = Height-ASLL Scatter Plot, Right = ASLL Histogram, Top = Dam Height Density Plot
Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

5.6.3 Variation of ASLL with volume

Figure 19: Variation of ASLL with Reservoir Volume



Notes: Centre = Volume-ASLL Scatter Plot, Right = ASLL Histogram, Top = Volume Density Plot
Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Figure 19 (scatter plot, centre) shows reservoir volume plotted against ASLL. Similar to the plot for dam height, there is a positive correlation between reservoir volume and ASLL. Unlike the height bands for the equivalent plot for dam height, ASLL values are not limited to less than one for the lowest volume bands. This is because the threshold for registration is 25,000 m^3, so there is no RFM data for reservoirs below this volume. Based on the sample of 40 SRRs (volume less than 25,000 m^3) from Objective 2 of this research, ASLL does tend to drop below one for volumes below 25,000 m^3.

Figure 19 (line graph, top) shows a density plot of the reservoir volume for “high-risk” and “not high-risk” reservoirs that are part of the RFM sample. These are very similar to the same plot for reservoirs volumes of dams in the public register shown in Figure 17 (line graph, top).

The histogram on the right-hand side of Figure 19 is identical to that of Figure 18.

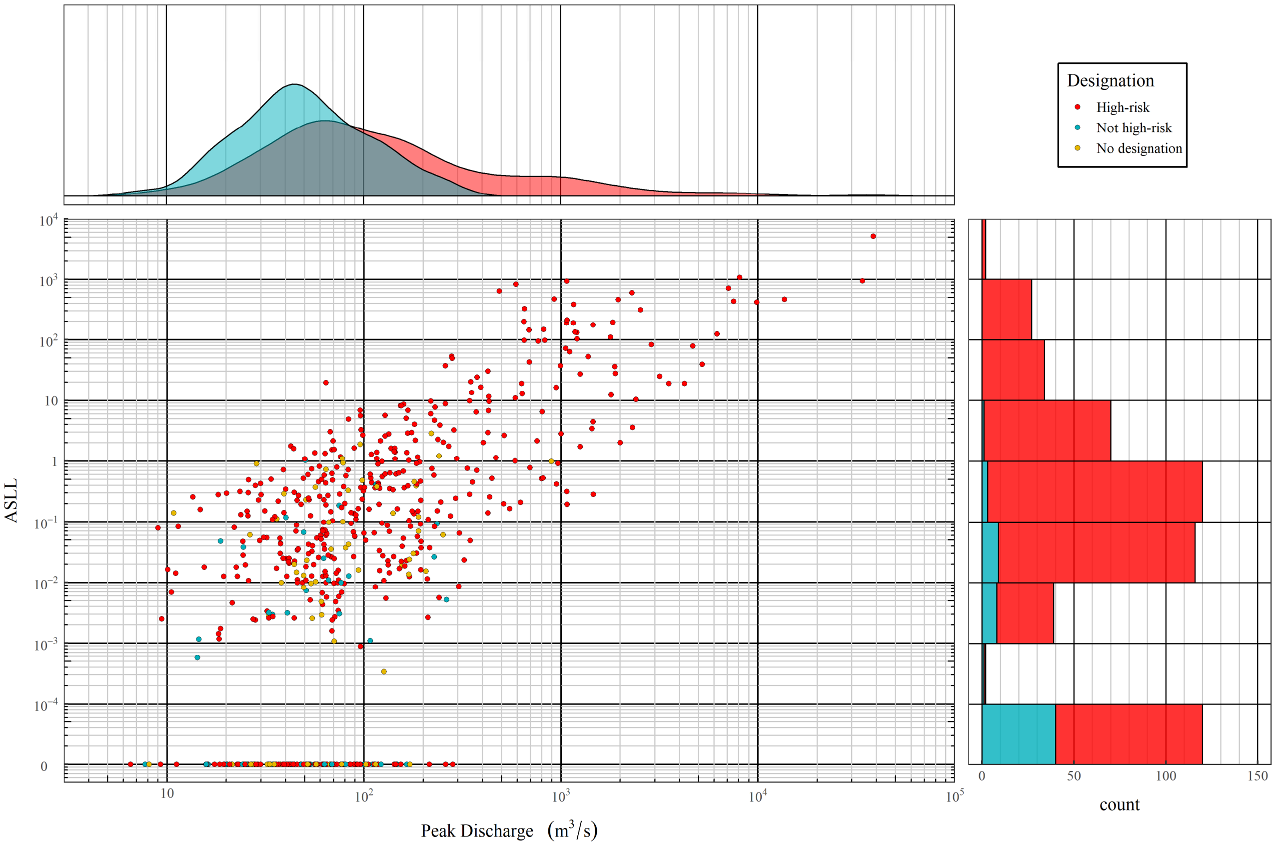
5.6.4 Variation of ASLL with peak breach discharge

Figure 20 (scatter graph, centre) shows peak breach discharge in the unlikely event of catastrophic (dry day) failure. There is, again, a positive correlation which, from inspection, appears to be more uniform than the correlations observed for height and volume. Below a breach discharge of 25 m^3/s, ASLL is below 0.4 for all sample data. Below a threshold of 40 m^3/s ASLL is always less than one for all sample data.

Figure 20 (line graph, top) shows the respective density plots for theoretical peak breach discharge for “high-risk” and “not high-risk” reservoirs. The most likely discharge, statistically, is 45 m^3/s for “not high-risk” reservoirs. It is 65 m^3/s for “high-risk” reservoirs. There are no “not high-risk” reservoirs with peak discharge greater than 300 m^3/s.

As before, the ASLL histogram shown in Figure 20 (bar chart, right) remains unchanged from that presented for volume or dam height.

Figure 20: Variation of ASLL with Discharge



Notes: Centre = Peak Discharge-ASLL Scatter Plot, Right = ASLL Histogram, Top = Peak Discharge Density Plot

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

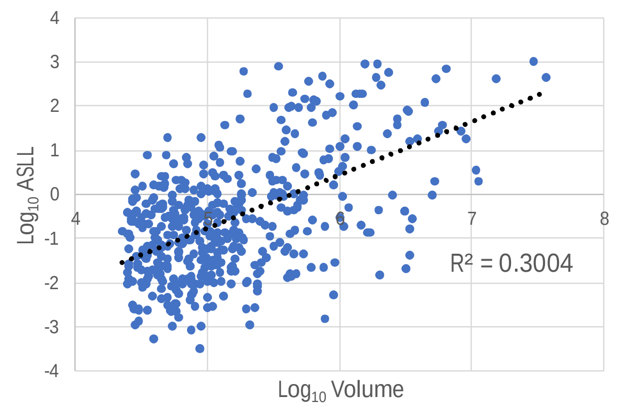
5.6.5 Regression analysis

To compare the correlations between the three dam characteristics and ASLL, regression analysis was carried out. Simple regression models were created for Volume-ASLL, Height-ASLL, (Volume x Height)-ASLL, and Peak Breach Discharge-ASLL. The coefficient of determination (R^2) is a measure of how well a regression line can map an independent variable to a dependant variable. The variation in scale for the two variables is large therefore it is visually beneficial to transform both variables by log$_{10}$. As zero values cannot be transformed using $\log_{10}$, some adjustment of the data is required where ASLL is zero. Two options were considered:

- Add 10^{-5} to all numbers, thereby bringing zero values onto the log scale
- Removal of all zero ASLL values

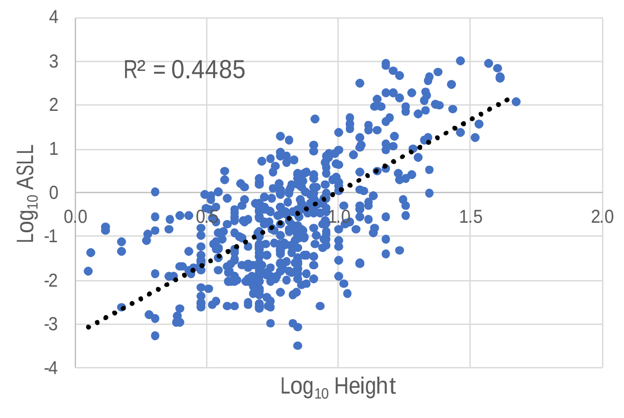
Addition of 10^{-5} to all numbers would be an insignificant change to the data, as the smallest ASLL is an order of magnitude larger than that. However, it has been observed that the effective inclusion of zero ASLL values reduces the coefficient of determination for all relationships tested. Therefore, to improve the coefficient of determination, all zero values were removed prior to regression and both variables were transformed by $\log_{10}$ for the four models. The regression lines were plotted using a linear relationship onto the log-transformed data. These are shown in Figure 21 to Figure 24. It is noted that if zero ASLL values were included the conclusions of the analysis would be unchanged despite the weaker correlations overall. Furthermore, it can be argued for some of the dams with 0 ASLL, the low consequences are more related to their distance from flood receptors than any particular dam height or volume. Therefore, there is limited value in their inclusion in this analysis, where the relationship between dam characteristics and dam failure consequences is being assessed.

Figure 21: Volume - ASLL Model



Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Figure 22: Height - ASLL Model



Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Figure 23: (Height x Volume) - ASLL Model

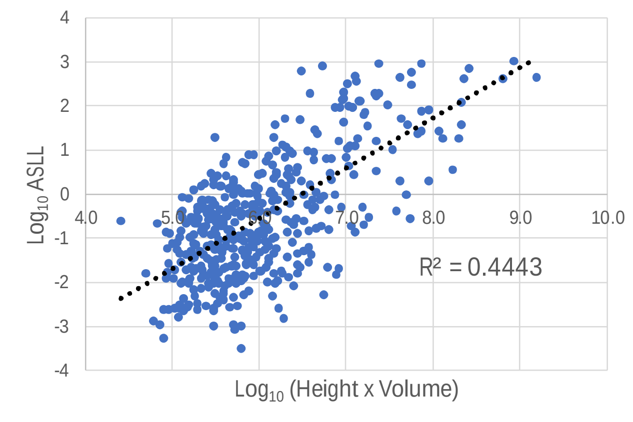
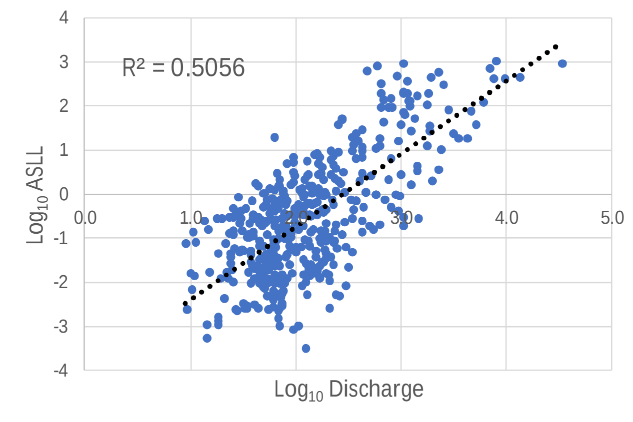


Figure 24: Peak Breach Discharge - ASLL Model



Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

Table 21: Linear Regression Summary

Regression Model	Volume - ASLL	Height - ASLL	(Height x Volume) - ASLL	Discharge - ASLL
R^2 Value	0.30	0.45	0.44	0.51

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the (Environment Agency, 2019)

Table 21 summarises the R^2 values for all the models. The results confirm that all three dam characteristics are correlated positively with ASLL. Height shows a stronger correlation than volume. Height x Volume shows a weaker correlation than height alone. Peak breach discharge, which is also a function of height and volume, shows the strongest correlation.

5.7 Current criteria for the definition of a reservoir

At the present time, volume is used to legally define a large raised reservoir in the England. This is enshrined in primary legislation under Section A1 of the Act. An argument in favour of retention of this system is that, to a degree, the legislation is working; since the implementation of Reservoirs (Safety Provision) Act of 1930, there have been no incidents which resulted in the loss of life due to failure of a reservoir. This is evidence that the current system protects the public from the risks of dam failure. Counting the number of years each dam in England has been free of loss of life since 1930 gives a value in excess of 100,000 dam-years. Since there have been no deaths during this time, there is evidence that it is likely that the probability of a fatality is better than 1 in 100,000 reservoir-years under the current regulatory system.

It could be argued that this has been down to luck, and that there are a large number of reservoirs below the statutory limit of 25,000 m^3 that can cause significant risk to life but have not failed. The Objective 2 Report (Mott MacDonald, 2018b) of this research demonstrated that there is likely to be about 1,500 SRRs (Small Raised Reservoirs - between 10,000 m^3 and 25,000 m^3) in England, of which about 500 would be “high-risk” if brought into the legal definition of a large raised reservoir in England. However, the report also concluded that the economic costs of regulating these reservoirs, of volume less than 25,000 m^3, is likely to outweigh the economic benefits. For more detail refer to the Objective 2 report. The Environment Agency administers an incident reporting system which typically records many incidents, some of them serious, at both statutory reservoirs and SRR’s in England every year. In many cases the incidents are identified and managed to prevent dam failure through the interventions of knowledgeable professionals such as panel engineers or flood risk managers.

5.8 Alternative criteria for the definition of a reservoir

This sub-section assesses the practicality of alternative criteria for the inclusion of a reservoir in the English public register of dams based on the research presented in sections 5.2 to 5.6.

5.8.1 Criteria 1 - Dam height

5.8.1.1 Introduction

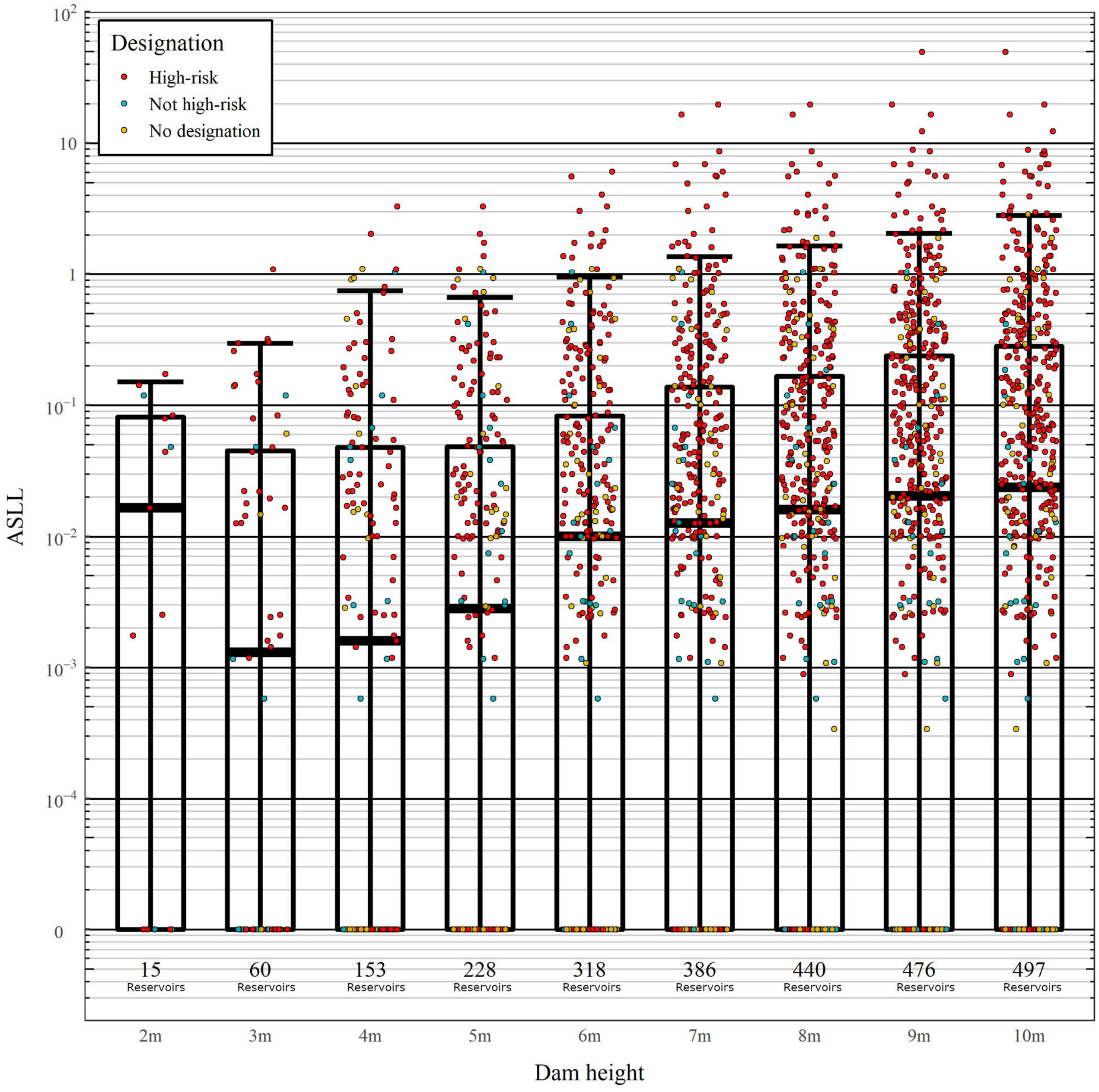
Based on the evidence presented in Section 5.6, dam height is a better indicator of the magnitude of dam failure consequences than reservoir volume. Therefore, it can be assumed that for two equally sized groups of reservoirs, with one chosen based on volume and the other on height, regulating the group chosen based on height would be a more effective way to manage the risks.

5.8.1.2 ASLL relationship with dam height

As described in section 2.1.8, this research has obtained ASLL values for a sample of 608 reservoirs analysed under the RFM project.

The impact of deregulating reservoirs over 25,000 m^3 on the basis of height is shown in Figure 25. It is noted that for any given dam height selected, new reservoirs would be regulated from the stock of reservoirs of volume lower than 25,000 m^3. These potentially newly regulated reservoirs are not shown in Figure 25 because such data is not available.

Figure 25: Reservoirs from the RFM sample that would be deregulated for different dam heights



Notes: Line = Median, Box = 25%ile and 75%ile, Whiskers = 5%ile and 95%ile, 10^{-5} nominally added to all ASLL values to show zero values on log scale

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

A key point to note is that even at lower heights of 2 m to 3 m, a significant number of high-risk reservoirs would be deregulated. This is considered unlikely to be acceptable, and it can therefore be concluded that there is little merit in changing the basis of regulation for dams over 25,000 m^3 unless there is also a change in the definition / interpretation of "high-risk".

5.8.1.3 Impact on number of registered reservoirs

Notwithstanding the above, it is informative to assess the impact of height based regulation on the population of "high-risk" reservoirs.

Changing the threshold above which reservoirs are regulated from a volume only threshold to a dam height only threshold would result in the deregulation of reservoirs that are below that height from the existing public register and the addition of new reservoirs that are below the 25,000 m^3 threshold but with a larger dam height. The research presented under section 5.6 indicates that height is a more risk-efficient way of regulating the population of reservoirs. Logically it then follows that providing the total number of regulated reservoirs were to remain approximately the same as it is now, and the height threshold is selected accordingly, the resulting risks to the public would be lower for the same regulatory cost. Table 22 provides an estimate for the total number of regulated reservoirs for a given dam height threshold.

Table 22: Change in total regulated reservoirs for a given dam height

Threshold	Reservoirs which would be deregulated	Additional Reservoirs which would be regulated*	Total Regulated Reservoirs
25,000 m^3 (as existing)	**0**	**0**	**2065**
1 m	3	1503	3565
2 m	59	1467	3473
3 m	211	1074	2928
4 m	454	608	2219
5 m	724	429	1770
6 m	993	215	1287
7 m	1230	143	978
8 m	1375	36	726
9 m	1485	36	616
10 m	1545	36	556

Notes: * for reservoirs above 10,000 m^3, estimated using data produced as part of Objective 2 (Mott MacDonald, 2018b)

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

"Reservoirs which would be deregulated" in Table 22 indicate the number of reservoirs that are currently on the public register based on their volume threshold, that would no longer be registered since they are below the dam height threshold.

"Additional Reservoirs which would be regulated" have been estimated using data from the desk-based Lidar study of water bodies in the north of England that was done as part of the Objective 2 report (Mott MacDonald, 2018b). This dataset identified 42 SRRs (10,000 m^3 to 25,000 m^3) in the north of England that were used as a representative sample for the estimated 1,503 SRRs in the whole of England. By analysing the dam heights of this sample, an estimate was made of the number of reservoirs that would be regulated from the total population if a dam height threshold was adopted. Therefore, there is much greater certainty on the number of reservoirs that would be deregulated against those that would be newly regulated.

It is noted that the change in proportion of "high-risk" reservoirs is not considered here. Under the current system about 90% of reservoirs could be "high-risk" and a more efficient way of selecting registered reservoirs would likely give rise to a modest increase in that proportion (assuming that the threshold for risk designation remains unchanged).

Although only of academic interest, it can be noted that the dam height which would result in the same number of reservoirs being regulated as at present is between 4 and 5 m.

Selection of a dam height would need to be based on risk to life to individuals and would come down to deciding a criterion for risk to life and commensurate dam height. At the conservative extreme this would be insignificant risk (as for LRRs). As shown in Figure 18 this could imply a dam height of less than 1 m but realistically a cut-off in the range of 1 m to 2 m is likely to be required to avoid regulating an impractical number of reservoirs. It must however be appreciated that this could be much more conservative (in terms of the number of dams regulated) than the current proposal of 10,000 m^3 which, although enshrined in legislation, is not believed to be based on any scientific rationale. If this approach were to be pursued, research would need to be commissioned to determine an appropriate height and to estimate the likely number of SRRs which would fall under the selected criteria.

Potential reservoirs are most readily identified from mapping which provides a surface area for the water body. If dams are to be regulated on the basis of height alone, this would potentially mean that all waterbodies would need to be investigated. This would be unrealistic and a practical way of limiting the search could be to adopt a minimum surface area criterion.

5.8.2 Criteria 2 - Combination of dam height and reservoir volume

The evidence presented so far as part of this task has shown that both height and volume determine the magnitude of dam failure consequences. This section considers the options for using a combination of height and volume for dam registration thresholds. The following are considered as threshold parameters for registration:

- Peak breach discharge (function of height and volume)
- Combination of height and volume threshold (both together triggers registration)
- Height threshold with a volume threshold safeguard (either triggers registration)

5.8.2.1 Peak breach discharge

Peak discharge due to dam failure as given by the breach equations is a function of dam height and reservoir volume (as well as geotechnical and other factors). The dam breach equations that are used to calculate peak discharge vary based on the type of dam. Regulation would be based on a specified peak discharge being exceeded.

In the regression analysis (see section 5.6.5) peak breach discharge showed the strongest correlation with ASLL, and therefore prioritising the regulation of reservoirs based on this parameter would increase the likelihood of the riskiest reservoirs being identified and would be the most efficient threshold system considered.

However, the estimation of peak discharge is based on empirical relationships which would be open to challenge. There is also no international precedent in the use of the breach equations for the regulation of reservoirs. This method is not therefore recommended.

5.8.2.2 Criteria combining height and volume threshold

There is international precedent for considering both height and volume to register reservoirs. For example, in New Zealand, reservoirs above 3 m and 20,000 m^3 need to be registered. However, this approach could lead to the deregulation of reservoirs which have one parameter which is very high while the other is below the threshold. Deregulation of these reservoirs would be risky as such dams would be likely to be of high consequence given that both height and volume have a positive correlation with consequence of failure.

5.8.2.3 Height threshold with volume threshold safeguard

Section 5.4 and section 5.6 demonstrated that while height has a stronger correlation to ASLL, volume was also correlated to ASLL and it was also possible for dams of low height and high volume to have a high ASLL. Therefore, if there were a wish to regulate by height rather than by volume, it would be prudent to include a volumetric ‘safeguard’ to ensure that such high-volume reservoirs are not deregulated. This is an approach consistent with international practice, in line with countries such and Finland, Norway and Austria.

In England, there are two approaches that could be used in choosing a volume threshold safeguard:

- Option 1 - Maintain the existing volumetric threshold of 25,000 m^3. This would in effect result in the regulation of SRRs based on height, without any impact on the population of LRRs. This option should be considered further if the objective is to bring the riskiest SRRs into regulation without the deregulation of any LRRs;
- Option 2 – Introduce a volumetric threshold to maintain regulation of high volume “high-risk” reservoirs below the height threshold. The volume selected would be dependent on the adopted height threshold. The approach would be to maintain regulation of a proportion of “high-risk” reservoirs which were below the height threshold and to recognise that the escape of a large volume could result in extensive flooding and environmental damage, road disruption etc. even if the risk to life is low by virtue of dam height.

5.9 Task 3 Summary

The purpose of this section is to review the appropriateness of the use of “volume” as the sole criteria for the definition of a reservoir under the English Act.

International practice was reviewed to understand how reservoirs are registered globally. Most countries use a combination of height and volume to determine the regulatory requirements that apply to reservoirs. The United Kingdom is the only country from the group that was analysed that uses volume alone to register reservoirs.

The dam failure incidents in the UK which resulted in loss of life were analysed. The size of the reservoir correlated with the loss of life due to its failure. Regression analysis showed that dam height was a stronger predictor of loss of life than reservoir volume.

An analysis of the English public register of reservoirs showed that larger dams are more likely to be “high-risk”. There was a clear height and volume threshold above which all reservoirs were “high-risk”, and any future change to the threshold would have to be below these values. Below these upper thresholds, there was significant overlap between “high-risk” and “not high-risk” reservoirs, which would make it difficult to choose a threshold for registration of a dam based on analysis of the public register alone.

Dam failure consequence data from the Reservoir Flood Mapping (RFM) study was analysed to derive further conclusions on the relationship between height, volume and consequence.

Regression models using dam characteristics to predict ASLL values were compared. Height showed a stronger correlation than volume, while peak discharge due to dam failure showed the strongest correlation. The order of strength of correlation with ASLL from strongest to weakest is:

1. Peak breach discharge - strongest
2. Height
3. Height x Volume
4. Volume - weakest

Based on the data available, peak breach discharge has the strongest correlation with dam break consequences. However, it has not been recommended as a differentiator due to the uncertainties of making an estimate based on an empirical relationship. There is also no known international practice for using breach discharge to select reservoirs for regulation.

Regulating reservoir by height rather than volume has clear merits, but would have the potential consequence of deregulating reservoirs which are currently high-risk. Such an approach is considered unlikely to be attractive unless combined with a change in the criteria for risk designation. However, there would clearly be merit in regulating SRRs by height rather than volume. If this approach were to be pursued, research would need to be commissioned to determine an appropriate height, based on an accepted level of risk to life, and to estimate the likely number of SRRs which would fall under the selected criteria.

If regulation by height were nevertheless to be considered for all reservoirs, there could be a benefit in also incorporating a volume threshold to ensure the continued regulation of existing “high-risk” reservoirs with high volumes.

This research is based on analysis of RFM data from ‘dry day’ dam break analysis only and the RFM project is still only about 30% complete. Upon completion of the RFM study the evidence presented in this report would benefit from an update based on the full set of data.

Any future research on this topic should give consideration to:

- Use of maximum hazard as a metric for measuring dam failure consequence
- Overcoming any general limitations in the RFM analysis methodology which are discussed in section 2.1.5
- Minimum height criteria for SRRs
- Estimation of number of SRRs based on minimum height criteria.

6 Task 4: Consider the case for further deregulation

6.1 Introduction

6.1.1 Background

The objective of this section is to consider the case for “not high-risk” designation or deregulation of certain types of reservoir.

6.1.1.1 “Not high-risk” designation

The driver for consideration of “not high-risk designation” is Section 2C of the English Act, which states the following:

> *2C (1) The appropriate agency may designate a large raised reservoir as a high-risk reservoir if:*
>
> *a) The appropriate agency thinks that, in the event of an uncontrolled release of water from the reservoir, human life could be endangered, and*
> *b) The reservoir does not satisfy the conditions (if any) specified in regulations made by the Minister*
>
> *2C (2) The conditions specified in regulations under Subsection(1b) may, in particular, include conditions as to:*
>
> *a) The purpose for which the reservoir is used*
> *b) The materials used to construct the reservoir*
> *c) The way in which the reservoir is constructed, and*
> *d) The maintenance of the reservoir*

It is important to note that this clause is related to risk designation. As such any new reservoir would require a Construction Engineer (under Section 7) and a risk designation would only come into force after the issue of the Final Certificate.

6.1.1.2 Deregulation

The driver for deregulation of reservoirs is Section A1 (8) of the Act which states the following:

> *The Minister may by regulation provide for specified things not to be treated as large raised reservoirs for the purposes of the Act*

These are currently defined in SI 2013 1896 as:

a) a mine lagoon
b) a quarry lagoon
c) a canal or other inland navigation
d) a road or railway embankment (with certain exclusions)

6.1.1.3 Comparison and approach taken

The differences between “not high-risk” reservoirs and deregulated reservoirs are:

- a structure which is of a type which is deregulated will not be registered under section 2(1) of the Act;
- a structure which is of a type which is deregulated will not require a Construction Engineer, or any of the other provisions of Sections 6 & 7 of the Act.

In contrast, a structure which is designated “not high-risk” will be registered and will require a Construction Engineer. It will remain on the public register and be subject to periodic risk status review under section 2D of the English Act. There are no formal mechanisms currently in place to review the status of any deregulated structures.

The approach taken in this report focuses first on the case for designating reservoirs as “not high-risk” as this is less onerous than full deregulation. If it is found that there are certain types of reservoir which merit a “not high-risk” designation, we would then investigate whether this should be extended to full deregulation.

6.1.2 Identification of reservoirs which could potentially be designated “not high-risk”

6.1.2.1 Consideration of the purpose for which a reservoir is used

No specific guidance is available on the interpretation of Section 2C (2) a). The “purpose for which a reservoir is used” does not necessarily impact on type of construction, and it is therefore conceivable that distinction on use could permit deregulation of any form of construction. In this situation is it difficult to see how reservoirs could have their “high-risk” designation revoked unless alternative legislation such as the Mines and Quarries Act prevailed.

A candidate for alternative legislation is the Water Supply (Water Quality) Regulations 2018 which puts drinking water quality under a monitoring regime regulated by the Drinking Water Inspectorate. In the context of service reservoirs this may mean that structural problems involving ingress from outside get picked up as water quality issues. It does not, however, seem rational to rely on monitoring to water quality to assure the structural safety of a reservoir.

At present no further candidates for “not high-risk” designation on the basis of use have been identified, and this option will not be considered further.

6.1.2.2 Consideration of materials, construction and maintenance

Although not explicitly stated in clauses 2C(2) b), c) and d), it is considered reasonable to interpret these clauses as applying to situations where the probability of failure of a reservoir, such as would result in an uncontrolled release of water, could reasonably be assessed to be below an acceptable threshold. On this basis, the following considerations would need to be addressed:

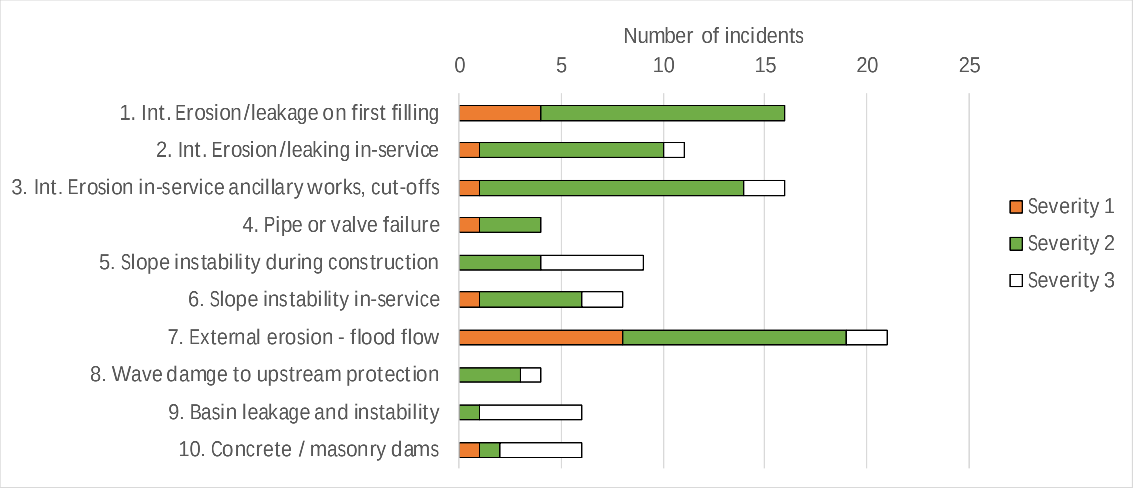
- How could the materials used, form of construction etc. be unambiguously defined?
- Would there need to be a limitation on size?
- If maintenance was a criterion for not designating a reservoir as “high-risk”, how could long term maintenance to an acceptable standard be guaranteed/monitored/verified if no inspections by panel engineers are undertaken?

There is no straightforward answer to the third bullet, and it is therefore difficult to see how a reservoir could be made “not high-risk” on the grounds of maintenance. This criterion will not therefore be pursued further.

To satisfy the first two bullets it would appear likely that a specific type of reservoir would need to be identified whereby there was a readily identifiable form of construction and the reservoir has a low risk of failure.

Figure 26 presents an analysis of incidents at UK reservoirs.

Figure 26: Distribution of incidents at reservoirs according to type and severity



Source: (CIRIA, 2014)

It is apparent that 63% of all incidents can be attributed to either overtopping in flood events or internal erosion.

It is therefore considered that any reservoir, irrespective of construction type, should not be treated as “not high-risk” on the basis of likelihood of failure where it is vulnerable to either overtopping in a flood event or internal erosion. On this basis a reservoir should not be treated as “not high-risk”, on the basis of likelihood of failure, where:

- it is an impounding structure with a risk of overtopping in extreme flood events;
- the design assumes some seepage, although potentially very low, through the structure or foundation with there being a possibility of internal erosion, heave or uplift.

Applying these criteria, the only plausible candidates for “not high-risk” designation are fully lined non-impounding reservoirs. These fall into two main categories:

- fully lined concrete service reservoirs;
- geomembrane lined farm dams.

Notwithstanding the above, it should be appreciated that reservoirs may still be not designated as “high-risk” on the basis of low consequences of failure.

6.1.2.3 Fully lined concrete service reservoirs

Fully lined concrete service reservoirs are a clear candidate subset for exclusion from the risk designation process and are discussed further in section 6.2.

6.1.2.4 Farm dams

Fully lined farm dams may meet the above criteria, but their typical form of construction is an earthfill embankment with a geomembrane liner. Such structures have two main vulnerabilities as follows:

- the liner is potentially vulnerable to damage;

- the structure as a whole is highly vulnerable to instability if it is overfilled (typically by uncontrolled pumping) and there is erosion of the embankments.

Given the above vulnerabilities it is not considered appropriate to exclude lined farm reservoirs from the risk designation process.

6.2 Research on service reservoirs

6.2.1 Numbers and types of service reservoirs

Statistics on service reservoirs, as extracted from the register of large raised reservoirs are presented in Table 23.

Table 23: Summary statistics on service reservoirs in the public register in England

	Service Reservoirs	All other reservoirs
Number of reservoirs	128	1937
Year of construction	Earliest: 1855 Median: 1971 Latest: 2013	Earliest: 1086 Median: 1914 Latest: 2017
Number constructed post 1976	41	540
Height	Min: 2.5 m Median: 6.3 m Max: 9.4 m	Min: 0.5 m Median: 5.9 m Max: 63.1 m
Volume	Min: 25 000 m^3 Median: 45 000 m^3 Max: 269 000 m^3	Min: 19 960 m^3 Median: 113 650 m^3 Max: 1.99×10^8 m^3
“High-risk”	115	1401
“Not high-risk”	0	237
No risk designation	13	299
Category A	31	611
Category B	13	273
Category C	12	390
Category D	4	219
No flood category	68	444

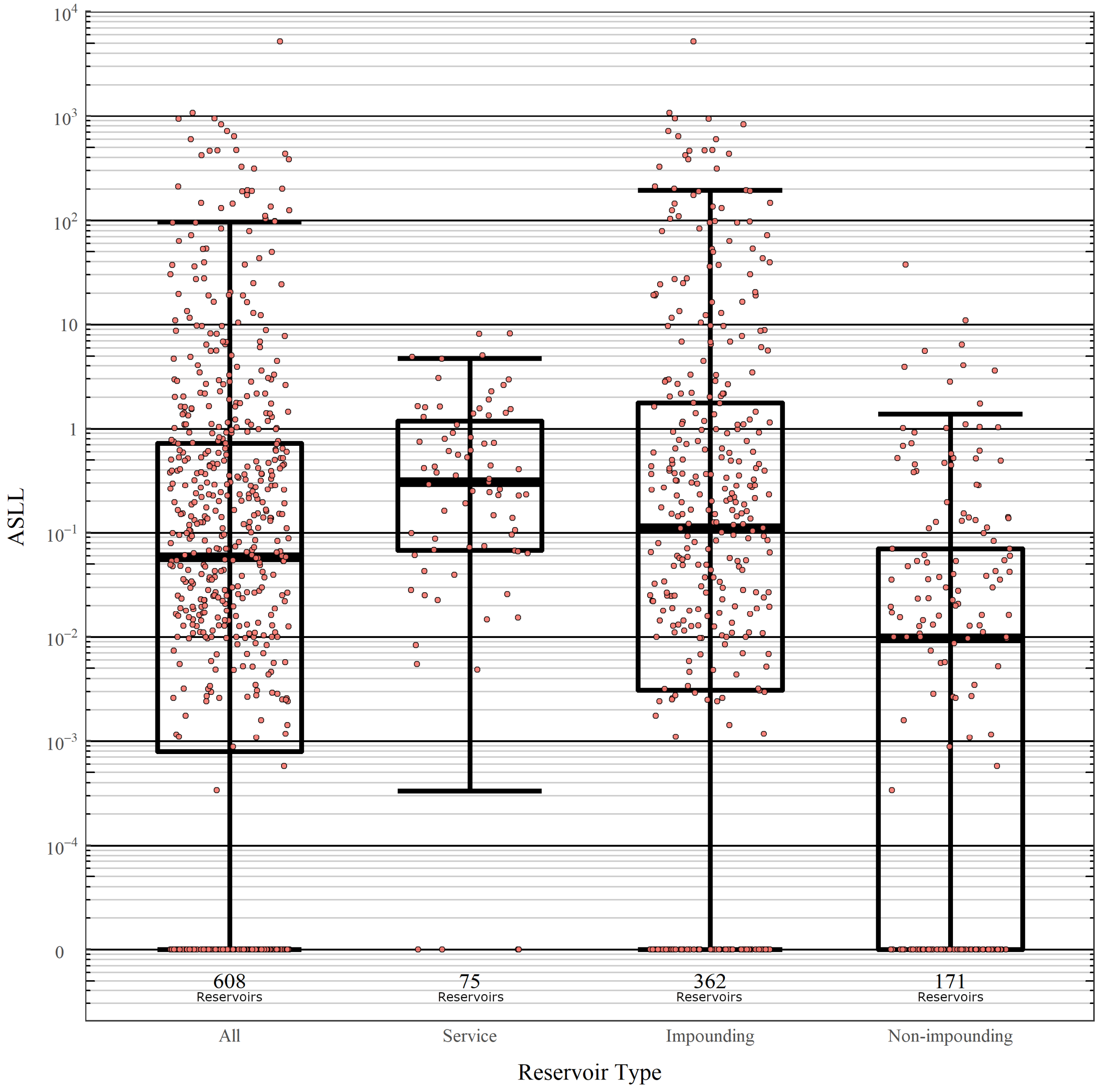
Notes: Population size = 2065 reservoirs
Source: (Environment Agency, 2019)

6.2.2 Hazard presented by service reservoirs

To further understand the failure consequences of service reservoirs, results from the RFM study introduced in 2 were analysed. The distribution of ASLL values for service reservoirs were compared to those of impounding and non-impounding (excluding service) reservoirs.

Figure 27 shows that the ASLL distribution for service reservoirs sits above the other categories. This demonstrates that services reservoirs present an elevated hazard compared to the overall UK population of reservoirs.

Figure 27: ASLL values of service, impounding and non-impounding reservoirs



Notes: Centreline = Median, Box = 25%ile and 75%ile, Whiskers = 5%ile and 95%ile, 10^{-5} nominally added to all ASLL values to show zero values on log scale

Source: Analysis by Mott MacDonald (2019) using RFM data provided by the EA (Environment Agency, 2019)

6.2.3 Records of incidents

A record of incidents at service reservoirs in England was tabulated and is presented in this section. In our literature search, we considered the following sources:

- CIRIA's Lessons from incidents at dams and reservoirs – an engineering guide

- Environment Agency's annual reports on the 'Post-incident reporting for reservoirs',
- Email correspondence and database search with structural-safety.org
- Internal discussions with service reservoir specialists
- General internet search

The following is a list of service reservoir incidents known to the authors:

- Mill Hill (1979) subsidence led to structural failure (CIRIA, 2014b) (Heslop & Millmore, 1988) (details in Table 24 below)
- Sheephouses (1962) roof failure due to high alumina content in cement (CIRIA, 2014b) (Neville, 2009)
  (details in Table 24 below)
- Dunsford Hill (1994) subsidence, successfully remediated (Hope, 2016) (details in Table 24 below)
- Barrow Hill (1965) roof failure (New Civil Engineer, 2019)
- Lanner Hill (1999) roof failure (Barhale, 2019) and (Research Gate, 2019)
- Sunnyhurst Reservoir (2016) nearby landslide (BBC, 2019)
- [Unnamed] (2006) subsidence likely due to sinkholes (Northumbrian Water Limited, 2019)
- [Unnamed] (2010) structural damage due to overfilling and pressurisation (Internal discussions, 2019)
- [Unnamed] (2017) water escaping through the roof vents caused instability of the surrounding embankments (Internal discussions, 2019)

Where the detail is known this is presented in Table 24 below. To the knowledge of the current authors, there has never been a failure of a service reservoir which has resulted in loss of life.

Table 24: Some Incidents at Service Reservoirs in England

	No. 1 Mill Hill Service Reservoir	Sheephouses Service Reservoir	Dunsford Hill Service Reservoir
Year of construction	1926	-	1994
Year of incident	1979	1962	1994 (during water test)
Construction	Mass concrete walls and reinforced concrete floor, roof, and columns. Divided into two compartments by a division wall.	-	-
Foundation	Drift deposits overlying Magnesium Limestone and Coal Measures.	-	Cut into a hillside over previously variably loaded ground
History	There was mining activity in the vicinity of the reservoir between 1929 and 1961. In 1978 an inspection was carried out under the Reservoirs (Safety Provisions) Act 1930 and replacement of the rubber lining was recommended. The Inspecting Engineer noted that "There was no apparent recent settlement of movement of the reservoir or surrounding land which might affect the stability of the structure."	-	-

	No. 1 Mill Hill Service Reservoir	**Sheephouses Service Reservoir**	**Dunsford Hill Service Reservoir**
Incident description	In 1979, within one week of commencement of the repairs “sudden subsidence occurred in the south-west corner of reservoir no. 1 and part of the structure collapsed. Within 2 hours reservoir no. 2 and the common division wall were also affected.”	-	“On first filling, the northern corner of the reservoir, where the shallowest excavation had occurred started to rotate outwards.”
Dam Height	6 m	-	-
Volume	110,000 m^3	-	20,000 m^3
Failure mode description	Mining caused widening of fissures in the Magnesium Limestone. Drift deposits migrated into the widened fissures leaving voids. The voids led to opening of movement joints and cracking to the walls, floor and roof. Leakage accelerated the migration of drift deposits into the limestone fissures. Voids enlarged. Repairs were carried out by grouting the voids and waterproofing the reservoir. Over time the waterproof lining deteriorated, and the situation worsened. “The loss of ground support caused the floor slab and column footings to collapse into the void rupturing the rubber lining and thus allowing the water to escape.” (Heslop & Millmore, 1988)	Reduction in strength of the high-alumina cement concrete in the pre-stressed concrete beam roof.	Assumed to be a bearing capacity failure.
Consequences	All of the water in the southern two compartments was released as well as the portion of storage held above the dividing wall between the southern and northern compartments. About 70,000 m^3 of water escaped in about six hours. All of the water drained into the underground strata and there was no sign of water at ground level following the incident. No threat to life or property. The structures were rebuilt away from the mining area.	The site of Sheephouses Reservoir is located in a remote location, involved no human activity and “excited little interest” (Neville, 2009)	Successfully remediated prior to commissioning.
References	(CIRIA, 2014b) (Heslop & Millmore, 1988)	(CIRIA, 2014b) (Neville, 2009)	(Hope, 2016)

Service Reservoirs in England have an excellent safety record; there has been no loss of life from service reservoir failures in the United Kingdom. Statistically: considering there have been a total of about 7,000 service-reservoir-years (Environment Agency, 2019) without loss of life there is evidence that the probability of loss of life from a service reservoir is likely to be less than 1 / 7 000 per service reservoir per year. This might be compared with the broader population of dams in England with a total number of reservoir-years of 208,522 (Environment Agency, 2019) with 315 lives lost (CIRIA, 2014b). This indicates a loss of life from reservoirs of all types in England of about 1 / 600 per reservoir per year. Since there has been no loss of life from reservoir failures in England since the Reservoir (Safety Provisions) Act 1930 came into force it may be more representative of present-day standards to consider statistics for the last 89 years which would be considerably less than 1 / 7,000 lives per reservoir per year. In addition to the test for societal risk, the RARS guide (Environment Agency, 2013a) gives an "individual risk limit" of 1 / 10,000 for any individual. This shows that there is insufficient historical data on service reservoir failures in England to provide evidence that the individual risk limit is satisfied for the sub-population of service reservoirs.

6.2.4 Review of inspection reports

As part of this research, a random sample of 25 Section 10 reports from service reservoirs were analysed. This information was provided confidentially. Key findings were as follows:

- 8 reservoirs were constructed during or after 1976, from which three do not have walls which require the support of the embankment. For the remaining five, it is assumed that the walls probably do not require the support of the embankment, but it is not specified.
- 17 reservoirs were constructed before 1976, from which seven have walls which require the support of the embankment, while three reservoirs do not. For the remaining seven reservoirs, it is assumed that they require the support of the embankment.
- 6 of the 25 reservoirs potentially had an overflow capacity which was less than the maximum inflow rate (with potential to pressurise the roof slab and exceed the design wall loads),
- Most service reservoirs are built on potentially erodible foundations
- 8 of the 25 reservoirs did not have underdrains

6.2.5 Review of legislation relating to service reservoirs

Table 25 below is adapted from *Ageing Service Reservoirs* (Hope, 2016) and provides a summary of legislation and governance for Service Reservoirs.

Table 25: Legislation and governance for Service Reservoirs

Criteria	Legislation / Process	Regulator / Overseeing Body
Water quality	Water Act 1945	Drinking Water Inspectorate
Safety	Health and Safety at Work etc. Act 1974	HSE
Security / resilience	Protection of National Infrastructure	CPNI / Defra
Protection against flooding	Reservoirs Act 1975	Environment Agency (England) NRW (Wales) SEPA (Scotland)
Emergency response to flooding	Civil Contingencies Act 2004	Local Resilience Forum
Funding	Asset Management Plans	Ofwat (economic regulator)
Customer Service	Continuity of supply	Ofwat (economic regulator)

Source: (Hope, 2016)

6.2.6 Summary

The research clearly demonstrates that there have been a significant number of incidents at service reservoirs, but there is no documented case of an actual, or imminent, uncontrolled large release of water from a reinforced concrete service reservoir constructed post-1978. That said there are reinforced concrete service reservoirs which have the potential to be overfilled and are founded on erodible foundations.

It is also notable that there is no other legislation which would ensure the safety of service reservoirs in the absence of the application of the English Act.

6.3 Appraisal of reinforced concrete service reservoirs

6.3.1 Introduction

Reinforced concrete service reservoirs are known to date back to the early 1900s (UK Water Industry Research Limited, 2017). Early examples are likely to have walls which are partially supported by external fill placed around the side of the reservoir.

The improvement in structural standards for water-retaining structures can be traced through the codes pertaining to the time.

Code of Practice for the Design and Construction of Reinforced-Concrete Structures for the storage of Liquids: 1938 (covered 1938 to 1960), clause 311(d) stated:

> "Earth Pressures. Where a reservoir wall is built in the ground or has earth embanked against it some deduction from the resultant loading on the wall may be made on this account, provided that:
>
>> (i) there is no risk of slip in the embankment or fear of a reduction in the earth pressure arising from shrinkage or other cause;
>>
>> (ii) the pressure allowed by way of a deduction shall be the minimum which can be relied upon under the most unfavourable conditions."

CP 2007:1960 (covered 1960 to 1976), clause 312(c) was slightly different to the above, stated:

> "Earth Pressures. Where a reservoir wall is built in the ground or has earth embanked against it some deduction from the resultant loading on the wall may be made on this account, provided that:
>
>> (i) there is no risk of slip in the embankment or fear of a reduction in the earth pressure arising from shrinkage or other cause;
>>
>> (ii) due consideration is given to the most unfavourable conditions possible, including the conditions under which the reservoir is to be tested for watertightness."

BS 5337:1976 (covered 1976 to 1987), clause 4.2 stated:

> "Allowance should be made for any active soil pressure on walls, but no relief should be given for any passive soil pressure on a wall on the face remote from a contained liquid."

BS 8007:1987 (1987 to 2010), clause 3.2 stated:

> "No relief should be given for beneficial soil pressure effects on the walls of containment structures in the full condition."

Successive codes generally became more stringent on the issue of resistance from the external soil, and from 1976 onwards the codes clearly did not permit any benefit from backfill material.

Since the introduction of the CESWI specification in 1978, there has been a requirement to test reservoirs prior to placing any fill against the outer wall faces. This effectively means that the fill, if present, will not be relied upon for support to the walls.

Since around 2000 there has been a move to using semi-precast construction, but this has not materially affected the form of the structures.

The stated minimum asset lives for reinforced concrete service reservoirs is 60 years, with first maintenance likely to be due after 25 years (UK Water Industry Research Limited, 2017).

6.3.2 Failure modes

Potential failure modes for reinforced concrete service reservoirs as identified in risk designation (Environment Agency, 2013b) are as follows:

For reinforced concrete service reservoirs which rely on external embankment for support of walls:

- Over-pumping leading to overspilling, followed by erosion of external embankments;
- Over-pumping leading to overspilling, followed by erosion of external embankments and foundation instability;
- Leakage leading to erosion of external embankments;
- Leakage leading to foundation instability;
- Pipe burst leading to erosion of external embankments;
- Pipe burst leading to foundation instability;
- Structural failure through deterioration;
- Foundation instability through subsidence.

For reinforced concrete service reservoirs which do not rely on external embankment for support of walls:

- Over-pumping leading to overspilling, followed by erosion of external embankments and foundation instability;
- Leakage leading to foundation instability;
- Pipe burst leading to foundation instability;
- Structural failure through deterioration;
- Foundation instability through subsidence.

Overspilling may occur if the inflow to a reservoir is greater than the overflow capacity at a time when the reservoir is full. There are known to be reservoirs where overspilling is possible and the safety of the reservoir relies of adherence to operational procedures and alarm systems. Depending on the construction of the reservoir, the overspill could either pass through openings in the roof, or in extreme cases it could cause failure of the wall / roof joint or column/roof/base connections.

Clearly there must be an elevated risk of failure for reinforced concrete service reservoirs which rely on external embankments for the support of the walls. Such structures are vulnerable to seepage or overflowing which could destabilise the embankments and remove / reduce the support to the walls. This opinion is supported by a bulletin on ‘Over-pumping of Service Reservoirs’ (Environment Agency, 2017b) which documents an over-pumping incident at a non-statutory service reservoir. It is concluded that reinforced concrete service reservoirs which rely on external earth pressure for the support of the walls should not be excluded from risk designation.

There is a stronger case for excluding reinforced concrete service reservoirs which do not rely on external embankments from risk designation. However, these still have credible failure mechanisms and are certainly likely to deteriorate structurally towards the end of their design lives. That said, it has to be accepted that in order for any failure mechanism to be critical, it has to lead to a progression of events which could result in an uncontrolled large release of water. This is perhaps hard to envisage: there would need to be an event where there was sufficient undermining of the wall foundations to cause catastrophic failure of one or more wall panels. Overall the likelihood of catastrophic failure, resulting in an uncontrolled large release of water, appears to be very low, but cannot be ruled out entirely.

6.4 Industry engagement

6.4.1 Introduction

As part of this research a questionnaire was sent to six of the major English water companies to solicit attitudes on potential exclusion of service reservoirs from risk designation. The questions asked were:

1. Would you support the deregulation *(“not high-risk” designation)* of some types of service reservoirs through exemption from the ambit of the Reservoirs Act 1975?
2. We would be grateful to hear about the most significant risks to reservoir safety that you have experienced while working with service reservoirs. This may relate to a certain failure mode or to a specific incident, either through descriptions or through reference to another source
3. Are there any specific types of service reservoir which you consider should, or should not, be deregulated in terms of:
    a. Materials? If so, which?
    b. Construction methods? If so, which?
    c. Other aspect? If so, which?

6.4.2 Summary of responses

6.4.2.1 Question 1

The responses to Question 1 (Would you support the deregulation of some types of service reservoirs through exemption from the ambit of the Reservoirs Act 1975?) were:

Unreserved support	2
Support subject to consideration of hazard	1
Neutral	1
Against	2

6.4.2.2 Question 2

The responses to question 2 (We would be grateful to hear about the most significant risks to reservoir safety that you have experienced while working with service reservoirs. This may relate to a certain failure mode or to a specific incident, either through descriptions or through reference to another source) identified the following issues:

- failure of pipework causing erosion of embankments / foundations
- over-pumping with inadequate overflow capacity (failure of control systems)
- embankment instability where the embankment supports brickwork of mass concrete walls
- leakage through foundation of brick reservoirs

6.4.2.3 Question 3

The six responses to Question 3 (Are there any specific types of service reservoir which you consider should, or should not, be deregulated in terms of materials, construction methods etc.) are summarised as follows:

- no service reservoirs should be deregulated (no reasons given)
- service reservoirs constructed post 1974 should be deregulated
- no service reservoirs should be deregulated because, irrespective of construction type, they can deteriorate over time and inflow rates may be changed
- service reservoirs which rely on surrounding fill for structural support should be regulated
- some service reservoirs could possibly be deregulated, but due to uncertainties over design nuances, foundation conditions and quality of construction, it would be difficult to exempt any particular type of reservoir
- modern reinforced concrete reservoirs should be deregulated

These responses are broadly consistent with the responses to Question 1.

6.4.3 Summary of findings

Overall this survey confirms the finding that reinforced concrete service reservoirs constructed post-1976 are the most credible candidate for deregulation, but there is no consensus for pursuing exclusion from the risk designation process.

It is noted that DWI requirements result in reservoirs being inspected at a similar frequency to that required by the Reservoir Act, but this is not considered to be sufficient grounds for deregulation.

6.5 Task 4 Summary

The finding of this research is that the only generic type of reservoirs which are potentially candidates for exclusion from risk designation under Clause 2C (2) are reinforced concrete service reservoirs constructed post-1976. Such structures are likely to have a lower probability of failure than other types of dam because they are:

- non-impounding and therefore not vulnerable to overtopping in extreme flood events;
- completely lined with reinforced concrete and therefore less vulnerable to seepage / erosion;
- internally stable and not reliant on potentially erodible embankments for support to the walls.

That said, reinforced concrete service reservoirs constructed post 1976 can still have vulnerabilities which mean they could present an unacceptable probability of failure. These include:

- loss of stability of foundations through erosion caused by over-pumping if overflow provision is inadequate and alarm systems fail to operate;
- loss of stability of foundation caused by a pipe burst;
- deterioration of the structure over time (potentially more applicable as structures approach the end of their design life).

Given the lack of surety that all reinforced concrete service reservoirs constructed post 1976 present an insignificant risk of failure it is recommended not to pursue risk designation exclusion for this type of reservoir. This opinion is supported by engagement with six major water companies which did not find there to be any consensus on this matter. By extension, there is also no case for deregulation under Section A1 (8) of the Act.

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Appendices

A. Extract from “Guidance for a new risk-based approach” (Halcrow, 2008)

Country	Details of statutory reservoir definition
Australia	Each state applies different risk-based criteria. New South Wales: A consequence-based regulatory approach has recently been endorsed by the State government, largely based on the population at risk. http://www.damsafety.nsw.gov.au/Policy/PolicyFramework.pdf Queensland: All referable dams subject to legislation. A dam is referable if failure impact assessment shows that there will be a population at risk (PAR) in the event of dam failure. In certain circumstances regulator can insist on impact assessment for smaller dams. PAR 2-100 = category 1, PAR 100+ = category 2. ANCOLD guidelines on ‘referable dams’: **>10m and >20,000m^3 or >5m and >50,000m^3**. Dam safety programmes should take into account capacity, category, risk and value of dam to owner. Tasmania requires dam owners to have permits unless the reservoir is not on a watercourse (off-line) and is less than **1,000m^3**.
Austria	Dams **>30m or >500,000m^3**, dams on the Danube or dams that could affect other countries subject to Federal guidelines. Other dams have provincial or district legislation.
Canada	Classified according to consequence of failure, physical characteristics of dam and probability of failure. This determines level of surveillance. British Columbia & Quebec: All dams **>1m and >1,000,000m^3 or >2.5m and >300,000m^3 or >7.5m**. Provision to apply regulations to **low capacity dams if high or very high consequence.**
Finland	**All dams >3m** and those **<3m if** volume impounded so large or substance impounded is such that in the event of accident it would **endanger life or property**.
France	Committee supervises all dams >20m. Frequency of surveillance on filling is linked to height of dam. Dams **>12m and 15,000,000m^3 must have emergency plans.**

Country	**Details of statutory reservoir definition**
India	All large dams regulated. Large dams defined as **>15m or 10-15m high and crest length greater than 500m or capacity >1,000,000m^3 or maximum discharge >2,000m^3/s** or the dam has special foundation problems. All technical documents are filed with a state Dam Safety Organisation which has the power to conduct investigations, arrange for independent safety reviews and pursue any remedial actions.
Latvia	Classified at design stage. Class A – endanger life & health or seriously damage environment. Class B – do not endanger life or health but would damage property or environment. Class C – do not endanger life or health, minor damage to property or environment.
New Zealand	Building consent required for all dams **>3m and >20,000m^3**. Permits are only issued if dam complies with Building Code.
Norway	3 categories of dam based on **consequence of failure** which is determined by number of dwelling units affected by dam failure. Category 3 is the highest hazard. Regulations apply to **category 2 and 3 dams >4m high or >500,000m^3 and category 1 dams >6m high or greater than 500,000m^3.**
Portugal	2 categories. First category – high dams >**15m and >1,000,000m^3 or pose a risk to life and economic concerns**. Second category – small dams and those that don't meet the criteria. Dams also classified according to hazard and performance characteristics.
Romania	All dams **>10m and 10,000,000m^3 and with inhabitants closer than 10km** must have an emergency plan.
South Africa	Classed on **size** (dam height) and **hazard potential** (based on potential loss of life & economic loss) into 3 categories. Higher category, size and hazard, the more the regulation. Keep a register of dams that pose a safety risk which are defined as those **>5m and >50,000m^3 or pose a risk to life and property.**
Spain	Dams classed according to **size, potential risk and form of construction**. Classed as large dam and subject to regulation if **>15m high or 10-15m, crest length >500m and capacity >1,000,000m^3 or discharge capacity >200m^3/s**. Small dams with special features may also be covered. 3 categories: Category A – loss of life and serious environmental and material damage; Category B – loss of life and important environmental and material damage;

Country	Details of statutory reservoir definition
	Category C – incidental loss of life and moderate material and environmental damage.
Switzerland	**All dams >10m high or >5m and >50,000m^3 regulated**. Other dams with specific safety concerns also regulated. Federal regulation covers dams >25m high or >15m and >50,000m3 or >10m and >1,000,000m3 or >500,000m3. Smaller dams supervised by cantons.
USA	Dams **>25ft (7.62m) high and 50 acre-ft (61,674m^3)** subject to Federal regulation. State regulation for smaller dams based on hazard, size and condition, which determines inspection frequency.