Department for Environment Food & Rural Affairs

Provision of Evidence on the Number of Small Raised Reservoirs in England and the Risk they Pose

FD2701 – Objective 2

March 2020

Llywodraeth Cymru Welsh Government

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Joint Flood and Coastal Erosion Risk Management
Research and Development Programme

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

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Objective 2 report - FD2701

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This is a report of research carried out by Mott Macdonald, on behalf of the Department for Environment, Food and Rural Affairs

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Executive summary

The scope of this report is to address Objective 2 of the Small Raised Reservoirs (SRR) Research Project. The report is split into separate chapters which are addressed individually below.

Number of small raised reservoirs

Within this research project small raised reservoirs are defined as reservoirs with raised volume in the range of 10,000 m^3 to 25,000 m^3. The number of small raised reservoirs in England has been reassessed based on an existing GIS dataset of water bodies and a desk study using Lidar data of 500 water bodies in the north of England. The approach taken was to estimate reservoir volumes for the sample based on reservoir surface area and dam height. This allowed a distribution of probability of raised volume within the required range (10,000 to 25,000 m^3) against surface area to be developed. It was then possible to estimate the total number of SRRs in England by applying the probability distribution to the full population of water bodies. Allowances were also made for flood storage reservoirs and service reservoirs which would not have been included in the GIS dataset.

It is estimated that there are 1,503 SRRs in England. A Monte Carlo analysis has been undertaken to assess the potential variation in the result. It is estimated with 95% confidence that the number of SRRs in England will be in the range of 1,204 to 1,861.

The value compares with a number of 1,186 from previous research. The reasons for the increase are:

- a change to the methodology has identified that SRRs exist across a much wider range of surface areas than previously considered
- the previous research appears to have underestimated the number of service reservoirs and flood storage reservoirs

Number of High Risk SRRs

The risk designation of SRRs has been assessed by undertaking “dry day” breach assessments on a sample of 50 SRRs. A trend has been identified where the percentage of reservoirs which would be designated “high risk” varies for upland and lowland reservoirs. Overall, it is estimated that, using the methodology adopted for this study, 34% of SRRs (i.e. 511 SRRs) would be high risk. The likely variation in this value for 95% confidence is 306 to 754.

SRRs in cascade

A significant proportion of this research was focused on developing a definition for cascade reservoirs. It was agreed within the project team that reservoirs on the same watercourse should only be considered as cascade reservoirs where the hazard presented by the cascade failure would be likely to be greater than that posed by high hazard individual reservoirs. On this basis the following criteria for pairs of cascade reservoirs were adopted (note that all criteria must apply in order to be defined as cascade):

- minimum volume of either reservoir to be 15,000 m^3 (i.e. combined volume of at least 30,000 m^3)
- maximum separation of reservoirs to be 5 km
- maximum surface area of downstream Large Raised Reservoir to be 50,000 m^2

- arrangement with upstream Large Raised Reservoirs not to be included in study

The same sample of 500 water bodies as used for identifying individual SRRs was used to identify SRRs in cascade. The findings from the sample were then extrapolated to the rest of England. It was concluded there are likely to be up to 86 SRR-SRR cascades and 45 SRR-LRR cascades in England. Of these it was estimated that up to 31 and 40 of the SRR-SRR and SRR-LRR cascades respectively could be “high risk”.

It should also be noted that an unregulated SRR can increase the probability of failure of a downstream reservoir in cascade. This does not however impact on risk designation because risk is currently based only on hazard only and does not take account of probability of failure.

Summary of number of reservoirs

Table 1: Key Findings

	Number in England	
	Most likely	**Range**
Water Bodies		
Water bodies with surface area between 3,000 and 50,000m^2	22,000	Not analysed
SRRs (including cascades of SRRs)		
SRRs	1,503	1,204 to 1,861
High risk SRRs	511	306 to 754
Cascades (excludes singular SRRs)		
SRR-SRR cascades[1]	29	1 to 86
High risk SRR-SRR cascades[1]	10	0 to 31
SRR-LRR cascades[1]	7	0 to 45
High risk SRR-LRR cascades[1]	6	0 to 40

Note 1. These are cascades under the restrictive definition adopted for this project. There will be a much greater number of occurrences of reservoirs on the same watercourse where the cascade definition is not restricted by considerations of volume, surface area and separation.

Findings of visits to SRRs

Site visits were made to 65 water bodies identified from the GIS dataset which were potentially SRRs. Of these 65 water bodies, 39 were confirmed to be SRRs. The reported condition of the SRRs was as follows:

- poor - 21%
- satisfactory – 56%
- good – 23%

Note that overall condition is an indicator of the level of maintenance at the site (i.e. coverage of the grass on embankments, the management of trees and/or mammal burrows in the embankment and the general condition of any structures) as opposed to the extent of remedial works required.

It was further estimated that around 70% of the SRRs would be likely to require some enhancement of spillway capacity if they were to be designated “high risk”.

Type and Ownership of SRRs

It is estimated that 61% of SRR are in private ownership, 29% are owned by water and sewerage companies and the remaining 10% are owned by a combination of public bodies, businesses and leisure facilities.

Benefits and costs of regulating SRRs

The benefits of regulating SRRs cannot be assessed in detail without knowledge of the reduction in probability of failure which would result from regulation. This could be a subject for further research. A high level estimation of quantified benefits has been undertaken based on the assumption that the probability of failure (POF) will decrease from 1 in 5,000 to 1 in 50,000 (per year) if an SRR becomes regulated.

The benefits of regulating SRRs have been calculated on the basis of damages derived from dam break assessments. Based on the sample of 40 SRRs that were modelled, the average "Average Societal Loss of Life" (ASLL) is estimated to be 0.012 and assuming that the POF is 1 / 5,000 for an unregulated SRR, which (considering that there are estimated to be 1,503 SRRs), implies a statistical loss of life from SRRs in England of about 0.0036 persons per year. This low theoretical loss of life aligns with the fact than no lives have been lost through the failure of SRRs in England in more than 100 years.

This analysis gives an estimated benefit of regulating all SRRs as follows:

- recurring annual benefit (all SRRs) = £22,300

If only cascade SRRs, as defined for this project, were to be regulated the estimated benefit would be:

- recurring annual benefit (cascades only) = £540

Costs have not been considered for the "Do Nothing" option, and although not easily quantifiable, there is a cost associated with having different laws and regulations in England, to other parts of the UK. Consistent laws and regulations can give rise to streamlined approaches, research efficiencies, common training and better understanding of the requirements for all stakeholders.

The estimated costs of regulating all SRRs, based on the best estimate number of SRRs, are:

- capital cost - £14.5 million
- recurring annual cost – £6.2 million

If only Cascade SRRs, as defined for this project, were to be regulated the estimated cost would be:

- capital cost - £0.5 million
- recurring annual cost – £0.2 million

It should be noted that:

- a full cost-benefit analysis has not been undertaken;
- guidance (Environment Agency; 2013c) supports justifiable costs up to 10 times higher than benefits by applying a Proportion Factor (PF) to account for errors and to ensure a robustly conservative approach. In this case, estimated costs are more than 100 times higher than estimated benefits, therefore application of PF would not tip the balance on the basis of this research.

1 Introduction

This report is the final deliverable for Aim 2 (Stage 1) of the Defra research project entitled *Applying a Risk-based Approach and Improving the Evidence Base Related to Small Raised Reservoirs* (FD2701).

1.1 Project Background

Since the 1980s reservoir safety in Great Britain (England, Scotland and Wales) has been legislated by the Reservoirs Act 1975 (the 1975 Act) 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 by Schedule 4 of the Flood and Water Management Act 2010 (FWMA 2010). This report is concerned with two of the provisions of FWMA 2010 which have still to be enacted for reservoirs in England. These are:

- clause A1(3) which makes provision for the threshold volume for a Large Raised Reservoir to be reduced from 25,000 m^3 to 10,000 m^3
- clause A1(5) which makes provision for "*a structure or area to be treated as "large" by reason of proximity to, or actual communication with, another structure or area*".

1.2 Purpose of this report

The purpose of this report is to provide evidence to inform decisions on whether provisions of the FWMA 2010 which have not yet been enacted should be brought into force. The report will consider Defra's aims, objectives and research questions, which are repeated verbatim in italics (as taken from the terms of reference) below:

1.2.1 Aim

To provide evidence on the number of small raised reservoirs (SRRs) between 10,000 m^3 and 25,000 m^3 and crucially the level of risk SRRs pose in order to consider a decision on implementing Phase 2 of Reservoir Safety Regulations.

1.2.2 Objective

Provide evidence on the number of SRRs and risk they pose, including those in cascade to enable Defra to carry out an Impact Assessment related to introducing legislation for SRRs between 10,000 m^3 and 25,000 m^3.

1.2.3 Research Questions (Items 1 & 2 covered in Mott MacDonald; 2018a)

3. *To refine evidence on the number of smaller reservoirs between a capacity of 10,000 m^3 and 25,000 m^3. This should include:*
    - *the number of reservoirs between 10,000 m^3 and 25,000 m^3. Is the current assessment of between 1,150 and 1,300 correct?*
    - *the location of reservoirs between 10,000 m^3 and 25,000 m^3*
    - *confirmation of the condition, construction type and materials of a representative sample number of smaller reservoirs.*

- *number of different types of reservoir (e.g. service reservoirs, concrete, earth embankments, reservoirs in cascade).*
- *ownership and undertakers of these smaller reservoirs between 10,000 m^3 and 25,000 m^3 and what sectors are represented (e.g. farmers, country estates, local authorities, etc.)?*

4. *Based on site visits, assess the risk of a representative sample of SRRs in the study areas using the current risk methodology and report on the number that would be "high risk". This should focus on the risk they pose to human life and infrastructure. This assessment could also include the following:*
   - *an estimate of the population at risk.*
   - *Likely Loss of Life.*
5. *To provide evidence on whether cascade reservoirs pose an elevated risk and should therefore be regulated. A number of reservoirs in cascade should be included in the sample above and assessment should include:*
   - *what are the benefits (e.g. reduction in loss of life) of bringing cascades into regulation?*
   - *estimate the current risk and how regulation would reduce the risk to life.*
6. *What will the impact of regulating SRRs be on:*
   - *regulatory authority?*
   - *reservoir undertakers?*
7. *What will be the cost of compliance per reservoir?*

1.3 Revisions to project scope

Due to the nature of the research project the scope was refined as the project progressed. The key documents / events which have defined the scope changes are:

- Inception Meeting (22/03/2017);
- Advisory Group Meetings (29/09/2017, 02/02/2018);
- Technical Notes on the research approach
  - Planning Site Visits (15/08/2017)
  - Review of the number of SRRs data available (01/12/2017)
  - Cascade Reservoirs: Approach (10/04/2018)
  - Reservoirs in cascade: Summary of analysis of first 200 water bodies (27/04/2018)

The impacts of these events / documents are set out in more detail in Appendix E.

1.4 Methodology

This research project has considered both a review / reappraisal of previous research and new research in specific areas. The new research which has been undertaken is as follows:

- visits to 65 water bodies which were potentially SRRs
- desk / Lidar study of 500 water bodies with surface areas in the range 5,000 to 25,000 m^2 in the north of England to establish dam heights and estimate reservoir volumes[1]. Development

[1] There is a risk that regional variations in reservoirs can lead to inaccuracies when this data is extrapolated to make assumptions about all reservoirs in the UK, however this area was chosen by the working group because it was known to contain a higher proportion of cascade reservoirs and reservoirs at both high and low elevations, both of which were required for this study.

of a probabilistic method to determine the likelihood of a water body of a specific size being an SRR:

- extrapolation of the research to develop a revised estimate on the number of SSRs in England
- dam breach modelling of 40 SRRs using the RFM 2016 "dry day" scenario to inform risk designation
- extrapolation of the research to develop a revised estimate on the number of "high risk" SSRs in England
- undertaking a sensitivity study to establish criteria for considering reservoirs to be in cascade
- assessment of the number of cascade reservoirs in a sample of 500 water bodies with surface areas in the range 5,000 to 25,000 m^2 in the north of England
- extrapolation of the research to develop an estimate on the number of "high risk" cascade SSRs in England

1.5 Structure of this Report

The structure of this report is as follows:

1. Introduction (this section)
2. Number of SRRs
3. Number of "High Risk" SRRs
4. SRRs in Cascade
5. Findings of visits to SRRs
6. Type and Ownership of SRRs
7. Benefits and costs of regulating SRRs
8. Discussion and conclusions

The sources of data identified in section 1.4 were used throughout the report depending on their suitability in deriving conclusions for that particular section.

The Glossary of Terms, References and Appendices can be found at the end of the report. Supporting technical information forms the appendices to this report. Appendix E covers the timeline of the project demonstrating the development of the research approach.

2 Number of SRRs

2.1 Introduction

The objective of this section is to develop a refined estimate of the likely number of SRRs located in England.

2.2 Previous estimates of the number of SRRs

2.2.1 Introduction to the previous research

Regional research studies, into the number of SRRs and more specifically the proportion that might be "high risk", have been commissioned by the Environment Agency since 2005. A consolidated report on the previous studies was prepared by Halcrow in 2013 (Halcrow; 2013).

The starting point for the studies was an automated GIS search for water bodies which interrogated the water layer from OS mapping. From this initial list of water bodies, a proportion were then considered further through desk studies, site visits and consultations.

The key statistics for the research relating to England were:

- **11,200** water bodies detected in England with surface area between **5,000 and 25,000 m^2**;
- **4,341** of which have a surface area between **10,000 and 25,000 m^2**;
- **1,466** of which were considered as part of a **high level desk study**;
- More than 100 of which were further considered through **site visits and/or consultations**.
- The 1,466 reservoirs considered in the high level desk study were distributed as follows:
  - Midlands - 908
  - South-west (Wessex) - 144
  - Anglian Central - 414
- **341** out of 1,466 water bodies were considered to be "raised" (as opposed to "undetermined" or "not raised")
- The outcomes of these studies are summarised in the following sections 2.2.2, 2.2.3, and 2.2.3. Figure 1, below, shows the locations of water bodies (green dots) which were assessed as part of a high level desk study under the previous research.

Figure 1: Previous Research Sample Study Areas

Source: Graphic by Mott MacDonald
Data from Halcrow; 2013

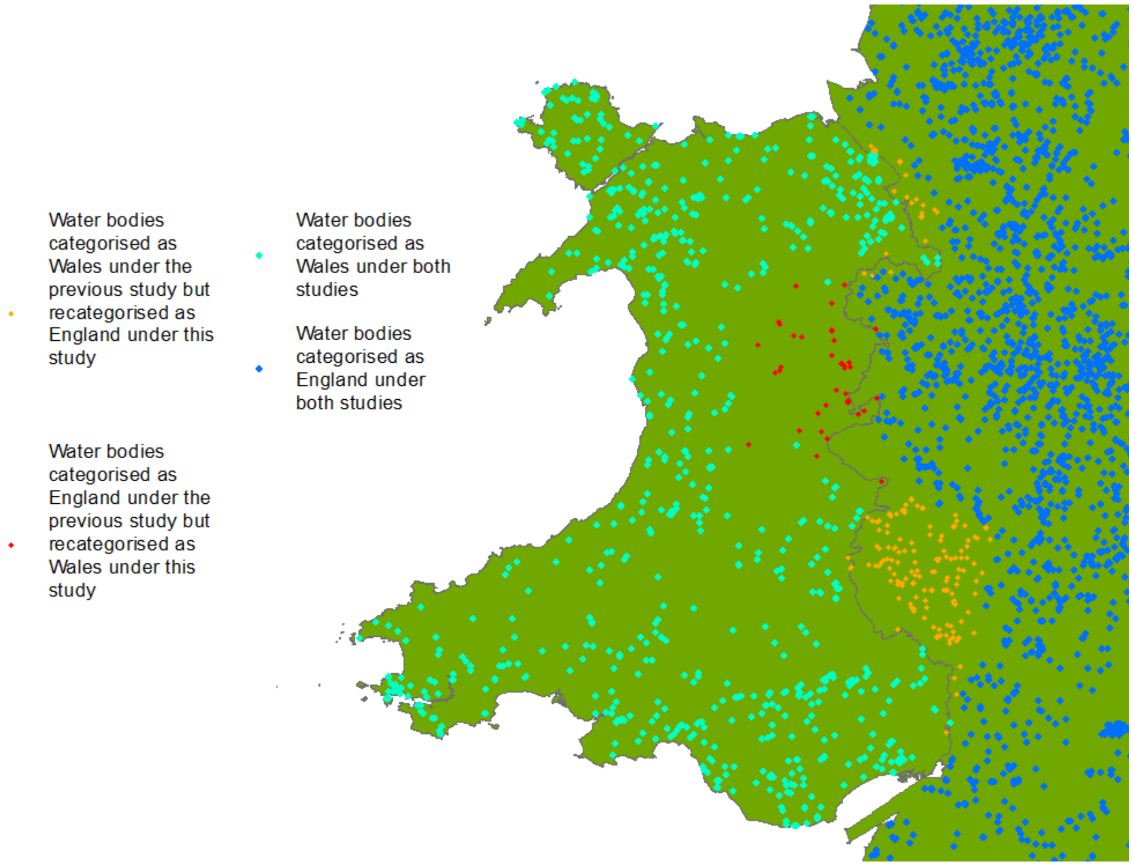
2.2.2 Water body database

The updated 2013 study used a database of water bodies across England and Wales which was identified automatically using GIS-based software which interrogated the Ordnance Survey water layers (Halcrow; 2009a) for water bodies with surface area between 5,000 m^2 and 25,000 m^2. Refer to Halcrow; 2009a and Halcrow; 2013 for more detail on the development of the water body database. Halcrow reported in the same study that their search algorithm was an improved version following the initial search carried out by ESRI. The new algorithm produced by Halcrow made improvements to differentiate between river widenings and online reservoirs (Halcrow; 2013). The water body database described here is the starting point for all subsequent estimates described in this report.

Current Mott MacDonald staff have experience using the search algorithm, including development of the algorithm and use of the database to review more than 2,000 water bodies in England and Wales. Based on this experience, including ground truthing checks carried out under the previous research, Mott MacDonald considers that the search algorithm is relatively robust. It has not been found to miss any reservoirs (other than those outside of the target surface area band) and tends to identify river widenings even where they are only created by small weirs. As such, the only significant limitation with the GIS search is that it is limited to a surface area band of 5,000 m^2 to 25,000 m^2. The algorithm does not differentiate between water bodies which are, or are not, raised and therefore detects both types of water body. It is also limited to visible water bodies, i.e. not flood storage reservoirs which are often dry, nor covered reservoirs such as service reservoirs. Other reservoirs that may not be identified include sludge or other process lagoons, or reservoirs that are ‘redundant’ or not currently filled.

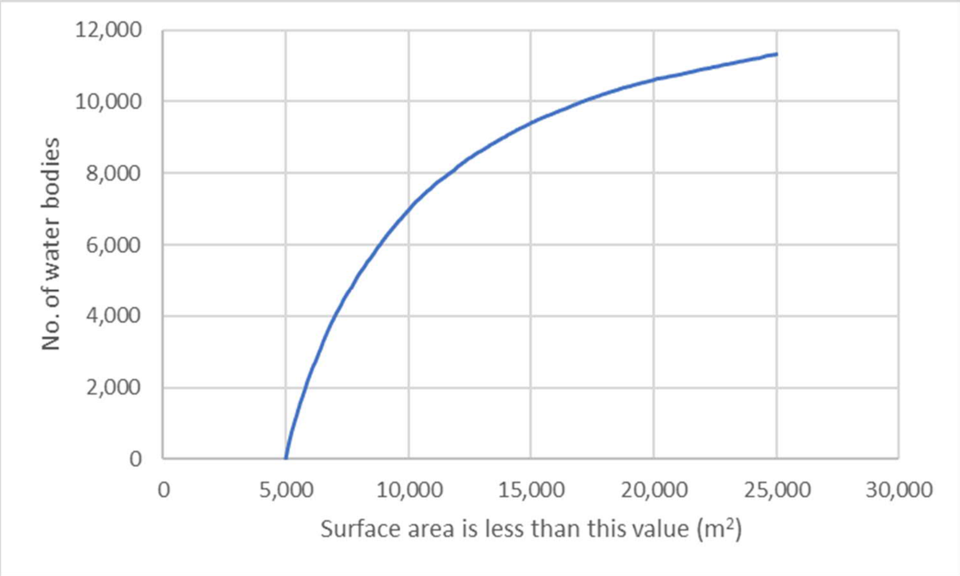
An error was identified in the division between the water bodies in England and Wales. This error was due to the disagreement between the border of Wales geographically and the border of the Welsh and English regions used under the previous research. This difference is illustrated in Figure 2. The impact is an increase in the estimation of the number of water bodies in England of about 1%, but no overall change for England and Wales together. This error was corrected prior to use of the data under this research project.

Figure 2: Correction of the representation of the England-Wales border



The results of the search, in terms of surface area, are shown in Figure 3 below. A total of 11,200 water bodies were identified (prior to the correction of the England-Wales border as described above) with a surface area in the range 5,000 to 25,000 m^2. Following correction of the England-Wales border that number rose to 11,334.

Figure 3: Number of water bodies in England with a surface area between 5,000 m² and 25,000 m² as analysed in the 2013 Halcrow study



Source: Data from the Halcrow GIS dataset. Chart produced by Mott MacDonald.

2.2.3 Previous Estimate of number of SRRs

2.2.3.1 Introduction

The Halcrow study attempted to estimate the number of SRRs both from assessment based on average depth and assessment based on volumetric estimations.

2.2.3.2 Previous estimate using average depth: method and results

The first methodology adopted by Halcrow to determine the number of SRRs was to first assess the percentage of water bodies which were raised, to then estimate the number of raised water bodies with a volume of 10,000 to 25,000 m^3 through consideration of average depth to convert volumes into representative surface areas, and to finally add on an allowance for service reservoirs and flood storage reservoirs.

The research assumed that the average depth of an SRR was 1.0 m. This is documented in reference Halcrow; 2013. In their report Halcrow recognise that this was a *"simplistic assumption"* and, indeed, we have been unable to trace any data which substantiates the value. A large number of site visits to SRRs had been undertaken by the Halcrow team for which bathymetric survey information was unavailable but this site experience informed engineering judgement with respect to the likely average reservoir depth, recognising that the true average could be less or greater than this. Halcrow stated in that document, *"There are no national studies to assess the robustness of this assumption across different regions so care is needed in applying the results of this study"*. On the basis of the assumed 1.0 m average depth it was then considered that SRRs with volumes between 10,000 m^3 and 25,000 m^3 would have surface areas of between 10,000 m^2 and 25,000 m^2.

The number of water bodies identified in England with a surface area between 10,000 m^2 and 25,000 m^2 was 4,341 (Halcrow; 2013). The calculation to determine the number that were raised is detailed in Halcrow; 2013, but in summary the following steps were taken (Halcrow; 2013):

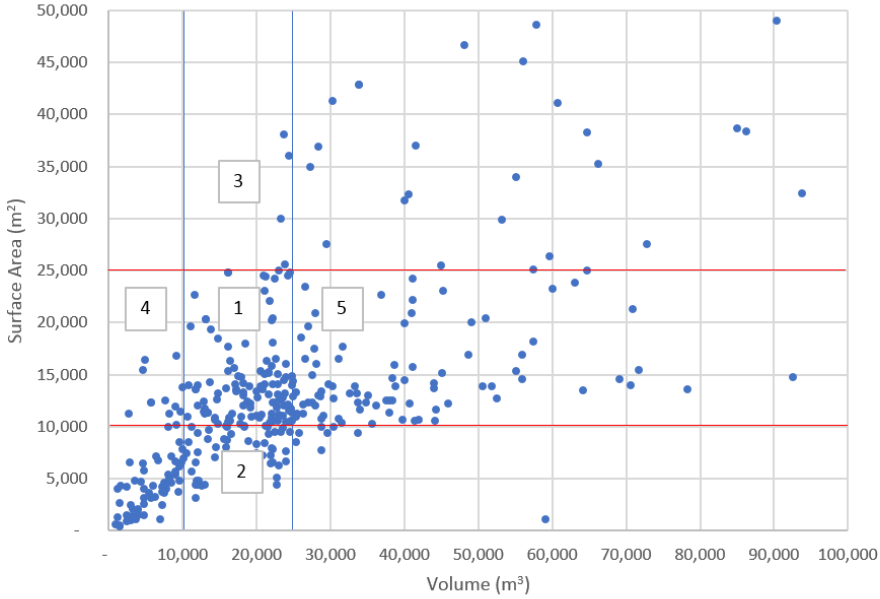
- review of OS mapping and satellite imagery was carried out for a desk-based evaluation of a sample of 1,807 water bodies in England (1,466) and Wales (341) with a surface area between 10,000 m^2 and 25,000 m^2 to assess whether the water body was:
  - Raised
  - Not raised;
  - Undetermined; or
  - Not applicable, for example where the water body is already registered as an LRR;
- site visits and/or consultations were then carried out for:
  - 50 “not raised” water bodies; from the subsequent reclassifications of that sample it was estimated that 2% of initially “not raised” reservoirs were actually SRRs;
  - 39 “undetermined” water bodies; from the subsequent reclassifications of that sample it was estimated that 28% of initially “undetermined” reservoirs were actually SRRs;
- these results were extrapolated from the sample data to the population as a whole giving an estimate of 1,078 SRRs (approximately 25% of water bodies in the same area band);
- 10% (108) was added to that figure to account for SRRs which were not captured by the GIS search, such as Service Reservoirs (SR) and Flood Storage Reservoirs (FSR).

Using this approach, the basic number of SRRs in England was estimated at 1,078. Including a further 10% allowance for SRs and FSRs increased the total to 1,186.

2.2.3.3 Appraisal of previous estimate using average depth

As part of previous research, data was collected on reservoir volumes and surface areas. The plot below shows a sample of data from Halcrow; 2009b of surface area plotted against reservoir volume. While there is clearly a relationship between volume and surface area, there is a large amount of scatter in the data.

Figure 4: Surface area and volume relationship



Source: Data from Halcrow; 2009b. Graph prepared by Mott MacDonald.

Considering this dataset, the reservoirs with estimated volumes between 10,000 m^3 and 25,000 m^3 lie between the two vertical blue lines, while the reservoirs with surface areas between 10,000 m^2 and 25,000 m^2 lie between the two horizontal red lines. Clearly the points between the red lines are a very different data set from those between the blue lines. For this sample, using the average depth method would over-estimate the number of reservoirs with volumes between 10,000 m^3 and 25,000 m^3 by 27%. The method would only be without error if all of the relevant data points fell within Zone 1, which would imply a unique relationship between surface area and volume and is clearly not the case.

It is also worth considering the sensitivity of the Halcrow method to the assumed average depth of an SRR. Analysis of the data gives the following results:

Table 2: Sensitivity analysis on the assumption of average reservoir depth

Average Depth (m)	Water Bodies (no.)	Change in result	Reservoirs (no.) assuming pro-rata increase with no. of water bodies
1.0	4,341	0%	1,186
1.1	4,729	9%	1,292
1.2	5,140	18%	1,404
1.3	5,589	29%	1,527
1.4	5,950	37%	1,626
1.5	6,293	45%	1,719
1.6	6,708	55%	1,833
1.7	7,024	62%	1,919
1.8	7,404	71%	2,023

Source: Data from Halcrow; 2013. Sensitivity analysis by Mott MacDonald.

This indicates that the previous research method is highly sensitive to the assumption of average depth and has the potential for a wide margin of error.

The sensitivity analysis does not consider average depths less than 1 m because the data is not available (this would correspond to surface area greater than 25,000 m^2).

2.2.3.4 Previous estimate using dam height: method and results

Halcrow also presented an alternative method based on the estimation of dam heights as opposed to assuming an average depth. Although discounted by Halcrow, this method is described here for completeness.

From the desk-based assessment of 1,466 water bodies in England, where they were raised reservoirs, dam heights were estimated by interpolating between contours on Ordnance Survey (OS) maps and by visual comparison to other features on aerial photographs. Dam heights were then used to estimate reservoir volumes (Halcrow; 2013) using the equations below.

Impounding reservoirs: $\mathbf{V = 0.282\ Ah}$

Non-impounding reservoirs: $\mathbf{V = 0.75\ Ah}$

Where: V = volume of the reservoir (m^3)

A = Surface area of the reservoir at top water level (full) (m^2)

h = Maximum embankment dam height (m)

Source: Halcrow; 2013

The results of the analysis of the sample are reproduced in Table 3 below:

Table 3: Halcrow estimation of number of SRRs based on estimates of reservoir volume

Region - Area	No. of water bodies assessed	Raised reservoirs of volume >10,000 m³	Percentage Raised
Midlands	908	145	16%
South West – Wessex	144	21	15%
Anglian – Central	414	43	10%
TOTAL	1,466	209	14%

Source: Halcrow; 2013

The proportion of water bodies in the sample which were estimated to have raised volume between 10,000 m^3 and 25,000 m^3 was then applied to the number of reservoirs of surface area between 10,000 and 25,000 m^2 in the broader population to establish an estimate of **626 SRRs in England**. Halcrow then concluded that section by stating:

"Taking a precautionary approach, these figures were dismissed in favour of the reservoir number estimates derived through surface area and the assumption of 1 m (average) water depth" (Halcrow; 2013).

2.2.3.5 Appraisal of previous estimate using dam height

This method is included for completeness and to demonstrate the spread of results using different methods. However, Mott MacDonald agrees with the dismissal of this estimate and further cites the following limitations:

- While the equations used were developed without pre-screening by surface area, the fraction of water bodies which were found to be SRRs was then applied to the existing dataset of water bodies which assumed that there are no SRRs outside the surface area range 10,000 m^2 to 25,000 m^2;
- the estimation of dam heights used only the data which was available at the time including OS contours and satellite imagery – this necessarily made the height estimates relatively crude.

2.3 Information provided by National Resources Wales (NRW)

Mott MacDonald have engaged with Natural Resources Wales (NRW) to learn from their experience of identifying SRRs. Findings from the discussions are:

- NRW have a list of 927 water bodies of all sizes / types
- NRW have 233 registered LRRs
- therefore, NRW have 694 (=927-233) listed water bodies where the volume may be in the range 10,000 m^3 to 25,000 m^3
- of the 694 listed water bodies:
  - 109 are confirmed as SRRs
  - 141 are confirmed as not being raised or having a volume less than 10,000 m^3
  - 438 are potentially SRRs

  - 6 are proposed reservoirs, which have not yet been constructed, or exempt e.g. covered under Mines and Quarries (Tips) Act 1969
- Halcrow identified 794 water bodies in Wales with areas between 5,000 and 25,000 m^2. Of these, about 60% are not included in the NRW data set
- there are therefore potentially another 476 (794 x 0.6) water bodies with areas between 5,000 and 25,000 m^2 which have not been picked up by NRW
- the total number of water bodies requiring assessment is therefore 1,170 (694+476)
- of these only 151 (13%) have been assessed to date

On the basis of this information it is too early to draw any useful conclusions from NRW on the reliability of the Halcrow study. It should however be noted that NRW are understood to have concentrated on registering the most “obvious” SRRs. It may therefore be that the 87% of all water bodies which have still to be assessed may not contain very many more SRRs. Since the registration process is led by the enforcement agency rather than self-registration, the information available is not appropriate to provide lessons learned at this time.

2.4 Information provided by undertakers

The following information has been received from undertakers. Not all undertakers were able to provide evidence which was relevant to this study. The consultation included organisations from the following categories:

- water companies
- public bodies;
- representation bodies; and
- charities.

The results are shown in Table 4 below.

Table 4: Non-exhaustive list of SRRs from consultation

Organisation	Service Reservoirs	Flood Storage Reservoirs	Other impounding reservoirs	Other non-impounding reservoirs	Total	Comments
Water & Sewerage 1	30	-	-	10	**40**	Database received
Water & Sewerage 2	7	-	3	-	**10**	Interview response
Water & Sewerage 3	26	-	4	4	**55**	Database received with some blank fields
Water & Sewerage 4	35	-	-	8	**43**	Email summary
Water & Sewerage 5	39	-	-	9	**48**	Report received
Water & Sewerage 6	20	-	4	1	**25**	Email summary
Water Only 1	4	-	-	6	**10**	Email summary
Public Body 1	-	3	-	-	**3**	Only applies to one localised area.

Organisation	Service Reservoirs	Flood Storage Reservoirs	Other impounding reservoirs	Other non-impounding reservoirs	Total	Comments
Charity 1	-	-	-	-	**9**	Email summary
Charity 2	-	-	4	3	**7**	Email summary
Total	**161**	**3**	**15**	**41**	**250**	Total of values in each column

Source: Information from MM consultations.
Individual categories do not necessarily equal totals because in some cases not all types were specified.

The results are anonymised. In some cases, comprehensive databases were received, whereas in others non-exhaustive, anecdotal and/or regional information was received. The list of stakeholders is also non-exhaustive, for example seven water companies were consulted out of 23 identified in England however larger organisations were targeted in order to capture as much data as possible.

These results are considered further when estimating the total number of SRRs in section 2.5.6.2.

2.5 Updated Estimate of number of SRRs

2.5.1 Summary of Approach

The requirement for estimating the number of SRRs is to first estimate the number of water bodies that are raised and to then estimate the proportion of those raised reservoirs which have a volume between 10,000 m^3 and 25,000 m^3, and which therefore qualify as SRRs.

Considering the high degree of scatter of the data in Figure 4 the average depth method (Halcrow; 2013) is likely to have a relatively high margin of error. Following a review of the previous methods for estimating the number of SRRs in England, Mott MacDonald proposed a refined analysis as described in the remainder of this section.

The approach is to consider a probability distribution where reservoir surface area is plotted on the x-axis and the probability of a reservoir being an SRR is plotted on the y-axis. The probability that a raised reservoir is an SRR can be estimated for a given surface area band by acquiring a random data set of reservoir surface areas and associated volumes. The probability is then the number of reservoirs in the area band with a volume of 10,000 to 25,000 m^3 divided by the total number of reservoirs in the area band. These probability distributions can then be applied to the broader population. To obtain a useful sample dataset to inform the probability distribution, a sample of 500 water bodies was analysed using the following steps:

- assess whether the water body is a raised reservoir?
- assess whether the raised reservoir is impounding (usually formed by placing a dam across a natural watercourse), fully bunded (formed by the construction of embankments on all sides of the reservoir) or partially bunded (usually near a water course with embankments constructed on not all side, such as with flood storage reservoirs)?
- estimate dam height of raised reservoirs using Lidar (received in January 2018);
- estimate volume of raised reservoirs based on a function of dam height and reservoir surface area (see section 2.5.3);
- analyse data to establish trends related to whether a water body is a reservoir or not;

- analyse data to establish probability distributions related to whether a reservoir is an SRR or not;
- apply the newly established relationships to the broader population of water bodies.

This approach is a refinement of the Halcrow method (Halcrow; 2013) which effectively took the probability that a reservoir is an SRR as 100% for surface areas between 10,000 m^2 and 25,000 m^2 and 0% for surface area <10,000 m^2 and >25,000 m^2. Throughout the study there is an assumption that the surface area measured from the GIS search is the surface area at top water level (TWL).

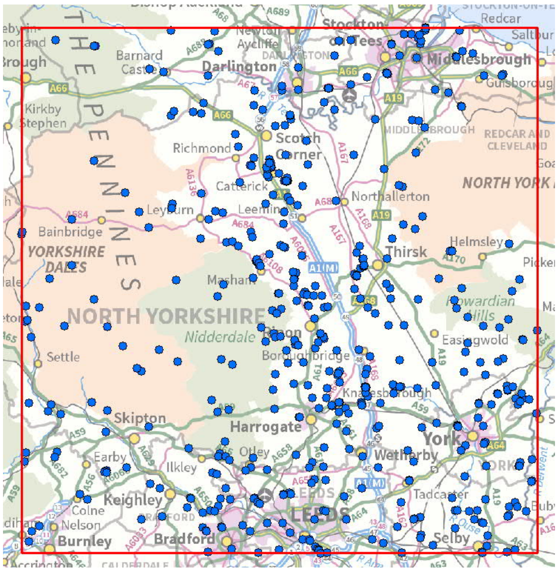
2.5.2 Data Acquisition

For this research an entirely new desk study of a sample of 500 water bodies was undertaken for an area in the north of England. The desk study new area, in which there are 500 water bodies with surface area between 5,000 m^2 and 25,000 m^2, is shown in Figure 5 and Figure 6.

Figure 5: Desk study sample area for this research project

Source: Contains Ordnance Survey data © crown copyright and database right. Box shown is approximate, precise coordinates are 379256,430665 to 471418, 524581.

Figure 6: Desk study sample area for this research project



Source: Contains Ordnance Survey data © crown copyright and database right. Box shown is approximate, precise coordinates are 379256,430665 to 471418, 524581.

This area was selected to:

- expand the existing body of research into the north of England;
- expand the existing body of research into an English upland area;
- be representative and of a significant size statistically, albeit achievable within the programmed timeframes;
- be representative of both upland and lowland areas, and
- ensure that a relevant number of reservoirs in cascade was found (refer to section 4 for separate research on SRRs in cascade).

Each water body in the sample was analysed using Lidar data to first determine whether the water body was raised. In the case of raised reservoirs, the dam height was then assessed and the reservoir categorised as impounding, partially bunded or fully bunded. An example of the Lidar output is shown in Figure 7 and Figure 8.

Figure 7: Lidar Output (plan view)

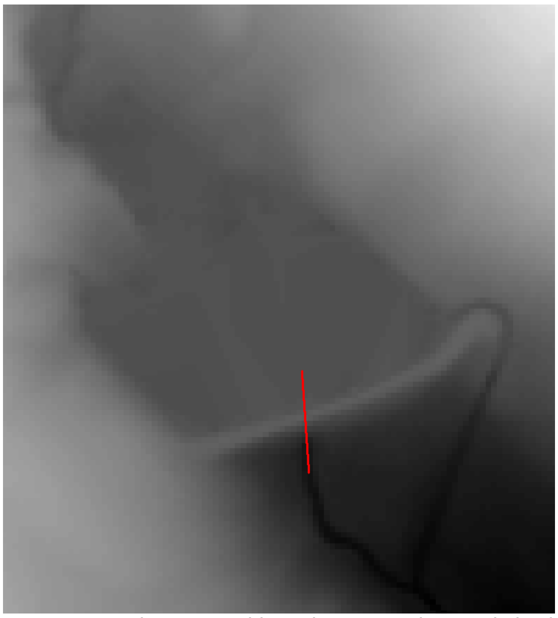
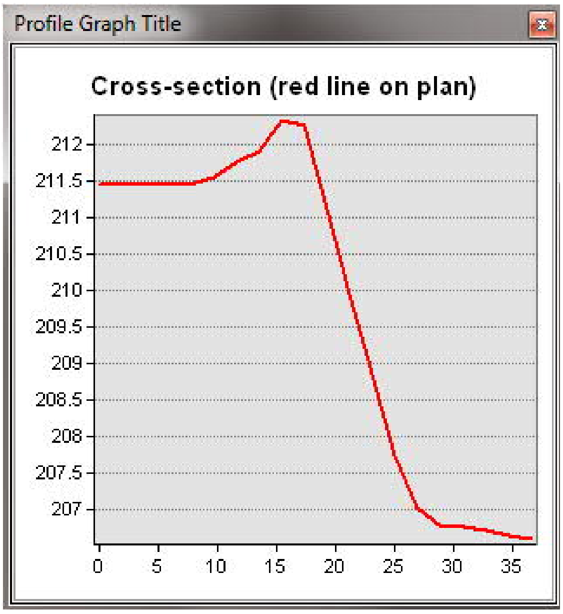


Figure 8: Lidar Output (cross section)



MM Water Body ID 361. Lidar colour ramp shows relative high as white and relative low as black. Cross section units = x:Chainage (m), y:Level (mAOD)

In undertaking the new desk study, it had to be recognised that considerable data was in existence from previous studies. However, this contained minimal information on dam height and was not therefore able to be assimilated into the new methodology. It was further considered to be beneficial to analyse a complete set of all water bodies, including those between 5,000 and 10,000 m^2 in a selected study area.

Key findings from the study were:

- water bodies analysed = 500 (no.)
- raised reservoirs identified = 140 (no.)
- impounding raised reservoirs identified = 76 (no.)
- fully bunded raised reservoirs identified = 27 (no.)
- partially bunded raised reservoirs identified (without obvious watercourse) = 34 (no.)
- modified natural lakes identified = 3 (no.)
- maximum dam height encountered on impounding reservoir = 15.1 m
- maximum dam height encountered on a non-impounding reservoir = 6.5 m

2.5.3 Dam height and maximum depth of water

2.5.3.1 Introduction

There are five levels which are significant and related to the definition of dam height for the purposes of this research:

i. Dam crest – top water level plus freeboard

ii. *"Top water level"* – defined in Statutory Instrument (SI) 2013 No 1677
iii. Downstream river bank
iv. Downstream river bed – *"toe"* in Statutory Instrument 2013 No.1677
v. Lowest *"bed of the reservoir"* – unless there is known information on reservoir siltation the lowest reservoir bed level is usually taken as (iv).

In the following discussion the parameters are defined as:

- V – reservoir volume (m^3)
- A – reservoir surface area (m^2)
- h – dam height (i minus iv) (m)
- d – maximum depth of water at top water level using the river bed (ii minus iv) (m)
- $d_{river\ bank}$ – maximum depth of water using the river bank (ii minus iii) (m)

The definition of "maximum height of the dam" under the Reservoirs Act 1975 in Schedules 1 and 2 of Statutory Instrument (SI) 2013 No 1677 is (i) minus (iv) for the purposes of recording the characteristics of the structure in the Prescribed Form of Record (PFR).

The reservoir volume (V) is the volume stored at top water level.

To estimate the escapable reservoir volume, it is necessary to be able to relate reservoir volume to surface area and water depth.

2.5.3.2 Impounding reservoir

An impounding reservoir can be idealised as a half right rhombic pyramid (cut diagonally across the base) which represents a reservoir where the ground level along the length of the dam slopes uniformly to a low point in the middle, the reservoir is triangular in plan and the base of the reservoir slopes uniformly from the dam to the far end of the reservoir. In this case the theoretical volume of the reservoir is:

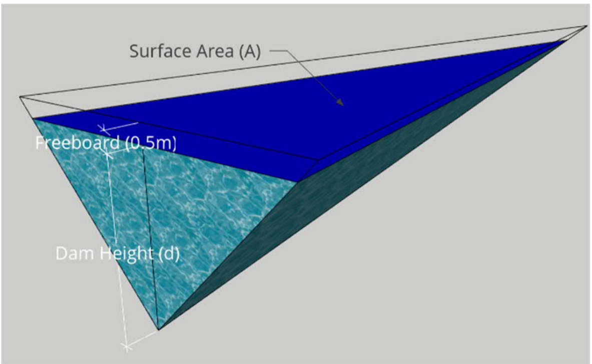
V = 0.33Ad.

For the purpose of this study it is assumed that the freeboard is 0.5 m, implying that:

d = h – 0.5.

This is shown in Figure 9.

Figure 9: Impounding reservoir volume



This expression is in close agreement with the method used by Halcrow (see section 2.2.3.4) where it was proposed that V = 0.282Ah. It should nevertheless be noted that depending of the shape of the reservoir, the coefficient in the formula can vary from 0.1 to 0.75 or higher. Typically, it would be expected that reservoirs are located in topographically favourable locations (for example where there is a narrowing in the contours at the dam axis) which would suggest that the coefficient should be greater than 0.33. However, this assessment has not taken into account the potential for siltation within the reservoir. In some instances siltation can significantly reduce the volume of water in the reservoir, and, if the silt is not mobile, it would not be included in the volume calculation. The effect of this would be to reduce the coefficient, which in turn would tend to make the required surface area of SRRs slightly larger. On balance, a coefficient of 0.33 is considered reasonable for this study.

2.5.3.3 Fully bunded reservoir

For a fully bunded reservoir the volume can be calculated theoretically by assuming a square, flat base and internal slopes at gradients of 1v:3h. In this case the expression for the volume is

$V_F = d(A^{0.5}-2dS)^2+2(A^{0.5}-2dS)Sd^2+(4/3)S^2d^3$

2.5.3.4 Modified natural lake

Due to their natural shape, a modified natural lake is assumed to have a volume of:

$V_{MNL} = dA$

2.5.3.5 Discussion of height measurement

Following a suggestion from the Advisory Group, consideration was also given to measuring dam height relative to the flood plain rather than the low point of the river channel. This approach would clearly have merit on a site where an incised channel runs through a flat floodplain and consideration of the height to the base of the channel could overestimate the reservoir volume. However, it was felt on balance that it was preferable to adopt a conservative, consistent approach, and dam height was therefore measured to the base of the river channel (lowest adjacent natural ground) on all reservoirs. This recognised the fact that the formula for calculating reservoir volume would be unconservative when applied to a flat floodplain.

A sensitivity assessment on dam height was nevertheless undertaken as outlined in Section 2.6.

2.5.3.6 Summary

To summarise this sub-section, for the purposes of this research project, the equations in Table 5 are used to estimate reservoir volume above natural ground level.

Table 5: Equations for estimation of reservoir volume

Description	Notation	Unit	Comment
Maximum dam height	h	m	(i) – (iv) Dam height measured from crest level to downstream toe.
Maximum water depth above natural ground level	d = h – 0.5m	m	(ii) – (iv) Maximum water depth from Top Water Level to downstream toe of dam.
Reservoir surface area	A	m^2	At Top Water Level, or as measured by the automated GIS search algorithm which

Description	Notation	Unit	Comment
			reads the OS mapping water layer.
Volume of an impounding reservoir	$V = (1/3)dA$	m^3	Based on the geometry of half of a right rhombic pyramid (cut diagonally across the base)
Volume of a fully bunded reservoir	$V_F = d(A^{0.5}-2dS)^2+2(A^{0.5}-2dS)Sd^2+(4/3)S^2d^3$	m^3	Assumes a square reservoir in plan with embankment side slopes at 1:3 (v:h)
Volume of a partially bunded reservoir	$V_P = 0.5V_F$	m^3	For a given maximum dam height and surface area a partially bunded non-impounding reservoir is assumed to have half the volume of a fully bunded impounding reservoir of the same maximum water depth and surface area.
Volume of a modified natural lake	$V_{MNL} = d.A$	m^3	Rim of modified natural lake assumed to be relatively steep.

2.5.4 Assessment of whether a water body is a raised reservoir

2.5.4.1 Introduction

For this research project each of the 500 water bodies in the sample was designated as a raised reservoir or not by studying Lidar data, OS mapping and available satellite imagery. The criteria for a water body being a raised reservoir was that there should be an embankment, or other structure, which impounds water to above natural ground level.

Previous research (Halcrow; 2013) also had an “undetermined” category when OS mapping and satellite imagery was not sufficient to determine whether the water body was raised or not. Under this project, given the higher quality of available data including the latest Lidar data, it was not considered necessary to have an “undetermined” category. The quality and coverage of Digital Terrain Model data was acceptable even where there was established vegetation.

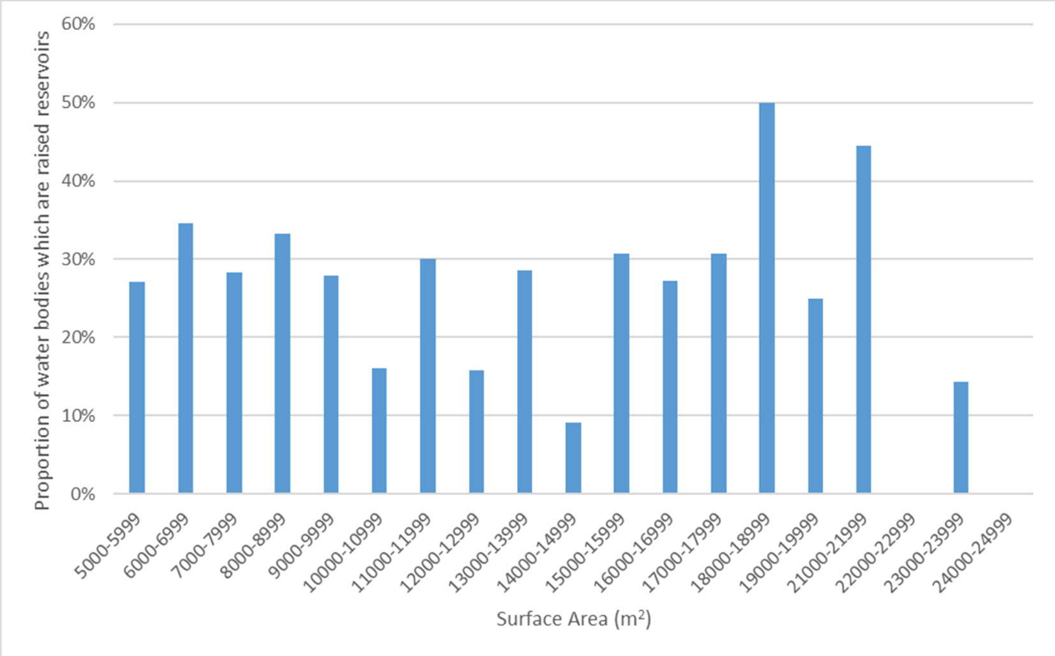
The latest Lidar data was received from Defra with 100% coverage in England. Vertical accuracy is typically quoted as ±0.15 m, although is often better. Horizontal resolution varies by up to 2 m. OS mapping and open rivers data was overlain by Lidar and analysed manually using GIS software. The analysis was carried out by a chartered engineer with supervisory oversight from an All Reservoirs Panel Engineer.

The outcome was a list of 500 water bodies of known surface area, designated “raised” or “not raised”, and with the dam height estimated for raised reservoirs.

2.5.4.2 Review of results by area band

Analysis of the results shows that there is no clear relationship between the surface area of a water body and the probability of that water body being a raised reservoir. The results are presented in Figure 10. Therefore, the probability of a water body being a raised reservoir is considered to be independent of the surface area of that water body. Later in the analysis when extrapolating data into new area bands a constant factor is therefore utilised to determine the proportion of water bodies which are raised reservoirs.

Figure 10: Proportion of water bodies which are reservoirs by area band – no clear trend



Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

2.5.4.3 Review of results by elevation

Analysis of the results shows a clear difference in the proportion of water bodies which are raised reservoirs between upland and lowland areas. Following analysis of the data, an upland/lowland cut-off was established at 100 mAOD, below which the proportion of water bodies which are reservoirs gradually increases and above which there appears to be no particular relationship but a higher average proportion than for the lower land water bodies. Figure 11 and Figure 12 show the proportion raised by upland and lowland areas based on the study sample.

Figure 11: Proportion of water bodies which are raised against elevation, z

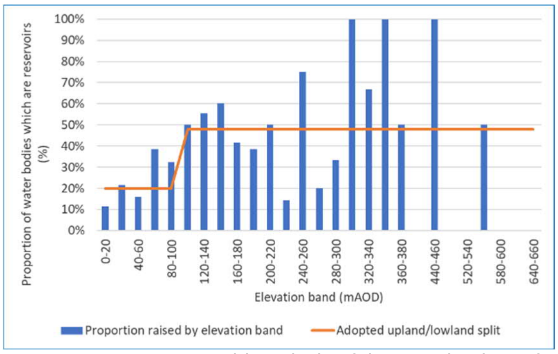
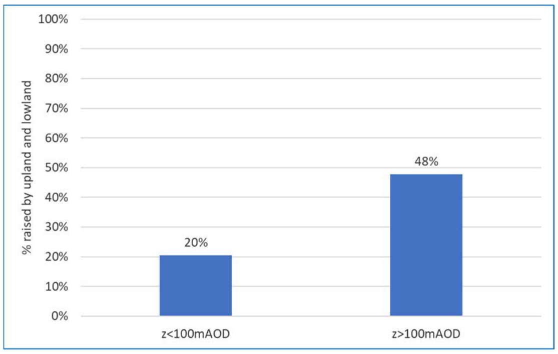


Figure 12: Proportion of water bodies which are raised for lowland and upland



Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

The conclusion was that below 100 mAOD 20% of water bodies are raised reservoirs, while above 100 mAOD 48% of water bodies are raised reservoirs. 100 mAOD is clearly a subjective cut-off point, considering the limited available data, but it should be recognised that splitting the data into two bands and recalculating using the results from the sample data can only be more refined than using one band.

2.5.4.4 Calculation of proportion of water bodies which are raised reservoirs

To calculate the proportion of the population of water bodies which are raised reservoirs the following data is considered:

- proportion of lowland water bodies which are raised reservoirs in the sample (P_{LR});
- proportion of upland water bodies which are raised reservoirs in the sample (P_{UR});
- proportion of water bodies which are in lowland areas in the population (P_L);
- proportion of water bodies which are in upland areas in the population (P_U).

By importing the X-Y coordinates for all water bodies in the population (and therefore in the sample) into GIS software, each water body has been associated with a Z value (mAOD) taken from the Lidar data and therefore assigned as upland or lowland. From this information the percentage of water bodies which are raised are calculated as shown below.

Table 6: Proportion of water bodies which are raised reservoirs by upland and lowland

	SAMPLE			POPULATION	
Elevation, z	Number of water bodies	Number of raised reservoirs	% raised	Number of water bodies	% of population
z < 100 mAOD	362	74	**20%**	9, 286	**82%**
z > 100 mAOD	138	66	**48%**	2,048	**18%**
ALL	500	140	28%	11,334	100%

Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

The proportion of upland water bodies in the sample (48%) is slightly higher than the proportion in the population (18%). In order to adjust the calculation to take account of the upland/lowland proportions of the population of water bodies, the proportion is recalculated as follows:

Proportion raised = $(P_{LR} \times P_L) + (P_{UR} \times P_U)$

$= (20\% \times 82\%) + (48\% \times 18\%) =$ **25%**

As described in section 2.2.3, the previous study (Halcrow; 2013) also estimated the proportion of water bodies which are raised reservoirs to be 25% (1,078 SRRs / 4,341 water bodies) which reinforces the findings of the above calculation.

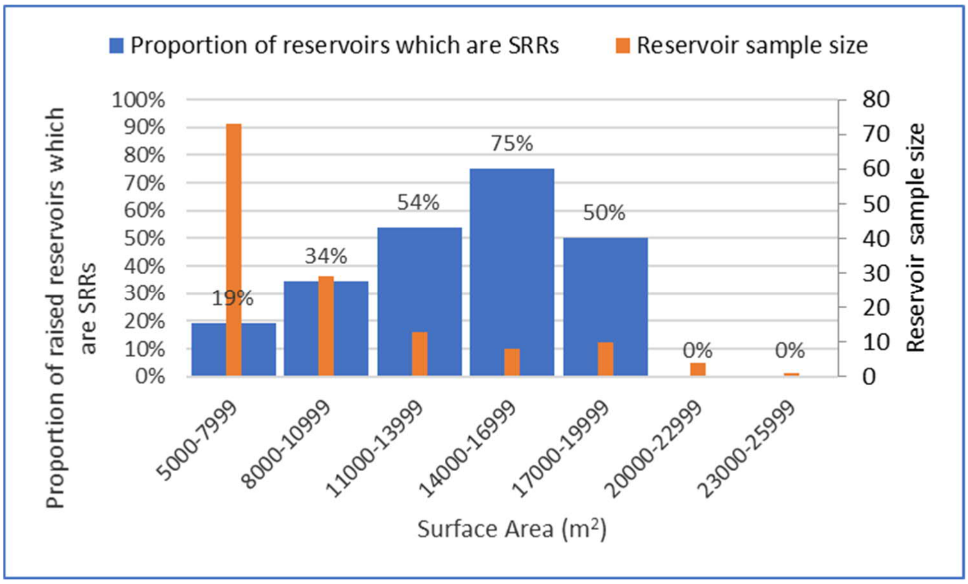
The 25% proportion is then applied to the full population of water bodies to estimate the number of raised reservoirs prior to considering whether those raised reservoirs are likely to be SRRs (having a volume of between 10,000 m^3 and 25,000 m^3). Refer to Table 11 which outlines the full calculation.

2.5.5 Assessment of whether a raised reservoir is a SRR with volume between 10,000 and 25,000 m^3

2.5.5.1 Sample data (surface area >5,000 m^2)

Analysis of the sample data by surface area bands gives the distribution shown in Figure 13 below.

Figure 13: Probability of a raised reservoir being an SRR by area band

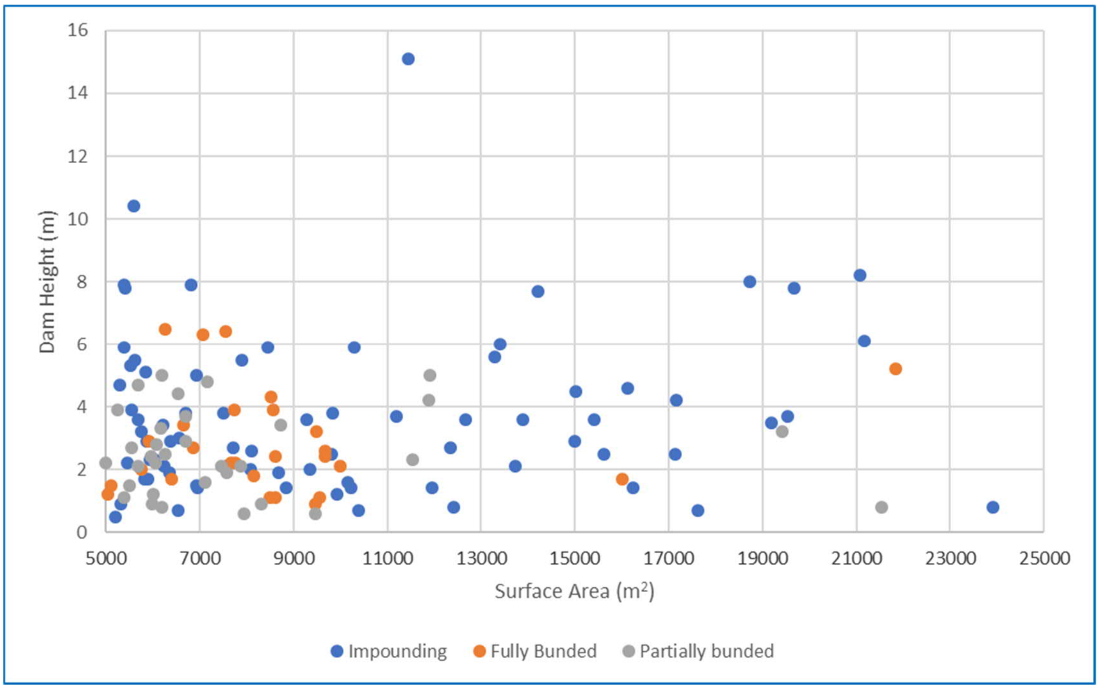


The plot shows that the 140 raised reservoirs identified from the 500 sampled reservoirs were heavily weighted towards the lower end of the area range. This is expected based on the distribution of the broader population in Figure 3. The fact that 19% of reservoirs in the 5,000 to 8,000 m^2 band were SRRs suggests that the lower limit of area for SRRs is significantly less than 5,000 m^2. This is discussed further in Section 2.5.5.2. In the 20,000 m^2 to 23,000 m^2 and 23,000 m^2 to 25,000 m^2 bands there were only 4 and 1 raised reservoirs respectively, none of which were SRRs. Whilst this could be interpreted as suggesting that there are no SRRs with area greater than 20,000 m^2, this is considered incorrect and it must therefore be accepted that the sample size was simply too small to be representative. This is discussed further in Section 2.5.5.3. See Figure 19 for assumed probability that a reservoir is an SRR following further analysis of lower and upper bands, as outlined in the following sections.

2.5.5.2 Water bodies of surface area <5,000 m^2

It is necessary to establish a new lower limit for surface area of an SRR prior to extrapolation of the data presented in Figure 12 to lower surface areas. A limit can be established based on a maximum credible dam height. Based on the reservoirs analysed, this is approximately 10 m for an impounding reservoir and 7 m for a fully bunded reservoir. It can be seen from Figure 14 that there is one outlier with a dam height of approximately 15 m; but the volume is estimated to be too large for an SRR and it is therefore discounted from the assessment of SRR surface area lower bound.

Figure 14: Dam height against surface area for the sample data



Note: Data points represent raised reservoirs (of any volume) of surface area between 5,000 m^2 and 25,000 m^2

Using maximum dam heights, the theoretical minimum surface area for the different types of reservoir can then be calculated. Table 7 below shows the calculation to estimate the lower limit.

Table 7: Adopted lower bound for surface area and corresponding estimated dam height

Description	Symbol	Unit	Inputs	Outputs	Comment
Volume	V_{min}	m^3	10,000	-	Adopted lower bound for an SRR
Freeboard	R_c	m	0.5	-	Assumed
Embankment slopes	S_{dam}	1:X	3	-	Assumed
Impounding reservoir: maximum dam height encountered	h_{Imax}	m	10	-	Figure 14 (outlier of 15m removed)
Impounding reservoir: maximum depth encountered	d_{Imax}	m	-	9.5	h_{Imax} - R_c
Impounding reservoir: minimum surface area	A_{Imin}	m^2	-	3,158	$V_{min} = (1/3).\ A_{Imin}.\ d_{Imax}$ From section 2.5.3.2
Fully bunded reservoir: maximum dam height encountered	h_{Fmax}	m	7	-	
Fully bunded reservoir: maximum depth encountered	d_{Fmax}	m	-	6.5	h_{Fmax} - R_c

Description	Symbol	Unit	Inputs	Outputs	Comment
Fully bunded reservoir: minimum surface area	A_{Fmin}	m^2	-	3,257	Assumes a square reservoir in plan to calculate the volume based on the estimated geometry by solving: $V_F = d(A^{0.5}-2dS)^2+2(A^{0.5}-2.dS)Sd^2+(4/3)S^2d^3$ From section 2.5.3.4
All reservoirs: minimum surface area	$\mathbf{A_{min}}$	$\mathbf{m^2}$	**-**	**3,000**	**Rounded minimum value from: $\mathbf{A_{Imin}}$ and $\mathbf{A_{Fmin}}$**

Table 7 above shows that the minimum surface area appears to be similar for impounding and fully bunded reservoirs. Rounding to the nearest 1,000 m^2, the adopted lower bound for surface area of an SRR, for the purposes of statistical analysis is therefore 3,000 m^2. The value is rounded to give regular bands of area and to reflect the accuracy of the input data in the calculation. The extrapolation is then only carried out for surface area as low as 3,000 m^2. Identifying this lower limit for surface area assumes the probability that a reservoir is an SRR, for surface area equal to 3,000 m^2, is equal to zero which enables sensible interpolation for the probability between 3,000 m^2 and 5,000 m^2.

2.5.5.3 Water bodies of surface area >25,000 m^2

Although the data from the sample of 500 water bodies suggests that there are no SRRs with surface area greater than 25,000 m^2, it is considered that this is unlikely to be true in practice. Data provided by the EA shows that 95% of LRRs with a volume of around 25,000 m^3 have a surface area of less than 50,000 m^2. It may therefore be concluded that nearly all SRRs will have a surface area of less than 50,000 m^2.

2.5.5.4 Extrapolation of number of water bodies outside 5,000 to 25,000 m^2

Without any data available from the existing Halcrow dataset for water bodies of surface area less than 5,000 m^2 or greater than 25,000 m^2 it is necessary to carefully extrapolate for these bands to give an indication of the number of reservoirs which would not have been identified by the automated GIS algorithm.

It is not possible to directly extrapolate the cumulative frequency curve in Figure 3 with any confidence. However, it has been found that by splitting the distribution into bands, a plot of number of reservoirs in each band against surface area appears to follow a power law which lends itself to extrapolation.

The data is shown in Figure 15 with a trendline fitted by Excel. The power law trendline is then illustrated as a straight line in log-log space in Figure 16.

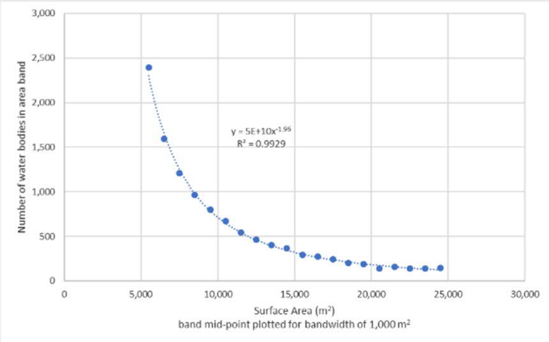
Accepting this fit to a power law, the relationship can then be extrapolated down to 3,000 m^2 and up to 50,000 m^2 as shown in Figure 17 and Figure 18. The following values (Table 8) can then be derived from this extrapolation.

Table 8: Estimated number of water bodies obtained through extrapolation

Area band	No of water bodies
3,000 to 5,000	9,114
20,000 to 35,000	1,584
35,000 to 50,000	656

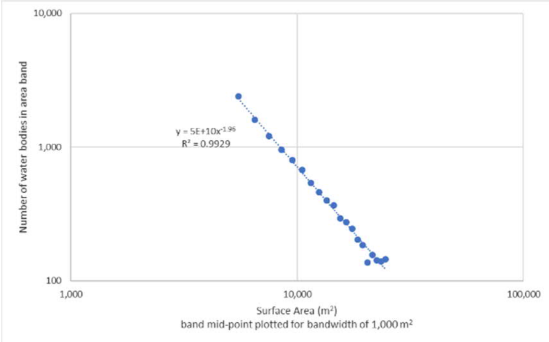
The table above does not show the number of water bodies with surface area between 5,000 m^2 and 20,000 m^2 because these were not extrapolated – real data was available. For reference, there are 10,612 water bodies identified with a surface area between 5,000 and 25,000 m². It is estimated that there is a total of approximately 22,000 water bodies with a surface area of between 3,000 and 50,000 m².

Figure 15: Surface area against no. of water bodies (linear space)



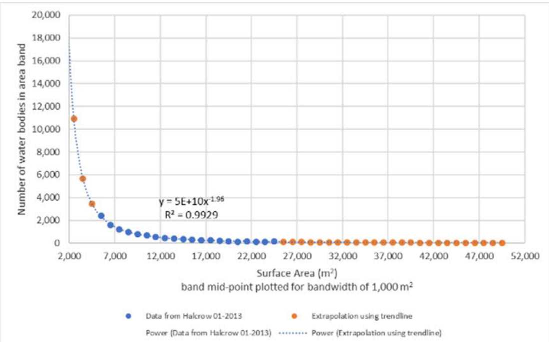
Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

Figure 16: Surface area against no. of water bodies (log-log space)



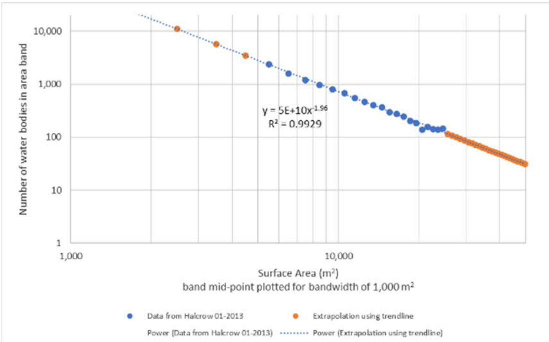
Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

Figure 17: Extrapolation of surface area against no. of water bodies (linear space)



Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

Figure 18: Extrapolation of surface area against no of water bodies (log-log space)



Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

2.5.5.5 Probability Distribution

Section 2.5.4 demonstrates that approximately 25% of water bodies are raised reservoirs, irrespective of surface area.

This section estimates the varying probability that a raised reservoir is an SRR across bands of surface area.

The data in Figure 13 provides probabilities for the area range from 5,000 m² to 20,000 m².

To establish an estimate of the probability that a reservoir is an SRR for the area band 3,000 m² to 5,000 m² it is considered appropriate to undertake linear interpolation as shown in Table 9 below.

Table 9: Probability that a reservoir is an SRR for relatively low surface areas

Row no.	Surface Area Band (m^2)	Surface Area Mid-Point (m^2)	Probability that a reservoir is an SRR	Notes
1	-	3,000	0%	Lower limit for surface area – see Section 2.5.5.1
2	3,000 – 5,000	4,000	5%	Linear interpolation between rows 1 and 3
3	5,000 – 8,000	6,500	19%	Based on findings from sample data – see Figure 13

In the range above 20,000m^2 it is more difficult to assess probabilities due to the scarcity of data generated by this research (see Section 2.5.5.5). It the absence of any new data it is considered that the only option is to fall back on the data in Figure 4. This shows surface area against volume, so within a certain area band, shows the total number of raised reservoirs and the number of SRRs. The following data in Table 10 can therefore be interpreted from Figure 4.

Table 10: Probability that a reservoir is an SRR for higher area bands

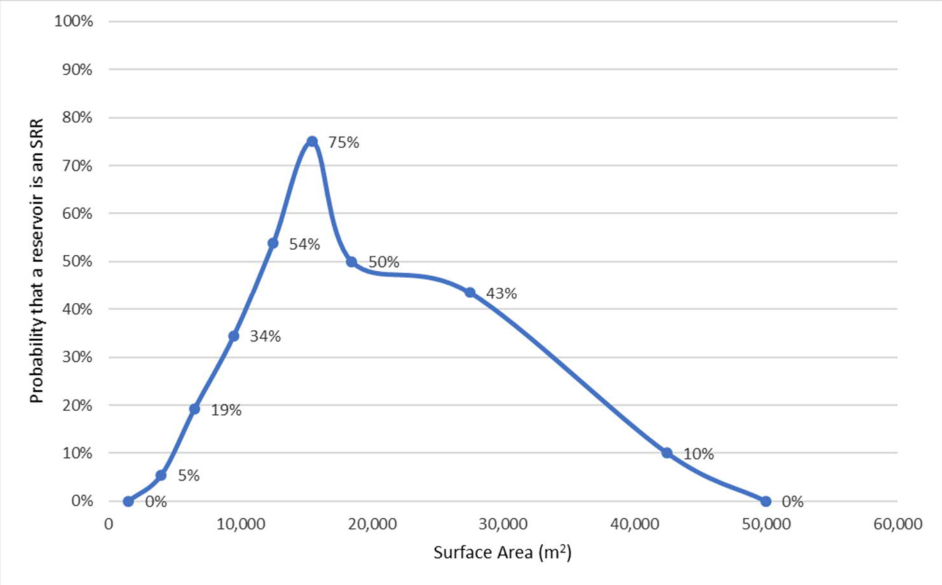
Surface Area Band (m^2)	Surface Area Mid-Point (m^2)	Number of reservoirs	Number of SRRs	Probability that a reservoir is an SRR
20,000 to 35,000	27,500	46	20	43%
35,000 to 50,000	42,500	18	2	10%

Source: Data from Halcrow; 2009b. Analysis by Mott MacDonald.

It should be noted that it had previously been considered inappropriate to use this data to estimate the probabilities because it could not be confirmed that the data had been taken from a random sample of raised reservoirs. For this reason, the data in Figure 4 is only being used where there is no alternative.

Combining the distributions shown in Figure 13, Table 9 and Table 10 gives the probability distribution shown in Figure 19 below. This curve has been smoothed between data points.

Figure 19: Probability that a reservoir is an SRR based on sample data



Source: Analysis by Mott MacDonald using GIS search database from Halcrow; 2013.

This section highlighted some of the limitations that are present in the probability curve shown in Figure 19. In particular for surface areas above 20,000 m^2, probabilities were calculated using data from a small sample (from Figure 4) and are therefore less reliable. However, it is worth recalling here that the similar function used in the Halcrow research had 100% between 10,000 m^2 and 25,000 m^2 and zero elsewhere, therefore the new research is a significant refinement on what was used previously.

2.5.6 Assessment of how many SRRs are there in England?

2.5.6.1 Estimate excluding SRs and FSRs

Following the approach in the previous sub-sections, Table 11 below summarises the calculation for the estimation of the number of SRRs in England. All results are calculated without rounding errors but presented as rounded for clarity.

Table 11: Number of SRRs in England (excluding SRs and FSRs)

						Probability that a reservoir is an SRR		
Surface Area Band (m^2)	**No. of water bodies**	**Probability that a water body is a reservoir**	**No. of reservoirs**	**No of reservoirs in sample**	**No of SRRs in sample**	**Mean Probability**	**Standard deviation**	**No. of SRRs**
0 – 3,000	>200,000	25%	>50,000	-	-	0%	0%	0
3,000 – 5,000	9,114	25%	2,314	-	-	5%	4.4%	127
5,000 – 8,000	5,202	25%	1,321	73	14	19%	4.4%	253
8,000 – 11,000	2,435	25%	618	29	10	34%	8.4%	213
11,000 – 14,000	1,404	25%	356	13	7	54%	13.3%	192

14,000 – 17,000	937	25%	238	8	6	75%	14.8%	178
17,000 – 20,000	634	25%	161	10	5	50%	15.1%	80
20,000 – 35,000	1,584	25%	402	46	20	43%	6.7%	175
35,000 – 50,000	656	25%	166	20	2	10%	6.2%	17
						TOTAL		**1,235**

Source: Analysis by Mott MacDonald using GIS search database from Halcrow; 2013.

It is estimated that, excluding SRs and FSRs, there are approximately 1,235 SRRs in England.

There is, however, considerable margin for error in this assessment due to uncertainties in the data. To address this, a Monte Carlo simulation has been undertaken. This allows the quantifiable variations in each piece of input data to be combined to estimate the 95th percentiles for the final number of reservoirs. The variables incorporated into the Monte Carlo analysis (i.e. mean and standard deviation of the probabilities) were as shown in Table 11. The analysis assumes that the percentages for each surface area band vary according to a normal distribution. The standard deviation for each band is calculated on the basis of the population size, sample size and the result in each sample using standard statistical functions.

The results of the Monte Carlo analysis are as follows:

Most likely number of SRRs (excluding SRs and FSRs)	1,235
Range of SRRs (excluding SRs and FSRs) for 95% confidence	937 to 1,592

2.5.6.2 Estimate of numbers of SRs and FSRs

Service Reservoirs (SR) and Flood Storage Reservoirs (FSR) would not be detected by the automated GIS search therefore these needed to be considered separately.

Consultations have been carried out with undertakers, including owners of SRs and FSRs. Findings of these consultations have been extrapolated by area of coverage. The consultations cover a wide range of density of population and cover the majority of England, therefore the extrapolation is valid, albeit with the potential for error.

The Figure 20 and Figure 21 below show the water companies in England, Scotland and Wales.

Figure 20: Water and Sewerage Companies

Source: Water UK

Figure 21: Water Supply Only Companies

Source: Water UK

There are 9 water and sewerage companies in England. As part of this research we obtained confidential information from 6 of the companies. These 6 companies represented 73% of the total area of England and therefore provided good coverage.

The results of the findings from the water and sewerage companies in England (see Figure 20) are presented in Table 12 for the number of service reservoirs (SRs) of volume between 10,000 – 25,000 m^3. Some information has been excluded from the table to protect the anonymity of the consultees.

Table 12: Estimate of SRs owned by Water and Sewerage Companies

Water and Sewerage Company	Area coverage (km^2)	SRs (no.) from consultation	SRs (no.) extrapolated by area coverage
1	A_1	30	-
2	A_2	7	-
3	A_3	26	-
4	A_4	35	-
5	A_5	39	-
6	A_6	20	-

Water and Sewerage Company	Area coverage (km^2)	SRs (no.) from consultation	SRs (no.) extrapolated by area coverage
SUB-TOTAL	96,905	157	-
7 - 9	34,722	No data	(34,722 / 96,905) x 157 = **56**
TOTAL	131,627	157 + 56 = **213**	

Source: Number of SRs from consultations undertaken by MM
Area data from Water UK mapping (see Figure 20 and Figure 21 above)

A similar process was followed for SRs owned by “water only” companies (see Figure 21) and FSRs owned by public bodies. The analysis is not presented here to maintain anonymity of the organisations involved. In summary it is estimated that:

- water and sewerage companies in England own 213 SRs which are SRRs;
- “water only” companies in England own 36 SRs which are SRRs;
- public bodies own 19 FSRs which are SRRs.

The number of FSRs is possibly lower than anticipated but Mott MacDonald experience suggests that many smaller, local council owned FSRs tend to contain some water permanently and would therefore have been picked up by the GIS search.

On this basis the total number of SRs and FSRs which are SRRs in England is estimated at 268. The estimated margin of error in this estimate is ± 10% which is equivalent to a standard deviation of 5% for input to the Monte Carlo analysis.

268 represents 22% of the total of 1,235 from the previous section (2.5.6.1). This is significantly higher than a value of 10% which was assumed in the Halcrow research. It should however be noted that the Halcrow value was based purely on an assumption that the percentage of SRs and FSR would be less amongst SSRs than amongst LRRs where it is 14%. The actual data now available would suggest that this may have been an underestimate.

2.5.6.3 Estimate of total number of SRRs including SRs and FSRs

Combining the analysis of the previous two sub-sections (2.5.6.1 and 2.5.6.2), and repeating the Monte Carlo analysis, it is estimated that the total number of SRRs in England is as follows:

- most likely number of SRRs in England 1,503
- range of SRRs in England for 95% confidence 1,204 to 1,861

2.5.6.4 Comparison with previous research

The value of 1,503 stated above is some 25% greater than the previous estimate of 1,186.

The average water depth of an SRR assumed in the previous study was 1.0 m whereas the average water depth for the SRRs identified in this study is 1.7 m. In practice the actual average depth is likely to be slightly greater than 1.7 m because this study did not pick up reservoirs with surface areas less than 5,000 m^2. Notwithstanding this limitation, if an average depth of 1.7 m had been assumed, the Halcrow approach would have identified reservoirs with surface areas between 5,900 and 14,700 m^2, and the total number of SRRs would have been estimated at 1,919 (reference Table 2), an increase against the previous estimate of 62%.

In response to the specific questions in the Terms of Reference (ToR) (see section 1.2.3) in can be concluded that the likely number of SRRs in England does not lie between 1,150 and 1,300.

2.6 Sensitivity study on dam height

As outlined in Section 2.5.3.5, a member of the Project Working Group suggested measuring dam height relative to the flood plain rather than relative to the low point of the river channel as a means of estimating reservoir volume.

A sensitivity analysis has been undertaken on the reservoirs analysed from the sample of 500 water bodies by reducing the estimated dam height, recalculating the volume, recalculating the probability distribution and determining the effect on the estimated number of SRRs. The analysis excludes service reservoirs and flood storage reservoirs.

For the purposes of the sensitivity check it was agreed by the Project Working Group to reduce the estimated dam height by 0.6 m to allow for the presence of a narrow stream bed within the flood plain. This sensitivity check was applied to all reservoirs within the surface area bands of 5,000 m^2 to 20,000 m^2. The bands above and below this range were dealt with as follows:

- For the area band 3,000 m^2 to 5,000 m^2, an estimate of the probability that a reservoir is an SRR was calculated using linear interpolation as was done for the main analysis (see Section 2.5.5.5);
- Sensitivity analysis was not undertaken on the surface area bands between 20,000 m^2 and 50,000 m^2 because the volume data for this range was originally calculated using a variety of methods (such as bathymetric surveys, estimations from as-builts etc.) therefore the sensitivity on dam height is not applicable.

Therefore, the range of reservoirs analysed in the sensitivity test was those with surface areas between 3,000 m^2 and 20,000 m^2. Based on the main analysis as outlined Section 2.5.6, the total number of SRRs in this surface area range is estimated at 1,043.

For the part of the population subject to the sensitivity analysis, if the dam height were reduced by 0.6 m, the sensitivity analysis indicates that the estimated number of SRRs would decrease by approximately 27%. As an illustrative example, if the number of SRRs in the upper area band does not change, as well as no change in the number of SRRs, SRs and FSRs, then the overall number of SRRs would decrease from 1,503 to 1,220. This is shown in Table 13.

Table 13: Summary of dam height sensitivity check

SRR Sub-set	Main Calculation	Sensitivity Check
Area 3,000 m^2 to 20,000 m^2 (excludes SRs and FSRs)	1043	760
Area >20,000 m^2 (excludes SRs and FSRs)	192	192
SRs	249	249
FSRs	19	19
TOTAL	1,503	1,220

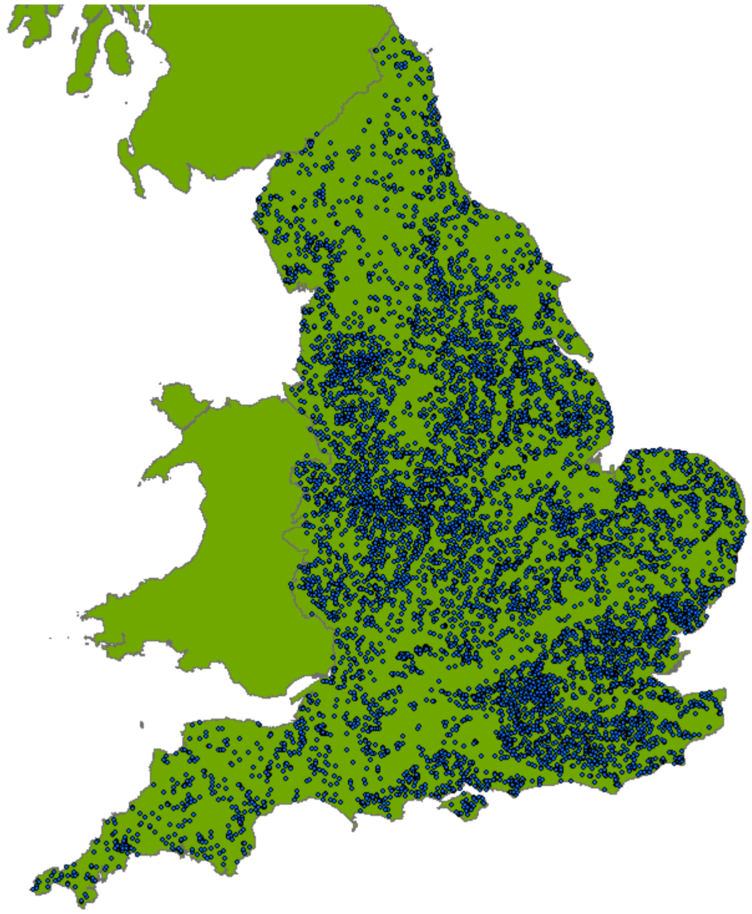
Within the surface area bands from 3,000 m^2 to 20,000 m^2 the reduction in estimated dam height returns a reduction in the estimated number of SRRs across all surface area bands. Although the surface area bands 20,000 m^2 to 50,000 m^2 are not part of this sensitivity analysis, in reality these upper bands would be expected to partially offset the decrease in the lower bands due to an anticipated increase in the number of SRRs where some of the dams which were previously estimated to be too large to form SRRs would now be reconsidered.

This sensitivity analysis shows that the number of SRRs is moderately sensitive to dam height, as would be expected. Further commentary on the method (and rationale) of measuring dam height is provided in section 2.5.3.

2.7 Location of SRRs

The SRRs are likely to be distributed randomly within the dataset of water bodies. Figure 22 shows the distribution of water bodies which demonstrates the likely spread of SRRs across the country.

Figure 22: Distribution of Water Bodies (blue dots) in England



Source: Halcrow; 2013 GIS Dataset

2.8 Conclusion

It is estimated that there is a total of 1,503 Small Raised Reservoirs in England and that there is 95% confidence that this value would lie in the range of 1,204 to 1,861.

3 Number of "High Risk" SRRs

3.1 Introduction

The objective of this section is to develop a refined estimate of the likely number of high risk SRRs in England.

3.2 Previous estimate of the number of "High Risk" SRRs

3.2.1 Previous Research: Method and Results

In order to estimate the number of "high risk" SRRs the previous research project considered a sample of 341 English SRRs across the Midlands, South West and Anglian regions (see Table 14 below) and assigned dam categories in accordance with the definition in Floods and Reservoir Safety (ICE; 2015).

Table 14: Results for SRR hazard classifications from Halcrow; 2013

Region	Total no. of SRRs	Category A	Category B	Category C or D	Fraction classified as Category A or B
Midlands	252	81	63	108	0.57
South West	32	4	12	16	0.50
Anglian	57	11	17	29	0.49
Total	**341**	**96**	**92**	**153**	**0.55**

Source: Table 3.6 of Halcrow; 2013

It was then assumed that Category A and Category B reservoirs would be "high risk" and that Category C and Category D reservoirs would be "not high risk".

According to section 3.3.2 of Halcrow; 2013; assuming that 55% of the predicted 1,186 SRRs would be "high risk" gives:

55% x 1,186 = **652 "high risk" SRRs**

3.2.2 Previous Research: Discussion

The assumption that Category A and B reservoirs would be "high risk" and category C and D reservoirs would be "not high risk" was a rational assumption at the time because the precise definition of "high risk" had yet to be finalised. The assumption was also in line with the methodology from the impact assessment on the changes to the legislation (Defra; 2011) which estimated that 45% of LRRs in England would be "high risk" on the same basis (but using data for LRRs).

Objective 1 of this research project was *"to evaluate the impact of the changes implemented in the first phase of the FWMA 2010 reservoir provisions in relation to large raised reservoirs (LRRs)".* The risk designation process was implemented by the Environment Agency in England. The outcome of the process has been that, of the LRRs that have been designated, only 12%, rather than the predicted 55%, of reservoirs have been designated as "not high risk" (Mott MacDonald; 2018a). Evaluation of the categorisation and risk designation processes has revealed that they are not compatible, and that it should not necessarily have been expected that Category C reservoirs would be designated "not high risk" (Mott MacDonald; 2018a).

3.3 Method

3.3.1 General

The basis of the research into the level of risk of SRRs, under this project, was to undertake risk designation determinations for 50 random SRRs. Dam break assessments were carried out for 40 of those SRRs. For the remaining 10 SRRs risk designation was determined through analysis of peak flow and inspection of the mapping, but without full dam break assessment. The 10 reservoirs adopted for this process were those taken from the random sample where there could be certainty of the risk designation without undertaking dam breach analysis. The agreed method for dam break assessment for the purposes of this research was the “dry day” scenario in accordance with the latest specification (Environment Agency; 2016).

3.3.2 Dam Break Assessments

3.3.2.1 Selection of sites for dam break assessment

Sites which were visited under this research project (see section 5) were given priority in the site selection for dam break assessment so that information gathered could inform the analysis where possible. Inevitably, not all sites which were visited were appropriate for dam break assessment. Table 15 below illustrates the process whereby sites were necessarily ruled out in a number of cases. It can be seen that of the 40 dam break assessments, 10 (no.) were visited. For information on the findings of the site visits refer to section 5.

For each selected site the raised volume of water was estimated based on measurements of dam height from Lidar. To ensure that risk designation was being applied to reservoirs of the correct volume, if the raised volume was estimated to be between 10,000 m^3 and 25,000 m^3 the site was retained, otherwise a new site was selected.

Table 15: Filtering sites visited for suitability for dam break assessment

Cumulative Filter	Number of reservoirs filtered out at each stage	Number of reservoirs remaining after filter applied
Visits	-	65
Filter out sites which are not reservoirs	26	39
Filter out sites where accurate measurement of dam height or depth of retained water was not possible	18	21
Recalculate estimate of volume based on actual dam height and surface area. For example for impounding reservoirs volume is assumed to be one third of dam height multiplied by surface area.	17	**10**

Source: Illustrative calculation to show reasons that a number of sites visited were excluded from dam break assessment

As required, new sites were selected randomly from the database of sites covered in desk studies in the previous research (Halcrow; 2013), again prioritising sites which had been visited followed by other sites for which there is existing information from desk studies. Where sites were selected from desk studies under previous research that existing data was used.

As such all selected sites are within the regions which have been studied to date including:

- Anglian;

- Midlands;
- South West; and
- Yorkshire and North East.

10 sites were identified for designation without dam break assessment. Those sites were considered to be the clearest designations; of those 10 designations four were designated as "high risk" and six were designated as not "high-risk". Dam break assessment was carried out for remaining 40 sites.

The locations of 50 sites for which risk designations were undertaken are shown in Figure 23 below.

Figure 23: Location of 50 Risk Designations

Source: Contains OS data © Crown copyright and database right (2018)

3.3.2.2 Specification

Consideration was given to whether dam breach assessment should be based on the 2009 RIM Specification (Environment Agency; 2009) or the more recent 2016 RFM Specification. The 2009 specification was used as an input to the risk designation of LRRs, but all flood maps are currently in the process of being remodelled using the 2016 Specification. To ensure consistency with the latest specification and to provide a measured and proportionate approach Mott MacDonald, Defra and the Working Group agreed that the modelling should be based on the "dry day" scenario from the 2016 RFM Specification.

It is nevertheless noted that neither the "dry day" nor the "wet day" scenario always provides the most conservative result and future risk designations will consider both "wet day" and "dry day" scenarios. However, a methodology for risk designation based on combined "wet day" and dry day" scenarios has not yet been established, so it was considered expedient to consider the "dry day" scenario only. Table 16 below summarises different specifications which were considered prior to selection of the specification.

Table 16: Comparison of Dam Break Specifications for Risk Designation

ASPECT	2016 DRY DAY (Environment Agency 2016)	2016 WET DAY (Environment Agency 2016)	2016 WET AND DRY DAY (Environment Agency 2016)	2009 (Environment Agency 2009)
Established methodology for risk designation	Not yet established – 2016 has not yet been used for risk designation but application should be straightforward.	Not yet developed – 2016 has not yet been used for risk designation. This is more complicated due to the need to analyse the incremental effect of the dam breach on the 1,000 year fluvial flood.	Not well established but will eventually become the standard method.	Established.
Consistency with existing risk designation process and historical reservoir inundation maps	This model run, when viewed in isolation, possibly risks missing receptors which would be counted under the wet day scenario.	This model run, when viewed in isolation, possibly risks missing receptors which would be counted under the dry day scenario.	Will supersede existing methodology.	Consistent with existing risk designation process which is currently being applied to statutory reservoirs.
Consistency for future risk designation and future reservoir inundation maps	Not consistent with existing risk designation process which is currently being applied to statutory reservoirs.	Not consistent with existing risk designation process which is currently being applied to statutory reservoirs.	Will supersede existing methodology.	Cannot be compared directly with future risk designation and reservoir inundation mapping.
Failure mode	Can be compared with future risk designation and future reservoir inundation mapping, although not fully without the wet day analysis.	Can be compared with future risk designation and future reservoir inundation mapping, although not fully without the dry day analysis.	Considers both overflowing and piping (for embankment dams).	Overflowing – more conservative peak flow.
Water level during breach, upstream of dam	Piping for embankment dams – less conservative peak flow.	Above crest (max 0.3m)- more conservative	Variable.	Above crest (max 0.5m) – more conservative.
Downstream river levels	Normal water level. Lidar picks up the actual water level on the day of survey.	0.1% Annual Exceedance Probability (AEP) flood.	Variable.	Downstream river levels taken into account using a factor incorporated into the breach flow hydrograph, giving a more conservative flow rate.
Minimum modelling requirements	1 model run	2 model runs	3 model runs	1 model run

Source: Environment Agency; 2009 and Environment Agency; 2016 were consulted. Table and text by Mott MacDonald.

3.3.3 Risk Designations

Following dam break modelling, standard risk designation forms for provisional designations were filled out for each of the 50 reservoirs (refer to Appendix C for risk designation forms and maps). The following key data is listed:

1. Reservoir Details, including:
   a. Reservoir name (and ID number from Halcrow; 2013)
   b. Location
   c. Grid Reference
   d. Reservoir volume at Full Supply Level (FSL)
   e. Dam height
   f. Maximum hazard designation
   g. Average Societal Loss of Life (ASLL)
   h. Number of breach locations modelled
   i. Max. unit discharge
   j. Max. properties at risk
   k. Max. population at risk
2. Correspondence received on reservoir flood maps – N/A for this project
3. Review of latest Section 10 Report - N/A for this project
4. Review of reservoir flood map
5. Is there infrastructure downstream that could endanger human life if damaged?
6. Recommendation by Qualified Civil Engineer (HIGH-RISK / NOT HIGH-RISK)

Following risk designation of 50 reservoirs the results were collated in a summary table which is presented in Appendix C.

Statistics presented in this report and in Appendix C are based on the automated outputs from the modelling using the National Receptor Database (NRD). There are cases where the results from the NRD differ slightly from the manual interpretation of the OS mapping and satellite imagery. The recommendation for risk designation is based on the results from the NRD as well as a comprehensive review of freely available mapping and satellite imagery.

The risk designation recommendations were made by an All Reservoirs Panel Engineer who was fully conversant with the process adopted by the Environment Agency for the risk designation of LRRs.

3.4 Comparison with LRRs

As part of this research the Environment Agency provided the following information, from their existing database, for all LRRs in England:

- risk designation;
- dam height;
- reservoir volume;
- reservoir surface area.

These data provided a useful comparison with the findings of the current research as detailed below.

3.5 Results

3.5.1 Risk designation

Of the 50 reservoirs assessed, 17 (34%) were considered to be "high risk" and 34 (68%) were considered to be "not high risk". A summary of the results is presented in Appendix C.

Average Societal Loss of Life (ASLL) was calculated for the 40 reservoirs which were modelled in detail. The average value of ASLL over the sample of 40 reservoirs is 0.012 with the spread of results summarised as follows:

- 26 SRRs from the sample of 40 showed an ASLL of zero;
- 39 SRRs from the sample of 40 showed an ASLL of less than 0.1;
- The maximum ASLL value was 0.3.

This demonstrates that most SRR failures would have a low ASLL, but there is a realistic chance that an occasional SRR failure could result in a large ASLL.

3.5.2 Analysis of trends

The data from the sample of 50 reservoirs has been analysed for the following trends:

- probability of being "high risk" against reservoir type (impounding / non-impounding);
- probability of being "high risk" against reservoir surface area;
- probability of being "high risk" against reservoir volume; and
- probability of being "high risk" against dam height.

Figure 24 to Figure 30 show the data for the SRRs compared with those for the LRRs.

No clear risk trends were identified for reservoir types, surface area or volume (Figure 25 to Figure 28). A trend was identified with dam height (Figure 29 and Figure 30). It is however considered that there is insufficient data to allow the overall percentage of "high risk" reservoirs to be calculated by any means other than applying the sample proportion to the overall population.

There is an apparent disparity in the data in that the percentage "high risk" for LRRs of 0 to 4 m high dams is 73% while the percentage high risk for SRRs 0 to 4 m high is 16%. This may be due to the peak outflow calculated for an SRR (2016 dry day specification) being significantly less than that calculated for an LRR (2009 specification) of similar height and volume due to the difference in the modelled reservoir level, the difference of the formula for calculating peak outflow and the "Factor of Safety" applied in the 2009 specification. Alternative explanations for this disparity are:

- that SRRs have a lower volume; but considering Figure 27 and Figure 28 below, for reservoirs of volume less than 100,000 m^3 there appears not to be any evidence from this research project that volume is linked to a higher probability of being "high risk";
- that even for this given range of dam height (0 to 4 m) the average dam height for SRRs is likely to be less than the average dam height for LRRs.

A comparison of the two methods for a typical SRR with dam height of 3 m and volume of 20,000 m^3 is shown in Table 17. It can be noted that, in this case, the peak outflow from the 2016 specification dry day breach is only 21% of the peak outflow from the 2009 specification.

Table 17: Peak flow comparison following dam break for a typical SRR

Specification	Dam Height (m)	Volume at TWL (m^3)	Area at TWL (m^2)	Breach Height (m)	Breach Volume (m^3)	Peak outflow (m^3/s)	Peak flow proportion of 2009 specification
2009	3.0	20,000	20,000	3.5	40,000	98	100%
2016 "dry day"	3.0	20,000	20,000	2.5	20,000	20	21%

Source: The 2009 RIM specification is referenced as Environment Agency; 2009. The 2016 RFM specification is referenced as Environment Agency; 2016.

Figure 24: Proportion of SRR sample which is "high-risk" by reservoir type

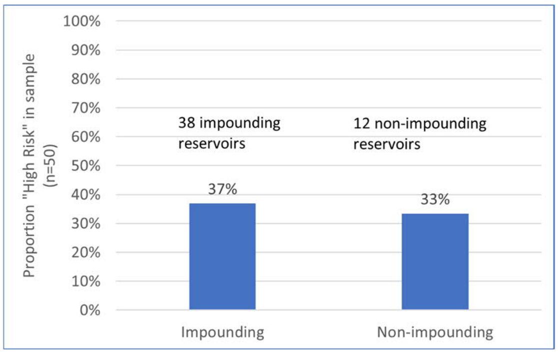


Figure 25: Proportion of SRR sample which is "high-risk" by surface area

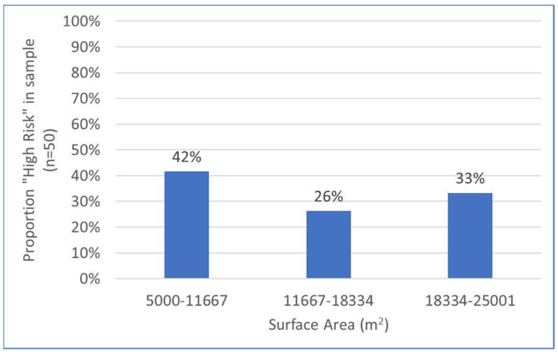
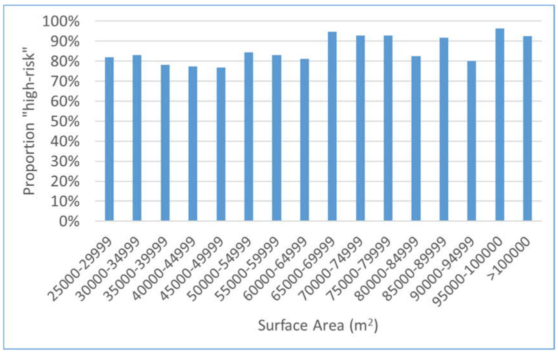


Figure 26: Proportion LRRs which are "high-risk" by surface area



Source: Environment Agency; 2018

Figure 27: Proportion of SRR sample which is "high-risk" by volume

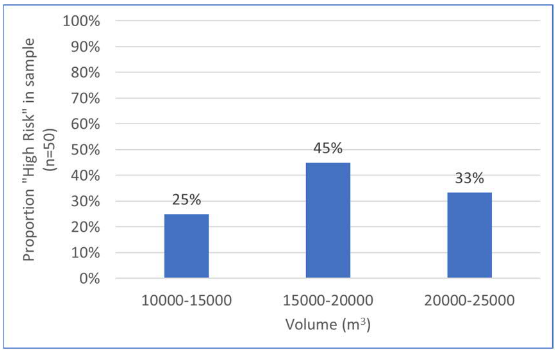
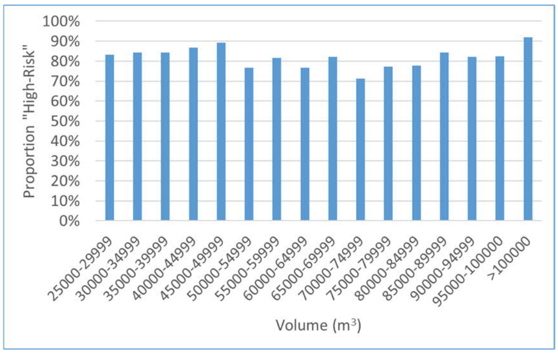


Figure 28: Proportion of LRRs which are "high-risk" by volume



Source: Environment Agency; 2018

Figure 29: Proportion of SRR sample which is "high-risk" by dam height

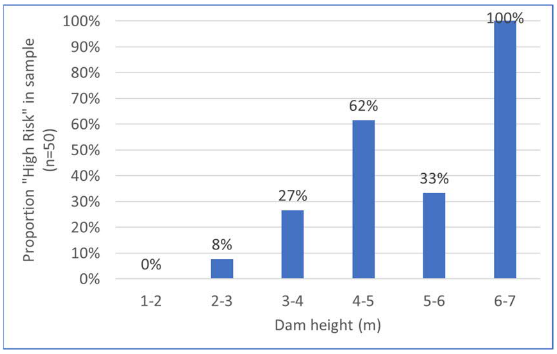
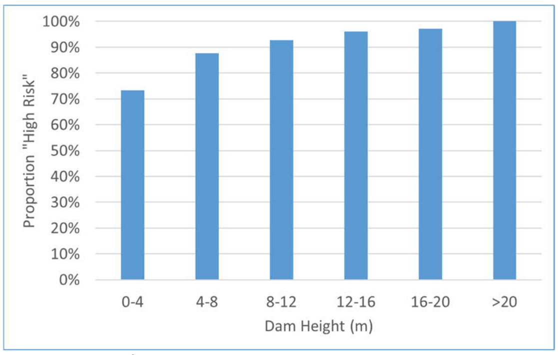


Figure 30: Proportion of LRRs which are "high-risk" by dam height



Source: Environment Agency; 2018

3.5.3 Proportion and number of SRRs with an anticipated "High Risk" designation

From the sample of 50 SRR risk designations, should those reservoirs be regulated under the Reservoirs Act 1975, it would be considered that:

- 34% would be "high-risk";
- 66% would be "not high-risk".

Based on the population size, sample size and the results it is estimated that for 95% confidence level of the margin of error in the above value is ±13%. This equates to a standard deviation of 6.5% for input to the Monte Carlo analysis.

There is also uncertainty relating to the dam breach methodology adopted for this study. The 2016 specification "dry day" scenario clearly generates much lower peak flows than the 2009 specification for SRRs. The impact of the "wet day" scenario depends on the relative magnitudes of the "dry day" outflow and the 1,000 year flood. If the dry day peak flow is greater than the 1,000 year flood then the area impacted is defined by the "wet day" scenario. Alternatively, if the "dry day" is less than the 1,000 year the area impacted is the "dry day" extent plus the incremental area of the "wet day" over the 1,000 year flood. Overall it was expedient for this project to adopt the "dry day" scenario as it reduced the modelling required and is considered to be a more realistic representation that than provided by the 2009 specification. That said, the use of just the "dry day" scenario is unconservative because consideration of both the "dry day" and the "wet day" scenario, considering the incremental impact above the 1,000 year fluvial flood extent, will inevitably identify an increased area of inundation.

3.5.4 Number of "High Risk" SRRs

Combining the analysis of the previous Section 3.5.3 with section 2.5.6.3 (number of SRRs) and repeating the Monte Carlo analysis, it is estimated that the total number of "high risk" SRRs in England is as follows:

Most likely number of "high risk" SRRs in England	511
Range of "high risk" SRRs in England for 95% confidence	306 to 754

This is similar to the previous estimate of 652 based on the Halcrow studies (Halcrow; 2013).

4 SRRs in Cascade

4.1 Introduction

FWMA 2010 enacted the ability for Ministers to implement legislation on reservoirs in cascade. At the time of this research project Ministers have not yet decided whether or how to legislate cascades and further evidence is being gathered under this project. Therefore, cascades are currently not considered in the determination of whether a reservoir falls under the ambit of the Reservoirs Act.

In determining the dam category in accordance with Floods and Reservoir Safety (ICE; 2015), and in determining whether a reservoir is "high-risk" or not; cascades of reservoirs downstream of an LRR are already considered, as recommended under Appendix 2 of Floods and Reservoir Safety and under the latest dam break specification (Environment Agency; 2016). However, reservoirs in cascade (large or small) which are upstream of the subject reservoir are not covered in the same way.

It is understood that Defra may consider legislating for cascade SRRs preferentially to the rest of the population of SRRs.

Specifically, this project aims to gather evidence on:

- the number of SRRs in cascade;
- the level of risk of SRRs in cascade.

4.2 Previous Research (Mott MacDonald; 2013a)

The Environment Agency commissioned Mott MacDonald to carry out the Reservoir Cascade Study (Mott MacDonald; 2013a) to advise on appropriate methodologies by which *"proximity to, or actual or potential communication with, another structure or area"* could be assessed.

The study does not directly inform this research project but is referenced for completeness. The study did however highlight the need to assess cascade reservoirs on a site-specific basis due to their complexity. The authors proposed the following process for implementation of the legislation:

1. GIS screening;
2. 2D hydraulic modelling of screened target reservoirs to determine those in cascade;
3. For those in cascade contact the Undertaker to inform them;
4. Undertaker registers reservoir.

4.3 Definition of Reservoirs in Cascade

4.3.1 Interpretation of FWMA 2010

Schedule 4 of the FWMA 2010 amended the Reservoirs Act 1975 by inserting section A1 (5):

"The Minister may by regulations provide for a structure or area to be treated as "large" by reason or proximity to, or actual potential communication with, another structure or area."

One interpretation of *"proximity to, or actual potential communication with, another structure or area"* could be multi-compartment reservoirs where the failure of one compartment could cause failure of an adjacent compartment. This scenario is already dealt with under the Reservoirs Act by treating multiple reservoirs as a single reservoir if there is a risk that the dividing wall could fail upon rapid drawdown (Mott MacDonald; 2013a).

The other interpretation of the wording in the Act is a "cascade failure" where a sudden release of water from an upstream reservoir flows into a downstream reservoir and exceeds the spillway capacity such that the dam of the downstream reservoir also fails. This subsequent failure may then go on to trigger further cascade failures downstream. This is the accepted interpretation for the purposes of this research project.

4.3.2 Combinations of Reservoirs in Cascade

Assuming an arrangement of two reservoirs in isolated cascade, it is considered that there are four combinations of SRRs and LRRs as shown in Table 18 below.

It is noted that there is currently no requirement for any existing reservoir to be able to safely absorb or pass through the breach flow from an upstream reservoir, therefore Table 18 below focusses on the regulation of the upstream reservoir which would reduce the potential for cascade failure of the downstream reservoir.

Table 18: Combinations of Reservoirs in Cascade

	Upstream LRR	Upstream SRR
Downstream LRR	• Both reservoirs regulated limiting the potential for cascade failure • Downstream reservoir taken into account for dam category and risk designation under latest guidance • NOT studied further under this project	• Upstream reservoir NOT regulated • Cascade arrangement NOT currently considered for dam category or risk designation • **Studied under this project**
Downstream SRR	• Upstream reservoir is regulated limiting the potential for cascade failure • Downstream reservoir taken into account for dam category and risk designation under latest guidance • NOT studied further under this project	• Both reservoirs NOT regulated • NO dam category • NO risk designation • **Studied under this project**

Where LRRs are the upstream reservoir in a cascade arrangement these combinations are omitted from further consideration under this study because in both cases:

- the upstream reservoir is already regulated limiting the potential for cascade failure; and
- the downstream reservoir is already considered as part of the risk designation and dam categorisation for the upstream reservoir.

Under this research project the project team and the working group agreed to consider combinations where SRRs are the upstream reservoir because in both of the above cases:

- the upstream reservoir is not regulated, typically giving rise to a relatively high potential for cascade failure; and
- the cascade arrangement is not currently considered as part of the risk designation or dam categorisation.

Cascades where an SRR is upstream of an SRR will be referred to as an SRR-SRR cascade in the remainder of this report. Cascades where an SRR is upstream of an LRR will be referred to as an SRR-LRR cascade in the remainder of this report.

4.3.3 Sensitivity Study on Cascade Reservoirs (Appendix D)

4.3.3.1 Introduction

As part of this research Mott MacDonald undertook a detailed sensitivity study in order to inform debate on the definition of cascade reservoirs. The full text of this sensitivity study is included in Appendix D.

Without a formal definition of reservoirs in cascade it would be impossible to estimate their number or level of risk. The objective of the sensitivity study was to identify options for the definition of cascade reservoirs in terms of height, volume, surface area and physical separation for the purposes of this research project.

The study modelled a dam breach and downstream attenuation for a range of input parameters assuming a generic river valley. The method followed is as described in the Interim Guide to Quantitative Risk Assessment (Defra; 2004). Refer to Appendix D for detail on the approach and its validity.

For each sensitivity plot two sensitivity variables were selected while keeping the other parameters constant. The following parameters were considered:

- the volume of the upstream reservoir;
- the height of the upstream dam;
- the cross section of the valley between the reservoirs;
- the longitudinal gradient of the valley between the reservoirs;
- the roughness of the valley between the reservoirs;
- the separation on the reservoirs.

The study was limited to pairs of reservoirs in cascade (as opposed to chains of several reservoirs) and the volume of an individual reservoir was limited to a maximum of 25,000 m^3 this being the current threshold for registration under the Reservoirs Act 1975.

4.3.3.2 Vulnerable Cascade Reservoirs

The Sensitivity Study (Appendix D) introduces a sub-set of cascade reservoirs where overtopping could lead to failure of the downstream reservoir. The worst credible situation which could provoke failure of the downstream reservoir is considered to be where the following conditions prevail at the downstream reservoir:

- it is already full to crest level as a result of fluvial flood event,
- it has small surface area providing minimal attenuation of an inflow,
- it has a 20 m length of crest which will overtop (possibly a low section within the overall crest).

In this situation a dam breach outflow of 5 m^3/s at the downstream reservoir could generate 300 mm of overflow at that downstream reservoir which could cause it to fail. Therefore, a cascade could be considered to be vulnerable to failure where the breach outflow from the upper reservoir exceeds 5 m^3/s at the lower reservoir.

4.3.3.3 Conclusions of the Study

The study showed that cascades are a complex issue and their definition is difficult. It was nevertheless clearly demonstrated that two reservoirs in close proximity, each of volume just under 25,000 m^3, would inevitably pose an elevated risk compared to a single reservoir of volume just over 25,000 m^3, all other parameters being equal. There is therefore clearly a potential case for considering cascades separately if there is a possibility that not all SRRs are to be regulated. As such, it was proposed that cascades be considered only where there is a high likelihood that they pose a higher risk than individual reservoirs. The reason for this was that it would be illogical to regulate cascade reservoirs in situations where they present less risk than individual SRRs. Based on the new research, the study suggested an arbitrary threshold for agreement with the project team and working group:

- a lower volumetric threshold for each reservoir, for example 15,000 or 20,000 m^3;
- a maximum separation of 5 km.

4.3.4 Agreed Definition of cascade reservoirs

Following the Sensitivity Study described in section 4.3.3 on 2nd February 2018 the project team and working group met and agreed on a working definition for the purposes of this research project as follows:

- SRR upstream of SRR
  - SRRs each with a minimum volume of 15,000 m^3 at a maximum separation (dam to dam along the line of the interconnecting watercourse) of 5 km;
- SRR upstream of LRR
  - SRR with a minimum volume of 15,000 m^3 upstream of an LRR with a maximum surface area of 50,000 m^2 at a maximum separation (dam to dam along the line of the interconnecting watercourse) of 5 km.

The surface area limit on downstream LRRs was adopted as being the maximum surface area at which the release from the upstream SRR might not be absorbed by the LRR without causing overtopping.

It is noted that, should the lower limit for regulation of reservoirs under the Reservoirs Act be reduced to 10,000 m^3 in England, this could open up the question of whether cascade combinations with total volume of more than 10,000 m^3 should be considered. This question is not considered further under this research project.

4.4 Method for estimating number of cascade reservoirs

To estimate the number of cascades in England the same sample of 500 water bodies was used as for the analysis of singular SRRs as described in section 2.5. This sample represents approximately 5% of the country and is shown on a map of England in both Figure 5 and Figure 6.

The area was agreed with the project team and the working group, and covers part of the north of England.

The sample is considered appropriate for research into cascades because:

- the area includes upland and lowland elevations. It is considered that cascades are typically only found in the upper parts of catchments in England and consideration of purely lowland areas would likely yield less meaningful results;
- it is representative; and
- it is of a significant size.

Following the analysis of the sample covered under section 2.5 it was found that out of 500 water bodies analysed there were:

- 140 raised reservoirs (excluding those which are already registered as LRRs);
- 53 of which have an estimated volume >10,000 m^3.

Notwithstanding the agreed definition, all raised reservoirs (excluding registered LRRs) with a volume greater than 10,000 m^3 were considered. Considering reservoirs with a lower volume ensured the availability of volume threshold sensitivity data which would otherwise have been missed. Also included in the sensitivity check were reservoirs with an estimated volume of slightly more than 25,000 m^3 which are not currently registered as LRRs. These were included in the sensitivity check to ensure that no reservoirs were missed completely.

Using a GIS platform, the process was then as follows:

- import background mapping, aerial imagery and Lidar data;
- import point file for all registered LRRs;
- import point file for the 53 non-statutory reservoirs with volume >10,000 m^3;
- analyse each non-statutory reservoir where there is another reservoir within 5 km recording:
  - whether each reservoir is an LRR or an SRR;
  - distance to downstream reservoir along the line of the watercourse;
  - volume of both reservoirs;
  - surface area of both reservoirs;
- based on the recorded data, establish which are cascade arrangements.

4.5 Results

Following analysis of 53 non-statutory reservoirs of volume >10,000 m^3:

- six cases were identified where a reservoir was within 5km of an upstream SRR;
- one SRR-SRR cascade arrangement was identified according to the definition; and
- zero SRR-LRR cascade arrangements were identified according to the definition.

The results are tabulated in Table 19.

Table 19: Results of Cascade Analysis

Upstream SRR			Downstream Reservoir				Cascade	
ID	Surface Area (m^2)	Volume (m^3)	LRR / SRR	Name or ID	Surface Area (m^2)	Volume (m^3)	Distance (m)	Cascade?
C10	15,006	12,005	SRR	C11	12,660	13,082	949	N
C11	12,660	13,082	LRR	Studley Royal Lake	45,088	60,000	807	N
C19	11,441	55,680	SRR	C30	5,418	13,184	819	N
C29	6,939	10,409	LRR	Roundhill	229,000	2,503,000	1,280	N
C46	**19,178**	**19,178**	**SRR**	**C45**	**15,415**	**15,929**	**1,334**	**Y**
C49	19,673	47,871	LRR	Waterloo Lake	144,000	616,000	1,220	N

Source: Mott MacDonald analysis of the GIS database from Halcrow; 2013

It can be seen that from the sample of 500 water bodies that six pairs of reservoirs were found of which only one met the agreed criteria. The reasons for the other five failing to meet the criteria were:

- case 1 (C10) – upstream and downstream SRR both less than 15,000 m^3 (Figure 31)
- case 2 (C11) – upstream SRR less than 15,000 m^3 (Figure 31)
- case 3 (C19) – downstream SRR less than 15,000 m^3

- case 4 (C29) - downstream LRR greater than 50,000 m^2
- case 5 (C46) – downstream LRR greater than 50,000 m^2

It should also be noted that there were many “apparent” cascade arrangements which were not picked up because either reservoir had a volume of less than 10,000 m^3. Satellite images of typical examples of such a cascade are shown in Figure 32.

Figure 31: Cases 1 (C10) and 2 (C11)

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 32: Apparent cascades not picked up due to low volume of one or both

Example A

Example B

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Two of those six cases listed have dam height >7 m which gives rise to a relatively high volume estimate, despite the current non-statutory status. As noted in section 4.4 these non-statutory reservoirs with estimated volume greater than 25,000 m^3 are included in the cascades study as SRRs so that they are not incorrectly omitted from the research.

It is further noted that all six cascades identified under the sensitivity test have a separation distance <1.5 km. This suggests that the agreed 5 km maximum separation may not be significantly constraining the number of cascades identified.

4.6 Extrapolation

To estimate the number of cascade reservoirs in England it is necessary to extrapolate the results to the broader population. It is only with extreme caution that such small numbers can be extrapolated to a broader population, although it is noted that statistically high or low results tend to have narrower margins of error for a given sample and population size.

The zero value for SRR-LRR cascades requires special consideration. Effectively zero is covering the range from 0.0 to 0.5, so for the purposes of extrapolation it should be taken as a value of 0.25.

Based on analysis of this sample alone it is concluded that there is:

- 1.0 SRR-SRR cascade out of 42 SRRs (2.4% of SRRs)
- 0.25 SRR-LRR cascades out of 42 SRRs (0.6% of SRRs)

Extrapolating these results directly to the number of SRRs from section 2.5.6.1 (1,235 excluding SRs and FSRs) gives:

- 29 SRR-SRR cascades
- 7 SRR-LRR cascades

Based on the sample size and the results it is estimated that for 95% confidence level of the margin of error in the above value is ±4.5% and ±3.0% for SRR-SRR and SRR-LRR cascades respectively. These values equate to a standard deviation of 2.3% and 1.5% respectively for input to the Monte Carlo analysis.

Taking the results above and repeating the Monte Carlo analysis, it is estimated that the total number of SRRs in England is as follows:

Most likely number of SRR-SRR cascades in England	29
Range of SRR-SRR cascades in England for 95% confidence	1 to 86
Most likely number of SRR-LRR cascades in England	7
Range of SRR-LRR cascades in England for 95% confidence	0 to 45

These cascades relate to pairs of reservoirs; this needs to be recognised in any subsequent considerations of regulatory burden. However, there is a valid argument that it is only the upstream reservoir in a cascade which needs to be regulated as it is the breach on the upstream reservoir which may trigger the cascade failure.

4.7 Level of risk of SRR cascades

For the purposes of this study, the definition adopted for cascades is that cascades should present a greater hazard than individual SRRs. It is thus clear, that, within the context of this report, cascade reservoirs present a higher hazard, and hence risk, than individual SRRs.

It should also be noted that an unregulated upstream SRR may significantly increase the probability of failure of a downstream SRR. This is because the probability of failure of the downstream SRR may become equal to the probability of failure of the upstream reservoir irrespective of the fluvial design standard of the downstream reservoir. That said, probability of failure is not currently taken into account in the risk designation process so this would not currently affect the risk designation.

Notwithstanding the above it must be appreciated that the procedure currently used for designation is binary; reservoirs are either “high risk” or “not high risk”. The relevance of increased risk is therefore to determine whether a higher proportion of cascade reservoirs would be “high risk” compared to individual SRRs. In this context it is considered that the impact of the increase in flow due to the breach of the downstream reservoir will change the risk designation from “not high risk” to “high risk” in only a minority of cases. This is because the flow is unlikely to increase by more than 100% (compared to the individual flow from either reservoir), assuming the reservoirs are of a broadly similar size, and the incremental increase in flood extent is likely to be relatively modest.

The potential for detailed dam break analysis of cascades was considered during the project, but it was decided not to undertake such work as the resources available were better utilised on more rigorous definition / identification of cascades (Mott MacDonald; 2018b).

It is further noted that the Reservoir Flood Mapping (RFM) project is currently underway and following completion (scheduled for 2019) there will be more evidence on the impact on cascades of LRRs (LRR-LRR).

4.8 Number of “high risk” SRR cascades

Without site specific analysis, there are too many variables to quantify the increased level of risk of SRR cascades compared to singular SRRs. The level of risk of cascades of SRRs compared to singular SRRs would only be considered significant if the cascade effect were expected to change “not high risk” singular SRRs to “high risk” cascade SRRs. While there is no research on this to date it is considered, as described above, that the probability that the cascade effect would change an SRR risk designation from “not high risk” to “high risk” is likely to be low and therefore that the level of risk of cascades of SRRs is similar to that for singular SRRs. Therefore, the proportion of SRR-SRR cascades which are “high risk” is estimated to be 34%, as derived in section 3.5.3.

In the same way the chances that an upstream SRR could cause a “not high risk” downstream LRR to become “high risk” is also likely to be low. Therefore, the proportion of SRR-LRR cascades which are “high risk” is estimated to be 88%, as described in the report for Objective 1 (Mott MacDonald; 2018a).

In summary it is estimated that the probability of:

- an SRR-SRR cascade being designated as “high-risk” would be 34% with a standard deviation of 6.4%
- an SRR-LRR cascade being designated as “high risk” would be 88% with a standard deviation of 0% (sample size equal to population size for the database of LLRs).

4.9 SRRs in Cascade: Conclusions

Combining the analysis of Sections 4.6 and 4.7, and repeating the Monte Carlo analysis, it is estimated that the total number of “high risk” SRRs in England is as follows

- Most likely number of “high risk” SRR-SRR cascades in England 10
- Range of “high risk” SRR-SRR cascades in England for 95% confidence 0 to 31
- Most likely number of “high risk” SRR-LRR cascades in England 6
- Range of “high risk” SRR-LRR cascades in England for 95% confidence 0 to 40

It should be noted that if all SRRs (i.e. between 10,000 m^3 and 25,000 m^3) were to be regulated, then these cascade reservoirs would be identified and regulated as singular SRRs according to the definition of cascades adopted under this project. Cascades are defined for the purposes of this project in Section 4.3.4.

5 Findings of visits to SRRs

5.1 Introduction

Site visits and consultations form an integral part of the broader body of research on SRRs going back as far as 2005. As stated in section 2.2.1 Halcrow visited or consulted on more than 100 water bodies from 2005 to 2013 to apply ground truthing to the body of research.

Mott MacDonald have significantly increased this type of research by:

- carrying out high level consultations with undertakers on portfolios of reservoirs including 225 SRRs (covered under section 6.3.1);
- visiting a further 65 water bodies (covered in the following sub-sections).

Figure 33: SRR in Yorkshire

Figure 34: SRR in Essex

5.2 Purpose of the site visits

The principal purposes of the site visits were:

- to assess the condition of SRRs across England;
- to add to the evidence base on sites which have a raised / not raised status of "undetermined" from previous desk studies;
- to collect data (height and freeboard) for dam break assessments and corresponding risk designations;
- ground truthing to better understand English SRRs:
  - for analysis of water bodies in GIS;
  - for dam break assessments;
  - for risk designation;
  - for analysing costs and benefits;
  - for understanding the types of SRRs;
  - for understanding ownership of SRRs
  - In the north of England;

– In an upland area.

5.3 Site Selection

In order to identify appropriate sites for inspection, desk studies were carried out using existing available data from previous research to locate water bodies of interest. The site visits were split into three categories:

- visits to non-statutory raised reservoirs in the Yorkshire and North East region (15 sites);
- visits to water bodies in the Midlands region with a raised/not "undetermined" status based on previous desks studies (22 sites); and
- visits to water bodies in the Anglian region with a raised/not "undetermined" status based on previous desks studies (28 sites).

Visits to water bodies with a raised/not raised category of "undetermined" were required to improve understanding of the "undetermined" water bodies. The previous research estimated that 28% of "undetermined" reservoirs were raised based on consultations/visits at 39 water bodies.

Following the site visits, the working group advised that new Lidar should be used to analyse a new sample of data and as such the "undetermined" category was no longer required due to the improved quality of data. For more information on the project timeline refer to Appendix E.

Visits to sites in Yorkshire and the North East were required to expand the study area into an upland area in the north of England.

It was considered that there would be limited benefit in visiting Service Reservoirs (SR) and that Flood Storage Reservoirs (FSR) would be difficult to locate. Therefore, SRs and FSRs were omitted from the site visits under this study.

Sites were targeted where public highways or footpaths were positioned in close proximity to the water body to ensure maximum probability of public access. Public footpaths and roads were close enough to almost all reservoirs to get a good impression of the general condition of the dam.

The sites are shown on a map in Figure 35.

Figure 35: Site visits undertaken on this project

Source: Contains OS data © Crown copyright and database right (2018)

Sites which were visited were given priority in the dam break analysis site selection so that information gathered could inform the analysis. Unfortunately, not all sites which were visited were appropriate for inclusion in the dam break assessment study (see Section 3.3.2.1). Table 15 (section 3.3.2.1) illustrates the process whereby sites visited needed to be ruled out in a number of cases.

Some sites had limited physical access, despite formal public rights of way. Where full access was not possible a general opinion was formed and all available information was gathered and supplemented through desk-based study using aerial imagery, Lidar, OS mapping and general research through internet search engines.

All reservoirs visited were embankment dams, none were of masonry or concrete. The site visits were of the following types of water body:

- 26 not raised reservoirs;
- 22 impounding reservoirs;
- 17 non-impounding reservoirs.

5.4 Condition Assessment

5.4.1 Introduction

Detailed information obtained from reservoir visits is included in Appendix B. This sub-section summarises the results from the condition assessment.

65 water bodies were visited with a surface area between 10,000 m^2 and 25,000 m^2, of which 39 were raised reservoirs. At the time it was considered that any raised reservoirs within that area band would also be SRRs (volume between 10,000 m^3 and 25,000 m^3). As the research progressed the criteria were refined as detailed in previous sections of this report. For the purposes of condition assessment, it was assumed that all 39 non-statutory raised reservoirs are SRRs since the general condition of reservoirs above and below 10,000 m^3 is not expected to differ significantly.

At each site, where access permitted, the following data was gathered:

- dam location (coordinates)
- dam type
- crest Level
- Top Water Level
- embankment toe level
- dam length
- overflow type, dimensions and approximate associated freeboard for all overflows
- description of any low level outlets or drawoff works
- general condition of upstream face protection, crest and downstream crest noting any evidence of instability
- evidence of seepage on the downstream face or downstream toe
- evidence on the degree of maintenance – vegetation clearance from the dam, spillways clear of blockage etc.
- apparent primary direction of flood flow in the event of a breach (can be useful to supplement LIDAR information at some sites)
- any other general comments relating to reservoir flood risk management
- photographs

5.4.2 Spillways

From previous research (Halcrow; 2012a) one of the major costs associated with bringing groups of SRRs up to the standard of statutory reservoirs is associated with new spillways or modifications to existing spillways. Typically, a statutory reservoir of any size would be required to have a formal spillway, usually in the form of:

- a concrete or masonry chute;
- a pipe through the crest of the dam;
- an open culvert; or
- a specially designed overflowable section of embankment.

Out of 39 SRRs visited:

- 23 (59%) had a spillway with no repairs noted;
- 1 (3%) had a spillway which required significant repair work;
- 15 (38%) sites have no obvious spillway system.

Of those which had a spillway which appeared to be in acceptable condition a proportion which would be designated "high risk" would likely require the spillway capacity to be increased following a flood study (or equivalent risk assessment for non-impounding reservoirs).

5.4.3 Freeboard

A closely related key cost item of regulating groups of new SRRs is associated with the adequacy of the freeboard. If the freeboard is considered insufficient at least one of the following would be required:

- dam raising to maintain existing top water level – capital cost implied;
- change in operational regime to reduce top water level – less storage implied; or
- lowering of spillway – capital cost and less storage.

Raising the dam crest could also increase the spillway capacity, therefore freeboard is linked to spillway capacity, which is covered under section 5.4.2.

The recommended freeboard of a statutory reservoir, as set out in FRSv4 (2015; ICE) is determined based on:

- dam category;
- flood rise allowance;
- wave overtopping allowance;
- risk assessment (subject to requirement).

In the absence of a detailed study for each of the reservoirs visited it is simplistically assumed that a freeboard of 0.75 m is required for “high risk” SRRs. On this basis out of 39 SRRs visited 14 cases (36%) were noted with insufficient freeboard.

5.4.4 Low level outlet

Low level outlets are not an absolute requirement for statutory reservoirs in all cases but are generally recommended so that the reservoir can be emptied in an emergency in case there is a need to:

- reduce the load on the dam; and
- reduce the volume of escapable water.

Out of 39 SRRs visited 36 cases were noted where no bottom outlet was found. High risk reservoirs where the dam height is greater than 5 m may need a low level outlet to be installed. Dams of lower height would need to be reviewed on a case by case basis.

5.4.5 Evidence of seepage

Wet areas of ground or flowing water at the toe of a dam can be an indicator of seepage problems which may require remedial works at some stage.

Seepage in the form of flowing water was not noted downstream of any of the dam sites. Six inspections out of 39 nevertheless reported wet ground at the downstream toe.

5.4.6 General condition

The overall condition of the reservoirs would need to be brought up to a satisfactory level if the reservoirs were registered as “high risk” in the future. Overall condition has been assessed based on the length and coverage of the grass on embankments, the management of trees and/or mammal burrows in the embankment and the general condition of any structures. A “good” or “satisfactory” overall condition does not indicate that the site does not need remedial works, for example a new spillway. The condition assessment is, rather, an indicator of the level of maintenance at the site.

At some sites access was limited to part of the site or a view of it. Reservoirs were assumed to be in a satisfactory general condition where the condition was neither notably good nor notably poor.

The photographs below show examples.

Figure 36: Example of "Good" Condition (Anglian Region)

Figure 37: Example of "Good" Condition (Yorkshire and North East Region)

Figure 38: Example of "Satisfactory" Condition (Anglian Region)

Figure 39: Example of "Satisfactory" Condition (Anglian Region)

Figure 40: Example of "Poor" Condition (Yorkshire and North East Region)

Figure 41: Example of "Poor" Condition (Midlands Region)

Out of 40 SRRs visited the general condition was categorised as follows:

- 8 SRRs (21%) in poor overall condition;
- 22 SRRs (56%) in satisfactory overall condition; and
- 9 SRRs (23%) in good overall condition.

5.4.7 Comparison with Previous Research

5.4.7.1 SRR General Condition Assessment

In December 2012 Halcrow issued the Flood Risk Assessment of Reservoirs for the Wessex Area (Halcrow; 2012b). The report formed part of the body of research later reported under Halcrow; 2013.

Halcrow undertook a condition assessment of 160 non-statutory reservoirs in Wessex through site visits. Condition was categorised as excellent, good, fair or poor and the results were as follows:

- 32 sites (20%) were "poor";
- 61 sites (38%) were "fair"; and
- 67 sites (42%) were "good" (43) or "excellent" (24).

Considering minor differences in the categorisation naming system, criteria and some subjectivity of condition assessment between dam engineers, the results are broadly in agreement with those in section 5.4.6. In particular the proportion of reservoirs in "poor" overall condition is approximately 20% under both studies.

Halcrow also made a high level assessment of which non-statutory reservoirs in South Wessex would require capital investment if designated "high risk". Out of 85 non-statutory reservoirs approximately:

- 20% required a technical study;
- 20% required management of trees;
- 10% required a dam raising;
- 20% required minor repairs to the dam;

- 40% required vegetation to be removed;
- 60% required upgrades to the spillway system.

These results validate the findings under this research project, and together these findings are developed further into costs under section 7.2.

5.4.7.2 SRR Condition Assessment by Mott MacDonald for a Water Company

In July 2013 Mott MacDonald carried out a condition assessment of five SRRs for a water company (Mott MacDonald; 2013b). Following a review of the site notes and photographs and adopting a consistent categorisation as for the sites visited under this project the sites are categorised as:

- 3 sites (60%) were in poor overall condition;
- 2 sites (40%) were in satisfactory overall condition;
- None of the sites were considered to be in good condition.

These sites were typically open lagoons for treatment works and in some cases were completely disused. Although typically inlet and outlet structures were generally appropriate to the type and use of the reservoir, the general lack of maintenance led to an overall "poor" condition at three sites out of five.

It is sometimes assumed that water companies have better reservoir maintenance standards for statutory and non-statutory reservoirs than individual private owners, but viewed in isolation this small study does not support that assumption.

5.4.7.3 SRRs Incidents Consultation by Atkins

Clearly reservoir safety incidents can occur at sites which are in "good" overall condition and conversely many years may pass without incident at a site which is in poor condition. However, for large groups of reservoirs, recorded incidents can be considered an indicator of poor condition. This is because the probability of failure is linked to condition.

In June 2013 Atkins carried out a consultation by contacting all Supervising Engineers and Inspecting Engineers (Atkins; 2013). 500 questionnaires were issued and 49 were returned documenting 53 separate incidents.

Incidents reported were mostly from recent years but also some incidents of high consequence were reported from as long ago as 1848.

In addition to appending all detailed responses to the questionnaire, the author gave three serious historical incidents summarised in Table 20.

Table 20: Serious Incidents at SRRs

Reservoir	Country	Year	Capacity (m^3)	Loss of Life
Skelmorlie	Scotland	1925	23,500	5
Bold Venture	England	1848	20,000	12
Clydach Vale	Wales	1910	15,000	5

Source: Atkins; 2013

The author argued that many SRRs are likely to be in poor condition:

"With the demise of industry in the areas where many of these dams exist (Yorkshire, Lancashire, Wales etc.) they have been left unattended, unmanaged, not maintained, not

visited…The majority of dams built which are under the 25000m^3 threshold were probably built with no formal engineering design or supervision."

It is therefore clear from historical evidence from Atkins; 2013, and supported by findings under this research project, that both probability and consequence of failure of SRRs (as a group – not all) are at tangibly high levels. This is also supported by the Environment Agency database of incidents recorded by the post-incident reporting system.

5.5 Summary

In summary:

- site visits were undertaken for ground truthing and condition assessment at 65 water bodies in the surface area range 10,000 m^2 to 25,000 m^2:
  - 39 raised reservoirs;
  - 26 non-raised water bodies;
- Some of the sites were taken forward to dam break analysis where:
  - They were non-statutory raised reservoirs;
  - Sufficient data was obtained at the site due to good access;
  - Volume was recalculated following the visit at between 10,000 m^3 and 25,000 m^3.
- data on "not raised" sites was gathered to inform the proportion of "undetermined" reservoirs which were actually raised; but refinements to the scope of the project meant that new data was analysed using high quality Lidar data and the "undetermined" status was no longer required;
- approximately 60% of SRRs had a spillway, but it is considered that about 70% of SRRs would require some spillway work or a new spillway if designated "high risk";
- approximately 40% of SRRs are considered to have insufficient freeboard;
- approximately 20% of SRRs are in a general poor condition indicating a lack of maintenance;
- previous research involving condition assessment broadly shows good agreement with the findings under this project;
- historical data on incidents at SRRs, some involving multiple loss of life, indicates that there is a realistic probability of failure of SRRs, which may be linked to poor condition.

6 Type and Ownership of SRR

6.1 SRRs by Type

6.1.1 This Research Project

Following desk-based assessment of 500 water bodies under this research project between surface area of 5,000 m^2 and 25,000 m^2; 42 were identified as SRRs. From 42 SRRs assessed:

- 23 (55%) were impounding SRRs;
- 19 (45%) were non-impounding SRRs; of which
  - 14 (33%) were fully bunded on all sides; and
  - 5 (12%) were partially bunded and partially formed against natural ground.

Partially bunded reservoirs are those which have no obvious water course and, although they may have a small surface drainage catchment, they do not impound a river and possibly rely on pumped inflow.

These proportions can be projected onto the broader population of 1,235 reservoirs (excluding SRs and FSRs) as follows:

- 679 impounding SRRs;
- 408 fully bunded SRRs;
- 148 partially bunded SRRs.

Furthermore, from consultations with water companies (section 2.5.6.2), it is estimated that there are approximately:

- 19 Flood Storage Reservoirs which are SRRs;
- 249 Service Reservoirs which are SRRs; of which
  - 213 are owned by water and sewerage companies;
  - 36 are owned by water only companies.

6.1.2 The Wessex Study

As a comparison, a sample of 160 non-statutory reservoirs from the Wessex Study (Halcrow; 2012b), was analysed:

- 139 (87%) were impounding reservoirs;
- 21 (13%) were non-impounding reservoirs.

The Wessex study shows lower proportions of non-impounding reservoirs and service reservoirs. It is not clear whether this is a regional difference or whether it is a product of the sampling method but it is known that the Wessex Study included reservoirs of volume less than 10,000 m^3.

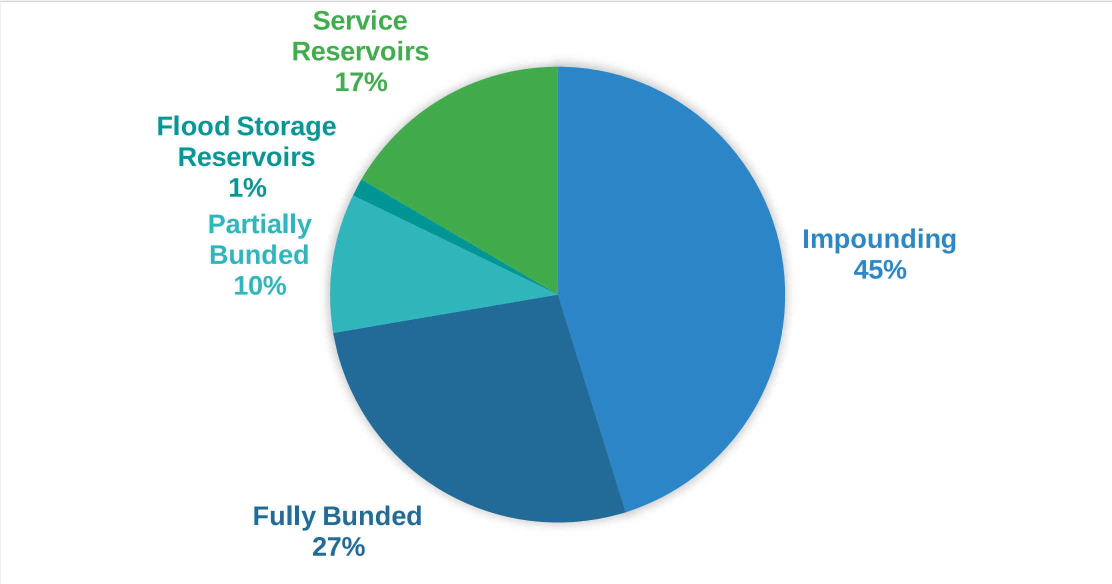
6.1.3 Summary of SRR Types

The results from this research project are summarised in Table 21 and Figure 42 below.

Table 21: SRR Types

Type	Estimated Number in England	Percentage
Impounding	679	45%
Fully Bunded	408	27%
Partially Bunded	148	10%
Flood Storage	19	1%
Service	249	17%
TOTAL	1,393	100%

Figure 42: Estimated numbers of SRRs by reservoir type



6.2 Construction material

6.2.1 This Research Project

Following desk-based assessment of 500 water bodies (excludes Service Reservoirs) between surface area of 5,000 m^2 and 25,000 m^2; 42 were identified as SRRs. From 42 SRRs assessed 100% were of earth embankment construction. The same 100% earthfill result was obtained from 39 site visits. This result represents all SRRs which are not service reservoirs or flood storage reservoirs.

For small samples of n≈50, a zero result represents the range 0% to 1% and should therefore be taken as the middle value of 0.5%, if the result is expected to be non-zero in reality.

This assumption can be projected onto the broader population of 1,235 SRRs (excluding SRs and FSRs) as follows:

- 1,229 (99.5%) embankment dams;
- 6 (0.5%) concrete/masonry dams.

It can be sensibly assumed that flood storage reservoirs (19 no.) are all of earth embankment construction.

It is estimated that there are 249 SRRs (18%) which are SRs which are likely to be constructed from concrete/brick.

Therefore, based on this data, it could be assumed that material properties of SRRs are:

- 1,248 embankment dams (1,229 + 19)
- 255 concrete / masonry / brick (249 + 6)

6.2.2 The Wessex Study

160 non-statutory reservoirs were analysed in the Wessex Study (Halcrow; 2012b):

- 152 (95%) earth embankments;
- 4 (2.5%) concrete; and
- 4 (2.5%) masonry.

This sample probably includes reservoirs of a volume less than 10,000 m^3 and therefore may not be entirely representative of SRRs. However, it has the advantage that it is of larger sample size and that most of the sites were visited by a reservoir engineer. None of the sites in this sample are SRs so it can be assumed that SRs were not included in the sample selection since this project predicts that 18% of SRRs are SRs.

6.2.3 Summary of SRR Construction Material

In England, it is estimated that there are:

- 1,248 (83%) embankment dams forming a SRR;
- 255 (17%) concrete / masonry / brick-constructed SRRs.

6.3 Ownership of SRRs

6.3.1 Data from consultations with water companies

From consultation with seven water companies, extrapolating for other water companies by surface area coverage, it is estimated that water companies own a total of 391 SRRs out of the total of 1,503 SRRs. This is 26% of SRRs. This estimate can be further broken down as follows:

- 300 SRRs (20%) belonging to water and sewerage companies;
- 91 SRRs (6%) belong to water only companies.

About two thirds of those SRRs owned by water companies are considered to be SRs.

6.3.2 Data from the Wessex Study

154 SRRs with some information on undertakers have been analysed from the Wessex Study (Halcrow; 2012b) and the data is summarised in Table 22 below.

Table 22: Undertaker Data from the Wessex Study

Undertaker category	No. in sample	Percentage
Quarry	1	0.5%
Charity	2	1%
Property Developer	2	1%

Undertaker category	No. in sample	Percentage
Fishing Club	3	2%
Water company	4	3%
Leisure Park (holiday, golf, safari)	6	4%
Public bodies	7	5%
Other private owner (not specified)	129	84%
TOTAL	**154**	**100%**

Source: MM data analysis from Halcrow; 2012b

This data does not include Service Reservoirs and as such it is likely that the proportion of reservoirs owned by water companies is disproportionately low. 84% of the data represents “private owners”, most of whom are likely to be owners of farms or large estates.

6.3.3 Summary of SRR ownership

Adjusting Table 22 by incorporating the data from water company consultation (section 6.3.1) gives the best estimate of SRR ownership based on the available data. This was then extrapolated to the broader population and tabulated below.

Table 23: Summary of SRR Ownership

Undertaker category	Percentage	Estimated no. in England
Water and Sewerage Companies	22%	300
Water only Companies	7%	91
Public bodies	4%	4% of 1,503 = 60
Leisure Park (holiday, golf, safari)	3%	3% of 1,503 = 45
Fishing Club	1%	1% of 1,503 = 15
Property Developer	1%	1% of 1,503 = 15
Charity	1%	1% of 1,503 = 15
SUB-TOTAL	39%	541
Other private owner	100% - 39% = 61%	1,503 – 541 = 962
TOTAL	100%	1,503

It is noted that some SRRs owned by leisure parks, fishing clubs, property developers and charities may also be captured under “private owners” therefore results should be treated with caution.

7 Benefits and costs of regulating SRRs

7.1 Benefits

7.1.1 Benefits of regulating SRRs in general

There are some non-statutory reservoirs with high standards of reservoir safety and good maintenance procedures. Regulation has the benefit of ensuring that a whole group of reservoirs are brought up to this high standard. Therefore, any benefits are considered in relation to the group of reservoirs under consideration, but do not necessarily apply directly to every reservoir.

A Guide to the Reservoirs Act (ICE 2014) states that "*it appears that each time safety legislation has been improved there has been an improvement in the dam safety record".* Indeed, since the first Reservoirs (Safety Provisions) Act 1930 was passed there have been no failures involving loss of life; although there have been failures of both statutory and non-statutory reservoirs (ICE 2014).

The overriding benefit is the reduction of the probability and consequence (for example through flood plans) of failure of the group of reservoirs. This key benefit, in the form of reservoir safety risk reduction, benefits:

- the public;
- the reservoir undertakers;
- the regulatory authority; and
- the reservoirs industry.

In addition to reservoir safety there are other benefits to the undertakers, taking the group of reservoirs as a whole:

- lower commercial risk of catastrophic failure;
- targeting reservoir investment;
- improved monitoring and management of leakage;
- improved monitoring practices;
- improved maintenance practices;
- improved security;
- regular advice from Qualified Civil Engineers (QCE).

A true benefit-cost analysis quantifies the benefits, but it is challenging when dealing with public safety in relation to the incremental probability of failure of a large group of reservoirs following a potential change in legislation. An estimate of benefit quantification is provided in section 7.1.3.

It must be emphasised that most of the 'costs' considered under section 7.2 are in the form of investments in reservoir infrastructure and in public safety, which is ultimately of considerable benefit to all parties involved. In the same way that "not high risk" statutory reservoirs do not require statutory inspections, if, following registration of SRRs, it can be shown that an SRR does not endanger human life, then under current guidance it would be designated as "not high risk" and there would be minimal cost to the undertaker. Conversely if the SRR is designated as "high risk" then there will clearly be considerable benefits of regulation in terms of reservoir safety.

From section 5.5 considering all SRRs, it is estimated that approximately:

- 20% are in poor condition overall;
- 40% do not have a spillway;
- 70% are expected to require some spillway works or a new spillway; and
- 40% have insufficient freeboard.

A portion of the remaining SRRs are likely to require further improvements following detailed study upon registration. By regulating SRRs, they would be brought up to the same standard as LRRs, which (if found to be "high-risk") are required to:

- be maintained to a reasonable standard;
- have sufficient spillway capacity; and
- have sufficient freeboard.

Maintaining this high standard would therefore clearly lower the risk to life from SRRs to what is "As Low As Reasonably Practicable" (ALARP).

7.1.2 Benefit of regulating cascades

The overriding benefits of regulating SRR cascades are similar to the benefits of regulating singular raised reservoirs as described in section 7.1.1. This sub-section specifically addresses additional benefits of regulating cascades.

Referring to Table 18, cascades where the upstream reservoir is an LRR are not covered under this project. The benefits of regulating reservoirs where the upstream reservoir is an SRR are principally:

- regulation of the upstream reservoir would limit the potential for the cascade failure to occur;
- regulation of the upstream reservoir would allow for the downstream reservoir and cascade effect to be considered during risk designation, dam categorisation and emergency planning for the upstream reservoir under current guidance.

Therefore, there would clearly be a benefit in regulating the upstream reservoir in a cascade situation.

There is less benefit in regulating downstream reservoirs in a cascade separately to singular reservoirs and doing so may not be justifiable. Registration of downstream SRRs, but not singular SRRs, would only make sense if the downstream reservoir were required to pass the flood wave from the upstream dam break, which is not consistent with existing dam safety legislation or guidance. This would be a separate research topic and is not considered further under this project.

In the same way that "not high risk" statutory reservoirs do not require statutory inspections, if, following registration of cascades, it can be shown that a cascade arrangement does not endanger human life, then under current guidance it would be designated as "not high risk" and there would be minimal cost to the undertaker. Conversely if the cascade arrangement is designated as "high risk" then there will clearly be considerable benefits of regulation in terms of reservoir safety.

It should also be noted that an unregulated SRR can increase the probability of failure of a downstream reservoir in cascade. This does not however impact on risk designation because risk is currently based only on hazard only and does not take account of probability of failure.

7.1.3 Quantifying benefits of regulating SRRs

7.1.3.1 General

A detailed cost-benefit analysis has not been undertaken under this project. Nevertheless, a high level assessment to estimate the public safety benefits from regulation of SRRs has been undertaken and is outlined in this section.

The general method was to estimate the average cost of a failure of an SRR assuming that a benefit proportionate to this value is realised if the SRR is regulated based on a decrease in probability of failure.

7.1.3.2 Probability of Failure

In terms of probability of failure of an SRR it has been assumed:

- that the current probability of failure of an SRR is 1 in 5,000 per year. This is based on four failures in England that have been documented by the Environment Agency from 2004 to 2017. This is assumed based on information provided by Alan Warren (Warren AL and Patten B; 2018) including subsequent consultation with the author. It should be noted that more incidents than this would probably have occurred as reporting for SRRs is not regulated and is not mandatory. A sensitivity test was carried out on probability of failure as reported later in this section.
- following regulation the probability of failure of an SRR would be reduced to 1 in 50,000. This is based on a high level assumption, agreed with the working group, that the probability of failure through regulation would reduce by one order of magnitude. This represents a 90% reduction in the costs of failure through regulation.

It should be noted that these assumptions are based on an order-of-magnitude level judgement in order to generate a starting point for decision-making. The data used to consider the current probability of failure spans only 14 years. There is no data on the effects of regulation on failure rates, other than the fact that there has been no loss of life caused by the dam failures over 88 years since the Reservoirs (Safety Provisions) Act 1930. In the 88-year period prior to the 1930 Act 325 lives were lost from failures of reservoirs of volume greater than 25,000 m^3 in England, namely at Dale Dyke (244) and Bilberry (81) (CIRIA; 2014). However, over the last two centuries other factors (such as construction methods and other legal and cultural changes) have certainly had an impact which makes a direct comparison difficult.

7.1.3.3 Damages in the event of a failure

The 40 SRRs used for the dam breach section of the risk designation exercise, detailed in section 3, were used as the basis for the calculation of damages in the event of a breach of an SRR. The dam breach modelling gives the Average Societal Loss of Life (ASLL) and Maximum Properties at Risk for each site. It should be noted that the automated generation of ASLL and property numbers based on the National Receptor Database is the basis for benefits analysis here. Detailed cross-checking with alternative sources such as Ordnance Survey mapping has not been incorporated for the purposes of benefits calculation. The average impacts of the failure of an SRR were found to be:

- Average “Average Societal Loss of Life” (ASLL) = 0.012 per SRR failure
- Average “Maximum Properties at Risk” = 1.7 properties affected per SRR failure

The spread of the results for ASLL is summarised as follows with further detail in Appendix C:

- 26 SRRs from the sample of 40 showed an ASLL of zero;

- 39 SRRs from the sample of 40 showed an ASLL of less than 0.1;
- The maximum ASLL value was 0.3.

This demonstrates that most SRR failures would have a low ASLL, but there is a realistic chance that an occasional SRR failure could result in a large ASLL.

The damages-related parameters used to develop an estimate of benefits were as follows:

- ASLL was multiplied by a value per person, known as the Value to Prevent a Fatality (VPF). The selected value is £1.7 million based on the guide to Risk Assessment for Reservoir Safety Management (RARS) guidance (Environment Agency, 2013c). This value was inflated to present day using the Consumer Price Index (CPI), which is typically used to inflate flood damages. VPF is calculated to be equivalent to approximately £2.0 million in January 2018.
- Maximum Properties at Risk was multiplied by a value per property to account for flood damage. The selected value is based on £44,000, based on the RARS guidance for damage from inundation up to 3 m. The dam breach assessments from this research project show that (in the event of a failure at all 40 sites) no properties would be flooded to a depth of more than 3 m. With inflation to January 2018 (using CPI), the flood damage value is calculated to be equivalent to approximately £58,000 per affected property. Note that this analysis does not include additional effects of water velocity and debris which could increase the damage.

7.1.3.4 Annual Benefits Assessment

To summarise findings and assumptions related to probability of failure (POF) and Average Societal Loss of Life (ASLL) from parts 7.1.3.2 and 7.1.3.3:

- Current POF = 1 / 5,000 per SRR per year;
- Regulated POF = 1 / 50,000 per SRR per year;
- Average ASLL = 0.012 persons per SRR failure.

Given that there are an estimated 1,503 SRRs in England and on the basis of the above bulleted findings and assumptions, the expected number of lives lost from SRR failures in England over a 100 year period is 0.4 persons (1,503 x 0.012 x 100 / 5,000). This is the data which has been used to estimate the benefits. This aligns with the fact that there have been zero lives lost from SRRs in England over the last 100 years (CIRIA; 2014).

On the above basis the cost of failure of a singular SRR has been calculated, and then multiplied up in accordance with the estimated number of SRRs in England (1,503 as per Section 2.5.6). Note that this includes both HR and NHR SRRs. The results of the calculation are shown in Table 24.

The cost in the first row represents the hypothetical cost should all SRRs in England fail simultaneously. This has then been scaled in proportion to an annual probability of 1 in 5,000 (assumed before regulation) and 1 in 50,000 value (assumed after regulation).

The analysis was repeated for cascades, assuming that a cascade failure would incur the same cost of failure as a singular SRR. The benefit of regulating a cascade may, in reality, be higher than the benefit of regulating a singular SRR but cascades are complex and this simplification has been adopted given the uncertainty around:

- whether one or both would be regulated;
- how high-risk cascades would be defined;

- cascades of several reservoirs; and
- the true damages from a typical cascade failure, given that dam break analysis for cascades was not undertaken under this project.

Consideration should be given to applying a factor of between 1.0 and 2.0 to the benefits of regulating cascades to account for the cascade effect.

Total number of cascades of 36 used as per section 4.6.

Table 24: Estimation of annual benefits of regulating SRRs

Scenario	Annual Probability of Failure (POF)	ASLL damages	Property damages	Total damages
ALL SRR INCLUDING CASCADES				
Total failure	1 in 1	£36,400,000	£87,700,000	**£124,000,000**
Before regulation	1 in 5,000	£7,290	£17,500	**£24,800**
After regulation	1 in 50,000	£730	£1,750	**£2,480**
Total annual benefit (1,503 SRRs)		£6,560	£15,800	**£22,300**
ONLY SRR CASCADES				
Total failure	1 in 1	£873,000	£2,100,000	**£2,970,000**
Before regulation	1 in 5,000	£180	£420	**£600**
After regulation	1 in 50,000	£20	£40	**£60**
Total annual benefit (36 cascades)		£160	£380	**£540**

For completeness the capital benefit (comparable to the capital cost) is assumed to be zero.

This analysis does not take account of the following:

- Damage to other infrastructure (e.g. roads, rail)
- People at risk on transportation links
- Business or industry at risk
- Community health impact
- Economic activity (e.g. agriculture, traffic delays)
- Organisational costs to emergency services and Environment Agency
- Environmental; including ecological, cultural heritage
- Negative publicity
- Other unforeseen benefits.

Therefore, the comprehensive benefits are expected to be higher than estimated here.

7.1.3.5 The Proportion Factor (PF)

In addition, a proportion factor (PF) as discussed in RARS (Environment Agency, 2013c) has not been applied under this analysis, and should be considered if comparing costs with benefits or undertaking benefit-cost analysis. This factor allows for the justifiable costs of preventing a fatality to be greater than the benefits, as per the equation below, to allow for errors in estimates of cost and benefits and to ensure a conservatively robust analysis.

Proportion factor (PF) = Cost to prevent a fatality (CPF) / Value to prevent a fatality (VPF)

The guidance gives examples of PFs for justifiable investments varying up to a factor of 10 for various industries and circumstances, 10 being for higher probability scenarios. According to RARS, *"Hughes and Gardiner (2004) present a disproportionality factor which varies with probability of failure (POF), from 3 at POF of 10^{-6} to 10 at POF of 10^{-4}."* (Environment Agency 2013c). Therefore, for detailed benefit-cost analysis, costs may be acceptable even if significantly higher than the benefits. The probability of failure for an SRR is considered to be of the order of 10^{-4}, in accordance with the discussion above in section 7.1.3.2. Therefore, it would not be unreasonable to adopt a PF of 10 as a starting point when considering the POF as well as the uncertainty in the estimation of costs and benefits and the importance of the potential consequences of the analysis.

7.1.3.6 Sensitivity Analysis

A sensitivity test was carried out on the probability of failure (POF) as follows:

- Pre-regulation POF changed from 1/5,000 (main calculation) to 1/1,000 (sensitivity);
- Post-regulation POF changed from 1/50,000 (main calculation) to 1/10,000 (sensitivity);

The working group suggested these POFs prior to a review of recent data on failures of SRRs (Warren AL and Patten B; 2018) which although not adopted for the main calculation, are tested here for sensitivity.

The resultant benefits for this scenario are shown below in Table 25.

Table 25: Estimation of benefits of regulating SRRs – sensitivity

Scenario	Annual Probability of Failure (POF)	ASLL damages	Property damages	Total damages
ALL SRR INCLUDING CASCADES				
Total failure	1 in 1	£36,400,000	£87,700,000	**£124,000,000**
Current	1 in 1,000	£36,400	£87,700	**£124,000**
After regulation	1 in 10,000	£3,640	£8,770	**£12,400**
Total annual benefit (1,503 SRRs)		£32,800	£78,900	**£112,000**
ONLY SRR CASCADES				
Total failure	1 in 1	£873,000	£2,100,000	**£2,970,000**
Current	1 in 1,000	£870	£2,100	**£2,970**
After regulation	1 in 10,000	£90	£210	**£300**
Total annual benefit (36 cascades)		£790	£1,890	**£2,680**

7.2 Costs

7.2.1 Introduction to costs

Estimates of costs for regulating SRR are predominantly based on previous research. The most relevant existing research is a study by Halcrow in 2012 (Halcrow; 2012b) of statutory and non-statutory reservoirs in the Environment Agency Wessex Region. The study included indicative estimates of the costs required to bring non-regulated reservoirs up to the standard required for regulated reservoirs. Mott MacDonald also have access to a confidential report (Mott MacDonald; 2013b) on the assessment of non-statutory reservoirs for a water company.

All costs detailed in this report are excluding VAT and to January 2018 prices. Where costs have been adopted from a literature review of other studies they have been inflated using construction prices indices. Halcrow; 2012b states that the price basis in that report is the *"end of phase 2"* which is assumed to be January 2012. Mott MacDonald; 2013b is assumed to be to price base of July 2013 as per the date of the report.

Costs exclude any costs to the enforcement authority of identifying the SRRs. The cost will depend on the adopted approach and the resources allocated; the potential methodology is discussed in section 8.2.6. Additional costs to the enforcement authority such as risk designation and mapping are included in the following sections.

It is emphasised that most of the "costs" considered under the following sub-sections are in the form of investments in reservoir infrastructure and in public safety, which is ultimately of considerable benefit to all parties involved. A true benefit-cost analysis would also quantify those benefits, but this would be difficult when dealing with public safety and an incremental change in probability of failure of a large group of reservoirs in the context of a potential change in legislation.

Costs are averaged across groups of reservoirs; so while some capital costs may seem low, for example for capital works, it may be that several sites require no works which reduces the average cost.

Costs have not been considered for the "Do Nothing" option, and although not easily quantifiable, there is a cost associated with having different laws and regulations in England, to other parts of the UK. Consistent laws and regulations can give rise to streamlined approaches, research efficiencies, common training and better understanding of the requirements.

7.2.2 Capital (one-off) costs

7.2.2.1 "Not high risk" SRRs

The capital cost allowance for a "not high risk" reservoir is based on an estimation by the EA (Environment Agency 2018b). The following elements are relevant to this section:

- The cost to identify additional SRRs is approximately £400 per SRR;
- The cost to map new SRRs is approximately £1,000 per SRR;
- The cost of risk designation for new SRRs is approximately £200 per SRR;
- The total of the above is approximately **£1,600 per SRR**.

7.2.2.2 "High Risk" SRRs (excluding SRs)

"High risk" reservoirs will be inspected by QCEs and subsequently studies and works may be required by law.

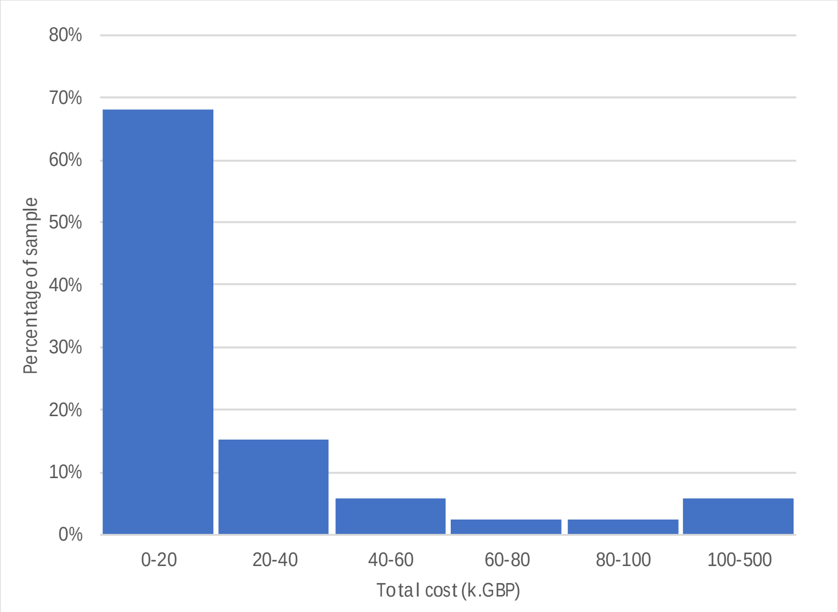
Halcrow visited 85 SRRs in South Wessex and carried out rapid flood and geotechnical risk assessments for each SRR (Halcrow; 2012b). They then estimated the capital costs to bring those SRRs up to the standard required of a "high risk" statutory reservoir (Halcrow; 2012b). Based on Mott MacDonald analysis of the Halcrow data (including increasing to account for inflation), the average cost, increased to account for inflation, is £27,600 with the equivalent costs at individual reservoirs varying up to about £0.5 million. Figure 43 shows the distribution of costs further, showing that the majority of costs are between £0 and £20,000. Table 26 outlines costs per remedial work type.

Table 26: Estimated capital costs required at a sample of SRRs across remedial work types

Remedial work type	Average cost per SRR /1000 GDP	Range of costs (exc. £0) /1000 GDP	Proportion of SRRs needing intervention
Raising	£3.1	£5 - £100	11%
Spillway	£12.4	£2 - £95	65%
Dense vegetation	£0.7	£0.5 - £5	35%
Trees	£0.9	£2 - £5	16%
Wave protection	£0.4	£2 - £15	5%
Discontinuance	£5.3	£400	1%
Grouting	£0.9	£10 - £30	5%
Dam repair	£2.6	£0.5 - £50	24%
Structure repair	£0.6	£2 - £20	5%
Pipework	£0.1	£5	1%
Study	£0.6	£0.5 - £5	16%
Total	**£27.6**	**£1 - £400**	**94%**

Source: Data from Halcrow; 2012b. Interpreted by Mott MacDonald

Figure 43: Estimated capital costs required at a sample of SRRs



Source: Data from Halcrow; 2012b. Interpreted by Mott MacDonald

The equivalent cost per reservoir from the assessment of 48 non-statutory reservoirs for a water company (Mott MacDonald; 2013b) was £7,000, but it is pertinent to note that none of these reservoirs were assessed to require significant capital works. As such it is considered that they may not be representative of the overall population of SRRs.

Both of these studies are likely to include reservoirs of volumes less than 10,000 m^3 and as such average costs for SRRs (which have volume greater than 10,000 m^3) may be higher. On balance it is considered prudent to adopt the higher of the two estimates. It is noted that in both reports it is assumed for each reservoir that it would be “high risk”.

It can therefore be assumed that, following "high risk" designation, the estimated average cost per "high risk" SRR to bring the reservoir up to the standard of a "high risk" statutory reservoir is therefore £27,600. Adding in the cost of £1,600 (see 7.2.2.1) for identification, flood mapping and risk designation gives a total estimate of **£29,200**.

7.2.2.3 Service Reservoirs

The above cost analyses do not include Service Reservoirs (SRs) and it is considered that SRs, in general, tend to be better maintained, designed and built and typically have lower probability of failure. Mott MacDonald; 2013b estimated the capital cost of bringing a "high risk" SR up to the standard of a "high risk" statutory reservoir at about £3,400. Adding in the cost of £1,600 (see 7.2.2.1) for dam break analysis and flood mapping gives a total estimate of approximately **£5,000**.

These costs include an estimate for:

- initial registration / potential appeals to risk designation;
- reservoir Flood Mapping (dam break analysis);
- one-off maintenance improvements;
- preparation of an emergency plan.

7.2.3 Recurring annual costs

Mott MacDonald; 2013b estimated the annual costs relating to SRRs for a water company. These are considered applicable and are adopted here. An additional £400 per SRR (whether high risk or not) has been included to account for the cost of regulation by the EA (Environment Agency 2018b).

Estimated costs adjusted to 2018 prices are:

- **£12,200** per year for "high risk" open SRRs;
- **£6,700** per year for "high risk" SRRs which are service reservoirs;
- **£400** "not high risk" reservoirs (cost of regulation only).

These costs include an estimate for:

- Supervising Engineer;
- Inspecting Engineer;
- Reservoir Safety Coordinator;
- additional remedial works arising from subsequent Section 10 inspections;
- crest levelling;
- weekly reservoir surveillance visits and Operations support;
- additional maintenance over and above current maintenance; and
- cost of regulation by the Enforcement Authority.

It should be noted that research commissioned by the EA (Environment Agency 2018c) into breach prediction, unpublished at the time of drafting this report, includes an indicative estimate of re-occurring annual costs of maintaining a dam (LRR) in England. This has been provided by the project working group and gives the following indicative costs, based on an average of 3 large dams[2] in England;

- £98,000 per year for large dams, £65,000 of which is for remedial works arising from Section 10 inspections
- £24,500 per year for 'other UK dams' (i.e. the remaining LRRs), £16,300 of which is for remedial works arising from Section 10 inspections. This was estimated based on an assumption that the costs would be 25% of the large dam cost.

These costs, from Environment Agency 2018c, include an estimate for:

- Surveillance
- Maintenance
- Management
- Emergency Planning
- 'Capital spend – precautionary' i.e. remedial works arising from Section 10 inspections

While these costs are higher than those by Mott MacDonald 2013b, the costs are based on LRRs, assumed to be high risk, which could generally be assumed to be more expensive.

7.2.4 Estimated total Costs for all SRRs in England

Unit costs have been established for SRRs which are, and are not, service reservoirs, as well as for SRRs which are, and are not, "high risk".

From section 6.1.3 there are estimated to be 1,503 SRRs in England of which 249 are estimated to be service reservoirs. From section 3.5.3, 34% of SRRs are estimated to be "high risk". Therefore, it is estimated that there are:

- 1,254 SRRs excluding SRs (1,503 – 249), of which
  - 426 "high risk" (34%)
  - 828 "not high risk" (66%)
- 249 SRRs which are SRs, of which
  - 85 "high risk" (34%)
  - 164 "not high risk" (66%)

Based on the unit costs estimated earlier in section 7 the cost estimate for capital cost and recurring annual costs are estimated in Table 27.

Table 27: Estimated costs for regulating SRRs

		Capital Cost		Recurring Annual Cost	
SRR Type	No.	Unit Cost / GBP	Total Cost / GBP	Unit Cost / GBP	Total Cost / GBP
HR SRR (excl. SR)	426	£29,200	£12,439,000	£12,200	£5,197,200
NHR SRR (excl. SR)	828	£1,600	£1,325,000	£400	£331,200
HR SR SRR	85	£5,000	£425,000	£6,700	£569,500
NHR SR SRR	164	£1,600	£262,000	£400	£65,600
Total (England)	**1,503**		**£14,500,000**		**£6,200,000**

[2] Based on the ICOLD definition; 15m height or greater from lowest foundation to crest or a dam between 5m and 15m impounding more than 3 million m^3. Accessed online [http://www.icold-cigb.net/GB/dams/definition_of_a_large_dam.asp]

7.2.5 Estimated total Costs for regulating SRRs in cascade

From section 4.9 it is estimated that there are:

- 29 SRR-SRR cascades of which 10 are estimated to be “high risk”; and
- 7 SRR-LRR cascades of which 6 are estimated to be “high risk”.

Based on the unit costs estimated earlier in section 7 the cost estimate for capital cost and recurring annual costs are estimated in Table 28 below. For the purposes of costing it has been assumed that for any cascades only the upstream reservoir would require regulation.

Table 28: Estimated costs for regulating SRR cascades

		Capital Cost		Recurring Annual Cost	
Cascade Type	No.	Unit Cost / GBP	Total Cost / GBP	Unit Cost / GBP	Total Annual Cost / GBP
HR SRR-SRR	10	£29,200	£292,000	£12,200	£122,000
NHR SRR-SRR	29 – 10 = 19	£1,600	£30,400	-	-
HR SRR-LRR	6	£29,200	£175,000	£12,200	£73,200
NHR SRR-LRR	7 – 6 = 1	£1,600	£1,600	-	-
Total (England)	**36**		**£500,000**		**£195,000**

It is noted that should singular SRRs be regulated (see section 7.2.4) SRR cascades would be covered and the costs in Table 28 would not apply.

7.3 Summary

7.3.1 General

Costs (and benefits) have not been considered for the “Do Nothing” option, and although not easily quantifiable, there is a cost associated with having different laws and regulations in England, to other parts of the UK. Consistent laws and regulations can give rise to streamlined approaches, research efficiencies, common training and better understanding of the requirements for all stakeholders. This same “cost” has also been excluded for cascades.

Unit costs, assumptions, inclusions and exclusions are further detailed in the preceding sub-sections. Costs and benefits are estimated to a January 2018 basis.

Total costs are generally rounded to the nearest £100,000. If singular SRRs are regulated, then cascades are covered anyway therefore the cost for cascade SRRs is a sub-set of the cost for the full set of SRRs. In this respect the two sets of costs and benefits cannot be summed.

The benefits of cascades are complex and there is limited evidence available for their quantification. Therefore, the benefit for regulation of a cascade of SRRs is assumed to be the same as for a singular SRR. Consideration should be given to applying a factor of between 1.0 and 2.0 to the benefits of regulating cascades to account for the cascade effect prior to any detailed comparison between costs and benefits.

RARS guidance (Environment Agency; 2013c) indicates that costs may justifiably be up to 10 times more than the benefits – this is known as the Proportion Factor (PF). PF should be taken into consideration for any detailed comparison of the costs and benefits. Given that the POF for an SRR is considered to be of the order of 10^{-4} it would not be unreasonable to adopt a PV of 10 as a starting point.

7.3.2 Benefits

Although a cost-benefit analysis has not been undertaken at this stage, a high level assessment to estimate the public safety benefits from regulation of SRRs has been undertaken, based on attributing a cost to ASLL and property damage and assuming a reduction in probability of failure by one order of magnitude from 1 in 5,000 to 1 in 50,000. The results of this are summarised in Table 29. It should be noted that the true benefit is likely to be notably higher when considering the wider impacts of failure.

Table 29: Average Benefit per Regulated SRRs

		Recurring Annual Benefit	
	No.	Benefit / GBP	Average Benefit per SRR / GBP
Cascade SRRs (only)	36	£540	£15
Singular SRRs (includes cascades)	1,503	£22,300	£15

For completeness the capital benefit (comparable to the capital cost) is assumed to be zero.

It should be noted that the value of the benefits are extremely sensitive to the assumed value for the reduction in probability of failure.

The majority of the estimated benefits are based on a reduction in loss of life from SRR failures. From the sample of 40 dam break assessments:

- 26 showed ASLL of zero;
- 13 showed ASLL greater than zero but less than 0.1;
- Maximum ASLL was 0.3.

This demonstrates that most SRR failures would be unlikely to result in loss of life, but that there is a realistic chance that occasionally the failure of an SRR may result in loss of life. This also demonstrates that the sample size is sufficiently small that, had there been one more (or one fewer) relatively high ASLL results in the sample, the estimation of benefits could change dramatically. Therefore, the results of the benefits assessment should be treated with caution, especially if used as a part of a more detailed benefit-cost analysis in the future.

7.3.3 Costs

A summary of the estimated costs is tabulated below.

Table 30: Average Cost per Regulated SRRs

		Capital Cost		Recurring Annual Cost	
	No.	Cost / GBP	Average Cost per SRR / GBP	Cost / GBP	Average Cost per SRR / GBP
Cascade SRRs	36	£500,000	£13,900	£195,000	£5,400
Singular SRRs	1,503	£14,500,000	£9,600	£6,200,000	£4,100

The overriding benefit is the reduction of the probability and consequence of failure of the group of reservoirs. This key benefit, in the form of reservoir safety risk reduction, benefits:

- the public;
- the reservoir undertakers;
- the regulatory authority; and
- the reservoirs industry.

In addition to reservoir safety there are other benefits to the undertakers, taking the group of reservoirs as a whole:

- lower commercial risk of catastrophic failure;
- targeting reservoir investment;
- improved monitoring and management of leakage;
- improved monitoring practices;
- improved maintenance practices;
- improved security;
- regular advice from Qualified Civil Engineers (QCE).

8 Summary and Discussion

8.1 Summary

This research project has addressed the objectives set out in the terms of reference. Detailed findings are set out in the preceding sections. Headline findings are detailed below:

8.1.1 Numbers of reservoirs

Table 31: Key Findings

	Number in England	
	Most likely	Range
Water Bodies		
Water bodies with surface area between 3,000 and 50,000 m^2	22,000	Not analysed
SRRs (including cascades of SRRs)		
SRRs	1,503	1,204 to 1,861
High risk SRRs	511	306 to 754
Cascades (excludes singular SRRs)		
SRR-SRR cascades[1]	29	1 to 86
High risk SRR-SRR cascades[1]	10	0 to 31
SRR-LRR cascades[1]	7	0 to 45
High risk SRR-LRR cascades[1]	6	0 to 40

Note 1. These are cascades under the restrictive definition adopted for this project. There will be a much greater number of occurrences of reservoirs on the same watercourse where the cascade definition is not restricted by considerations of volume, surface area and separation.

Therefore, the total amount of SRRs (as defined in this study as between 10,000 m^3 and 25,000 m^3) to be registered is estimated as 1,503 with a range of 1,204 to 1,861.

It should be noted that if all SRRs are registered, this would include all the SRR cascade reservoirs.

8.1.2 Benefits of regulating reservoirs

The estimated average and total benefits for regulation of SRRs and subsequent remedial works are given in Table 32. The limitations of these estimates are described in detail in Section 7.1.3.

Table 32: Average Benefit for Regulated SRRs

		Recurring Annual Benefit	
	No.	Total Benefit / GBP	Average Benefit per SRR / GBP
Cascade SRRs	36	£540	£15
Singular SRRs	1,503	£22,300	£15

8.1.3 Costs of regulating reservoirs

The estimated average and total costs for regulation of SRRs and subsequent remedial works are given in Table 33.

Table 33: Cost Summary for Regulating SRRs

		Capital Cost		Recurring Annual Cost	
	No.	Cost / GBP	Average Cost per SRR / GBP	Cost / GBP	Average Cost per SRR / GBP
Cascade SRRs	36	£500,000	£13,900	£195,000	£5,400
Singular SRRs	1,503	£14,500,000	£9,600	£6,200,000	£4,100

8.2 Discussion

8.2.1 Further Research Suggestions from the Advisory Group

Throughout the project, research suggestions have been made and where possible incorporated into this project. Where the recommendations were outside the scope of this project they are captured here.

Recommendations were made to:

- consider the use of river bank level, rather than bed level in calculation of dam height and therefore volume estimation and/or dam break analysis. To date there is no evidence to support this change and it would involve a change to the legislation which defines dam height;
- consider whether UK legislation should include dam height as a qualifying criterion for registration. Many other countries use dam height as a qualifying criterion. There is an argument that dam height is more influential than volume in terms of peak flow following catastrophic failure and research under this project shows that risk designation of SRRs is relatively sensitive to peak flow;
- review the current approach to risk designation. This will partly be covered under Objective 3 of this project if progressed. Mott MacDonald recommends a review of the scope of Objective 3 to ensure that it remains relevant following Stage 1 of this project and in light of the latest available research on risk designation in Scotland.

8.2.2 Number of SRRs

It is considered that the methodology for assessing the number of SRRs is superior to that used in previous studies. Possible uncertainties do however result from the existing GIS dataset covering reservoirs with a minimum surface area of 5,000 m^2 and a maximum surface area of 50,000 m^2. Whilst this may cover the majority of SRRs it has been shown that the surface area of small raised reservoirs is likely to be in the range of 3,000 m^2 to 50,000 m^2. There could therefore be benefit in repeating the GIS search with the minimum area reduced to 3,000 m^2 and the maximum increased to 50,000 m^2.

This research covered a sample of 500 water bodies in the north of England. The north of England was originally chosen to extend earlier research. However, the project developed such that the new sample had to be treated in isolation. Given this situation the sample of 500 water bodies is relatively small and there could be benefit in analysing similar sized samples in other parts of England.

8.2.3 Number of cascade reservoirs

It is considered that this project made good progress in developing a definition for cascade reservoirs. It must however be appreciated that the definition is predicated on the assumption that cascade reservoirs might be regulated preferentially to single SRRs. This is a reasonable assumption as it is clear that where the reservoirs are of sufficient size a cascade failure can definitely present a greater hazard than individual SRRs. However, if all SRRs are to be regulated there is no need to make a distinction for cascades unless there is a will to consider reservoirs with a volume less than 10,000 m^3.

This study only identified a very small number of cascades. Extending the research with a similar study in another part of England would clearly give greater confidence to the findings.

8.2.4 Risk presented by Small Raised Reservoirs

This research was based on dam break assessments using the “dry day” scenario detailed in the 2016 RFM specification. This was chosen because it represented the current best practice in dam breach assessment. It must however be recognised that consideration of the “wet day” scenario as well could increase the percentage of SRRs which were found to be “high risk”. The wet day scenario was not considered in this research because there was no provision for undertaking the hydrological modelling necessary to determine the 1,000 year fluvial flow to which the wet day dam breach outflow must be added. If there is a wish to refine the estimate of the number of high risk SRRs it would be worthwhile to repeat the analysis undertaken for this study with the wet day scenario. It must also be appreciated that the sample size of dam breaks was very small in relation to the total number of SRRs and undertaking additional assessment would help to improve the confidence in the findings.

8.2.5 Benefits of regulating SRRs

The benefits of regulating SRRs have been calculated on the basis of damages derived from dam break assessments and the assumption that regulation would reduce the probability of failure by one order of magnitude.

From the sample of 40 dam break assessments:

- 26 showed ASLL of zero;
- 13 showed ASLL greater than zero but less than 0.1;
- Maximum ASLL was 0.3.

Based on the sample of 40 SRRs, the average ASLL is estimated to be 0.012 and this study assumes that the POF is 1 / 5,000 for an unregulated SRR. This aligns with the fact that no lives have been lost through the failure of SRRs in England in more than 100 years.

8.2.6 Identification / registration of Small Raised Reservoirs

At this point it is worth considering the tasks involved in registering all SRRs in England. As a minimum, the tasks would be as follows:

- extend GIS search to water bodies with surface area between 3,000 and 50,000 m^2 (22,000 Water bodies likely to be identified)
- undertake desk based assessment using Lidar data on all 22,000 (estimated) water bodies with surface area 3,000 and 50,000 m^2
- identify potential SRRs
- identify owners of potential SRRs
- undertake field visits to confirm depth of water at TWL and recalculate volume

- undertake hydrographic surveys on reservoirs where SRR status could not be confirmed by visual observations (this could be contentious so could apply to most reservoirs where the estimated volume was less than 15,000 m^3)

Whilst this is clearly a major task, it is pertinent to note that it is not the approach being taken by NRW. NRW are focussing initially on registering what are the most obvious SRRs, many of which have been identified through previous studies. It may therefore be worth considering a phased approach to registering SRRs in England which can be tailored to fit available resources. In the first instance this might involve limiting the search on surface areas to a lower limit of 10,000 m^2 rather than 3,000 m^2. In this context it is also worth noting that there are likely to be around ten times as many SRRs in England as in Wales.

Glossary of Terms

Table 34: Definitions

Term	Definitions
Area	Environment Agency geographical designations post 31 March 2014. This designation is not typically used in the previous research and as such the "regions" are used for consistency.
cascade	Commonly considered to be a number (minimum two) of reservoirs on the same watercourse such that a failure of the upstream reservoir could cause failure of the downstream reservoir. Under this project a more specific definition has been agreed as detailed in section 4.3 in order to refine the limits of number of reservoirs, volume, surface area, and separation.
"high-risk"	Having a "high-risk" designation in accordance with Environment Agency; 2013a. Where reference is made to a "high-risk" small raised reservoir; this indicates that, should the reservoir fall under the full force of the Reservoirs Act 1975 in the future, it is considered that it would be designated as "high-risk".
Large raised reservoir	In accordance with the previous research the same definition is adopted: *"this term is commonly applied to reservoirs of over 25,000 cubic metre (m^3) raised storage capacity. Such reservoirs are currently regulated within the ambit of the Reservoirs Act 1975."* (Halcrow; 2013)
Non-statutory reservoir	A raised reservoir not falling under the ambit of the Reservoirs Act 1975 as amended by Flood and Water Management Act 2010, in England, at the time of writing.
Region	Environment Agency geographical designations prior to 1 April 2014. This term is more commonly used in the previous research than the new "areas" and as such is adopted in this report for consistency.
Reservoir	In accordance with the previous research the same definition is adopted: *"a man-made water body which has been formed by creating a dam to raise some or all of the water volume above the natural level of the surrounding ground."* (Halcrow; 2013). It is further noted that the term "raised reservoir" is used within this report and has the same meaning. In any instance where it is unclear as to whether a water body is a reservoir, further clarity and detail of the definition can be found within the Reservoirs Act 1975 (as amended by FWMA 2010) and corresponding guidance (ICE; 2014).
Small raised reservoir	In accordance with the previous research the same definition is adopted: *"commonly applied to any reservoir of 25,000 m^3 or less (non-statutory reservoirs). For the purposes of this report the term is used to refer to reservoirs with raised volume in the range of 10,000 m^3 to 25,000 m^3 as this is the range for which reservoirs may need to be registered under the Flood and Water Management Act 2010 (FWMA) in addition to LRRs."* (Halcrow; 2013)
This research project	Research commissioned by Defra in 2017 and carried out by Mott MacDonald. This research project is denoted by the Defra reference FD2701.
Water body	In accordance with the previous research the same definition is adopted: *"a significant accumulation of open fresh water. A water body might be natural or man-made."* (Halcrow; 2013). Although the term is commonly used to describe any accumulation of water, within this project the term is limited to water bodies that were picked up in the Halcrow GIS study; crucially the algorithm produced by Halcrow differentiates between river widenings and online reservoirs (Halcrow; 2013).

Table 35: Acronyms

Short Form	Long Form
AEP	Annual Exceedance Probability
ALARP	As Low As Reasonably Practicable
AOD	Above ordnance datum
ASLL	Average Societal Loss of Life
CPF	Cost to Prevent a Fatality
FSL	Full Supply Level
FSR	Flood Storage Reservoir
FWMA	Flood and Water Management Act (2010)
HR	"High Risk" (relating to reservoir risk designation)
IOS	Interests of Safety
LRR	Large Raised Reservoir (volume >25,000m^3)
MM	Mott MacDonald
NHR	Not "High Risk" (relating to reservoir risk designation)
NRD	National Receptor Database
NRW	Natural Resources Wales
OS	Ordnance Survey
PAR	Population at Risk
PF	Proportion Factor
POF	Probability of Failure
RARS	Risk Assessment in Reservoir Safety Management
RFM	Reservoir Flood Mapping
RIM	Reservoir Inundation Mapping
SR	Service Reservoir
SRR	Small Raised Reservoir (volume 10,000m^3 to 25,000m^3)
SRR-LRR	Small Raised Reservoir upstream of a Large Raised Reservoir
SRR-SRR	Small Raised Reservoir upstream of a Small Raised Reservoir
TWL	Top Water Level
VPF	Value to Prevent a Fatality

References

The following documents have been referenced throughout this study:

- 1994; Wright CE; UK reservoir failures and safety legislation. Dams and Reservoirs 4(3): 20-21
- 2004; Defra; Interim guide to quantitative risk assessment for UK reservoirs (January 2004)
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- 2009a; Halcrow; GIS based Reservoirs Investigation (Undated, metadata file “last modified” date 21.03.2009)
- 2009b; Halcrow; Small Reservoirs Pilot Study, Technical Note, Past Project Reservoir Data Analyses, Ref. WH\SRPS\11 (September 2009)
- 2009; Environment Agency; Reservoir Inundation Mapping Specification (June 2009)
- 2010; Halcrow; Small Reservoirs Pilot Study, Pilot Study Report, Issue 1, Revision 0
- 2010; Environment Agency; Scoping the risk assessment process for small reservoirs, Ref. FD2640/TR1 (April 2010)
- 2011; Defra; Flood and Water Management Act 2010: Commencing Schedule 4 on reservoir safety – Impact Assessment
- 2012; Mott MacDonald; Portfolio Risk Assessment Stage 2, Non-statutory Reservoirs, Sludge Lagoons (Report 1 of 2) (February 2012)
- 2012a; Halcrow; Report on Pilot Studies, Document 1, Version 1 (July 2012)
- 2012b; Halcrow; Flood Risk Assessment of Reservoirs, Document WHR1286, Version 1, Wessex Area, Phase 3 – Final Combined Report, Version 3.0 (December 2012)
- 2013; Halcrow; Small Raised Reservoirs Research, Version 2.1 (January 2013)
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- 2013b; Mott MacDonald; Assessment of Non-Statutory Reservoirs over 10,000 m^3, 3rd Issue (July 2013)
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- 2013a; Environment Agency; Reservoir Risk Designation Guidance, Version 1.0 (August 2013)
- 2013b; Environment Agency; Small Reservoirs Simplified Risk Assessment Methodology Guidance Report (August 2013)
- 2013c; Environment Agency; Guide to risk assessment for reservoir safety management (March 2013)
- 2014; CIRIA; Lessons from incidents at dams and reservoirs – an engineering guide, SP167, CIRIA, London
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- 2015; ICE; Floods and Reservoir Safety, Fourth Edition, ICE Publishing, London
- 2015; Mott MacDonald; Portfolio Risk Assessment, Stage 2, Non-Statutory Reservoirs, Raw Water Reservoirs (Report 2 of 2) (February 2015)
- 2016; Environment Agency; Reservoir Flood Mapping Specification (Report ENVFCPMM00277B00) (July 2016)

- 2017; Mott MacDonald; Evidence for Post Implementation Review; Evaluating the Impact of the First Phase of the FWMA 2010 Reservoir Provisions in Relation to LRRs, Revision D (October 2017)
- 2018a; Environment Agency; Emergency Response Report (The database of Large Raised Reservoirs) (01/03/2018)
- 2018a; Mott MacDonald; Evidence for Post Implementation Review; Evaluating the Impact of the First Phase of the FWMA 2010 Reservoir Provisions in Relation to LRRs (07/03/2018)
- 2018b; Mott MacDonald; Cascade Reservoirs Approach (Revision C) (10/04/2018)
- 2018b; Environment Agency; Email correspondence between Tony Deakin and James Penman (02/10/2018)
- 2018c; Environment Agency; FRS17071 Scoping Research to improve Dam and Levee Breach Prediction (unpublished, in draft at time of writing)
- 2018; Warren AL and Patten B; ‘Learning from reservoir incidents – a summary of the causes and management of incidents in the UK’, in Smart Dams, proceedings of the British Dam Society conference, Swansea University

Appendices