Department for Environment Food & Rural Affairs

Environment Agency

delivering benefits through evidence

Guide to risk assessment for reservoir safety management

Piloting summary report

Report – SC090001/R3

Flood and Coastal Erosion Risk Management Research and Development Programme

The Environment Agency is the leading public body protecting and improving the environment in England.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned by the Environment Agency's Evidence Directorate and funded by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme.

Published by:
Environment Agency, Horizon House, Deanery Road, Bristol, BS1 5AH

www.environment-agency.gov.uk

ISBN: 978-1-84911-305-2

Further copies of this report are available from our publications catalogue: http://publications.environment-agency.gov.uk or our National Customer Contact Centre: T: 08708 506506
E: enquiries@environment-agency.gov.uk.

Author(s):
Alan Brown
Michael Wallis

Dissemination Status:
Publicly available

Keywords:
Reservoir, Dam, Risk Analysis, Safety, Risk Assessment, Failure, Breach, Consequences, Tolerability, Evaluation

Research Contractor:
HR Wallingford, Howbery Park, Wallingford, Oxfordshire. OX10 8BA
+44 (0) 1491 835381
HR Wallingford Ref no: MCR4751-RT003-R02-00

Environment Agency's Project Manager:
Dave Hart, Evidence Directorate

Collaborator(s):
Atkins Ltd, Jacobs, Sayers & Partners, RAC Engineers & Economists, Stillwater Associates, Samui Ltd, United Utilities

Project Number:
SC090001/R3

Evidence at the Environment Agency

Evidence underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us, helps us to develop tools and techniques to monitor and manage our environment as efficiently and effectively as possible. It also helps us to understand how the environment is changing and to identify what the future pressures may be.

The work of the Environment Agency's Evidence Directorate is a key ingredient in the partnership between research, guidance and operations that enables the Environment Agency to protect and restore our environment.

This report was produced by the Scientific and Evidence Services team within Evidence. The team focuses on four main areas of activity:

- **Setting the agenda**, by providing the evidence for decisions;
- **Maintaining scientific credibility**, by ensuring that our programmes and projects are fit for purpose and executed according to international standards;
- **Carrying out research**, either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available.

Miranda Kavanagh

Director of Evidence

Executive summary

It is a considerable challenge to ensure acceptable performance from dam assets and to manage risk in the short to longer term through physical interventions to maintain, repair, improve or replace assets, while avoiding unnecessary expenditure. The wide variety of dam types and forms and their physical settings complicates the task. Within this complex setting, the concepts of risk and performance provide dam managers with a consistent framework to analyse and understand the critical components of their dam, and to target effort in further data collation, assessment or intervention appropriately.

A scoping study conducted by the Environment Agency in 2009 (SC070087/R1) established the need to update the *Interim Guide to Quantitative Risk Assessment for UK Reservoirs*, originally published in 2004, to provide a tool for the management of reservoir safety. It was recommended that this update should include a review of the risk management framework so that this meets a wider range of reservoir owner/undertaker and industry needs as well as fitting with current UK government flood risk assessment policy and practice.

Reservoir safety management involves managing the risk of an uncontrolled release of the contents of a reservoir. This new document has sought to explain and guide the user through the steps of the risk informed approach to reservoir safety management. This provides an introduction and explanation of basic concepts and a detailed application of the methods and appropriate links to other reference documents and guidance.

This report presents the evaluation of the results and outputs of risk assessments completed on a sample of reservoir dams in England and Wales using the methods in the new guide. The results were calibrated and validated using established ranges of reservoir risk measures for the UK as well as previous risk assessments and engineering judgement.

The results indicate that the guidance, when properly applied, should not lead to a change in the range of results compared with evidence from previous studies. However, the findings also confirm that care is needed in the application of the methodologies and that confidence in the outputs relies on good engineering judgement. Reviews of the outputs are important steps in the process and should be conducted as recommended in the guidance.

Acknowledgements

This document has been prepared by the Environment Agency with significant assistance from HR Wallingford and Stillwater Associates. The data were provided from pilot studies conducted during the development of the updated guidance on risk assessment for reservoirs guidance published in May 2013 by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme.

The pilot risk assessments were conducted by engineers at Jacobs, Atkins Ltd and HR Wallingford with assistance from the reservoir owners and engineers who provided funding, data and information on the reservoir dams including:

- Severn Trent Water
- Dŵr Cymru Welsh Water
- United Utilities
- Bristol Water
- Northumbrian Water
- Canal and River Trust

Contents

1	**Introduction**	**1**
2	**Overview of the pilots**	**2**
2.1	Methodology / approach	2
2.2	Methodological balance and key simplifications in the lower tiers	4
3	**Outcomes from the pilot assessments**	**6**
3.1	The results of the assessments	6
3.2	Refinements to the guide	6
3.3	Review of pilot results / outputs	7
4	**Conclusions**	**11**
References		**12**
List of abbreviations		**13**
Appendix A: Methodologies matrix		**14**
Appendix B: Example assessment outputs		**18**
Example Tier 1 output		19
Example Tier 2 output		27
Appendix C: Tables of results		**33**
Appendix D: Plots of results		**36**

Table 2.1	Main characteristics of the dams piloted in the study	2
Table 2.2	Summary of the tiered analysis system	4
Table 2.3	Compromise between accuracy of output and simplicity incorporated in the guidance	5
Table 3.1	Summary of adjustments to elements of the methodology	6
Table 3.2	Evaluation of the assessment for reasonableness of the results	9
Table 4.1	Areas for potential research to improve future guidance	11
Table C1	Tier 1 pilot results	34
Table C2	Tier 2 pilot results	35

Figure D1	Dam height vs. reservoir volume	37
Figure D2	Cumulative distribution of total probability of failure	38
Figure D3	Probability of failure of internal threats – New South Wales method vs. Interim Guide method	39
Figure D4	Annual probability of failure vs. date of construction	40
Figure D5	Cumulative distribution of average societal life loss	41
Figure D6	Average societal life loss vs. damages	42
Figure D7	Probability of failure Tier 1 vs. Tier 2	43
Figure D8	Average societal life loss Tier 1 vs. Tier 2	44
Figure D9	Tier 2 risk as F-N chart	45
Figure D10	Tier 1 risk as F-N chart	46

1 Introduction

This report assesses the results of the piloting of the risk assessment methodology conducted on a range of UK reservoirs as part of the joint Defra / Environment Agency Flood and Coastal Erosion Risk Management Research and Development Programme funded project SC09001 'Risk Assessment for Reservoirs'. This project produced updated guidance on risk assessment in reservoir management (Defra/Environment Agency 2013a,b).

The assessment set out to test whether the outputs of the new risk assessment methodology are reasonable, or whether the methodology needed some adjustment to obtain reasonable estimates. The basis of validation of the output was to use the published data listed in section 15.2.4 of Volume 2 of the guidance (Defra/Environment Agency 2013b) and to compare the results with previous risk analyses where available.

2 Overview of the pilots

2.1 Methodology / approach

A number of dam owners in England and Wales generously supported the development of the risk assessment for reservoirs guidance by offering dams from their portfolios to trial the new methodologies and guidance (Environment Agency 2013a,b).

The project team defined an 'ideal' requisite list and combination of characteristics for dams that would represent the widest possible population of UK dams and also meet the requirements for the trials. From those dams offered by owners the team selected a range of ages, sizes and types that most closely matched the 'ideal' list of characteristics. Table 2.1 lists the main characteristics of the dams selected.

Table 2.1 Main characteristics of the dams piloted in the study

	Composition	Height (m) (approx.)	Reservoir capacity (m^3) (approx.)	Consequence category
1	Earth embankment	6	300,000	C
2	Earth embankment	9	>500,000	C
3	Earth embankment	12	50,000,000	A
4	Earth/clay core	12	1,100,000	A
5	Earth/clay core	13	>20,000,000	A
6	Earth homogenous	14	1,600,000	A
7	Concrete	17	>600,000	A
8	Earth/clay core	20	2,200,000	A
9	Composite concrete/earth	25	41,000	A
10	Earth/ shale – zoned/clay core	48	20,000	A
11	Concrete buttress	72	50,000,000	A

As well as structure type, height, reservoir capacity and consequence category, several other 'ideal' requirements were met by the choice of dams including:

- age (from ~40 to over 200 years old)
- penetrating structures (for example, pipes and cut-offs)
- range of construction methods and materials
- range of condition grades
- reservoir system type (that is, cascade, rural, urban and so on)
- spillways

The best match of dams with parameters close to the 'ideal' list were made from the dams on offer. However, the range of characteristics of the dams meant some selection criteria had to be compromised compared with the 'ideal' list. For example, no

‘B’ consequence category dams were offered. However, two dams on the final list are borderline; they have been categorised as A and B at different times and their classification remains debateable. As shown in Figure D6 in Appendix D, the sample does cover a wide range of average societal life loss (ASLL) and damages. Because the focus of the trials was more about testing the methods for determining probabilities of failure than the consequences (which have more established/less contentious analysis methods), the consequence categorisation was considered less of a governing parameter than others in terms of choice of dam. (At the time, the reservoir risk categorisation method was also under review.)

Risk assessments were conducted on 12 dams including nine embankment dams and three concrete dams. One embankment dam was the associated saddle dam to one of the concrete dams for which risk assessments were combined to provide the overall probability of failure (POF).

A first round of piloting (Phase 1) was conducted by members of the project team on a small number of these dams to check the capability and appropriateness of the methods developed. Some refinements (see section 3) and calibrations were then made to the methods and guidance before a second round (Phase 2) was undertaken by agroup of engineers who had been involved in the development of the guidance. Engineers with a range of experience were deliberately chosen to test the usability of the guide. The results of these assessments were collated and validated using established and known ranges of reservoir risk measures for the UK, previous risk assessments and engineering judgement. Where available, previous risk assessments for some dams were also consulted to examine and evaluate differences in the results obtained.

A limiting factor in the pilot studies was the ability to test all three tiers of the methodology (Table 2.2). Although the approaches and analytical methods in Tiers 1 and 2 were applied, the testing was not extended to include those outlined in Tier 3. Tier 3 analyses are complex and costly to perform; they will be undertaken by a team of specialist engineers, using numerical/computer models. Piloting these techniques would not have added l value to the guidance or benefited the user group. Where application of Tier 3 analyses would have benefitted an assessment (for example, to reduce uncertainty or improve accuracy), this was identified in the pilot reporting as part of the assessment process and captured as a recommendation (making such recommendations to move to another tier or type of analysis is an outcome of the risk assessment methodology itself).

Table 2.2 Summary of the tiered analysis system

Tier	Type of risk assessment	Description
1	Qualitative	Ranking of potential failure modes, order of magnitude likelihood and consequences using a descriptive risk matrix Optional sensitivity analysis
2	Simplified quantitative	Threshold analysis using hand calculations (that is, with a basic calculator) Optional sensitivity analysis
3	Detailed quantitative	Range of levels – include system response curves, with range of initiating events (threats) using computer software for risk calculations Ways of dealing with uncertainty range from formal sensitivity to full uncertainty analysis

2.2 Methodological balance and key simplifications in the lower tiers

As outlined in Table 2.2 the tiered approach requires different levels of assessment methodology and analysis from the simplified to the more complex as required by the tier. There were detailed discussions during the development of the guidance over the balance between the following three aspects:

- simplicity of use
- need for transparency in the process (so non-experts can do the calculations themselves, and thus gain confidence in risk assessment output)
- accuracy of output

The devised solution (confirmed by the initial phase of piloting) is summarised in Table 2.3.

The risks of the accuracy of the output being overestimated are also reduced by recommending that users complete an assessment of confidence in the components of the risk assessment (in Step 2f of the guidance).

Table 2.3 Compromise between accuracy of output and simplicity incorporated in the guidance

Element of risk assessment	Compromise	Practical drawbacks
Failure modes identification	Tier 1 structured as core threats,* with user to identify additional failure mode, rather than brainstorming from blank page	Increased risk of overlooking critical failure mode
Partitioning of load domain	Tier 1 and 2 both consider single 'dam critical' load rather than curves of load vs. probability, which are then integrated with curves for system response.	May overlook critical response at intermediate load. Position of step may not be best estimate.
Reservoir level vs. time	Assume normally full.	Although this is valid for many UK reservoirs (for example, amenity lakes), it will be conservative where the lake is well below top water level (TWL) for significant proportions of the year.
System response	Tier 1 and 2 both consider single (step) response (probability), rather than two (or multiple) point fragility curve.	As above
Consequence scenarios	Tier 1 and 2 limited to one and two scenarios respectively.	Less accurate (probably conservative)
Tools to identify and quantify number of receptors	Tier 1 and 2 allow use of published 1:25,000 scale map, rather than requiring computer based assessment.	Less accurate identification and quantification of receptors
Presentation of risk output	Tier 1 and 2 limited to total probability, rather than individual failure modes (and uncertainty bounds on those estimates)	Need to drill down into individual failure mode to understand the critical threats

Notes: * Analysis undertaken when developing the Interim Guide (Brown and Gosden 2004) and other portfolio risk analysis in UK concluded that the threat to UK reservoirs from earthquakes is not significant compared with other threats. Earthquakes have therefore not been included as a core threat in Tier 1 or Tier 2 (unless there is a liquefiable foundation). Where mining activity has been commonplace in the area of the dam, the effects of subsidence on the dam may be included. However, such analyses are likely to be very site-specific and specialist, and would warrant a Tier 3 analysis. The susceptibility of all dams and reservoirs to acts of vandalism or terrorism should be considered as part of routine reservoir safety management and are not considered further separately in the guidance.

3 Outcomes from the pilot assessments

3.1 The results of the assessments

Example Tier 1 and Tier 2 risk assessment report forms from the pilots are shown in Appendix B. The outputs from all 11 risk assessments have been collated and are tabulated in Appendix C. An evaluation and validation of the results of the risk assessments is given in section 3.3.

3.2 Refinements to the guide

The methods of analysis considered for the guidance included a range of tried and tested methods (that produce reasonable results), some of which had not been used together before. Some methods were different approaches to the analysis of the same issue (for example, determination of dam condition) and a decision had to made about which to adopt. We considered which methods are appropriate for each level of asessment (Tier 1, 2 or 3). The pilots tested the approach 'in the round' andthe ability of the analyses to deliver appropriate results for the level of detail of the tier in which they are used. The project team agreed on the methods outlined in the matrix in Appendix A. (Example outputs for main stages of the analyses were subsequently included as part of the guidance document.)

As a result, aside from the many There were changes made to the guide during its development addressing comments from the project team and steering group reviews, the methodology in the draft guide (issued January 2013) was also refined where the piloting suggested that the output was 'not reasonable' (and the results of the pilots adjusted for the revised methodology) as summarised in Table 3.1.

Table 3.1 Summary of adjustments to elements of the methodology

Tier	Element of methodology	Aspect causing concern	Change
1+2	Probability of failure of embankments due to slope instability	Probability of failure too high	Added conditional probability of release of reservoir, given slope failure.
2	Routing of dam break failure	Rate of attenuation too low	Added advice to use Tarrant et al. (1994) to set maximum distance for extent of total and partial destruction.
2	Method for annual probability of failure (APF) due to internal threats	Two methods provided: New South Wales and cumulative scoring	Simplified to one method (conservative).
2	Upstream dam	Not included	Added text explaining why.
2	Probability of failure due to water coming out of chute	Including bends is too complex	Methodology dealing with bends moved to Part 2.

3.3 Review of pilot results / outputs

A number of tests were applied to the data to check the reasonableness of the outputs from the reservoir risk assessments. These tests are listed in Table 3.1. These and the comments provided should be considered in conjunction with the plots in Appendix D.

The criteria used to assess reasonableness included:

- Ref. 1 – as described in Chapter 15 of Volume 2 of the guide (Defra/Environment Agency 2013b)
- Ref. 2 – *Application of the Interim Guide to Quantitative Risk Assessment across multiple dam owners by multiple Jacobs offices* (Brown et al. 2008)
- EJ – Engineering judgement

For inter-tier comparison purposes, numeric values were assigned to (Tier 1) probability and consequence levels as per Table 15.3 of Volume 2 of the guide (Defra/Environment Agency 2013b).

3.3.1 Tier 1 review

The Tier 1 outputs were assessed by converting the verbal description to numeric value for the mid-point for that range, using Table 15.3 (in Volume 2 of the guide) and then plotting overall probability and consequences against Tier 2. Although the results were reasonable in overall terms, some further adjustments were made for stability of concrete dams and average societal life loss (ASLL), which were under predicting the magnitude of risk.

3.3.2 Tier 2 review

The overall range of total probability of failure using the Tier 2 methods is reasonable, varying from 10^{-2} to 5×10^{-6}. Similarly the overall range of estimated ASLL is reasonable; varying from 0.01 to between 1,000 and 5,000, and the range of plots on a F-N chart corresponds to the previously noted range of results for UK dams.

The outlier on Figure D3 in Appendix D can be attributed to the inclusion of the spillway of the dam in the pilot risk assessment that wasn't considered in the New South Wales (NSW) method (see section 17.3 of Volume 2 of the guide). This failure mechanism dominated other internal threats.

Figure D5 shows one dam with a very low ASLL (which is correct – one dam was in a very rural and remote location with no consequences). No other dams in the sample returned an ASLL <400.

Figure D6 shows one dam with relatively low damages (~0.15) but with a very high ASLL. This is attributed to the exclusion of direct damages (only third party damages were included in the calculation).

Figure D7 indicates that there is a general consistency in overall probability of failure between Tiers 1 and 2, although Figure D8 suggests that Tier 1 may slightly underscore ASLL. Figure D10 reflects the less precise results and wider spread from Tier 1 (as expected) compared with those of Tier 2 in Figure D9.

Further comments on all of the plots shown in Appendix D are given in Table 3.2.

The approach and structure of method was generally found to be sound and the concepts easily understood. However, issues were encountered around some aspects of application of the Tier 2 guidance. These included the following.

- Poor engineering judgement used on some aspects of the reservoir risk assessments appeared, on review, to have led to some erroneous results. This required guidance or adjustment by those more experienced in such assessments. These anomalies were picked up by the review steps as intended during the assessments.
- Some elements of the guide were not clear to the user and led to misunderstandings. Amendments and improvements were made to the guidance where these were identified.
- Risk assessments for concrete arch and buttress dams require the application of specialist Tier 3 approaches in addition to those of Tier 2.
- Flexibility built into guidance can be both beneficial and problematic. Where options are available, information on how to decide on an appropriate route or choice of analysis is required. There is a limit to how far a guidance document can only go in providing this and it may require the user to refer to other more detailed sources of information. The guidance provides references to the most relevant sources. It also highlights the importance of involving more than one person in the assessment (especially for Tier 2) and establishing at the beginning of the risk assessment process (as recommended in the guidance) the potential failure modes and the subsequent analyses to be undertaken.

Table 3.2 Evaluation of the assessment for reasonableness of the results

Plot	Test for reasonableness	Ref. *	Figure **	Comment
Height of dam vs. reservoir volume			D.1	Dams in pilot tend to be larger than UK median.
Probability of failure	Test			Embankment dams
Cumulative distribution of total APF	Is output consistent with published range for UK dams?	Ref. 1 Figure 15.3	D.2	Yes (that is, 10^{-2} to 10^{-6})
Internal threats – total from NSW vs. total from Interim Guide	How do the two methods compare?	EJ	D.3	Yes – only one exception where differences in failure modes included vary
APF vs. date of construction	Is output consistent with published range for UK dams?	Ref. 1 Figure 15.4	D.4	Yes – although sample skewed towards post-1950 dams with POF of 10^{-5} to 10^{-6}
Consequences				
Cumulative distribution of ASLL	Is output consistent with published range for UK dams?	Ref. 1 Figure 15.2	D.5	Yes > 1000 to 0.01
ASLL vs. third party flood damage	Is output consistent with published range for UK dams?	Ref. 2 Figure 2	D.6	Yes. Broadly £1M/ life, although higher dams with higher fatality give lower than this
Tier 1 vs. Tier 2	Does Tier 1 give output which is consistent with Tier 2?			
Probability		EJ	D.7	Yes – reasonable fit
Consequences		EJ	D.8	Possibly some underscoring at Tier 1
Risk		EJ	See F-N charts D.9 and D.10	Broadly the same outcomes of intolerable, ALARP and broadly acceptable
Risk				
F-N chart	Is output consistent with published range for UK dams?	Ref. 2 Figure 2	D.9 (Tier 1) D.10 (Tier 2)	Yes

Notes: * See section 3.3.
** In Appendix D of this report
ALARP = as low as reasonably practicable

4 Conclusions

The pilot risk assessments successfully tested the main aspects of the guidance. Although a small sample of UK dams was used, the evidence provided from the pilot risk assessments suggest that the method and approach adopted in the guidance, when properly applied, should not lead to a shift in the range of results compared with evidence from previous studies (see section 15.2.4 in Volume 2 of the guide).

As with any such analyses, the studies did highlight that:

- care should be taken in the application of the methodology
- confidence in the outputs relies on good engineering judgement and previous experience – especially when applying Tier 2 quantitative analyses
- reviews of the outputs are important steps in the process and should be conducted as indicated in the guidance

A number of areas for potential research in the supporting science to improve risk assessment guidance for reservoirs are listed in Table 4.1. In addition, further opportunities for future improvement should be collated from researchers and users and evaluated where these become apparent.

Table 4.1 Areas for potential research to improve future guidance

Subject	Tier	Opportunities for further development / research
Estimation of flood frequency	1	Provide an envelope of peak flood discharge vs. catchment area, similar to 'Craeger' curves but with the curve set to reflect UK conditions
Fault trees	2	Further guidance on the creation and detailing of fault trees for different structures and failure scenarios
Fragility curves	3	Development of guidance on creation of (bespoke) fragility curves

References

Brown, A.J. and Gosden, J.D., 2004. *An Interim Guide to Quantitative Risk Assessment for UK Reservoirs*. London: Thomas Telford.

Brown, A.J., Yarwood, G., King, S. and Gosden, J.D., 2008. *Application of the Interim Guide to Quantitative Risk Assessment across multiple dam owners by multiple Jacobs offices*, Proceedings British Dam Society 15th Biennial Conference, Warwick, 10–13 September 2008, Paper 13, pp. 65-79.

CEH (Centre for Ecology & Hydrology), 1999. *Flood Estimation Handbook*. Five volumes. Wallingford: Centre for Ecology & Hydrology.

Defra/Environment Agency, 2013a. Guide to Risk Assessment for Reservoir Safety Management. Volume 1: Guide. Evidence Report SC090001/R1. Bristol: Environment Agency.

Defra/Environment Agency, 2013b. Guide to Risk Assessment for Reservoir Safety Management. Volume 2: Methodology and supporting information. Evidence Report SC090001/R2. Bristol: Environment Agency.

Fell, R., Foster, M., Davidson, R., Cyganiewicz, J., Sills, G., Vroman, N. and Davidson, R, 2008. *Risk Analysis for Dam Safety. A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping, Draft guidance document dated August 21, 2008*. URS Australia Pty Ltd. Sydney, Australia [Prepared for the US Bureau of Reclamation and US Army Corps of Engineers].

ICE (Institution of Civil Engineers), 1996. *Flood and Reservoir Safety*, 3rd edition. London: Thomas Telford.

NERC (National Environment Research Council), 1975. *Flood Studies Report.* Five volumes. London: NERC.

Tarrant, F.R., Hopkins, L.A. and Bartlett, J.M., 1994. Inundation mapping for dam failure – Lessons from UK experience. In: *Reservoir Safety and Environment*, Proceedings 8th Biennial British Dam Society Conference, 14–17 September 1994, Exeter, pp. 282-291. London: Thomas Telford.

List of abbreviations

ALARP	as low as reasonably practicable
APF	annual probability of failure
ASLL	average societal life loss
IE	internal erosion
NSW	New South Wales [method]
PMF	probable maximum flood
POF	probability of failure
QRA	qualitative risk assessment
RIM	reservoir inundation mapping

Appendix A: Methodologies matrix

Step		Tier 1	Tier 2	Tier 3
1a	Failure modes identification (FMI)	Reviews all available information. Interview supervising engineer and reservoir owner. Identifies potential failure modes (likely using core failure modes). Classifies credible and significant failure modes.	As Tier 1	As Tier 2 and, in addition, involve reservoir team. Detailed description of each credible and significant failure mode. Uses preliminary event trees or fault trees.
1b	Identify potential consequences	Subjective, review of step 1a implications		
1c	Review, scope risk analysis	Subjective, determines the risk assessment scope		
2a	Likelihood of failure due to internal threats			
	Embankment dams	Uses a matrix of intrinsic condition and current condition.	Uses the probability of failure for the average dam from historic data. Then adjusts to the specific dam using condition mapping score, and adjusts to probability.	Uses event trees.
	Concrete and masonry dams	Uses a matrix of intrinsic condition and current condition.	Simplified event trees using limited calculations based on sliding and overtopping.	Uses event trees built on detailed analysis and use of US Bureau of Reclamation toolbox on piping failure (see Fell et al. 2008).
	Service reservoirs		Simplified event trees using limited calculations based on cantilever walls and piping.	
2b	Likelihood of failure due to external threats			
	Floods and waves (overtopping)	Simple assessment of weir capacity, spillway capacity	As *Floods & Reservoir Safety* (ICE 1996) Appendix 1	Full *Flood Studies Report* (FSR) (NERC 1975) and *Flood*

Step		Tier 1	Tier 2	Tier 3
			approach	*Estimation Handbook* (FEH) (CEH 1999) analysis
	Stability analysis – embankment dams	Review against similar dams.	Slope stability charts (earthquake not normally critical)	Stability / seismic analysis
	Stability analysis – concrete and masonry dams	Review against similar dams.	Stability analysis, including earthquake	Stability analysis, including earthquake
	Stability analysis – service reservoirs	Review against similar dams.	Stability analysis, including earthquake	Stability analysis, including earthquake
	Other external threats	Not normally considered.	Not normally considered.	Not normally considered.
2c	Dambreak and flood routing	Existing maps or proportion of dam height plus estimated inundation area	Simplified breach (Froehlich) and modified CIRIA C542	Full breach analysis and inundation modelling
2d	Consequence analysis	Uses a qualitative assessment of broad scale number of houses, using a 25,000 scale map	Uses as simplified quantitative assessment using 25,000 map and drive down valley	Uses a GIS-based assessment.
2e	Determine level of risk	Uses a matrix plotting the likelihood of downstream flooding and the magnitude of consequences given downstream flooding.	Uses the conditional probability of the failure mode and the consequence scenarios to determine the probability of risk.	Uses a quantitative assessment considering multiple failure modes and consequence scenarios.
2f	Review outputs	Subjective, determines the risk assessment structure		
3a	Review tolerability of risk	Review on tolerability/ALARP matrix.	Review tolerability/ALARP matrix and F-N chart.	Review

Step		Tier 1	Tier 2	Tier 3
3b	Review options to reduce risk	Review	Review	Review
3c	Proportionality	Review (broadly)	Review (qualitative)	Review (qualitative)
3d	Other considerations	Review	Review	Review
3e	Review and make recommendations	Recommendations may include undertaking a Tier 2 or 3 assessment	Recommendations may include undertaking a Tier 3 assessment	Recommendations

Appendix B: Example assessment outputs

Example Tier 1 output

Summary Sheet – Tier 1 Assessment

Dam details	
Dam name	X Dam
Grid reference	ST XXX XXX
Location, description	X km NE of nearby town / village in area / region X
Dam age	X years
Dam height	X m
Reservoir volume	XXXXXXXX m^3
Flood category	X
Assessment reference	XX/XX/XXXX-XX (assessor's name)
Date of assessment	--/--/----

Step 1 - Risk identification

Failure mode ID	Description of failure modes			Credible?	Justification	Significant?	Justification
	Initiation (threat)	Progression (failure mode)	Breach				
Internal							
Db10	High water level during flood Deterioration	Cracked core and internal erosion of embankment fill	Full breach	Yes	Puddle clay core with selected fine material both sides before general fill. Chimney drain in middle of downstream shoulder of unknown grading. Unlikely to be in filter compatibility. Risk of sandstone bands in general fill	Yes	Too many unknowns. However no signs of significant settlement apart from adjacent to the spillway works. Several features present aimed at reducing risk (zoning of embankment, chimney drain and rock toe), suggesting that vulnerability is weighted more towards unlikely than likely.

Df10	High water level during flood Deterioration	Internal erosion from embankment into soil foundation	Embankment collapse	Yes	Two possible mechanisms: (a) clay core directly into foundation; and (b) downstream shoulder into foundation; sand blanket could protect but grading unknown; grading of alluvium unknown but potential for presence of sands/gravels	Yes	Too many unknowns. Provision of sand blanket suggests that vulnerability is weighted more towards unlikely than likely.
Ds10	High water level during flood Deterioration	Internal erosion from embankment into rock foundation	Embankment collapse	Yes	Sides of clay core at interface between general foundation stripping level and concrete cut-off is the area of risk; not certain of treatment in this area; could be a particular issue where sandstone bands intersect the core foundation.	Yes	Too many unknowns. No evidence of treatment of sandstone bands suggests that vulnerability is weighted more towards likely than unlikely.
Df10	High water level during flood Deterioration	Internal erosion in foundation	Embankment collapse	Yes	Concrete cut-off through foundation; as built records show extended where fault found	No	Unlikely to be a significant through 5 ft thick concrete wall.

Di10	Deterioration of foundation along interface	Internal erosion along outside of outlet culvert	Full breach	No	Concrete tunnel fully embedded in concrete cut-off; away from cut-off not clear if cast against marl or backfilled. Concrete cut-off at interface between wet and dry sections of culvert	No	Located just outside alluvium in marl; reliant on effectiveness of 5 ft thick concrete cut-off
Di10	Deterioration of foundation along interface	Internal erosion along outside of spillway	Partial breach Collapse of spillway walls and erosion of slot through abutment	Yes	Cut-off wall extends under spillway but upstream of road bridge; thus vulnerable area between cut-off and road bridge; base is concrete slab with open (previously bitumen filled) joints. Side walls mass concrete with rear of wall drainage; Side walls probably continuous spillway with no joints.	Yes	However, spillway is situated high up on abutment and would only lose limited depth of reservoir. Single estimate of consequences would overestimate the impact.
External							
Fl.1	Flood	Overtopping of crest and erosion of downstream face	Full breach	Yes	Risk of blockage at bridge	Yes	
Fl.2	Flood	Overtopping of chute and erosion of fill	Full breach	No	Chute entirely within abutment and directed well downstream of toe		

AW.5	High water level, wave overtopping, extreme rainfall	Downstream slope failure, followed by loss of freeboard and erosion of downstream face from overtopping flow	Full breach	Yes		Yes	Take through but crest road likely to result in low risk of loss of reservoir

Step 2 – Risk analysis

Probability of failure			
Failure mode ID	Progression (failure mode)	Likelihood	Comments
Internal			
Db10	Cracked core and internal erosion of embankment fill	Moderate	Visited once every seven days to take underdrain readings; walkover supposed to take place monthly but in practice is less frequent. No symptoms of general seepage (other than near spillway) apart from that collected in toe drains. Toe drain flow is occasionally opaque and sump filled with silt in 2011. Flows are not plotted so trends are difficult to discern. Recent peak is around 1 l/s.
Db10	Internal erosion from embankment into soil foundation	Moderate	
Db10	Internal erosion from embankment into rock foundation	High	
Di10	Internal erosion along outside of spillway	High	Collapse of spillway walls and erosion of slot through abutment
External			
Fl1	Overtopping of crest and erosion of downstream face	Low	Embankment collapse
AW5	Downstream slope failure, followed by loss of freeboard and erosion of downstream face from overtopping flow	Moderate	Embankment collapse
Overall likelihood of failure		High	

Consequences			
Receptor	Measure	Consequence scenario	Comments
Human health	Human life (properties used as surrogate)	4	Over 2,000 properties at risk
	Community health assets affected	4	Hospital, six schools and five sewage treatment works, that is, one CH1 and several CH2, mostly at moderate risk (few areas fall into partial or total destruction zones). Because of number of assets, classify as very high.
Economic	Non-residential / commercial properties affected	4	Around 200 buildings
	Transport distribution	4	Six A-roads, railway and canal. Because of number affected, classify as very high.
Environment	Designated sites / affected areas		Not investigated as already very high risk.
Cultural heritage	Designated sites, listed buildings, scheduled monuments affected		Not investigated as already very high risk.
Overall consequence class		4	

Level of risk					
Likelihood of downstream flooding	**Potential magnitude of consequences given downstream flooding**				
	Level 0	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Extreme	ALARP	ALARP	ALARP	Unacceptable	Unacceptable
Very High	Tolerable	ALARP	ALARP	ALARP	Unacceptable
High	Tolerable	Tolerable	ALARP	ALARP	RISK
Moderate	Tolerable	Tolerable	Tolerable	ALARP	ALARP
Low	Tolerable	Tolerable	Tolerable	Tolerable	ALARP
Very Low	Tolerable	Tolerable	Tolerable	Tolerable	Tolerable

Step 3 – Risk evaluation

Recommendations	
Failure mode	Recommendation / Comments
	Undertake a Tier 2 analysis

Additional comments
A lesser consequence scenario should be considered for failure mode Di10. All significant dam failure scenarios are considered. Internal erosion risk into the rock foundation and along the spillway channel govern probability of complete failure. Although failure associated with the spillway will only release part of the reservoir. Total consequences governed by large population affected by peak discharge, which is three times probable maximum flood (PMF) inflow to reservoir. Gaps are around improving the understanding of the risks of internal erosion.

Example Tier 2 output

Dam details		
Dam name		X Dam
Grid reference		ST XXX XXX
Location, description		X km NE of nearby town / village in area / region X
Date built		X years
Dam height		X.XX m
Reservoir volume		XXXXXXXX m^3
Flood category		X
Assessment reference		XX/XX/XXXX-XX (assessor's name)
Date of assessment		--/--/----

Step 1 – Risk identification

Failure mode ID	Description of failure modes			Credible?	Justification	Significant?	Justification
	Initiation (threat)	Progression (failure mode)	Breach				
Embankment dam – Internal							
Db.10	Body of the dam deterioration	Internal erosion (IE)	Full breach	Yes	Earth embankment	Yes	Core threat
Df.10	Foundation deterioration	IE	Full breach	Yes	On glacial deposits, probably boulder clay	Yes	
Ds.10	Deterioration of dam/ foundation	IE from embankment into foundation (or vice versa)	Full breach	Yes	Earth embankment, on glacial deposits, probably boulder clay	Yes	

Di	Deterioration of dam/ foundation	IE along concrete/ embankment dam interface	Full breach	Yes	Historically most likely source of leakage	Yes	
Embankment dam – External							
FL.1	Flood	Scour, overtopping	Full breach	Yes	Impounding reservoir	Yes	
Eq.6	Seismic	Crack/ internal erosion along concrete – embankment interface	Full breach	Yes	Uncertainty of interface behaviour	No	Protected by filter
Concrete dam – Internal							
Df7	Foundation deterioration	Sliding in foundation	Blocks move downstream	Yes	Core threat	Yes	Core threat at Tier 1
Ds7	Pipe burst in tower	Floods drainage gallery and ‘relief wells’ – increase in uplift and sliding		Yes		Yes	4 × 900 mm pipes into tower. No large diameter exit (galley concreted in)
Df7	Blockage of foundation drains	Rise in pore pressures, sliding in foundation	Blocks move downstream	Yes		No	NW monitor flows, carry out periodic flushing
Concrete dam – External							
FL6	Flood (excessive inflow)	Failure on lift joint	Blocks slide/ overturn	Yes		Yes	2003 S10 states horizontal cracks due to shrinkage
FL7	Flood (excessive inflow)	Failure at foundation contact	Blocks slide/ overturn	Yes	Physically possible	Yes	More likely than earthquake
Aw6	Ice	Overturning on lift joint		Y		No	Mesh reinforcement on spillway section, ice modest proportion of load on 25 m high dam

Step 2 – Risk analysis

Probability of failure					
Failure mode ID (Table 7.2)*	Initiation	Progression (failure mode)	Probability		Comments
Embankment – Internal		Method	NSW – base (corrected for condition)	Interim Guide (modified)	
Db.10	Embankment deterioration	Internal erosion (IE)	2.5×10^{-8} (2×10^{-9})	1.5×10^{-6}	Draft RARS used for pilots (v2.15) has two alternative methods. The final RARS guide adopted the QRA and it those values that are used here.
Df.10	Foundation deterioration	IE	4×10^{-5}, (4×10^{-6})		
Ds.10	Deterioration of dam/ foundation	IE embankment into foundation	7.7×10^{-7} (8×10^{-8})		
Di	Deterioration of dam/ foundation	IE along concrete/ embankment dam interface	No method available	1.2×10^{-7}	Treat as if buried structure.
Embankment – External					
FL.1	Flood	Scour, overtopping	9×10^{-7}		Flood calculations in 1997 S10 show routed PMF 445 m^3/s out. Assume failure when flood at two-thirds height crest wall (that is, crest wall is mortared stone 0.45 m wide, 1.2 m high so fails under wave load).
Concrete – Internal					
Df7	Foundation deterioration	Sliding in foundation	1.3×10^{-6}		
Ds7	Pipe burst in tower	Floods drainage gallery and 'relief wells'	4.4×10^{-7}		POF reduced as is new pipe, modern concrete dam that should have reasonable strength on lift joints.
Concrete – External					
FL6	Flood	Failure on lift joint	3.7×10^{-9}		Maximum water level 491.13 mOD (0.55 m above underside of spillway bridge). Risk of blockage set to zero as no trees.
FL7	Flood	Failure at foundation contact	3.6×10^{-9}		
Eq6	Seismic	Failure on lift joint	7.4×10^{-8}		
		Overall	$\mathbf{4.3 \times 10^{-6}}$		

* Volume 2 of guide
RARS – Risk Assessment for Reservoir Safety

Dambreak			
Breach flow	Downstream extent	Inundation mapping	Comments
Needed to get Q/W and thus fatality rate. Peak flow 5000 m3/s (takes 4 hours to empty)	Reservoir inundation mapping (RIM) unhelpful, as includes breach from cascade failures of xxxx and xxxxx and extends 70 km to sea	Use RIM mapping on internet. Adjust rapid dambreak by increasing rate of attenuation so limit of total destruction is at 35 km.	

Consequences		
Base measure of consequences	Value	Comments
Highest individual vulnerability	80%	Fatality rate 100% × Exposure (% of time in house, Table 9.2 in Volume 2 of guide) 80% = 80%
Average societal life loss (ASLL)	176	
Damages (£ million)	55	
Other indicators of consequences	Level	Comments
Community health assets	3	Assume power supply would be affected
Transport	3	A-roads likely to be affected
Agriculture		Not checked
Environment, habitats and species	4	Many designated sites (that is, SSSI, NNR, SAC)
Cultural heritage		Not checked
Level of risk		
Total probability of failure	Value	Comments
	4.3×10^{-6}	Overall for embankment and concrete dams combined

Consequence of failure	Risk			
Parameter	Units	Value	Units	Value
Average social life loss	Societal life loss per year	176	Lives per year	7.6×10^{-4}
Individual vulnerability	Individual risk of death per year	80%	Chance per year	3.5×10^{-6}
Economic damage to third parties	Damage to third parties (£ million)	£55 million	£ per year	£237 million
Other: Specify				

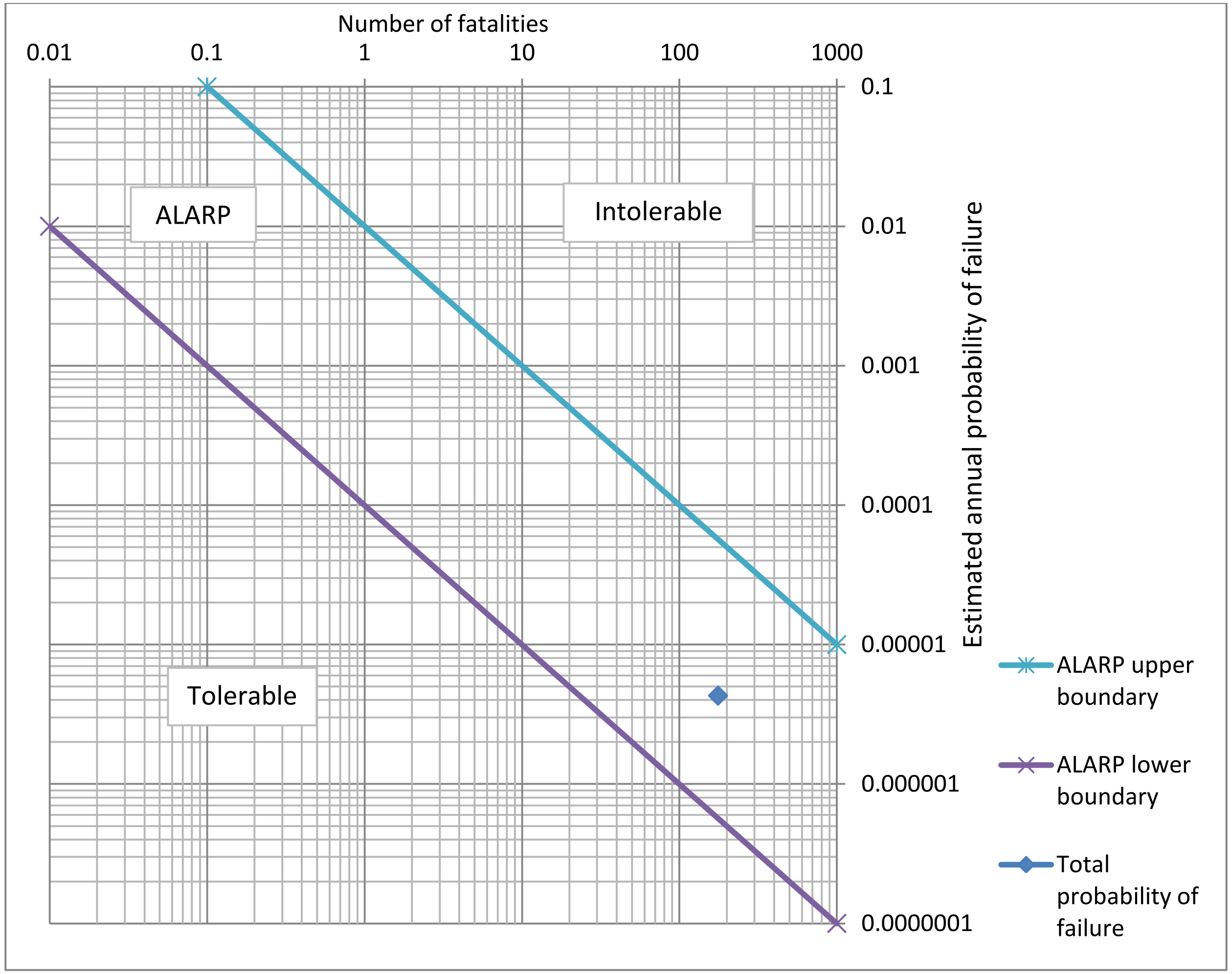
NNR = National Nature Reserve; SAC = Special Area of Conservation; SSSI = Site of Special Scientific Interest

Step 3 – Risk evaluation

Tolerability of risk			
	Value	Tolerability	Comments
Highest individual risk (HIR)	3.5×10^{-6}	ALARP	
Average societal life loss (ASLL)	7.6×10^{-4}	ALARP	
Economic damage to third parties	£237,000	-	
Community health assets	3	-	Power supply assumed to be affected
Transport	3	-	Disruption to A-roads likely
Agriculture	-	-	Not checked – consider requirement for further analysis
Environment	4	-	Consider likely extent of impacts to designated sites (that is, SSSI, NNR, SAC)
Cultural heritage	-	-	Not checked – consider requirement for further analysis

Options for risk reduction					
		Likelihood of failure		PV of project cost (= 30× annual cost)	Cost to save a life
Aim	Options	Existing	After risk reduction works		
Improve detection	Increase frequency of visual from weekly to twice a week.	3.7×10^{-6}	Assume reduce POF by factor of five	£300,000	£19 million

PV = present value


Number of fatalities
0.01
0.1
1
10
100
1000
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
Estimated annual probability of failure
ALARP
Intolerable
Tolerable
ALARP upper boundary
ALARP lower boundary
Total probability of failure

Appendix C: Tables of results

Table C1 Tier 1 pilot results

Likelihood of failure			**Embankment**								**Concrete**		
(Table 4.1)	Threat	Failure mode	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**10**	**11**	**12**
FL.1	Flood/ scour	crest erosion	L	M		H	L		L	M	H	L	
Fl.2	Flood/ scour	chute		M			VL						
Fl.6	Flood/ scour	body of dam		M							H		L
Fl.7	Flood/ scour	found'n instability		M						M		L	
Wi.5	Waves	stability	H			L	M	E	L				
Internal threats													
Db.10	body of dam	int'l erosion	M	M	L	M	H		L	H			
Df.10	deter'n of found'n	int'l erosion	H	L	L	M	L	VH	L	H			
Di.10	appurtenant wks	int'l eros'n culvert		M	L	M	L	H	L				
Di.10	appurtenant wks	into erosion spilwlay	H				VL	H					
Db.6	body	body of conc' dam											L
Df.7	foundation	diff'l settlement									L		
DS.7	Pipe burst	found'n ailure											L
	Total		**H**	**M**	**L**	**VH**	**H**	**VH**	**M**	**H**	**H**	**L**	**L**
	Plots		**3.3E-04**	**3.3E-05**	**3.3E-06**	**3.3E-03**	**3.3E-04**	**3.3E-03**	**3.3E-05**	**3.3E-04**	**3.3E-04**	**3.3E-06**	**3.3E-06**
Consequences													
	ASLL		4	1	VH	0	4	2	4	H	2	3	4
			30	0.03	30	0.003	30	0.3	30	30	0.3	3	30
	Damage		4	1		1	4	3		3	1	4	4
	Other		4	1	Not asses	2	3	4		4	1	3	3
			Transport			Econ	Econ + Cult H	Transport		Environ	Transport	Des Sites	Transport + Envir
	Overall		**4**	**1**	**4**	**2**	**4**	**4**	**4**	**3**	**2**	**4**	**4**
Risk													
Tolerability	Societal		**Unacceptable**	**Tolerable**	**ALARP**	**Tolerable**	**ALARP**	**Unacceptable**	**ALARP**	**ALARP**	**Tolerable**	**ALARP**	**ALARP**

Table C2 Tier 2 pilot results

	Likelihood of failure				Embankment									Concrete		
Threat	comb (Table 4.1)	threat	failure mode		1	2	3	4	5	6	7	8	9	10	11	12
Floods	FL.1	Flood/ scour	Overtopping		1.0E-06			1.3E-03	1.0E-06	8.8E-07	9.0E-07	7.5E-06	2.8E-08	1.0E-04		3.7E-09
	FL.2	Flood/ scour	Chute													
	FL.7	Flood/ scour	stability		1.0E-07			2.5E-02								3.6E-09
		FLOODS MAX			***1.0E-06***	***0.0E+00***	***0.0E+00***	***2.5E-02***	***1.0E-06***	***8.8E-07***	***9.0E-07***	***7.5E-06***	***2.8E-08***	***1.0E-04***	***0.0E+00***	***3.7E-09***
EQ	EQ.6	stability	lift joint												4.8E-06	7.4E-08
		Seismic													1.0E-06	
		seismic Max												***0.0E+00***	***4.8E-06***	***7.4E-08***
Other External																
		waves/ rainfa	slope failure		4.5-8				1.9E-06		4.2E-07					
Internal erosion Method 1 NSW																
	Db.10	body of dam	int erosion		2.0E-07	6.7E-04	3.4E-06	7.0E-05	4.0E-04		1.1E-07	4.0E-09	2.5E-06			
	DF.10	det of fdn	int erosion		5.0E-07	6.7E-05	1.6E-06	7.0E-06	1.0E-05		1.1E-06	2.8E-07				
	DS.10	emb into fdn	into erosion		2.0E-07	1.7E-06	6.5E-08		4.0E-07		1.4E-08	1.7E-08				
		Int threats - Sum NSW			***9.0E-07***	***7.4E-04***	***5.1E-06***	***7.7E-05***	***4.1E-04***		***1.2E-06***	***3.0E-07***	***2.5E-06***			
Internal erosion Method 1 NSW + Condition																
	Db.10	body of dam	int erosion			2.0E-04										
	DF.10	det of fdn	int erosion													
	DS.10	emb into fdn	into erosion								7.7E-07					
		Int threats - Sum NSW + condition adjustemnt			***0.0E+00***	***2.0E-04***	***0.0E+00***	***0.0E+00***	***0.0E+00***		***7.7E-07***	***0.0E+00***	***0.0E+00***			
Internal Erosion Method 2 QRA																
	Db.10	body of dam			4.0E-06		1.0E-05	3.5E-05	2.1E-05	3.8E-05	2.5E-08	4.8E-10	3.6E-06			
	DI.10	appurtenant	spillway		3.0E-05		7.0E-07			4.7E-04						
	DI.10	appurtenant	outlet						2.0E-05			4.3E-08				
		Embankment Int Erosion -Sum QRA			***3.4E-05***	***2.0E-04***	***1.1E-05***	***3.5E-05***	***4.1E-05***	***5.1E-04***	***8.0E-07***	***4.3E-08***	***2.5E-06***	***0.0E+00***	***0.0E+00***	***0.0E+00***
Other Internal																
	Db.6	body	body of con dam										5.3E-06	1.0E-04		
	Df.7	fdn	diffs settlement								4.0E-05		1.1E-06	4.0E-06		1.3E-06
	DS.7	Pipe burst	backpressure on drains												5.5E-06	4.4E-07
		Total All (NSW)			*1.9E-06*	*7.4E-04*	*5.1E-06*	*2.5E-02*	*4.1E-04*	*8.8E-07*	*2.1E-06*	*7.8E-06*	*2.5E-06*			
		Total All	(QRA)		3.5E-05	2.0E-04	1.1E-05	2.5E-02	4.2E-05	5.1E-04	4.2E-05	7.5E-06	1.0E-05	2.0E-04	1.1E-05	1.8E-06
Consequences																
		ASLL			999.0	0.010	174.00	0.00	100.0	47.0	176.0	54.0	1230	8.9	1230	176.0
		Highest Individual vulnerab		%	80%	20%	11%	0%	80%	80%	80%	70%	80.00%	80%	80.00%	80.0%
		Damage		£M	180	0	105	0	300	1	55	11	0.132	3.400	0.132	55.00
Risk																
		ASLL		lives/ yr	**3.50E-02**	**2.00E-06**	**1.86E-03**	**0.00E+00**	**4.20E-03**	**2.39E-02**	**7.34E-03**	**4.07E-04**	**1.23E-02**	**1.82E-03**	**1.39E-02**	**3.20E-04**
		IR		risk/ yr	2.80E-05	4.00E-05	1.18E-06	0.00E+00	3.36E-05	4.07E-04	3.34E-05	5.28E-06	8.00E-06	1.63E-04	9.04E-06	1.45E-06
		Annual damage		£/yr	£6,300	£35	£1,124	£0	£12,600	£576	£2,293	£83	£1	£694	£1	£100
		Other												H		
ALARP																
		Societal			Unacceptable	Tolerable	ALARP	Tolerable	ALARP	Unacceptable	ALARP	ALARP	Unacceptable	ALARP	Unacceptable	ALARP
		Individual risk			ALARP	Tolerable	ALARP	Tolerable	ALARP	Unacceptable	ALARP	ALARP	ALARP	Unacceptable	ALARP	ALARP
		Works recomemdned?			No	No	No	No	No	Yes	Yes	No	No	Yes	No	Yes

Appendix D: Plots of results

Figure D1 Dam height vs. reservoir volume

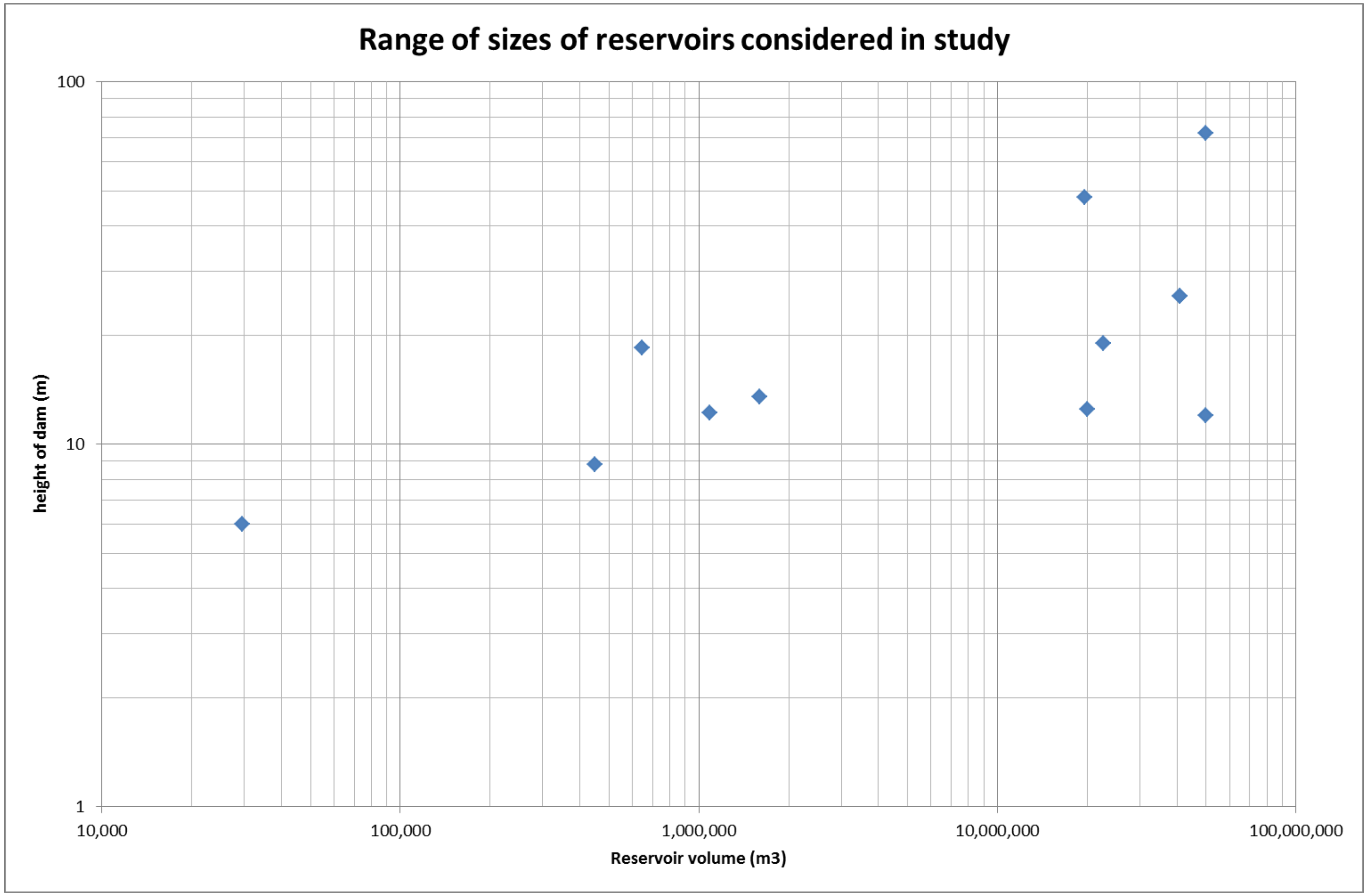


Figure D2 Cumulative distribution of total probability of failure

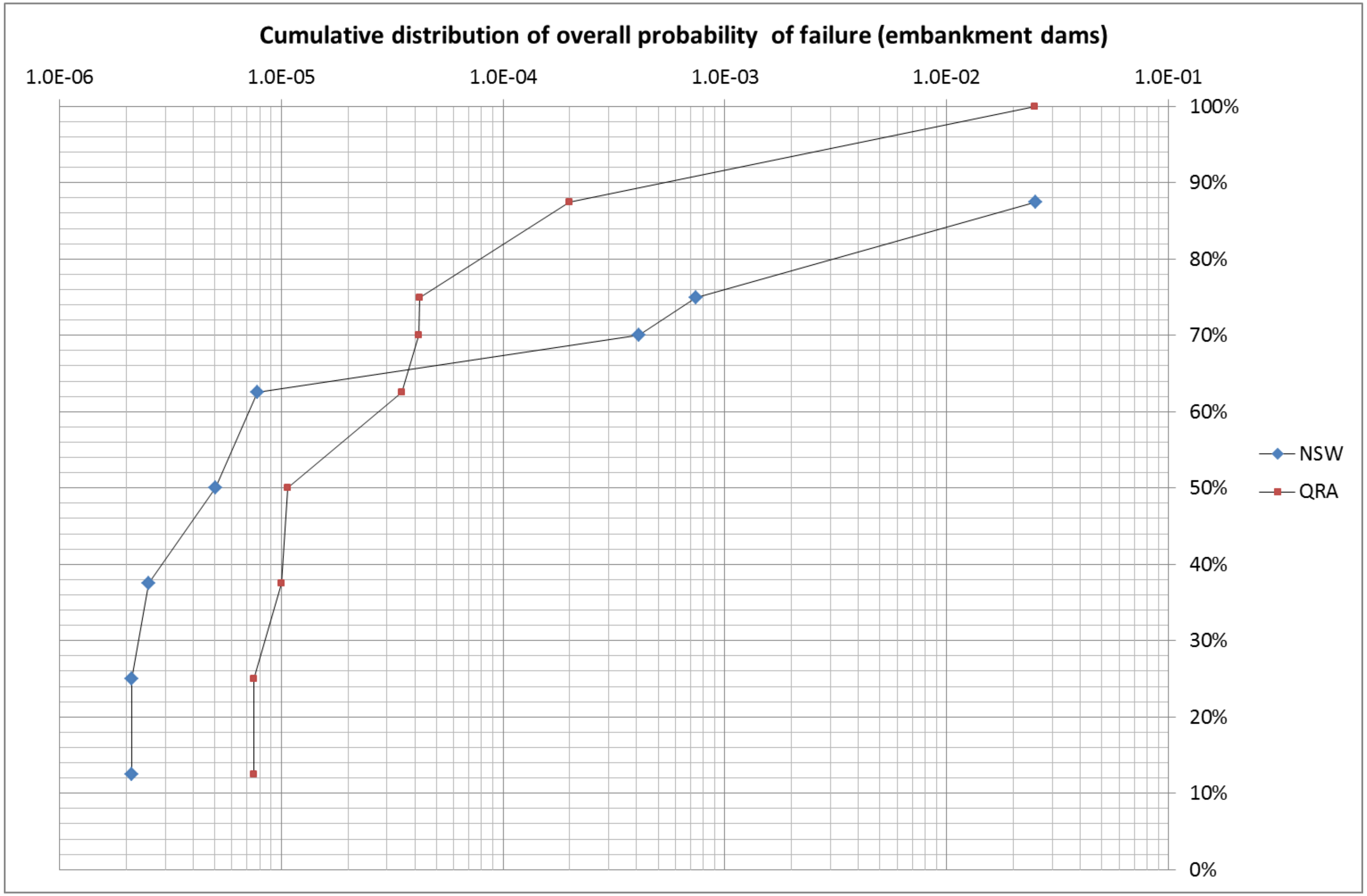


Figure D3 Probability of failure of internal threats – New South Wales method vs. Interim Guide method

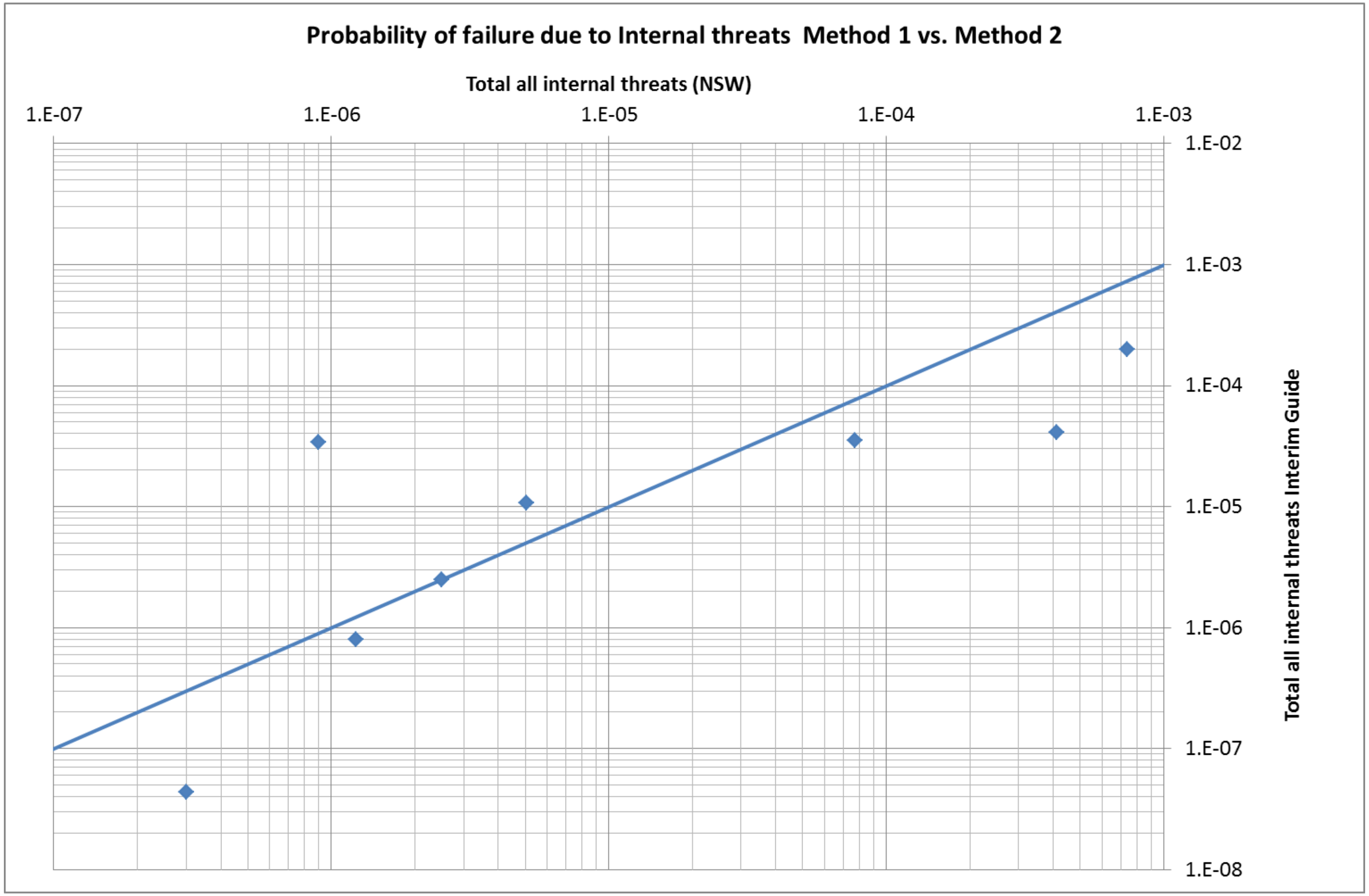


Figure D4 Annual probability of failure vs. date of construction

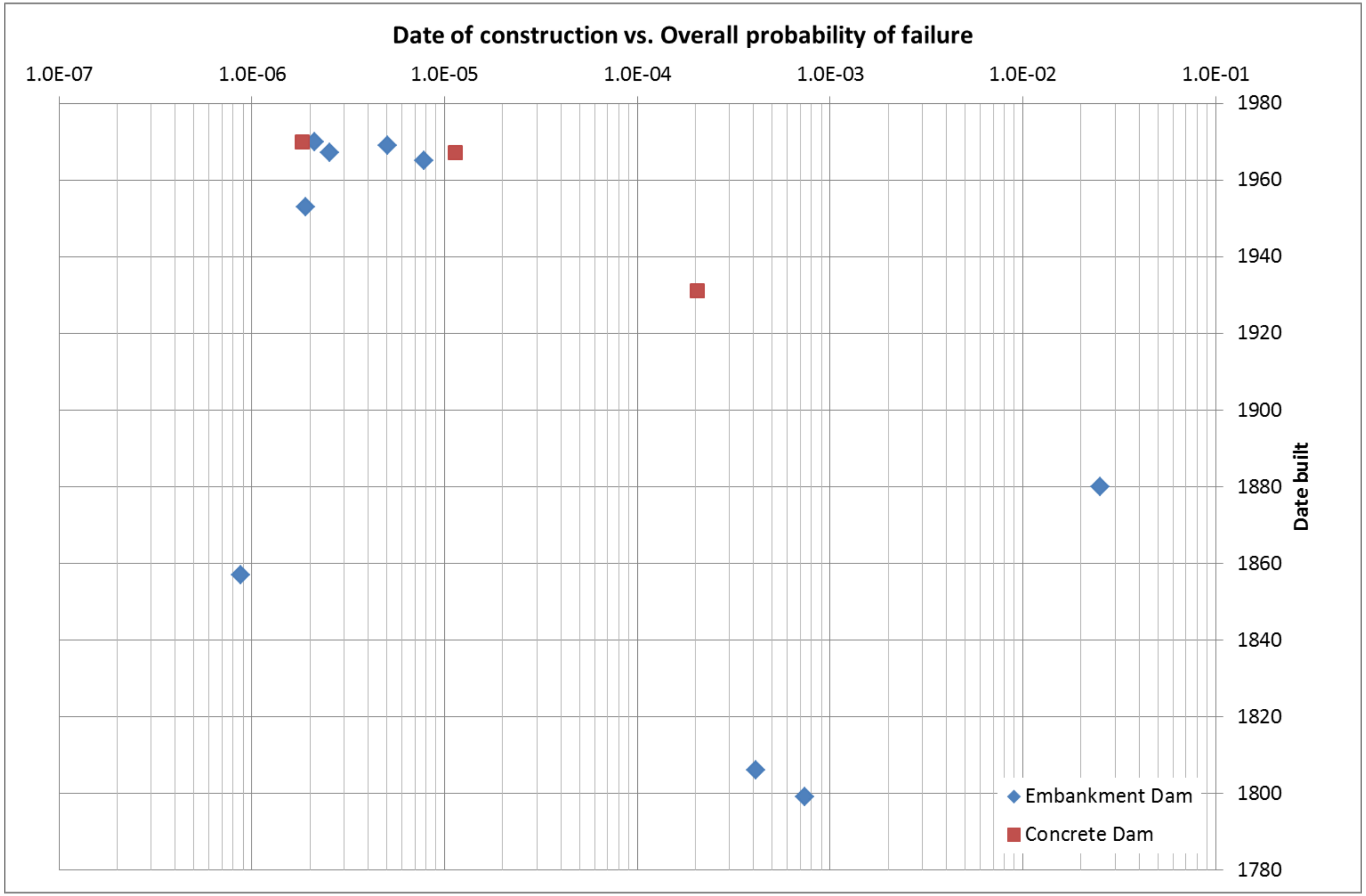


Figure D5 Cumulative distribution of average societal life loss

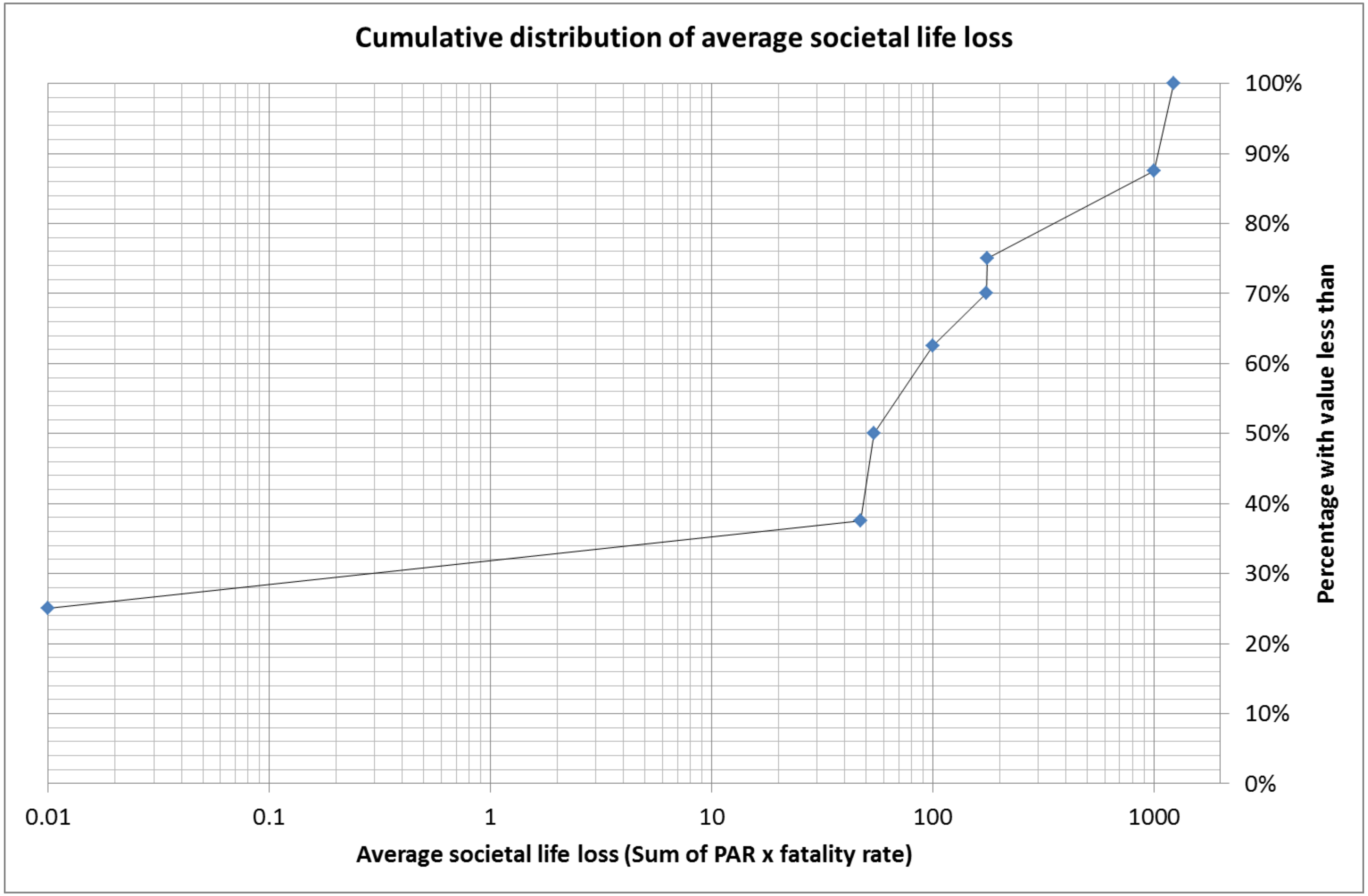


Figure D6 Average societal life loss vs. damages

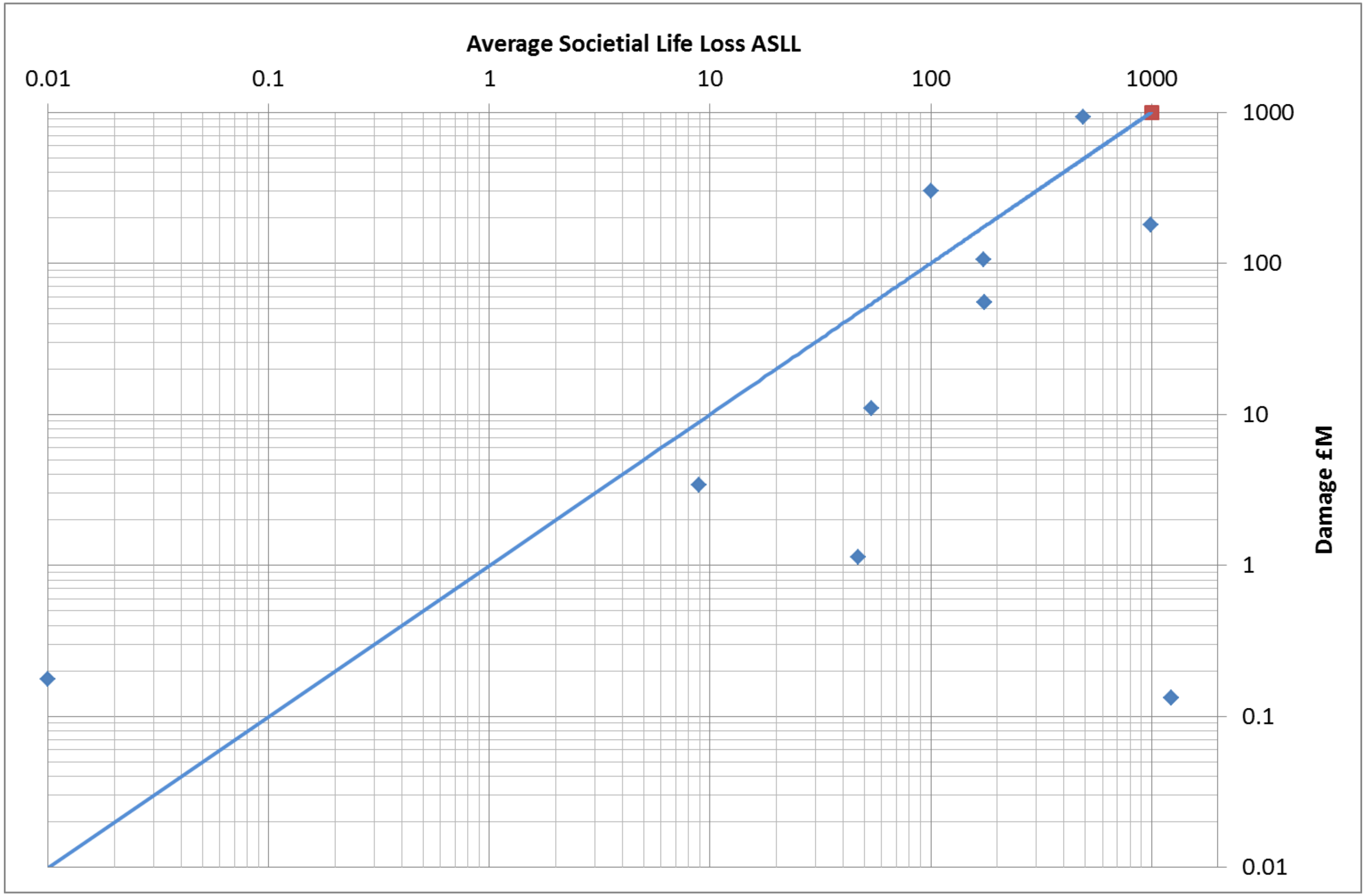


Figure D7 Probability of failure Tier 1 vs. Tier 2

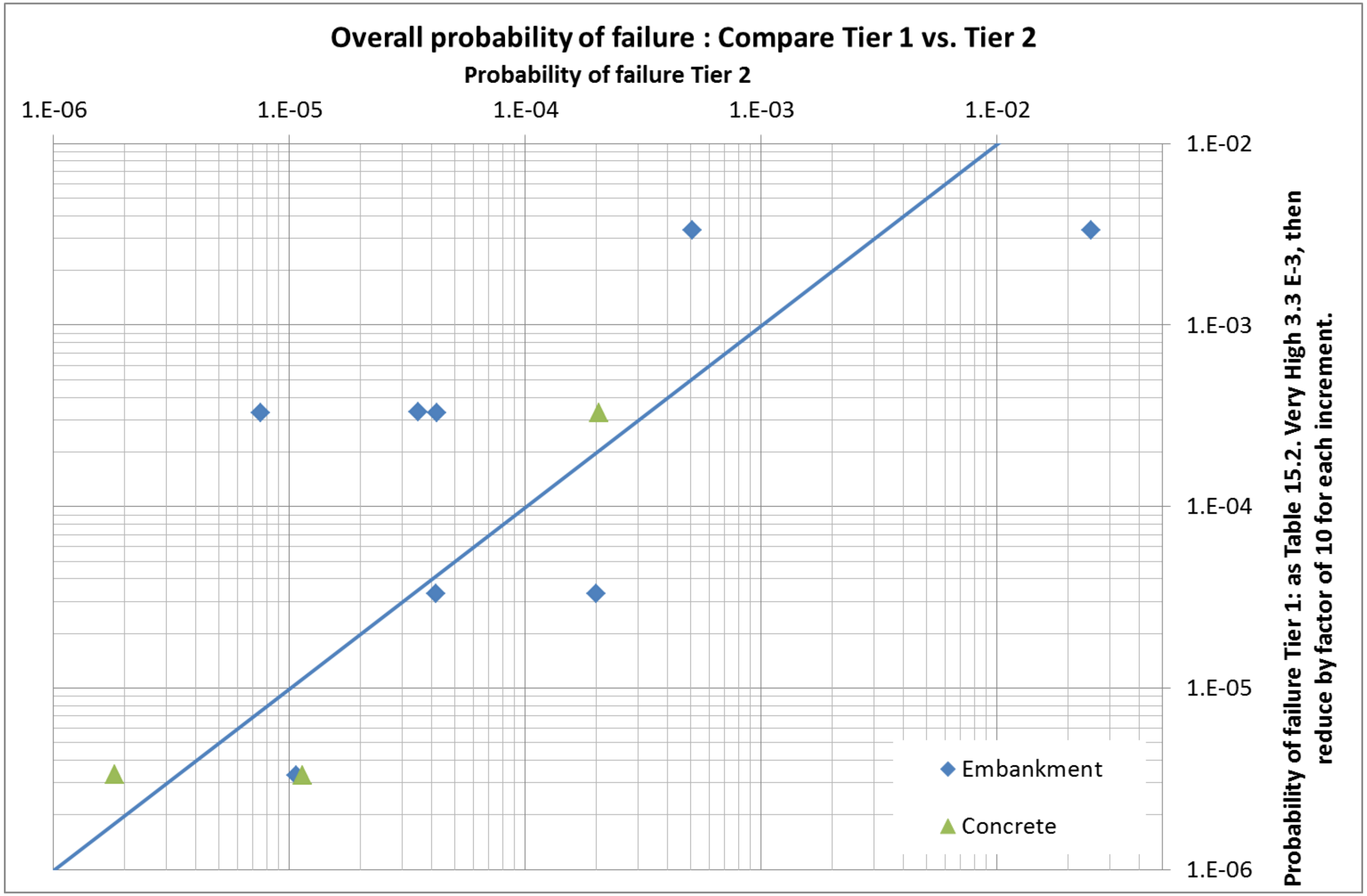


Figure D8 Average societal life loss Tier 1 vs. Tier 2

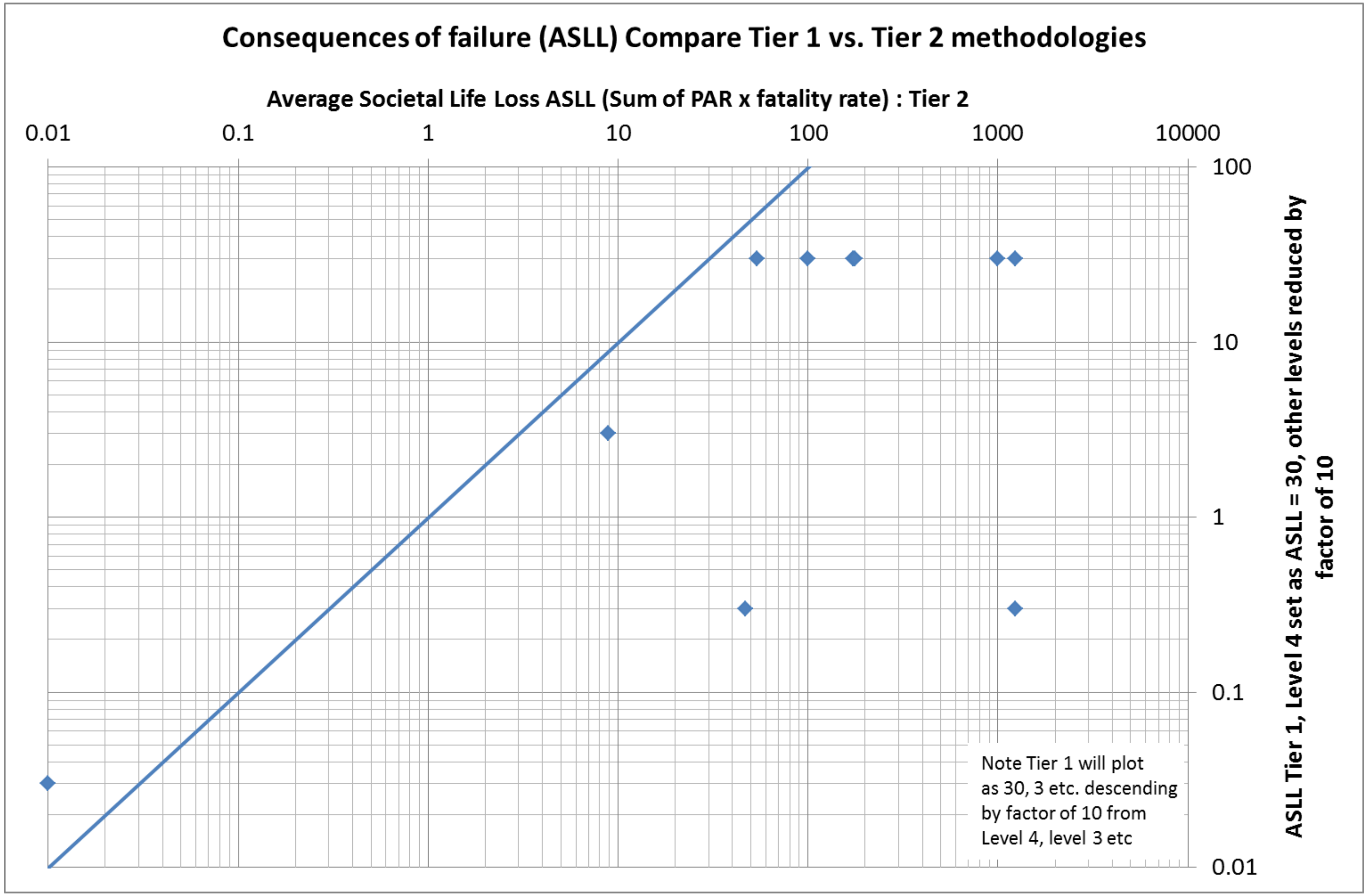


Figure D9 Tier 2 risk as F-N chart

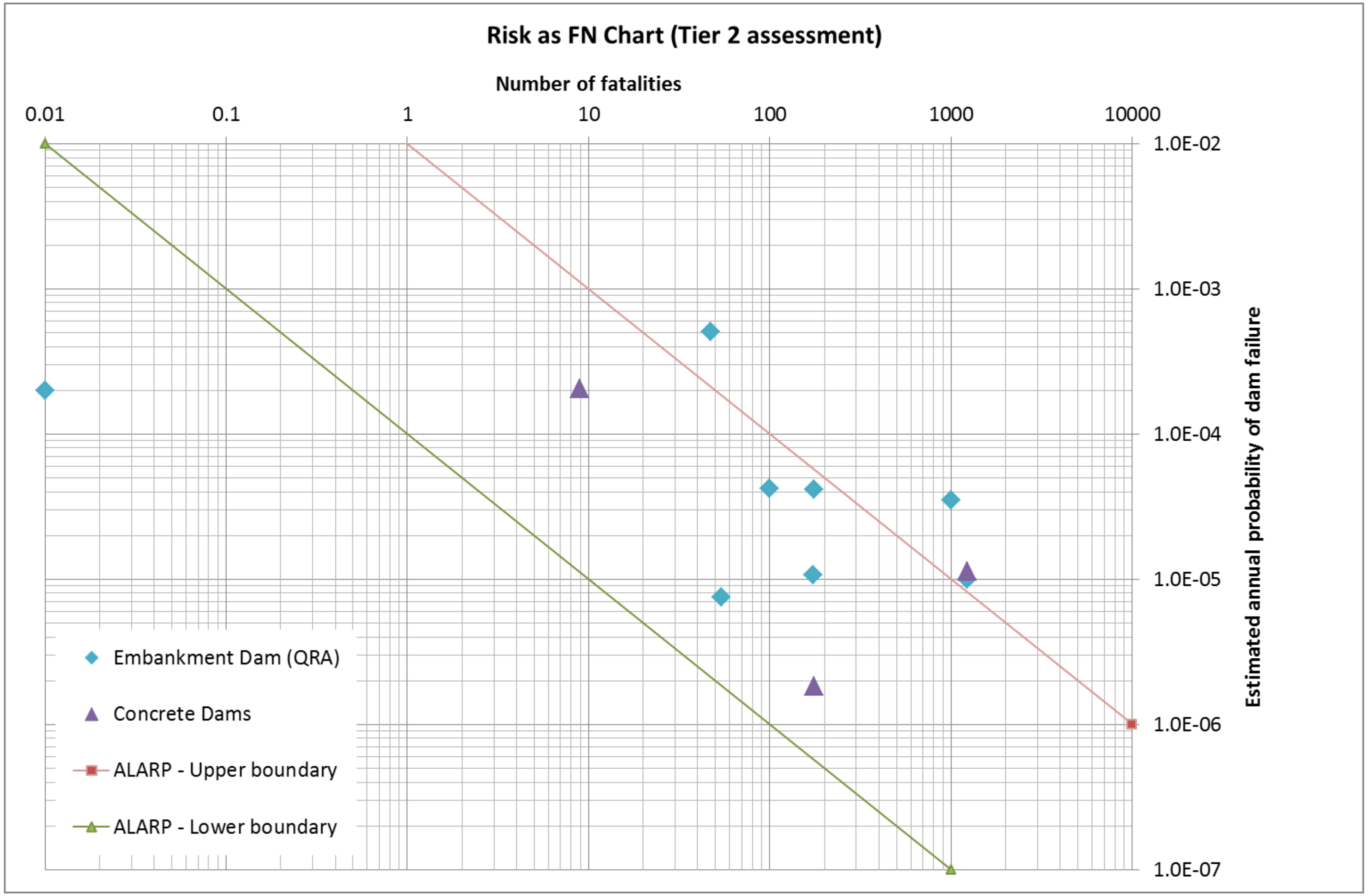
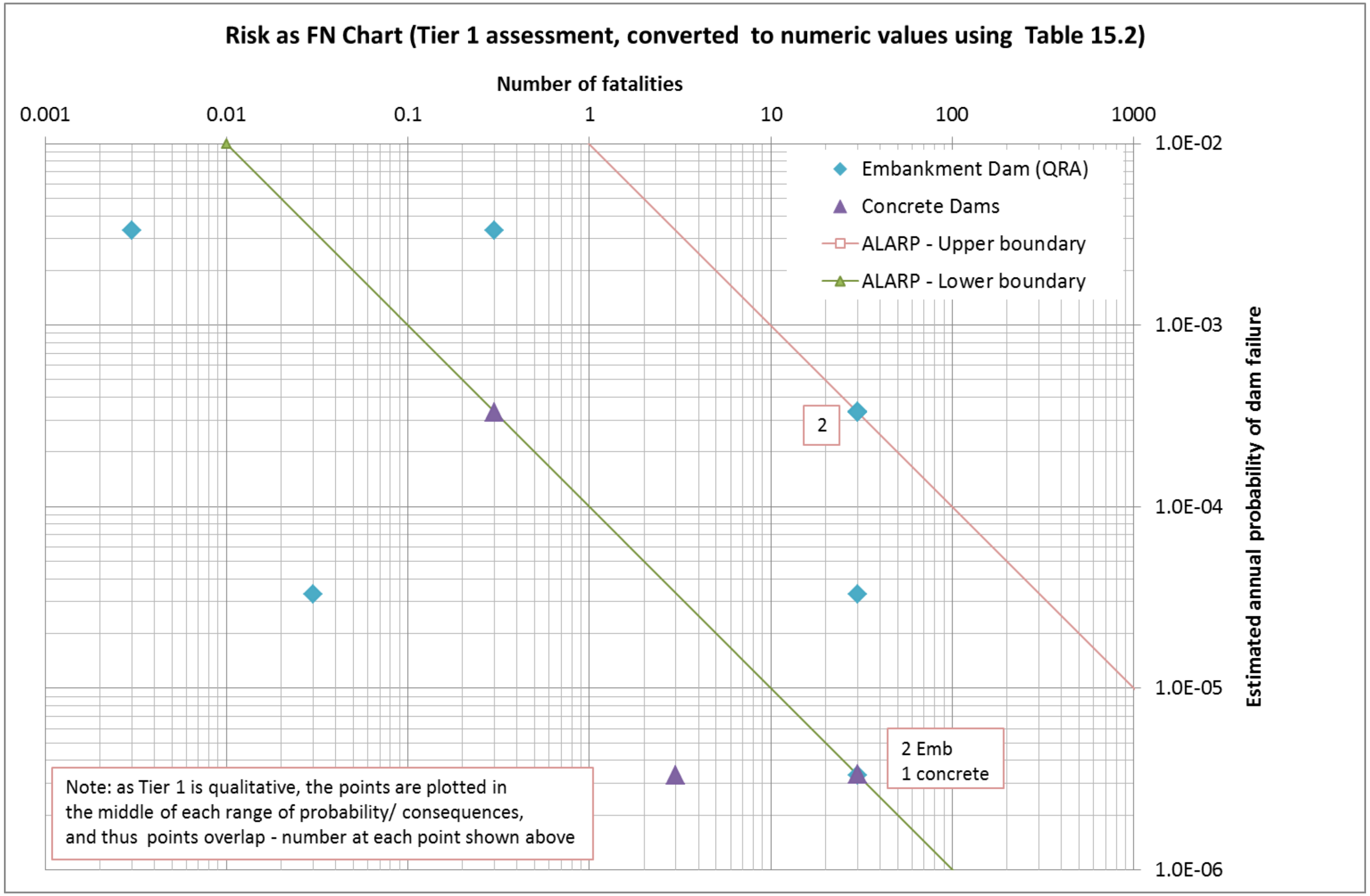


Figure D10 Tier 1 risk as F-N chart



We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

Published by:

Environment Agency
Horizon House, Deanery Road
Bristol BS1 5AH
Tel: 0117 934 4000
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk

Further copies of this report are available from our publications catalogue: http://publications.environment-agency.gov.uk or our National Customer Contact Centre: T: 08708 506506

E: enquiries@environment-agency.gov.uk.

Would you like to find out more about us, or about your environment?

Then call us on

08708 506 506* (Mon-Fri 8-6)

email

enquiries@environment-agency.gov.uk

or visit our website

www.environment-agency.gov.uk

incident hotline 0800 80 70 60 (24hrs)

floodline 0845 988 1188

* Approximate call costs: 8p plus 6p per minute (standard landline).
Please note charges will vary across telephone providers

Environment first: This publication is printed on recycled paper.