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CITY OF LONDON

Hampstead Heath, Highgate Wood and Queen's Park Committee

Date: **MONDAY, 23 SEPTEMBER 2013**

Time: **1.45pm**

Venue: **COMMITTEE ROOM - 2ND FLOOR WEST WING, GUILDHALL**

Members:
Jeremy Simons (Chairman)
Virginia Rounding (Deputy Chairman)
Deputy Michael Welbank
Deputy John Barker
Dennis Cotgrove
Karina Dostalova
Revd Dr Martin Dudley
Clare James
Professor John Lumley
Barbara Newman
Deputy John Owen-Ward
Tom Sleigh
Alderman Robert Hall (Ex-Officio Member)
Alderman Ian Luder (Ex-Officio Member)
Councillor Melvin Cohen
Martyn Foster
Councillor Sally Gimson
Tony Ghilchik
Charlotte Kemp
Maija Roberts

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Lunch will be served in the Guildhall Club at 1pm

John Barradell
Town Clerk and Chief Executive

AGENDA

a) Hampstead Heath Ponds Project - Quantitative Risk Assessment (Pages 1 - 34)

Hampstead Heath Ponds Project Quantitative Risk Assessment – Interim Report with accompanying Position Paper (copies attached).

Agenda Item 9a

CITY OF LONDON

Hampstead Heath Ponds Quantitative Risk Assessment

Interim Report

Notice

This document and its contents have been prepared and are intended solely for The City of London Corporation's information and use in relation to the Hampstead Heath Ponds Project.

This document has 30 pages including the cover.

Document history

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1.0	Draft for Discussion	TRW	TB	MJW	MJW	19-07-13
2.0	Initial Draft	TRW	TB	MJW	MJW	06-08-13
3.0	Initial Draft v2 (not issued)	TRW				
4.0	Draft v3	TRW	TB	MJW	MJW	28-08-13
5.0	Final Issued	TRW	TB	MJW	MJW	29-08-13

Client signoff

Client	The City of London Corporation
Project	Hampstead Heath Ponds Project
Document title	Hampstead Heath Ponds Quantitative Risk Assessment – Interim Report
Job no.	5117039
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Glossary

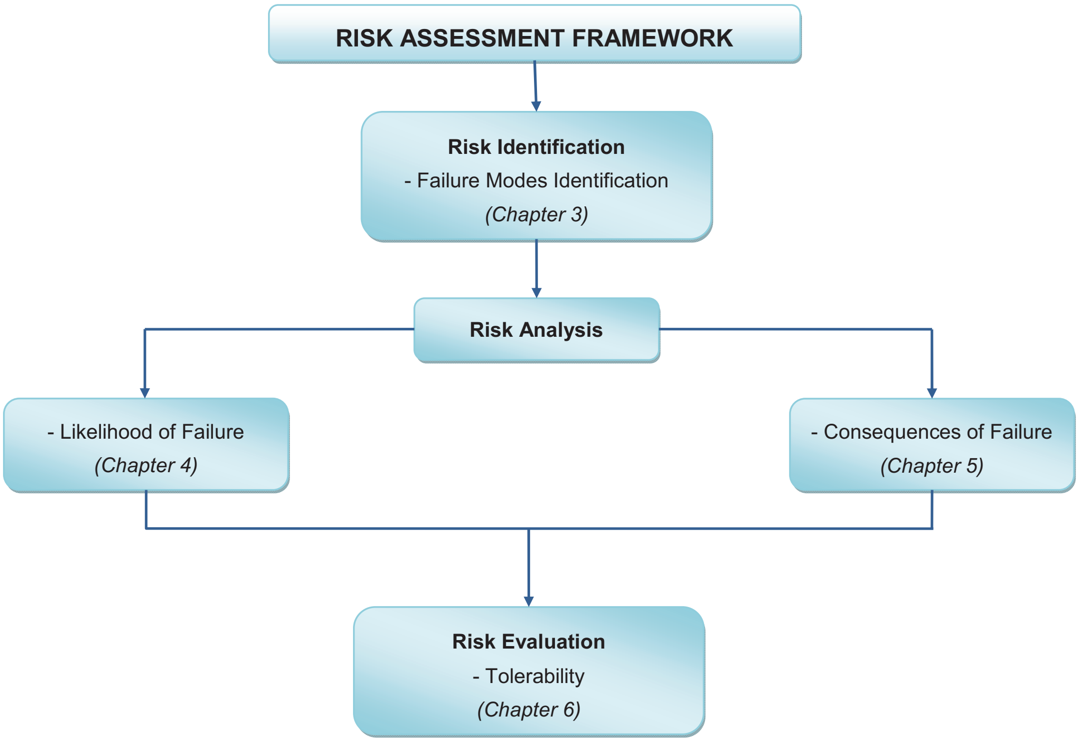
ALARP	As Low As Reasonably Practicable
ASLL	Average Societal Loss of Life
DEFRA	Department for Environment, Food and Rural Affairs
D	Depth (m)
F-N	Frequency – Number of lives likely lost (generally presented as a chart/graph)
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
HSE	Health and Safety Executive
NRD	National Receptor Database
PAR	Population at Risk
PMF	Probable Maximum Flood
RARS	Guide to Risk Assessment for Reservoir Safety Management (DEFRA 2013)
Q	Discharge/flow (m^3/s)
QRA	Quantitative Risk Assessment
RARS	Risk Assessment for Reservoir Safety Management
SRP	System Response Probability
V	Velocity (m/s)
W	Width of flood plain (m)

Executive Summary

This report sets out the findings of an interim Quantitative Risk Assessment (QRA) for the Hampstead Heath ponds. QRA is normally undertaken at the end of an options appraisal to understand the trade-off between cost and residual risk; the approach allows an insight into the proportionality of costs of competing measures.

In this instance the stakeholders requested an initial QRA to understand the scale of the risk currently faced. The assessment has been undertaken using the latest DEFRA Guidelines for QRA and sensitivity testing has been undertaken to try to show the scale of the outcomes, taking account of the fact that the QRA is not normally used in this way. It is to be noted that the purpose of this document is to provide the methodology and results of the QRA of the existing Hampstead Heath Ponds and is not to be used for design purposes. It is also to be noted that the DEFRA guidelines, and the QRA process, are not a statutory requirement for the management of reservoirs within the UK.

The process adopted for the QRA is presented in the below flow chart. This is the typical process for a QRA as defined in the latest DEFRA Guidelines for QRA. The flow chart also indicates the chapter within the report where the specific areas are covered.



The QRA demonstrates that the most likely mode of failure of the individual ponds is from prolonged overtopping, with high velocity of water flow over the embankments during a flood event. Hydraulic modelling previously carried out as part of the fundamental review shows that for many storms, including those of relatively low return periods, many of the dams are overtopped and may fail.

The QRA also shows that the consequences on failure of the ponds, in terms of Average Societal Loss of Life (ASLL), are very sensitive to the number of basement flats within the inundation zone.

It should be noted that the ASLL estimates do not include potential life loss related to transport infrastructure. These losses could be considerable given the number of 'A' roads, underground and mainline links, and stations, notably Kings Cross and St Pancras stations, within the at risk area.

An example 'cascade' failure of all the ponds within the Highgate chain has been assessed to provide an indication of the tolerability of the event. The results from the assessment have been plotted on the so-called F-N chart which assigns various combinations of probability (F) and consequence (N – number of lives likely lost) to bands of societal tolerability. These bands are not statutory limits as societal tolerance can vary in different situations, but once again allows an insight for the purposes of comparing costs and outcomes for competing options. The limits used here are taken from the RARS Guidelines which are based the Health and Safety Executive Guidelines "Reducing Risks, Protecting People: HSE's decision making process" (R2P2, 2001). For the example scenario, the risk calculated in this way falls in the unacceptable range indicating that the risk of failure of all the ponds in Highgate chain, in their current condition, is unacceptable when applying the methodology within the DEFRA guidelines.

The relationship for "no warning" time has been adopted as the City of London have suggested that the maximum warning time that could be provided to residents downstream of the Hampstead Heath Ponds in the event of a failure is around 40 minutes. This warning limit was based on earlier work by Haycock which examined the time it would take to overtop the embankments if all the ponds were emptied before the design flood arrived. The report went on to state "The maximum time delay of 41.4 minutes for the overtopping of the crests will not provide enough additional warning to make a positive significant difference to the emergency action plan or meet the statutory reservoir requirements. It has been stated that a warning time of two hours is required to make a significant difference to the number of people at risk." As it is not practicable to expect the ponds to be empty prior to the arrival of the design flood, and the nature of the City of London's monitoring system, the "no warning" approach is considered appropriate.

1. Introduction

1.1 This interim Quantitative Risk Assessment (QRA) has been carried out in accordance with the Guide to Risk Assessment for Reservoir Safety Management (RARS) published in March 2013 by the Environment Agency / DEFRA (DEFRA 2013). This guide is the latest industry standard for assessing the risk from failure from reservoirs within the United Kingdom. It is an update of the Interim Guide to Quantitative Risk Assessment for UK Reservoirs (DEFRA 2004).

1.2 This QRA has been carried out for the existing condition of the Hampstead Heath Ponds. QRA can be applied in this way, however, it is more typically applied to compare the risk associated with various options to allow for risk-based decision-making. This QRA should not be used as the basis of design.

1.3 The QRA has been undertaken in accordance with a 'Tiered' assessment methodology as detailed in the RARS guide.

2. Approach

2.1 The risk assessment framework approach adopted for this assessment is presented in Figure 2.1.

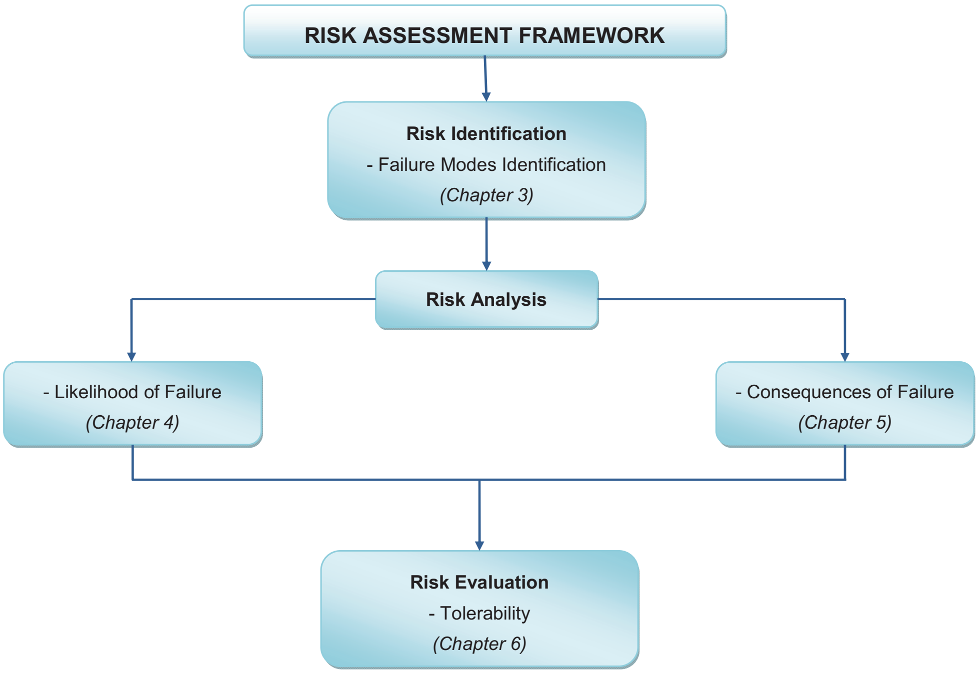


Figure 2.1 – Risk Assessment Framework

3. Failure Modes Identification

3.1 The first stage of the QRA involves identifying the potential failure modes. This was carried out based on the type of construction and the current condition of the ponds. The identified potential failure modes for the ponds are presented in Table 3.1.

Table 3.1 – Identified Failure Modes

Description of Failure Modes			**Credible?**	**Justification**	**Significant?**	**Justification**
Initiation (threat)	**Progression**	**Breach**				
Internal						
Normal Operating Conditions	Internal erosion in embankment	Embankment collapse	Yes	Take forward for a precautionary analysis	Yes	Take forward for a precautionary analysis
External						
Flood	Overtopping of crest and erosion of embankment fill	Embankment collapse	Yes	Embankment downstream face could erode	Yes	Likely to have large consequences
Normal Operating Conditions	Slope failure and erosion from either loss of freeboard or reduction in seepage path length	Embankment collapse	Yes	Take forward for a precautionary analysis	Yes	Take forward for a precautionary analysis

4. Likelihood of Failure

4.1 The assessment of the likelihood of failure of each of the Hampstead Heath Ponds is presented below. For simplicity the assessment is based on the individual likelihood of failure of each pond and does not take into account any failure of upstream ponds in the cascade. For example, for the overtopping probabilities of failure it is assumed that upstream ponds overtop but do not fail.

Internal Erosion

4.2 Internal erosion involves the loss of material from within an embankment to the point where the erosion is so severe that it causes the embankment to fail. For internal erosion to occur a defect needs to be present within the embankment to initiate the erosion, such as a crack or poorly compacted layer. Normal seepage through the embankment can then concentrate at the defect causing an increase in flow velocity and subsequent removal of fine material. If the embankment material downstream of the defect is not able to filter and trap the material being removed it will continue to erode and a 'pipe' will open up in the embankment. Once the pipe gets to a point where it is too large to support itself it collapses, causing the embankment to fail.

4.3 To carry out a detailed assessment of the probability of failure of an embankment from internal erosion a significant amount of information is needed regarding the embankment material properties. This information does not currently exist, and the probability is considered from inspection to be of low likelihood in normal operating conditions. Therefore for the Hampstead Heath ponds the probability of failure from internal erosion has been assessed in accordance with a Tier 2 assessment of the RARS guideline.

4.4 The Tier 2 approach requires assessment of the embankment form of construction (intrinsic condition) and the current condition of the embankment (current condition) to estimate the probability of failure. This is carried out by firstly applying the recommended typical probability based on historical failure probabilities and then applying several factors based on the construction and condition of the embankment being assessed. Typically the factors take account of the type of embankment and culverts through the embankment and any known existing issues such as seepage and settlement. Where possible existing data has been used to apply these factors, such as embankment settlement derived from existing annual crest topographic surveys.

4.5 The results obtained by carrying out the Tier 2 assessment on each of the Hampstead Heath embankments are provided in Table 4.1.

Table 4.1 – Internal Erosion Probabilities of Failure

HIGHGATE CHAIN	**Internal Erosion**	
Stock Pond	1.50E-06	1 in 667,000
Ladies Bathing Pond	1.50E-06	1 in 667,000
Bird Sanctuary	2.00E-07	1 in 5,000,000
Model Boating	6.00E-07	1 in 1,667,000
Men's Bathing Pond	2.00E-05	1 in 50,000
Highgate No. 1 Pond	1.50E-06	1 in 667,000

HAMPSTEAD CHAIN	**Internal Erosion**	
Vale of Health Pond	1.50E-06	1 in 667,000
Viaduct Pond	1.50E-06	1 in 667,000
Mixed Bathing Pond	1.50E-06	1 in 667,000
Hampstead No. 2 Pond	1.50E-06	1 in 667,000
Hampstead No. 1 Pond	6.00E-07	1 in 1,667,000

Overtopping

4.6 The failure of the pond embankments due to overtopping is a function of the following:

- Overtopping depth;
- Overtopping velocity;
- Duration of overtopping;
- Embankment fill material properties; and
- Type and condition of the surface grass covering.

4.7 In order to assess the probability of failure of the embankments in relation to the above the overtopping depths, velocities and durations were assessed for various flood events, termed loading conditions, based on information obtained from the flood model as presented in the Assessment of Design Flood Report (Atkins 2013). The results of this are shown in Table 4.2.

4.8 In the Design Flood Assessment Report, application of the Defra guidance for the estimation of the 1,000 year and 10,000 year floods resulted in a similar overtopping depths for both the events. This comes about because the 1,000 year flood was based on Flood Estimation Handbook (FEH) rainfall and the 10,000 year flood on Flood Studies Report (FSR) rainfall. Similar overtopping depths for a 1,000 and 10,000 year events gave rise to an anomaly in the QRA as it would be expected that the overtopping depths would be different for different events. In order to overcome this anomaly, the 1,000 year flood was re-estimated using FSR rainfall so that it was consistent with the 10,000 year flood.

Table 4.2 – Overtopping Results

Pond	5 year			20 year			50 year			100 year			1000 year			10,000 year			PMF		
Highgate Chain	Max. Depth (m)	Peak Velocity (m/s)	Duration (hrs)	Max. Depth (m)	Peak Velocity (m/s)	Duration (hrs)	Max. Depth (m)	Peak Velocity (m/s)	Duration (hrs)	Max. Depth (m)	Peak Velocity (m/s)	Duration (hrs)	Max. Depth (m)	Peak Velocity (m/s)	Duration (hrs)	Max. Depth (m)	Peak Velocity (m/s)	Duration (hrs)	Max. Depth (m)	Peak Velocity (m/s)	Duration (hrs)
Stock Pond	0.15	2.62	10.42	0.18	2.95	11.17	0.20	3.17	11.42	0.22	3.34	11.25	0.25	3.60	12.00	0.32	4.13	9.25	0.45	5.07	12.17
Ladies Bathing Pond	-0.08	0.00	0.00	0.02	0.50	0.50	0.06	1.14	1.33	0.08	1.41	2.00	0.12	1.75	2.17	0.19	2.32	2.08	0.24	2.66	2.83
Bird Sanctuary Pond	-0.13	0.00	0.00	0.05	0.98	0.92	0.11	1.63	1.75	0.15	1.91	2.33	0.19	2.25	2.42	0.29	2.84	6.75	0.45	3.73	3.08
Model Boating Pond	-0.52	0.00	0.00	-0.03	0.00	0.08	0.07	1.68	1.42	0.11	2.30	2.17	0.16	2.83	2.33	0.24	3.63	6.17	0.37	4.72	3.08
Men's Bathing Pond	-0.57	0.00	0.00	-0.30	0.00	0.00	0.09	1.77	10.17	0.14	2.30	10.50	0.18	2.65	11.83	0.26	3.26	7.42	0.38	4.12	11.83
Highgate 1 Pond	-1.32	0.00	0.00	-1.32	0.00	0.00	-0.34	0.00	0.00	-0.07	0.00	9.17	0.01	0.51	11.00	0.19	2.64	8.75	0.35	3.86	11.58
Hampstead Chain																					
Vale of Health Pond		0.00			0.00			0.00		-0.02	0.00	0.00	0.00	0.06	0.00	0.09	1.67	2.75	0.15	2.34	5.58
Viaduct Pond		0.00			0.00			0.00		-0.07	0.00	0.00	0.03	1.07	1.33	0.07	1.91	2.42	0.12	2.75	3.75
Mixed Bathing Pond		0.00			0.00			0.00		0.08	1.55	7.33	0.10	1.70	9.00	0.19	2.57	9.58	0.31	3.38	5.83
Hampstead 2 Pond		0.00			0.00			0.00		0.06	1.24	4.58	0.07	1.34	6.00	0.17	2.34	7.42	0.27	3.15	3.83
Hamstead 1 Pond		0.00			0.00			0.00		-1.11	0.00	0.00	-0.77	0.00	0.00	0.06	1.48	5.75	0.19	3.07	3.33

🟧	Overtopped
⬜	Not Overtopped
🟪	Auxiliary Spillway Overtopping

Note: A Negative Max. Depth (m) number indicates that the water level is below the embankment crest and no overtopping occurs.

4.9 The results indicate that overtopping of the ponds occurs in the Highgate chain for the majority of flood events, whilst overtopping only occurs during the 1,000 year flood and larger events for the Hampstead chain ponds.

4.10 Without undertaking specific 'in-situ' overtopping tests on the existing embankments the amount of overtopping that would cause erosion of the embankments and their subsequent failure is not known. In addition there are no definitive publications in probabilistic terms for overtopping failure probabilities of embankments due to the varying nature of embankments and associated grass cover. However, from literature typically an embankment of average grass cover is able to handle velocities of up to a maximum of around 2 to 3 m/s, for a duration of around 2 to 5 hours, before erosion will begin to occur and lead to embankment failure (CIRIA 1987). Whitehead et al. indicates that the critical flow velocity for the failure of grass cover can vary between 1.5 and 2.5 m/s for varying grass quality and a duration of 5 hours (Whitehead et al., 1976).

4.11 It should be noted however that the above provides an indication of when erosion will begin to occur but not when the erosion will be severe enough to cause complete failure of the embankment. General industry accepted figures indicate that failure would definitely occur if 0.6 metres of flow depth overtopped an average earth embankment, and a probability of failure of around 0.25 (25%) would be likely with an overtopping depth of 0.1 to 0.3 metres.

4.12 In order to estimate the probability of failure of the Hampstead Heath pond embankments from overtopping an assessment of their resistance to erosion and failure was undertaken in relation to the above typical overtopping failure velocities and depths. As the embankments vary in geometry, fill materials and vegetation cover quality, a generally conservative approach was taken in order to develop one probability of failure relationship that covers all the embankments. This assumes the steepest of the existing embankment downstream slopes, relatively granular embankment fill material and medium to poor embankment grass cover, with some large trees on the embankment.

4.13 Based on the above, the system response probability (SRP) curve shown in Figure 4.1 was produced to estimate the probability of failure of a Hampstead Heath pond embankment due to different flow velocities, or 'loadings', in accordance with the Tier 3 approach (DEFRA, 2013). The curve indicates that there is a 20% to 40% probability of overtopping causing erosion of the embankment fill, and subsequent complete failure of the embankment, when the overtopping velocity is 2 to 3 m/s (crest overtopping depth of around 0.15m to 0.25m). The probability increases to 100% when the velocity is 5 m/s (crest overtopping depth of around 0.4m).

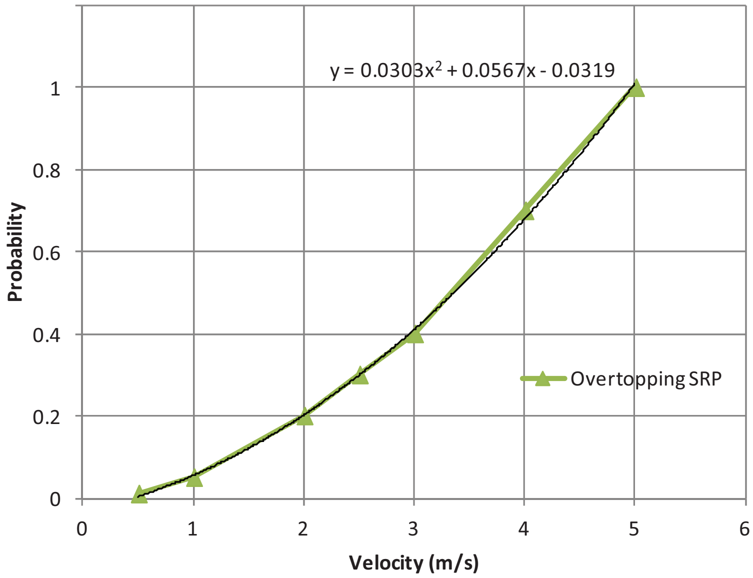


Figure 4.1 – Overtopping System Response Probability Curve

4.14 The above SRP curve was applied to the velocities provided in Table 3.2 for the range of flood events. The resulting probabilities were then multiplied by the annual exceedance probability of the flood event occurring, for each flood event, to obtain the annual probability of failure from the flood event. For example, for 1 in 1,000 year flood event the probability of failure from overtopping was multiplied by 1/1,000 or 0.001.

4.15 The PMF event does technically not have an annual exceedance probability. However, the RARS Guideline (DEFRA, 2013) suggests that when undertaking a QRA an annual exceedance probability for the PMF event should be based on the following average assignments of return periods given in Table 2 of Floods and Reservoir Safety (ICE 1996):

0.5 PMF – 1 in 10,000 AEP

0.3 PMF – 1 in 1,000 AEP

0.2 PMF – 1 in 150 AEP

These relationships are then to be plotted on lognormal probability paper and extending to the PMF. This results in the annual exceedance probability for the PMF of 1 in 400,000 ($2.5\text{x}10^{-6}$ /year). This has been adopted for this QRA.

4.16 The results were then summed across the range of flood events to estimate the 'area under the curve' of a plot of return period versus overtopping SRP. This area represents the overall probability of failure of the embankment due to overtopping, for all flood events. The results for each of the Hampstead Heath embankments are provided in Table 4.3.

4.17 The results indicate that the overall probability of failure from overtopping for all flood events for all ponds ranges from 7.69×10^{-2}, or 1 in 13, for Stock Pond, to 1.25×10^{-5}, or 1 in 80,000 for Highgate No. 1 Pond. It is to be noted however that the probabilities in Table 4.3 are based on the overtopping from the floods flows for the particular reservoir only and not any additional overtopping from breach and failure of any of the embankments within the chain.

Table 4.3 – Overtopping Probabilities of Failure

HIGHGATE CHAIN	Overtopping	
Stock Pond	7.69E-02	1 in 13
Ladies Bathing Pond	3.75E-03	1 in 270
Bird Sanctuary	1.07E-02	1 in 95
Model Boating	7.54E-03	1 in 130
Men's Bathing Pond	6.81E-04	1 in 1,500
Highgate No. 1 Pond	1.25E-05	1 in 80,000

HAMPSTEAD CHAIN	Overtopping	
Vale of Health Pond	8.70E-05	1 in 11,500
Viaduct Pond	4.25E-04	1 in 2,355
Mixed Bathing Pond	2.16E-03	1 in 465
Hampstead No. 2 Pond	1.44E-03	1 in 695
Hampstead No. 1 Pond	8.08E-05	1 in 12,500

Slope Instability

4.18 Slope instability involves the slip of a section of the embankment allowing an escape of water which causes erosion of the slipped area and eventual failure of embankment. Slope instability can occur for several reasons however for an existing embankment it is normally due to a change in conditions such as an increase in the phreatic surface (the level of water in the embankment due to normal seepage) within the embankment as a result of increased internal seepage. This causes the embankment to saturate decreasing the shear strength of the embankment material. If the associated loading is greater than the strength of the embankment material the embankment will become unstable and slip, causing failure of the embankment.

4.19 To carry out a detailed assessment of the probability of failure of an embankment from slope instability a significant amount of information is needed regarding the embankment material properties. As this information does not currently exist for the Hampstead Heath ponds a simplified approach has been adopted in accordance with a Tier 2 assessment of the RARS guideline.

4.20 The Tier 2 approach requires assessment of the embankment form of construction, including the geometry, and the current condition of the embankment to estimate the probability of failure. This is carried out by firstly applying the recommended typical probabilities based on historical failure probabilities and then applying several factors based on the type and condition to the embankment being assessed. A factor is also applied based on the frequency of the surveillance of the reservoir, to take account of possible detection of the early signs of slope instability which may lead to subsequent remedial action which could prevent the failure from occurring.

4.21 The results obtained by carrying out the Tier 2 assessment on each of the Hampstead Heath embankments are provided in Table 4.4. The results are for failure during normal operating conditions assuming the ponds are full to their top water level.

Table 4.4 – Slope Instability Probabilities of Failure

HIGHGATE CHAIN	Stability	
Stock Pond	1.39E-05	1 in 70,000
Ladies Bathing Pond	3.70E-05	1 in 30,000
Bird Sanctuary	8.33E-07	1 in 1,200,000
Model Boating	3.17E-05	1 in 32,000
Men's Bathing Pond	2.78E-05	1 in 36,000
Highgate No. 1 Pond	5.05E-06	1 in 200,000

HAMPSTEAD CHAIN	Stability	
Vale of Health Pond	5.56E-05	1 in 18,000
Viaduct Pond	3.70E-05	1 in 30,000
Mixed Bathing Pond	5.56E-06	1 in 180,000
Hampstead No. 2 Pond	2.78E-05	1 in 36,000
Hampstead No. 1 Pond	4.44E-06	1 in 225,000

4.22 The results indicate that the probability of "sunny day" failure from slope instability for the ponds ranges from 5.56 x 10^{-5}, or 1 in 18,000, for Vale of Health Pond, to 8.33 x 10^{-7}, or 1 in 1,200,000 for Bird Sanctuary Pond.

Summary

4.23 A summary of the annual probability of failure, from all failure modes and loading conditions, of each of the individual Hampstead Heath Ponds is provided in Table 4.5. Since these are independent (mutually exclusive) events the total probability is the sum of the individual probabilities.

Table 4.5 – Summary of Probability of Failure for each Individual Pond

HIGHGATE CHAIN	Overtopping	Internal Erosion	Stability	TOTAL	
Stock Pond	7.69E-02	1.50E-06	1.39E-05	7.69E-02	1 in 13
Ladies Bathing Pond	3.75E-03	1.50E-06	3.70E-05	3.79E-03	1 in 265
Bird Sanctuary	1.07E-02	2.00E-07	8.33E-07	1.07E-02	1 in 95
Model Boating	7.54E-03	6.00E-07	3.17E-05	7.58E-03	1 in 130
Men's Bathing Pond	6.81E-04	2.00E-05	2.78E-05	7.29E-04	1 in 1,400
Highgate No. 1 Pond	1.25E-05	1.50E-06	5.05E-06	1.91E-05	1 in 52,000

HAMPSTEAD CHAIN	Overtopping	Internal Erosion	Stability	TOTAL	
Vale of Health Pond	8.70E-05	1.50E-06	5.56E-05	1.44E-04	1 in 7,000
Viaduct Pond	4.25E-04	1.50E-06	3.70E-05	4.63E-04	1 in 2,200
Mixed Bathing Pond	2.16E-03	1.50E-06	5.56E-06	2.16E-03	1 in 465
Hampstead No. 2 Pond	1.44E-03	1.50E-06	2.78E-05	1.47E-03	1 in 680
Hampstead No. 1 Pond	8.08E-05	6.00E-07	4.44E-06	8.59E-05	1 in 11,650

4.24 The results indicate that the failure due to overtopping from flooding is the greatest threat to the ponds by several orders of magnitude.

4.25 The results also indicate that the annual probabilities of failure for the individual ponds are high when considering the Health and Safety Executive (HSE) requirement that the probability of life loss for the individual at greatest risk should be less than 1 in

10,000/year (1x10^{-4}) (HSE 2001). Whilst an estimate of the loss of life for the individual dams has not been calculated their failure could result in loss of life. However, as the ponds are in cascade it is unlikely that failure of a single individual pond would occur without subsequent failure of other ponds downstream, and possibly further loss of life. This is described further below.

Cascade Failure Scenario Probability

4.26 The above probabilities of failure are for failure of individual ponds only, from all credible failure modes and loading conditions. However, as the ponds are in a chain or 'cascade' the failure of one pond is likely to cause failure of one, or more, downstream ponds. In order to assess this, two example scenarios have been developed incorporating the above failure modes; one for the Highgate chain and one for the Hampstead chain.

4.27 The Highgate chain scenario assesses the failure of Stock Pond and subsequently all the downstream 'cascade' ponds in the Highgate chain. The failure probabilities for Stock Pond are based probabilities of failure presented in Section 4 and include flood overtopping (PMF and 100 year events), normal operating failure; slope instability and internal erosion. The failure probabilities of subsequent downstream ponds were based on the overtopping depth and velocities from the breach of the upstream ponds and the relationship outlined in Section 4.

4.28 The probabilities failure of all ponds in the Highgate chain for the above scenario are presented in Table 4.6.

Table 4.6 – Summary of Probability of Failure for Highgate Chain Cascade Failure Scenario

Flood	4.41E-02	1 in 23
Normal Operating - Internal Erosion	6.07E-07	1 in 1,650,000
Normal Operating - Stability	1.50E-09	1 in 670,000,000
TOTAL	**4.41E-02**	**1 in 23**

4.29 The Hampstead chain scenario assesses the failure of Vale of Health Pond and subsequently all the downstream 'cascade' ponds in the Highgate chain, but not including Viaduct Pond as it is not 'downstream' of Vale of Health. The failure probabilities for Vale of Health Pond are based probabilities of failure presented in Section 4 and include flood overtopping (PMF and 1,000 year events), normal operating failure; slope instability and internal erosion. The failure probabilities of subsequent downstream ponds were based on the overtopping depth and velocities from the breach of the upstream ponds and the relationship outlined in Section 4.

4.30 The probabilities failure of all ponds in the Hampstead chain for the above scenario are presented in Table 4.7.

Table 4.7 – Summary of Probability of Failure for Hampstead Cascade Failure Scenario

Flood	5.18E-04	1 in 1,930
Normal Operating - Internal Erosion	6.07E-07	1 in 30,200
Normal Operating - Stability	1.50E-09	1 in 670,000,000
TOTAL	**5.51E-04**	**1 in 1,800**

4.31 Once again the results from both of the above example scenarios indicate that overtopping from flooding is the main contributing failure mode for each pond chain. Stock Pond is more likely to fail during the lower annual exceedance probability floods than Vale of Health due to the greater amount of overtopping during these events.

4.32 The results of the above probability assessment for these example scenarios are combined with the outcome of the consequence assessment to arrive at an assessment of the tolerability of the risks, as discussed below.

5. Consequences

Average Societal Loss of Life Assessment

5.1 The assessment of the consequences of failure of the Hampstead Heath ponds has been based only on the possible loss of life at this stage of the QRA. The methodology for assessing the loss of life is provided below in accordance with the RARS guidance (DEFRA, 2013). Details of the hydrological and hydraulic modelling, and associated embankment breach model, developed to assess the potential loss of life are provided in Appendix A.

Methodology

5.2 The approach to calculating the Average Societal Loss of Life (ASLL) is in accordance with the Guide to Risk Assessment for Reservoir Safety Management (DEFRA 2013).

5.3 The methodology can be split into two stages, as outlined below:

- Stage 1: Population At Risk (PAR): the flood outlines were extracted from the InfoWorks 1D-2D model for the various flood annual exceedance probabilities and overlain on the National Receptors Database (NRD) mapping. A count of the number and type of properties within the flood outline was then carried out and for each residential property the PAR was calculated based on 2.35 people per property. This number was then reduced to account for assumed occupancy rate (80%) during an event. For each non-residential property the number of people affected is linked to the floor area of the property (one person per 40m²). This number is then reduced based on an assumed occupancy rate of 25%. This approach is set out in Table 9.2 of the guidance. This provides the number of people at risk per property, which is then combined with the fatality rate in the next stage to estimate the loss of life.
- Stage 2: ASLL: the maximum depth (D) and velocity (V) values from the InfoWorks 1D-2D model were extracted and applied to the properties within the flood outline. For each property the Q/W value (discharge per unit width, or a measure of average depth of flow across an area) was calculated based on 0.67*(D*V); the relationship between DV and Q/W is specified in Table 9.2 of the guidance. The fatality rate based on the Q/W value was then assessed using the No-Warning curve in Figure 9.1 of the guidance (as shown in Figure 5.1). For each property the PAR was then combined with the fatality rate to estimate the ASLL.

  The relationship for "no warning" time has been adopted as the City of London have suggested that the maximum warning time that could be provided to residents downstream of the Hampstead Heath Ponds in the event of a failure is around 40 minutes. This warning limit was based on earlier work by Haycock which examined the time it would take to overtop the embankments if all the ponds were emptied before the design flood arrived. The report went on to state "The maximum time delay of 41.4 minutes for the overtopping of the crests will not provide enough additional warning to make a positive significant difference to the emergency action plan or meet the statutory reservoir requirements. It has been stated that a warning time of two hours is required to make a significant difference to the number of people at risk." As it is not practicable to expect the ponds to be empty prior to the arrival of the design flood, and the nature of the City of London's monitoring system, the "no warning" approach is considered appropriate.

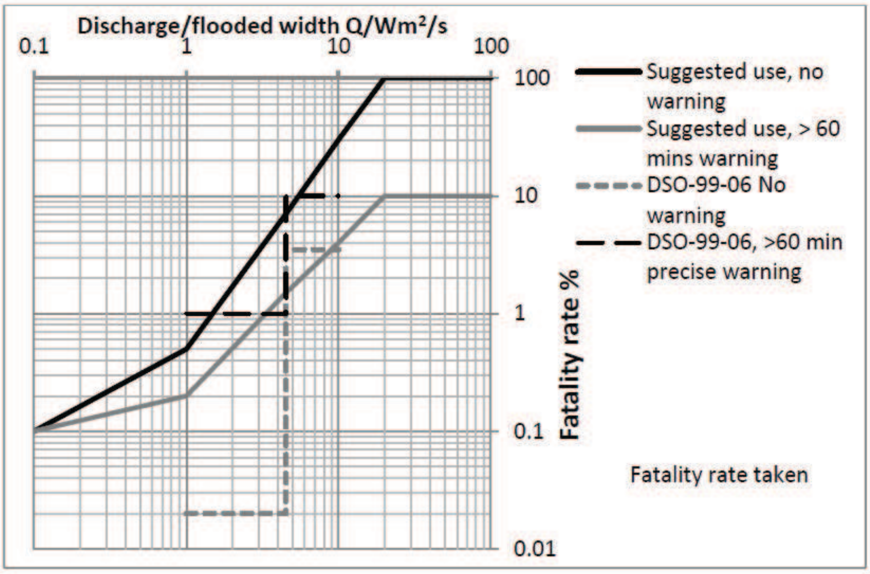


Figure 5.1 - Figure 9-1 from the guidance (suggested relationship of fatality rate to force of water)

5.4 The following property types were removed from the assessment: electricity sub-stations, ponds, public telephone, play areas, post boxes and shelters.

It should be noted that this ASLL does not include potential life loss related to transport infrastructure. These losses could be considerable given the number of 'A' roads, underground and mainline links, and stations, notably Kings Cross and St Pancras stations, within the at risk area. In the normal case, where the QRA is used for comparing options for resolving risk, these 'transient' consequences would effectively balance out in the comparison.

5.5 For the PMF event, there are 8,645 flats, out of a total of 11,115 residential properties in the at risk area. As this property type dominates the residential total, the assumptions applied to flats are likely to have a significant impact on the ASLL totals. At this stage, with the large number of properties involved, the differentiation between basement, ground floor and above ground floor properties has been has been based on assumed distributions between property types. The assumptions have been assessed using sensitivity tests.

5.6 The NRD indicates which flats are ground floor and which are upper, but does not indicate which are basement flats below ground level. Site visits and existing knowledge of the risk area suggests that there are a large number of basement flats in this area of London. The level of risk for a basement flat is clearly greater than that of ground and above floor flats. This is assessed in one of the sensitivity tests.

5.7 It was not considered appropriate to include all of the 8,645 flats in the assessment as a large number will be above ground floor and may not be directly impacted by flood waters. The sensitivity of ASLL totals to the inclusion of above ground floor flats has therefore been tested.

5.8 The baseline case includes all properties (i.e. houses, terraces, non-residential properties) plus all flats specified as being on the ground floor; these are the base elements of all the sensitivity tests. The following sensitivity tests were completed:

- Baseline case plus 100% fatality rate applied where DV is greater than 7. Table 9.2 of the RARS guidance (DEFRA 2013) states that where DV>7 a building is completely destroyed. It was therefore considered appropriate to apply a 100% fatality rate where buildings are completely destroyed;

- Baseline case with increased fatality rate to 100% for 25% of ground floor flats assuming these are basement flats in the at risk area. This was considered a reasonable estimate of the percentage of basement flats in relation to ground floor flats in the study area and the 100% rate is also reasonable given the 'underground' nature of the flat with very limited egress;
- Baseline case plus above ground floor flats at the following percentage inclusions: 75%, 50% and 25%. It was considered appropriate to include a percentage of the above ground floor flats, as a proportion would be affected by the flood waters.

5.9 No sensitivity tests were considered necessary for the assumptions relating to Non-Residential Properties.

Results

5.10 The following tables summarise the results from the assessment for the PMF event only. Table 5.1 compares the number and type of properties in the at risk area between the overtopping and breach scenarios during the PMF event.

Table 5.1 - Property types in the PMF at risk area

Property Type	Number in at risk area – PMF Overtopping	Number in at risk area - PMF Breach
Non-residential properties	848	1,504
Residential Properties	8,443	11,115
Total Flats	6,601	8,645
Flats (ground floor only)	2,318	2,976
Total Properties	**9,291**	**12,619**

5.11 Table 5.2 compares the ASLL under the PMF overtopping scenario, including the variations based on the differences in assumptions regarding flats.

Table 5.2 - PMF Overtopping ASLL for each sensitivity test

No.	Scenario	Maximum PAR	PAR (including occupancy factor)	ASLL
1	Baseline Case (including flats specified as ground floor)	14,333	8,960	5
2	Baseline Case (plus 100% fatality where DV>7)	14,333	8,960	5
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	14,333	8,960	1,095
4	Baseline Case (plus 25% of above ground floor flats)	16,849	10,973	6
5	Baseline Case (plus 50% of above ground floor flats)	19,365	12,986	7
6	Baseline Case (plus 75% of above ground floor flats)	21,881	14,999	8

5.12 Table 5.3 compares the ASLL under the breach scenario, including the variations based on the differences in assumptions regarding flats.

Table 5.3 - PMF Breach ASLL for each sensitivity test

No.	Scenario	Maximum PAR	PAR (including occupancy factor)	ASLL
1	Baseline Case (including flats specified as ground floor)	20,139	12,074	19
2	Baseline Case (plus 100% fatality where DV>7)	20,139	12,074	37
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	20,139	12,074	1,414
4	Baseline Case (plus 25% of above ground floor flats)	23,469	14,738	23
5	Baseline Case (plus 50% of above ground floor flats)	26,800	17,402	27
6	Baseline Case (plus 75% of above ground floor flats)	30,130	20,067	32

The results in the above tables indicate that the ASLL is highly sensitive to the number of basement flats in the inundation area. This number is also seen to be the most representative of the actual situation likely to be encountered if a breach were to occur. As a result the *Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)* results have been adopted for the example scenario below.

Cascade Failure Scenario Consequences

5.13 Assessment of the PAR and ASLL has been undertaken for various pond breaches associated with the example scenarios of failure of Stock Pond and Vale of Health Pond and subsequent failure of all other ponds in the chains, as described in Section 4. The results are presented in Table 5.4 and 5.5.

Table 5.4 – Breach ASLL for Highgate Chain Cascade Failure Scenario

No.	Scenario	Maximum PAR	PAR (including occupancy factor)	ASLL
1 in 100 year flood causing overtopping failure of Stock Pond and all Highgate chain ponds to breach				
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	17,564	10,596	1,244
Sunny day slope stability failure of Stock Pond causing all Highgate chain ponds to breach				
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	15,769	9,344	1,079
Sunny day internal erosion failure of Stock Pond causing all Highgate chain ponds to breach				
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	0	0	0

Table 5.5 – Breach ASLL for Hampstead Chain Cascade Failure Scenario

No.	Scenario	Maximum PAR	PAR (including occupancy factor)	ASLL
1 in 1,000 year flood causing overtopping failure of Vale of Health Pond and all Hampstead chain ponds to breach				
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	17,353	10,549	1,271
Sunny day slope stability failure of Vale of Health Pond causing all Hampstead chain ponds to breach				
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	13,921	8,549	1,044
Sunny day internal erosion failure of Vale of Health Pond causing all Hampstead chain ponds to breach				
3	Baseline Case (plus increased fatality rate of 100% for 25% of flats – basement flats)	0	0	0

5.14 The results from Table 5.4 and 5.5 were annualised in relation to the associated probability of failure, for the associated failure mode, to enable addition of the ASLL numbers. The total annualised loss of life was then divided by the total annual probability of failure to obtain a single ASLL for the failure of all the ponds in the chain, when taking into account the possible failure modes for the scenario, and their probabilities of occurring. The resulting ASLL for the Highgate chain scenario was 709 and for the Hampstead chain scenario, 830.

6. Risk Tolerability

Societal Risk

6.1 As described in the RARS guideline (DEFRA 2013), to assess the tolerability of failure of the ponds the results of the probability of failure and ASLL are plotted on an F-N, as shown in Figure 6.1. The societal risk point plotted on the chart falls into one of the following three categories as divided by the 'ALARP' boundaries:

A1 'Broadly Acceptable' – risks compared with these that people live with every day, and that they regard as insignificant and not worth worrying about.
A2 'Unacceptable' – risks are generally believed by individuals and society to be not worth taking regardless of the benefits.
A3 'Within the range of Tolerability' – individuals and society are willing to live with the risks so as to secure certain benefits, provided that they are confident that they are being properly managed, and that they are being kept under review and reduced still further if and as practicable.

6.2 The above categories are as presented in the RARS guidelines and are adapted from the HSE guidelines "*Reducing Risks, Protecting People: HSE's decision-making process*" (R2P2) (HSE 2001). It is noted that the RARS guidance (March 2013) states:

"For reservoirs below the threshold of 25,000 cubic metres, safety regulation is managed by the Health and Safety Executive (under the Health and Safety at Work (etc) Act 1974) and local authorities (under the Building Act 1984). This guide, and in particular the Tier 1 assessment, was designed with these applications in mind and should also be considered applicable to owners of non-classified reservoirs."

6.3 A key principle in achieving Tolerable Risk under the HSE Guidelines (HSE, 2001) is "*reducing risks as low as reasonably practicable*" (ALARP). This principle is discussed in the R2P2 guidelines (HSE 2001) included in Appendix 3 of that document.

6.4 The assessment of tolerability of the example cascade failure scenario presented in Section 4 and 5 is shown in Figure 6.1. The probability of failure of the Highgate chain ponds is 4.41×10^{-2} as detailed in Section 4 and the ASLL 709 as described in Section 5. The probability of failure of the Hampstead chain ponds is 5.51×10^{-4} as detailed in Section 4 and the ASLL 830 as described in Section 5.

6.5 The resulting risks from both example scenarios both plot in the Unacceptable zone, as show in Figure 6.1, with the Highgate chain scenario representing a high risk than the Hampstead chain. This is due to the higher probability of Stock Pond failing due overtopping in lower annual exceedance probability floods than Vale of Health Pond.

6.6 The ALARP upper and lower boundaries shown in Figure 6.1 are as presented in the RARS guidelines and are adapted from the HSE guidelines "*Reducing Risks, Protecting People: HSE's decision-making process*" (R2P2) (HSE 2001).

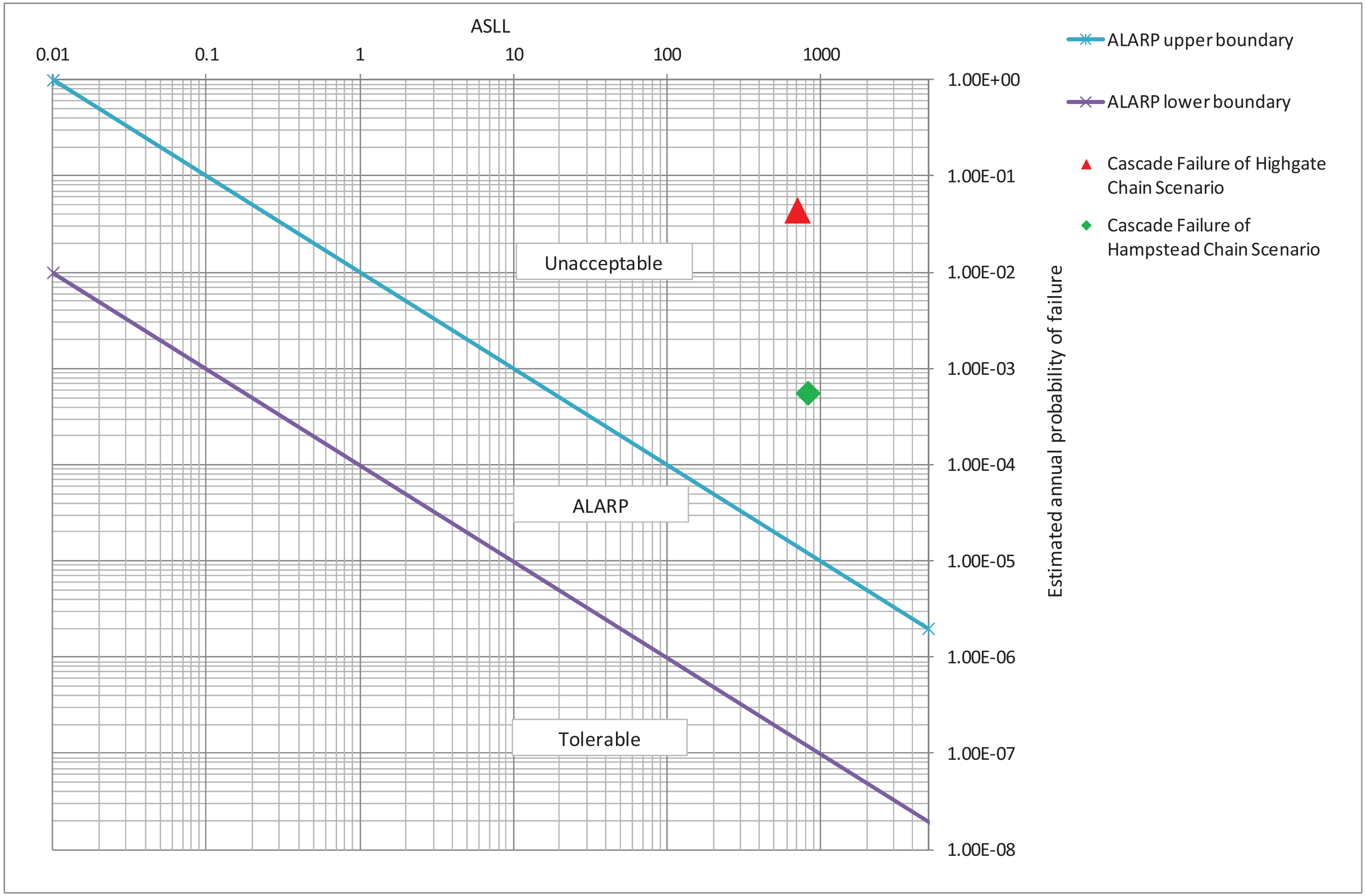


Figure 6.1 Assessment of Risk Tolerability

7. References

CIRIA (1987). Design of Reinforced Grass Spillways.

E. Whitehead, W. Bull, and M. Schiele (1976). A guide to the Use of Grass in Hydraulic Engineering Practice.

Guide to Risk Assessment for Reservoir Safety Management (RARS) published in March 2013 by the Environment Agency / DEFRA (DEFRA 2013).

HSE (Health and Safety Executive) (2001). Reducing risks, protecting people: HSE's decision-making process. Risk Assessment Policy Unit. HSE Books, Her Majesty's Stationery Office, London, England.

Institution of Civil Engineers (1996). Floods and reservoir safety, 3rd edition. Thomas Telford.

Appendix A – Hydrological and Hydraulic Modelling

Hydrological Modelling

A1 Hydrological modelling was undertaken to provide input to the hydraulic model and was generated using current industry-standard best practice. The design flood events modelled are the 'standard' extreme events for reservoir safety studies (1 in 1,000 year, 1 in 10,000 year and the Probable Maximum Flood (PMF)) as defined by the Guidance on Floods and Reservoir Safety, and a range of lower return period events (1 in 5 year, 1 in 20 year, 1 in 50 year and 1 in 100 year) which were examined for the purpose of determining the current Standard of Protection (SoP) of each dam.

A2 The assessment is based on a combination of the Flood Estimation Handbook (FEH)1 and Flood Studies Report (FSR)2 rainfall-runoff methods and is in line with all the appropriate current industry guidelines on normal and extreme flood estimate including:

- Floods and Reservoir Safety, 3rd Edition, ICE, 1996
- Floods and Reservoir Safety: Revised Guidance for Panel Engineers, Defra, 2004
- URBEXT2000 - A new FEH catchment descriptor. Calculation, dissemination and application. R&D Technical Report FD1919/TR
- Flood Estimation Handbook (FEH) Manuals Vols., 1-5, IOH, 1999

A3 Further details concerning the hydrological modelling can be found in the Atkins report "Assessment of Design Flood", March 2013.

A4 The critical storm duration for the PMF event, applied in the breach assessment is 9.5 hours. Table A.1 below contains the peak flows for the 100-year, 10,000-year and PMF events.

Table A.1- Summary hydrological inflows

Pond Catchment	Maximum Flow (m^3/s)		
	1 in 100 year	1 in 10,000 year	Probable Maximum Flood (PMF)
Highgate Chain			
Stock	2.74	6.86	15.54
Ladies Bathing	3.63	9.10	20.35
Bird Sanctuary	5.82	14.53	31.88
Model Boating	6.15	15.65	33.71
Men's Bathing	6.57	17.02	36.48
Highgate No 1	7.02	18.44	39.10
Hampstead Chain			
Vale of Health	0.57	1.45	3.32
Viaduct	0.31	0.78	1.78

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[1] The Flood Estimation Handbook (FEH) is the current standard UK method for estimating rainfall, and flood frequency and flows, developed by the Centre for Ecology and Hydrology in 1999.

[2] The Flood Studies Report (FSR) was the first UK-wide flood estimation method developed in 1975 by IoH. FEH largely supersedes the FSR.

Pond Catchment	Maximum Flow (m^3/s)		
	1 in 100 year	1 in 10,000 year	Probable Maximum Flood (PMF)
Mixed Bathing	2.46	6.31	14.15
Hampstead No 2	2.81	7.27	16.14
Hampstead No 1	3.34	8.49	18.82

Hydraulic Modelling

A5 A linked 1D-2D hydraulic model of Hampstead Heath was constructed using InfoWorks RS modelling software, version 12.0.3 as part of the earlier stages of the Hampstead Heath Pond Project. This model has been applied for the breach modelling and ASLL assessment.

A6 The representation of reservoir as 1-dimensional units linked to the overland flow routes all the way around the perimeter of the reservoir will best represent the overflow from the reservoirs during extreme flood events. Further details concerning the hydraulic modelling can be found in the Atkins report "Assessment of Design Flood", March 2013.

A7 Flows across the floodplain were modelled in 2D using a 2D simulation polygon with a maximum triangle size of $150m^2$. All ground elevations were taken from the DEM, with no changes made. A universal Manning's n roughness value of 0.02 was used for the entire modelled floodplain area on the Heath. This is a widely recognised value for short-grassed areas with relatively deep flowing water as would be the case in the extreme floods. All channels and the catch pit on the Hampstead Chain were modelled in the 2D domain.

A8 The only changes to the 1D-2D model for the breach assessment was to extend the 2D domain downstream to the River Thames to allow flood water to propagate to a natural downstream boundary, and apply a higher Mannings 'n' roughness value of 0.05 to account for the built up nature of the downstream area. The LiDAR used to extend the 2D domain is the same data source as that used in the original model. Figure A.1 shows the Hampstead Heath InfoWorks Model schematic, and shows the difference between the original and breach assessment 2D domain extents.

Figure A.1: Schematic showing boundary area included in the hydraulic model

A9 Flow-time boundary nodes were used to provide each modelled pond with two hydrological inflows:

- A flow hydrograph representing the event runoff from the catchment to each pond (i.e. runoff from land draining into the pond); and
- A flow hydrograph representing the volume of rainfall that would enter the pond directly from rainfall falling onto the pond surface.

A10 Model run parameters were the same as those applied in the baseline overtopping modelling.

Overtopping Assessment

A11 The hydraulic model was run with the PMF event with no breach of dams/embankments to assess the impact of overtopping in isolation, and for comparison against the breach scenario. The difference in ASLL can be used to gauge the residual risks posed by the dams breaching during the PMF. The Sunny Day flows will also be tested to assess the residual effect of the PMF event, and thus identify the risks associated with the PMF event, and the risks related to the retained volume in the ponds.

Breach Assessment

A12 The breach assessment is based on a worst case scenario in which all the dams/embankments breach. The flow contribution from Kenwood Pond, at the top of the Highgate chain, is included in the model however the embankment has not been breached.

A13 Breach parameters were estimated using the Froehlich assessment methodology to calculate breach width. Assumptions include the breach starts 1 hour after the start of overtopping, the time to final breach is 1.5 hours after the start of breaching and the height of the breach is the full height of the dam. The key breach parameters for each pond are displayed in the following table.

Table A.2 - Summary breach parameters

Pond Name	Pond Element						
	Dam length (m)	Dam elevation (mAOD)	Storage Volume (m^3)	Dam height (m)	Breach base level (mAOD)	Breach start time (hrs)	Time to final breach (hrs)
Highgate Chain							
Stock	59.65	81.65	6400	4.5	77.15	3:30	1.5
Ladies Bathing	23.39	76.87	14200	3.73	73.14	5:05	1.5
Bird Sanctuary	60.46	72.57	13000	2.1	70.47	5:10	1.5
Model Boating	73.02	71.87	46000	5.3	66.57	5:40	1.5
Men's Bathing	122.16	68.16	55000	4.7	63.46	5:55	1.5
Highgate No 1	129.98	63.77	42800	3.81	59.96	6:10	1.5
Hampstead Chain							
Vale of Health	129.83	105.44	17800	5.7	99.74	5:50	1.5
Viaduct	65.40	89.97	5000	4.27	85.70	6:00	1.5
Mixed Bathing	69.98	75.46	11900	4.4	71.06	6:00	1.5
Hampstead No 2	104.71	74.91	25400	5.19	69.72	6:00	1.5
Hampstead No 1	120.74	70.91	50600	4.44	66.47	6:40	1.5

POSITION PAPER REGARDING QUANTITATIVE RISK ASSESSMENT FOR THE HAMPSTEAD HEATH PONDS PROJECT

By Dr Andy Hughes, Panel Engineer

EXECUTIVE SUMMARY

Currently dam safety is controlled by the Reservoirs Act, 1975, and there is a “standards based approach” where dams are considered to be “high risk” if lives of 10 or more people are endangered by a reservoir collapse. The future implementation of the Floods and Water Management Act 2010 will alter the definition so that dams are considered to be “high risk” if lives of 1 or more people are endangered.

Quantitative Risk Assessment (QRA) for reservoirs is not currently a statutory requirement. QRA is typically used as best practice for identifying potential failure modes, comparing the risk of reservoir schemes, evaluating the risk of reservoirs prior to, and post, remedial works and prioritising works across a portfolio of reservoirs.

QRA would not normally be undertaken at this stage of the project and was carried out in this instance in response to a request from stakeholders to try to gain an appreciation of the existing risk presented by the Hampstead Heath ponds.

Atkins has undertaken an interim QRA using the latest RARS guidance (2013). Previous studies by CARES/Haycock used the slightly different 2004 Guidance. Both studies confirm that there is a unacceptable risk to life from failure of the ponds during a flood event.

INTRODUCTION

This position paper presents a review by Dr A K Hughes, in his capacity as the currently retained All Reservoirs Panel Engineer for the Hampstead Heath Ponds, on the application of Quantitative Risk Assessment (QRA) for assessment of risks to life presented by the Ponds, taking into account the separate assessment by CARES in 2009 (ref 1) and by Atkins Ltd in 2013 (ref 2).

CURRENT STATUS OF CATEGORISATION OF DAMS

Currently in the UK the risk presented by dams is assessed in accordance with Flood and Reservoirs Safety; An Engineering Guide, 1996, which acts as supporting guidance to the Reservoirs Act 1975. Dams are categorised into four types (Category a to D), depending on the likelihood of a breach causing damage and/or endangering life, with Category A dams having the highest consequence of failure. The assessment of population at risk, made by the Inspecting Engineer under Section 10 of the 1975 Act, is often based on his/her judgement supported by the guidance and any inundation mapping that may be available. Where lives in a community (generally *‘considered to be not less than about 10 persons’*) are considered to be endangered, Category A dams are required to be able to safely pass the design flood. The design flood for Category A reservoirs is the Probable Maximum Flood (PMF) and the dam is required to pass the routed outflow of the PMF.

It should be noted that the recently implemented part of the Floods and Water Management Act, 2010, has revised the categorisation of reservoirs to “high risk” and “not high risk”. High risk reservoirs are those which endanger the life of at least one person.

This is a standards based approach; if there are lives which can reasonably be seen to be endangered the dams should be designed or modified to “virtually eliminate” the probability of collapse. To avoid failure, the excess water which the dam cannot retain in a flood must be passed safely by a spillway, or over and around the dam, without causing the dam to collapse. To virtually eliminate probability of collapse, the PMF has been used as the benchmark for Category A dams since if this extreme low probability event can be safely accommodated it is reasonable to state that probability of collapse has been virtually eliminated.

We all live with risk all the time in our normal lives. In some other areas of life a more risk based approach has been adopted, where an explicit balance, or trade-off, is made between the probability of endangering life and the cost which may be incurred to reduce or remove that risk. The concept of a tolerable level of risk implies that such a balance can be arrived at. Currently the Inspecting Engineer is relied upon to use his/her judgement as to the risk but not to make an explicit trade-off.

In response to this wider view of risk, methodologies have been in development over the last few years, under the aegis of DEFRA. These methodologies offer a more technical and quantitatively based route to assessing types of failure and probabilities of failure for individual dams. The Interim Guide to Quantitative Risk Assessment for UK Reservoirs was published in 2004. Further developments during its trialing, which exposed some difficulties of application in the absence of significant and often unobtainable data, resulted in the issue of the Guide to Risk Assessment for Reservoir Safety Management in 2013 (RARS).

There is no statutory requirement to apply RARS to the categorisation of dams in the UK as the standards based approach is still current for dams with storage capacity greater than 25,000m^3.

RARS guides the engineer through a process for estimating probabilities of failure of dams from a number of failure modes, including overtopping leading to collapse. This is a screening tool where the probability estimates remain somewhat subjective. To improve the estimates more investigating is required to reduce levels of uncertainty. RARS is for the moment best used for making comparisons between options, since the subjectivity which is necessarily applied commonly does not have a significant impact on the overall outcome.

OVERVIEW OF STUDIES

Both the CARES report and the Atkins report follow a similar process:

- Adopt the currently available hydrological information
- Assess the probability of failure of the embankments/chain of embankments
- Assess how the water released from the ponds affects the downstream catchment in terms of depth and velocity of flow
- Estimate the number of properties at risk and the number of people at risk from the inundation
- Estimate the likely loss of life based on a relationship between the people at risk and the depths and velocity of possible flows.

There are differences in inputs, processes used for the various steps and the outcomes recorded as noted below.

HYDROLOGY

The starting point for any assessment of the probability of failure of dam embankments is the estimation of the flows to which the system is subjected. The basic process is to establish the rainfall intensities and depths for various return periods, and to estimate based on several factors including soil type, slope, vegetation type, how the rain onto the catchment area runs off the land into the pond systems. For each return period assessed hydrographs are calculated which show the flow rate of water into the system over the duration of the flood.

The CARES study relied on hydrographs and modelled flows derived by Haycock (ref 3) and the Atkins study relied on information from the Atkins Assessment of Design Flood report (ref 4).

As previously commented upon the Haycock study developed higher flows than the Atkins study for the longer return period events; the reason for this is essentially that Haycock assumed that a greater proportion of any rain falling in a storm would run off the Heath and contribute flow to the system than Atkins did when using the industry standard methodology.

PROBABILITY OF FAILURE

Failure modes

The failure modes of an earth embankment generally fall into a few categories: internal erosion of material as water flows through the body of the dam; external erosion of the dam embankment or foundation due to extended durations of water overtopping the embankment crest and instability of the dam slopes. CARES only reviewed erosion due to overtopping and subsequent breach; this is reasonable as in essence the probability of internal erosion or slope instability is not likely to be significant in relation to overtopping. The Atkins assessment included these failure modes for completeness.

Probabilities estimated
In the CARES study the 2004 Interim Guide is used as the basis for the estimation. It is not clear how the cascade effect is included in the assessment although CARES note that the most significant impact on the failure probability is the probability of the uppermost embankment in the chain collapsing.

The Atkins study uses the RARS 2013 methodology and specifically includes the cascade effects, examining the probabilities of failure of individual ponds for different flood events and combining these appropriately to estimate the failure of the cascades. As for the CARES study, Atkins noted that the most significant effect on the probability of failure is the probability of the uppermost embankment in the chain collapsing.

Although slightly different methodologies have been adopted for the assessments, and the resulting probabilities of failure numbers are not exactly the same, both studies concluded that the estimated probability of failure of the Hampstead heath Ponds are within the unacceptable range.

IMPACT DOWNSTREAM

Both CARES and Atkins produced sophisticated 2D flood models showing how the flows released from failed cascades would spread downstream. The 2D model allows an assessment of extent but more importantly the depth and velocity which are the parameters of the flood flow which most affect likely loss of life. The LISFLOOD model used by Haycock on which CARES based their “persons at risk” and “likely loss of life” is comparable in structure and process to the InfoWorks RS model used by Atkins; InfoWorksRS is widely used in the UK being the modelling suite preferred by the Environment Agency for flood modelling in England and Wales.

Both Atkins and CARES used the current LiDAR data provided by City of London, so the base mapping for both studies is of high quality.

The way in which the breach which releases the water is developed and modelled is dealt with differently in the two studies. The CARES report uses information from Haycock where the breach is instantaneous, thereby releasing the water with great rapidity. In the Atkins study breaches are developed over a period of 1-2 hours, based on the Froelich assessment method, one of the standard breach models.

The CARES report notes that the instantaneous release is likely to result in higher hazard downstream than if a breach develops in a more timed fashion. Clearly there is a significant difference if the breach develops instantaneously or over hours. A slower breach is considered more realistic.

Both CARES and Atkins studies approach the assessment of Population at Risk in a similar way using the same map information about buildings, although the flood envelopes differ due to the differences in input hydrographs and breach modelling as noted above. The Population at Risk were converted to a Likely Loss of Life (LLOL) using the same relationship between Population at Risk and the likely loss of life.

CARES LLOL estimates based on no warning were around 500 however it is unclear what fatality rate was applied to the basement flats and the number of basement flats that were taken into consideration. Atkins LLOL estimate for the PMF and failure of both ponds chains was around 1,400 on the basis that 25% of properties are basement flats and there would be a 100% fatality rate for the inundated basement flats.

It is difficult to compare the estimates in the absence of the details of the number of basement flats and the fatality rate adopted by CARES for inundated basement flats. However, from both studies it is estimated that hundreds, if not thousands, of lives would be lost on failure of the Hampstead Heath Ponds. This is clearly unacceptable in relation to the current guidance.

CONCLUSION

The City of London, as the owner or undertaker for the reservoirs, some of which are currently covered by the 1975 Act, and all of which may be covered by the Flood and Water Management Act 2010, needs to virtually eliminate the probability of collapse. It is noted that eliminating the probability of collapse will not eliminate flooding downstream from overtopping during extreme events, which could in such events lead to loss of life

As yet the QRA approach is not used for making decisions about whether or not works to dams are required to avoid loss of life, as a threshold approach is currently applied. As such it is not a requirement to quantify the likely loss of life prior to assessing options to virtually eliminate the probability of collapse where lives are reasonably assessed as being at risk.

Risk based approaches such as the QRA are common in other areas of life and DEFRA has been developing the QRA approach since the Interim Guide was published in 2004. However, currently there is no legal requirement for undertaking QRA assessments on reservoirs. Consistent use of the QRA approach over time should improve the reliability and objectivity of the outputs.

Earlier work by Haycock and CARES established that there is a notable probability of collapse of the Hampstead Heath Ponds chains under longer return period storm events and a notable risk to life from such collapse. Atkins has revised the work carried out by Haycock and CARES using current guidance and state of the art methodologies and confirms that there is a notable probability of collapse of the Hampstead Heath Ponds chains under both shorter and longer return period storm events and a notable risk to life from such collapse.

Both CARES and Atkins use the same basic process to attempt to quantify the likely loss of life, although there are differences in inputs and in some details of the guidance between the 2004 and 2013 guides and differences in outputs as a result. Both parties concur that the principal mode of failure of the Hampstead Heath Ponds is erosion due to extended overtopping of the embankments during flood events, and the estimated probabilities of failure are high. In addition, both parties also concur that significant loss of life is estimated upon failure of the ponds, bringing the overall risk of failure into the unacceptable range.

References:

1) CARES (July 2009). Flood Risk Assessment for Three Ponds, Hampstead and Highgate.
2) Atkins (August 2013). Hampstead Heath Ponds Quantitative Risk Assessment – Interim Report.