APPENDIX 1

Hampstead Heath Ponds Project
Assessment of Design Flood

Summary

March 2013

Introduction

Studies carried out by Haycock Associates in 2006 and 2010 suggested that during 'extreme rainfall events,' the earthen dams retaining the ponds on Hampstead Heath cannot be relied on to store the additional volume of water. Excess flood water would flow over the top and round the sides of the dams possibly leading to breach.

If the dams are breached the water normally stored in the ponds will also be released and combine with the flood water – very quickly and in a completely uncontrolled way – with risk to life and property downstream. The Haycock studies used bespoke methodologies raising concern that the results were not consistent with using accepted industry standard methods – for instance the magnitude of the floods could have been over-estimated.

To address these concerns Atkins has undertaken further detailed work as part of a fundamental review to assess the largest flood that the dams could face – known as the Probable Maximum Flood or PMF - and to check if the dams will withstand it.

This fundamental review of storm events and resulting flows through the ponds has been carried out using industry standard methods, based on established guidance from the Department for Environment, Food and Rural Affairs (Defra) and the Institution of Civil Engineers (ICE).

Atkins' new work shows flood peaks are generally 30% to 50% lower than those estimated by Haycock and there will be less water to deal with. However even at these smaller floods the dams will overtop and breaches are possible, with risk to life and property.

This means that works will need to be undertaken to make the dams safe. To reduce the risk to life and property downstream some work will need to be done to ensure the dams can pass the PMF safely.

This document provides a summary of the detailed analysis undertaken by Atkins as part of a fundamental review, its results and implications.

It explains:

- How Atkins determined the design flood
- Where results differ from those from earlier studies
- Computer modelled results of passing flows through each pond and the expected flows over and around the dams
- The expected effects of the overtopping flows on the dams.

The full technical report will be available on the City of London Corporation website.

Approach to the Hydrology Study

An early task for this new phase of work was a hydrology study to estimate the likely size of floods for a range of 'significant rainfall events'. Methods of deriving these estimates, that are recognised as industry best practice and have been developed over a number years. These methods were used for the fundamental review.

Primary sources included:

- Flood Estimation Handbook (FEH), 1999, Centre for Ecology and Hydrology.
- Flood Studies Report (FSR), 1975, and the supplementary report issued in 1985, Institute of Hydrology.
- Applicable guidance and updates to these as appropriate.

Hydrological studies provide the range of possible flood flows and their likelihood at the chosen location. Estimated flood flows are normally described as having a given return period (e.g. 1 in 1,000 years), or chance of occurrence in any given year (0.1% chance). The information obtained for each return period is shown as graphs of flow rates over time; as a storm builds, flows increase to a peak and then decrease to the conditions before the storm. These patterns of flow rates were used to check how water levels in the ponds would behave over the duration of each flood event.

This part of Atkins' study was followed by an assessment of how the ponds are likely to behave in response to these flood flows.

When rain falls on the Heath, although some water soaks into the ground and some runs off the surface of the ground and drains into the ponds. Rain falling over the surface of the pond also adds water directly to the pond. The extra water in the pond raises the water level until it starts to overflow through the pipes connecting each pond to the next pond downstream. When the rate of the water entering the ponds exceeds the rate it can flow out through the outlet pipe, the water level in the pond will continue to rise and will reach a stage where water flows over the top of the dam.

This behaviour can be described mathematically and a number of software packages are used routinely in industry to simulate it. The package Atkins used to simulate the performance of the ponds during floods for this study, InfoWorks RS, is considered to be one of the most reliable and is widely used in the industry. The package includes elements to closely represent the ponds and the surrounding land. The flow rate over time series for each pond was used in the model to simulate flows down the chain of reservoirs.

Future work will assess the volume of water that would be released if a breach occurred, and to examine options for reducing the risk of an uncontrolled release of such a large volume of water.

Flood Estimation

In Table 1-1 below, flood estimates derived by Haycock in 2010, using bespoke methods and those derived by Atkins in 2013, using standard methods and software in line with current industry best practice, show quite significant differences. The estimates prepared by Atkins, are 30% to 50% less than those from Haycock. Atkins' estimates included the contribution of the area around the grounds of Kenwood House.

It is important to understand why the estimates differ and the implications of these differences. Despite the reduced flow estimates the ponds are still likely to overflow, as shown later in Table 1-4 and work will be needed to improve safety for the downstream population.

Table 1–1 Comparison of Flood Estimates Haycock (2010) and Atkins (2013)

Pond Catchment	Maximum Flow (m^3/s)					
	1 in 100 year		1 in 10,000 year		Probable Maximum Flood (PMF)	
	Haycock	Atkins	Haycock	Atkins	Haycock	Atkins
Highgate Chain						
Stock	2.34	2.74	14.49	6.86	28.98	15.54
Ladies Bathing	2.85	3.63	18.15	9.10	36.30	20.35
Bird Sanctuary	3.76	5.82	24.14	14.53	48.28	31.88
Model Boating	4.15	6.15	31.23	15.65	62.46	33.71
Men's Bathing	4.48	6.57	34.13	17.02	68.26	36.48
Highgate No 1	4.79	7.02	36.84	18.44	73.68	39.10
Hampstead Chain						
Vale of Health	1.64	0.57	4.67	1.45	9.34	3.32
Viaduct	0.85	0.31	6.04	0.78	12.08	1.78
Mixed Bathing	2.49	2.46	22.80	6.31	45.60	14.15
Hampstead No 2	2.58	2.81	25.62	7.27	51.24	16.14
Hampstead No 1	2.78	3.34	26.30	8.49	52.60	18.82

The key factors that influence the estimates and that are explained more fully in the subsequent paragraphs below and include:

- The amount of rainfall that runs off the ground and enters the ponds i.e. percentage run-off
- The depth and the duration of the rainfall events i.e. how many millimetres fall during the storm and how long the storm lasts ie rainfall estimation
- The method used to convert rainfall to the rate of flow into the ponds ie conversion of rain to run-off
- The method used to determine the PMF.

Percentage Run-off

Key to estimating flood magnitude is the amount of rainfall that soaks into the ground and the amount of rainfall that drains off the surface of the ground into the watercourse. This is called 'run-off' and is expressed as a percentage of the total volume of rain that falls.

Atkins applied the method in the Flood Estimation Handbook (FEH) to estimate run-off. The information in the FEH required more detailed consideration when applied to Hampstead Heath because the footpaths and compacted soils nearby allow more rain to run-off during a storm. The more compacted the ground, the less the rainfall will soak into the ground. On the basis of the soils information provided by FEH, the distribution of soil types from the Heath soils map and an estimate of the area of compacted soil, Atkins used the FEH equations for run-off to derive an appropriate percentage run-off for floods from the Heath. The Atkins results and a comparison with the Haycock recommendations, which were based on a small number of infiltration tests, are shown below.

- Atkins percentage run-off for estimation of the Probable Maximum Flood 76%
- Atkins percentage run-off for estimation of the 100 year flood 53%
- Haycock recommendations (all events) 80% to 90%

In other words, appropriate application of the industry standard method yields lower percentage run-offs than recommended by Haycock leading directly to lower overall volumes of water going to the ponds for any given event.

Rainfall Estimation

Over the years, rainfall data for the UK has been gathered from many rain gauges around the country and statistically analysed to provide data for estimating floods with various probabilities of occurrence. The rainfall depths used for flood estimates for Hampstead Heath are shown in the table below.

Table 1–2 Hampstead Heath Design Rainfall depth and duration for varying events

Event	Rainfall Depth (mm) for varying storm durations			
	1.5 hours	2.5 hours	4.5 hours	9.5 hours
1 in 5	20.4	25.9	30.7	38.0
1 in 20	36.0	40.8	47.3	56.9
1 in 100	60.8	67.5	76.3	89.0
1 in 1,000	127.7	137.8	150.3	167.8
1 in 10,000	135.0	150.0	164.0	183.1
Probable Maximum Precipitation	Not required	187.9	208.5	235.0

The industry standard estimates are based on data from many rain gauges and were therefore used in preference to the data collected by the Hampstead Heath Scientific Society. While the Hampstead Heath data provided a useful record of rainfall over about 100 years, from a statistical perspective, it is not suitable to provide design rainfall depths for the 1 in 1000 period events up to the PMF needed for this study i.e. up to the 10,000 year flood, as this would involve significant extrapolation beyond the useful range of the rainfall data.

The rainfall data in Table 1–2 with other rainfall durations were used to establish the duration of the storm that produces the largest floods. This is termed the ‘critical duration’. Atkins found that the critical duration varied from 1.9 hours to 3.9 hours for floods up the 10,000 year flood and was 9.5 hours for the Probable Maximum Flood. The critical duration for the PMF is longer ie 9.5 hours because the amount of rainfall that becomes runoff is much greater for longer PMF storms than for normal storms. The Haycock study adopted a 4.4 hour duration throughout.

Conversion of Rainfall into Run-off

The next step is to convert the estimated rainfall per event into run-off i.e. the amount of water which will run over the surface and drain into the ponds. The conversion of rainfall into run-off is called the “rainfall – run-off model”. Atkins applied the latest standard rainfall – runoff model in the FEH.

Haycock developed a bespoke rainfall – run-off model for the Heath and applied a 90% run-off percentage. It is likely that use of the high percentage run-off was the main factor contributing to larger size floods proposed by Haycock.

Estimation of the Size of a Range of Floods

Atkins applied the appropriate rainfall distributions and durations described above, to arrive at a range of floods with return periods up to 10,000 years and PMF. Specific flow rate with time durations were developed for each flood. To derive the PMF, Atkins used the extreme rainfall information called the Probable Maximum Precipitation (PMP) available from the Flood Studies Report (FSR) and the appropriate rainfall run-off model as given in the FEH.

By comparison, Haycock estimated the 10,000year flood flow rate with time relationship using the bespoke model and scaled up the flows by a factor of 2. Haycock’s application of this factor is strictly suitable for the ‘rapid method’ in Floods and Reservoir Safety (1996) only and is not applied when a detailed hydrological investigation has been carried out to estimate the PMF.

Although works will be required to cope safely with the PMF, as the Atkins estimates are 30% to 50% lower, the extent of the works required should be less than those proposed by Haycock.

Hydraulic Modelling

The InfoWorksRS models for the ponds on the Heath prepared by Atkins took into account that water could flow round the ends of the dams and out of the side of the ponds as well as over the crests. This better representation of real conditions was not available in the software package, STELLA, applied by Haycock.

The information provided by the InfoWorksRS hydraulic model included consideration of:

- How the flow over the crest of the dam varies over time
- How the water level varies over time as the floods pass through the reservoir systems.

This was used to estimate:

- The average frequency with which water will flow over the crest of the dams (see Table 1-3)
- The maximum depth of water flowing over the crest of the dams (see Table 1-5)
- The maximum speed of the water flowing down the outside face of the dam (See Table 1-5).

Table 1–3 Average Frequency of Flood Causing Water to Flow over the Dam Crests

Average Frequency Range	Pond Names
Up to 5 years	Stock Pond
5 years to 20 years	Ladies Bathing, Bird Sanctuary
20 to 50 years	Model Boating, Men’s Bathing
50 years to 100 years	Highgate No 1, Mixed Bathing, Hampstead No 2
100 years to 1,000 years	Vale of Health, Viaduct
1000 to 10,000 years	Hampstead No 1

The following table, Table 1-4, shows the proportion of the PMF flood that can be stored before water starts to flow over the crest of the dams.

Table 1–4 Pond Storage Capacity with Respect to Probable Maximum Flood (PMF) Volume

Chain	Pond	Total PMF volume in (m^3) including spills from the upstream pond	Min. Crest Level (m AOD)	Top Water Level TWL (m AOD)	Pond Surface Area m^2	Available storage (m^3) above TWL	% of inflow PMF can be stored
Highgate	Stock	114,438	81.65	81.06	4,401	2,597	2
	Ladies Bathing	153,055	76.87	76.00	6,926	6,026	4
	Bird Sanctuary	171,407	72.57	71.95	7,694	4,770	3
	Model Boating	116,765	71.62*	71.35	16,280	4,379	4
	Men’s Bathing	217,067	68.16	67.59	18,250	10,403	5
	Highgate No 1	275,972	63.50	62.45	13,660	14,343	5
Hampstead	Vale of Health	25,539	105.44	105.04	8,646	3,458	14
	Viaduct	13,444	89.97	89.50	3,329	1,565	12
	Mixed Bathing	67,020	75.46	74.95	7,148	3,645	5
	Hampstead No 2	89,542	74.91	74.39	10,910	5,673	6
	Hampstead No 1	117,819	70.91	69.39	15,190	23,089	20

* indicates the minimum level of the auxiliary spillway

Column 8 Table 1-4 shows Highgate No 1 can store a small amount (5%) whilst the other ponds can only store between 3% and 20%. This means much of the floodwater will overflow during the PMF, with the existing dams providing temporary storage for some rainwater that will eventually leave the Heath ponds as water levels subside. The volume of storage at the Kenwood ponds was investigated and judged to be insignificant.

The speed of the flow on the outside slope of the dams is used to assess the vulnerability of slope to erosion damage and possible breaching with loss of the entire contents of the pond. The estimated velocities for the design flood - PMF are summarised in Table 1-5 below. This information was not provided by Haycock.

Table 1–5 Estimated Depth of Overtopping and Speed of Water on Outside Slope of Dams

Chain	Pond	Peak overtopping discharge (m3/s)	Crest length (m)	Slope	Maximum depth of overtopping (m)	Peak velocity, over existing embankment (m/s)	Overtopping duration (hrs)
Highgate	Stock	10.95	43	0.30	0.45	5.07	9.25
	Ladies Bathing Left Bank	2.99	46	0.18	0.24	2.66	2.08
	Bird Sanctuary	17.01	100	0.17	0.45	3.73	6.75
	Model Boating	16.09	78	0.32	0.37	4.72	6.17
	Men's Bathing	30.74	147	0.25	0.38	4.12	7.42
	Highgate No 1	32.18	100	0.24	0.62	5.42	8.75
Hampstead	Vale of Health	2.13	130	0.24	0.15	2.34	4.00
	Viaduct	1.40	55.5	0.44	0.12	2.75	3.75
	Mixed Bathing	7.28	44	0.22	0.31	3.38	4.92
	Hampstead No 2	9.13	100	0.22	0.27	3.15	3.83
	Hampstead No 1	7.60	112	0.31	0.19	3.07	3.33

At the speeds shown in Table 1-5, standard guidance suggests that the dam slopes would need reinforcement to prevent erosion that could lead to a breach of the dam. The velocities shown are based on a uniform surface; in reality the outer slopes are uneven with trees and other coarse vegetation which will contribute to locally greater speeds. In addition coarse vegetation is readily pulled out by flowing water. These factors will exacerbate erosion damage to the slope. Solutions will be investigated which will prevent water from flowing over dam crests by channelling the water around the dams as described below.

Atkins believes that there is the potential to limit the overall impact of the works on the Heath by limiting the number of dams on which work will be undertaken and to make use of 'soft' engineering solutions – based on reinforced grass. The flow of water around the dams, using spillways in areas out of the general view of the public will be the favoured approach.

In Conclusion

Floods estimated by Atkins were generally 30% to 50% lower than those estimated by Haycock. Even with reduced flood volumes water will still flow over the dam crests in events ranging from the 1 in 5 year to the PMF events**.** For example Stock Pond will overtop during the 1 in 5 year event while Hampstead 1 pond will start to overtop between the 1 in 1000 year flood and the 1 in 10,000 year flood. The speeds of the flows on the outer slope in conjunction with the uneven nature of the slopes with coarse vegetation are such that the dam embankments are likely to suffer erosion damage which in some cases could lead to a breach. This means that to reduce the risk of breaching, improvements will need to be made to some of the dams to enable them to cope with these floods, although the extent of the work needed should be less than that proposed by Haycock.