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East Lothian Council

Musselburgh Flood Study

Final Report

August 2012

JACOBS

Document Control Sheet

BPP 04 F8
Version 14 July 2012

Client:	East Lothian Council	Project No:	B1592000
Project:	Musselburgh Flood Study		
Document Title:	Final Report		
Ref. No:			

	Originated by	Checked by	Reviewed by	Approved by
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DATE 01/05/2012	INITIALS BS	INITIALS RHF	INITIALS RHF	INITIALS LMcG
	Document Status	For comment		

REVISION	NAME Birol Sokmener	NAME Ronnie Falconer	NAME Ronnie Falconer	NAME Laurence McGregor
DATE 14/08/2012	INITIALS BS	INITIALS pp LMcG.	INITIALS pp LMcG.	INITIALS LMcG.
	Document Status	FINAL		

REVISION	NAME	NAME	NAME	NAME
DATE	INITIALS	INITIALS	INITIALS	INITIALS
	Document Status			

REVISION	NAME	NAME	NAME	NAME
DATE	INITIALS	INITIALS	INITIALS	INITIALS
	Document Status			

REVISION	NAME	NAME	NAME	NAME
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	Document Status			

Contents

1 Introduction

The town of Musselburgh in East Lothian, which is located along both banks of the River Esk, has been subjected to episodes of flooding over many centuries. Figure 1 shows the location of Musselburgh and the River Esk. It is understood that some of these flooding incidents were very serious such as those on 13 August 1948 and 21 September 1891, for which evidence showing the date and the peak flood level were marked as floodmarks on the walls of, now demolished, Inveresk Mill. The peak water levels for these events were 6.99mAOD and 7.37mAOD respectively which were approximately 1.0m above the ‘bank full' level.

Although the history of flooding in Musselburgh goes as far back as over a century ago, the most recent and largest flood event which affected the entire region including Musselburgh occurred in 1948.. Since then a number of other events have occurred causing flooding mostly of Eskside but none of these events were on the scale of the 1948 event.

Despite relatively frequent flooding incidents on the River Esk in Musselburgh, only a small number of investigations to understand the causes of flooding and possible mitigation measures have been carried out. One of these studies was carried out by Babtie Shaw and Morton (now Jacobs Engineering UK Ltd) in 1993. The study was preliminary in nature and only used limited channel survey information. It involved construction of a MIKE 11 based mathematical model of the River Esk through Musselburgh to predict the peak water levels for a number of flood probabilities in order to assess the likely risk of flooding in Musselburgh.

In view of the apparent increasing frequency of high flow events in the River Esk, East Lothian Council considered that a detailed and updated assessment of the flood risk in Musselburgh should be carried using the more detailed mathematical modelling techniques now available to produce a set of plans providing information on the indicative extent of flood inundation for a range of joint probability river flow and tidal events.

The study has involved:

- ***The hydrological assessment of flood flows in the River Esk in Musselburgh using methodologies set out in the Flood Estimation Handbook[1].***
- ***The assessment of extreme tide levels at the mouth of River Esk.***
- ***Transfer of the existing mathematical model of the River Esk from the MIKE11 river modelling software platform to the ISIS modelling platform (which is considered as the current industry-standard).***

[1] Flood Estimation Handbook, Institute of Hydrology, 1999

- ***Extension of the model and improvement of representation of key areas using additional channel cross-section and LIDAR survey information.***
- ***Model calibration or sensitivity analysis depending on the availability of historical flow and water level information.***
- ***Undertaking joint probability analysis of flood flows and extreme tides.***
- ***Undertaking model simulations.***
- ***Preparation of a report and plans showing the indicative extent of inundation for a range of flood events.***

This report details the work undertaken and the findings of the study together with recommendations for further investigations.

Figure 1 – Location Plan

2 Hydrological Assessment

2.1 Estimation of Design Flows

As stated in the previous section, the town of Musselburgh has suffered from flooding from the River Esk for many years. A number of investigations have been undertaken by various consultants assessing the risk of flooding for residential developments in Musselburgh. These required the estimation of design flood flows in the river and used methodologies that were current at the time.

Flows in the River Esk are monitored in Musselburgh using a velocity-area gauging station located in a section with steep banks upstream of Olive Bank Road bridge. The gauging station is operated by the Scottish Environment Protection Agency (SEPA) and is also used for flood warning purposes. The low-flow control is a rock bar and the high flow control is formed by the Olive Bank Road bridge buttresses. It is understood that the control exerted by the bridge at extreme flood flows diminishes and the controlling physical influence then becomes the channel downstream of the bridge. The flows in the River Esk have been recorded at Musselburgh Gauging Station since December 1961. It is believed that the high flow control (bridge buttresses and downstream channel) have remained unchanged during this period.

The high flow data recorded by the station was reviewed in detail during the HiFlows-UK study which was initiated in 2001 in collaboration by Environment Agency (EA), Scottish Environment Protection Agency (SEPA) and River Agency Northern Ireland (RANI)[2]. The study involved the review of gauging station performances at high flows, their indicative suitability for flood analysis, and improving high flow rating equations.

The HiFlows-UK study identified that the Musselburgh high flow rating equation has been changed 12 times over the past 50 years as it appeared to be affected by periodic dredging and accretion of a bar on the right bank. The development and removal of the bank has clear implications to the stage–flow relationship at low and medium flows but it is less clear how this affects the flood flows where the control on the stage-flow relationship is formed by the downstream buttresses and channel. Consequently two annual maximum peak flow series were considered:

- ***Using rating equations 1 to 12 since 1961 (i.e. the flows provided by SEPA based on use of rating equations 3 to 12).***
- ***Using rating equation 11 for all stages recorded since 1961(i.e. the flows listed in HiFlows-UK)***

[2] http://www.environment-agency.gov.uk/hiflows/91727.aspx

The flows are given in Table 1. (Note that the SEPA data comes as values per calendar year whilst the HiFlows-UK data are provided as values per hydrological year [1 Oct to 30 Sept]).

SEPA Amax series			HiFlows-UK Amax series		
Calendar Year	Date	Peak flow (m^3/s)	Water Year	Date	Peak flow (m^3/s)
1962	12 Sep 1962	96.7	1961	11 Sep 1962	87.8
1963	23 Nov 1963	81.3	1962	05 Mar 1963	71.0
1964	11 Oct 1964	37.4	1963	23 Nov 1963	78.9
1965	26 Sep 1965	89.8	1964	26 Sep 1965	94.5
1966	14 Aug 1966	176.0	1965	13 Aug 1966	154.6
1967	16 May 1967	51.5	1966	19 Dec 1966	56.1
1968	5 May 1968	102.0	1967	05 May 1968	92.0
1969	22 Nov 1969	77.1	1968	01 Nov 1968	69.5
1970	31 Oct 1970	77.1	1969	22 Nov 1969	73.4
1971	24 Mar 1971	66.4	1970	31 Oct 1970	70.3
1972	17 Feb 1972	36.1	1971	17 Feb 1972	33.8
1973	22 Dec 1973	17.6	1972	11 Dec 1972	17.8
1974	17 Dec 1974	40.5	1973	17 Mar 1974	48.3
1975	18 Sep 1975	67.9	1974	18 Sep 1975	70.3
1976	15 Oct 1976	63.2	1975	03 Apr 1976	30.8
1977	25 Jan 1977	71.9	1976	25 Jan 1977	74.1
1978	15 Nov 1978	44.6	1977	30 Oct 1977	42.8
1979	8 Dec 1979	55.3	1978	15 Nov 1978	52.5
1980	25 Nov 1980	97.1	1979	08 Dec 1979	65.7
1981	2 Oct 1981	106.0	1980	25 Nov 1980	110.0
1982	3 Jan 1982	126.0	1981	03 Jan 1982	114.4
1983	1 Jun 1983	78.6	1982	23 Nov 1982	118.9
1984	3 Nov 1984	155.0	1983	04 Feb 1984	79.0
1985	21 Sep 1985	108.0	1984	03 Nov 1984	166.7
1986	30 Dec 1986	47.4	1985	21 Dec 1985	71.8
1987	18 Jul 1987	46.9	1986	30 Dec 1986	61.9
1988	2 Jan 1988	41.6	1987	02 Jan 1988	56.8
1989	11 Jan1989	37.4	1988	11 Jan 1989	49.7
1990	6 Oct 1990	175.0	1989	17 Feb 1990	74.1
1991	23 Feb 1991	68.9	1990	06 Oct 1990	216.4
1992	8 Jan 1992	105.0	1991	08 Jan 1992	134.2
1993	9 Oct 1993	102.0	1992	15 May 1993	113.9
1994	11 Dec 1994	79.8	1993	10 Oct 1993	130.6
1995	31 Jan 1995	41.4	1994	12 Dec 1994	104.3
1996	18 Dec 1996	57.0	1995	16 Nov 1995	42.4
1997	20 Feb 1997	66.7	1996	21 Feb 1997	53.3
1998	2 Nov 1998	95.6	1997	11 Dec 1997	34.6
1999	12 Dec 1999	57.4	1998	03 Nov 1998	80.3
2000	26 Apr 2000	180.5	1999	27 Apr 2000	180.4

SEPA Amax series			HiFlows-UK Amax series		
2001	19 Aug 2001	58.1	2000	07 Nov 2000	108.1
2002	22 Oct 2002	107.4	2001	24 Jan 2002	50.6
2003	22 Jan 2003	54.7	2002	22 Oct 2002	111.0
2004	2 Feb 2004	53.1	2003	02 Feb 2004	58.9
2005	8 Jan 005	90.3	2004	08 Jan 2005	95.3
2006	16 Nov 2006	53.1	2005	12 Oct 2005	59.3
2007	21 Nov 2007	69.1			
2008	7 Aug 2008	90.2			
2009	4 Sep 2009	66.1			
	Median	69.0		Median	72.6

Table 1 - Two alternative annual maximum flow series for the River Esk at Musselburgh

Differences in flow values were discussed with SEPA[3] who recommended the use of the SEPA flow estimates. Based on this recommendation (by the gauging authority responsible for the monitoring) the analysis in this study has been based upon the SEPA dataset.

Design flows were calculated using both the FEH pooling group and single site statistical methods described in the Flood Estimation Handbook. The pooling group method requires the estimation of an index QMED flood, which in this case comes directly from the gauged record, and the generation of flood growth factors that are used to multiple this index flood to provide estimates of rarer events. The growth factors are produced during a process (pooling) that identifies hydrologically similar catchments, likely to share similar flood characteristics. The “pooled” catchments’ flood records are then standardised and analysed as if belonging to a single gauge to provide an estimate of the appropriate growth factors to apply to the index flood. The benefit being that the pooled data has a much larger sample of floods from which to extract the likely flood behaviour. However it is reliant on being able to select hydrologically similar catchments.

Conversely the single site statistical analysis only uses the flood record from the gauge at the site. Its relevance (assuming no significant catchment change has occurred during the record) is fully specific to the target catchment, but is hampered by only a limited length of record that can only sample a relatively small proportion of the full population of the likely floods from the catchment. Appendix A presents the detailed audit trail of the analyses. Figure 2 presents a summary of the predicted flows based on the two methods. The dotted extrapolation of the “single site” curve indicates that these estimates are less robust due to the limited record length.

[3] The discrepancies between the annual maximum estimates were not fully resolved.

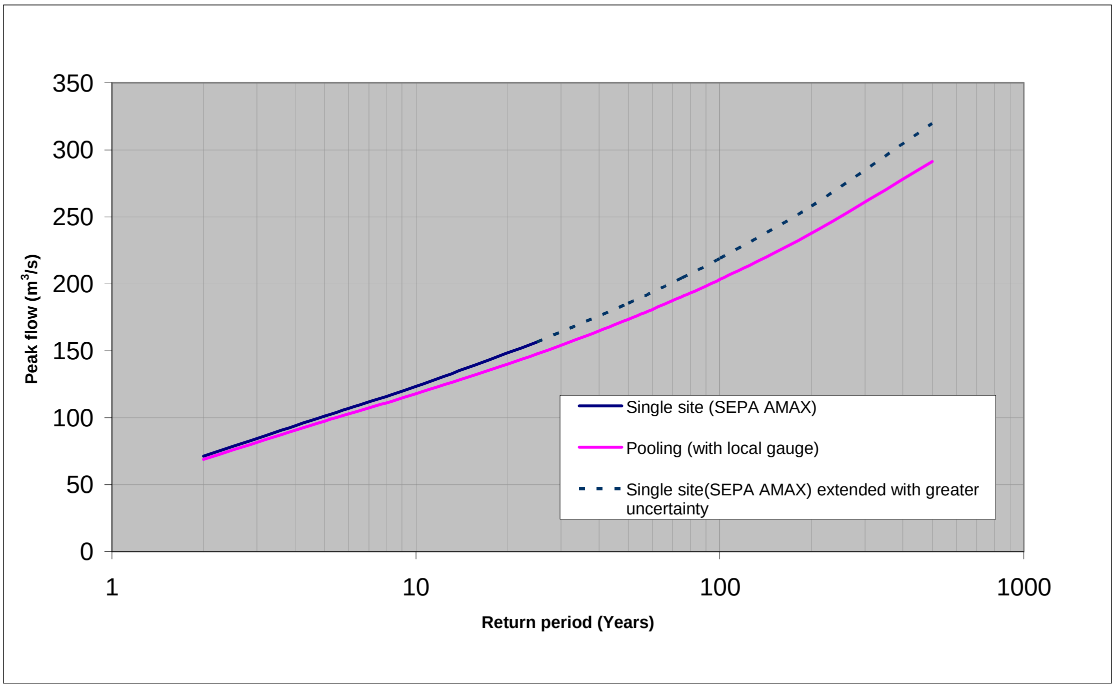

Figure 2 - Summary of the predicted design flows for the River Esk at Musselburgh. [Single site curve is based on only the flow record from the gauge at Musselburgh, whilst the pooling group curve offers an alternative and frequently favoured FEH method].

The results of the two methods are reasonably consistent. The Flood Estimation Handbook guides the analysis towards accepting the pooling group estimate of the flood frequency curve at the higher return periods. However given that the differences between the Hiflows and SEPA estimates of flood flows were not fully resolved, the Hiflows values tending to be slightly higher, it was judged prudent to accept the single site analysis flood frequency curve as the preferred design flows. These are tabulated in Table 2.

Annual Exceedence Probability[4]	Return Period (years)	Growth Factor*	Flow (m^3/s)
50%	2	1.03	71
20%	5	1.47	101
10%	10	1.79	123
4%	25	2.27	156
2%	50	2.69	185
1.33%	75	2.96	204
1%	100	3.17	219
0.5%	200	3.74	258
0.2%	500	4.63	320

* Growth factor - factor that relates the design flow to the QMED estimate of the index flood

Table 2 - Design flows for the River Esk at Musselburgh

2.2 Estimation of Design Hydrograph Shape

The shape of the flow hydrograph determines the volume of water that passes along the river channel at a given location during a particular event. Both the peak flow rate and the shape of the hydrograph (i.e. volume) are important in terms of determining the risk of flooding along the watercourse.

Where recorded flow is available the most widely used method in determining the shape of the design flood event hydrograph is based on the analysis of the recorded flow hydrographs which represent the general characteristics of the river system at that location. The recorded flow hydrographs for the larger flow events of such as 1993, 1998, 2000, 2005 and 2008 in the River Esk at Musselburgh Gauging Station record were analysed to determine the dominant shape of larger flood event hydrographs.

Figure 3 shows the recorded hydrographs used for the analysis. These are plotted to a common scale for ease of comparison.

[4]Annual Exceedance Probability (AEP) is the probability associated with a particular flood event expressed as the chance of occurring in any one year. Flood probability is also sometimes referred to as flood ‘return period’ – the period during which a flood of a particular magnitude will be equaled or exceeded when taken on average over a very long period of time. An event of return period 50 years (T) has an AEP of 1/T*100 or 2%.

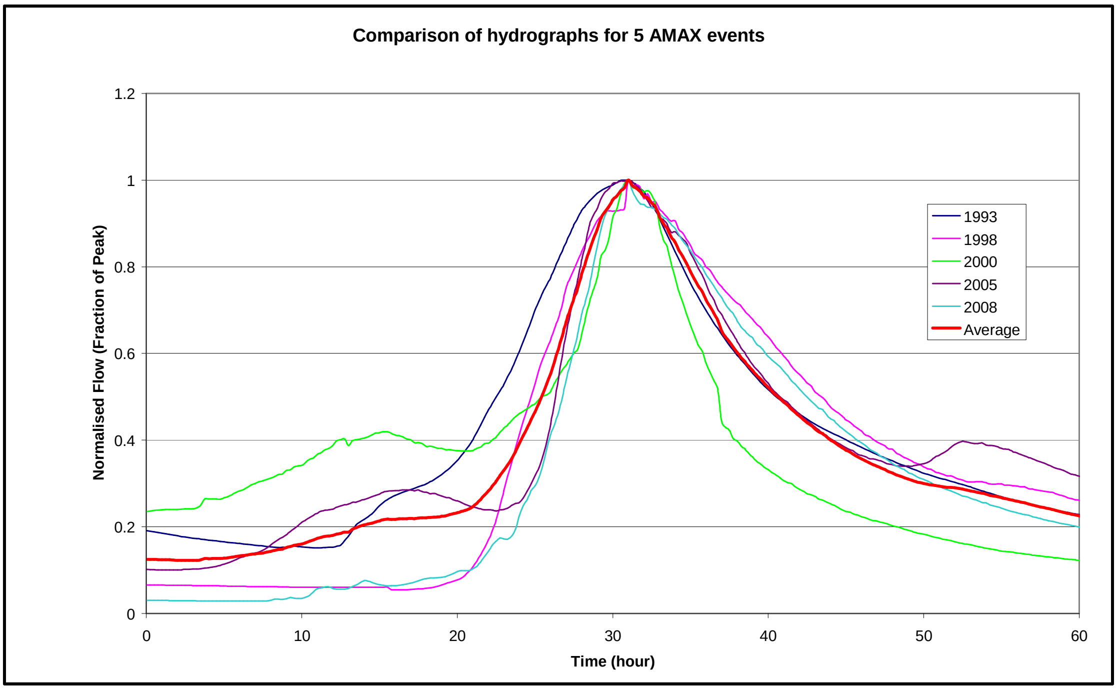

Figure 3 - Estimation of design hydrograph shape at Musselburgh Gauging Station

As can be seen in Figure 3 the hydrographs for large flow events in the River Esk in Musselburgh generally follow a characteristic hydrograph shape with little variation between events and the shape of any one of these hydrographs might be chosen. However it is considered that the average hydrograph which is generated by normalising the hydrographs of these five extreme events would be more representative of the flood event hydrograph shape likely to occur over a range of high flow flood events.

2.3 Climate change allowance

Climate change is projected to increase extreme rainfall events across Scotland and this in turn will influence future flood flows. It is standard practice to make an allowance to design flows for future climate change. In Scotland, as for the rest of the UK, the advice has been to test the sensitivity of the system to a 20% increase in design flows based on the guidance given in Supplementary Note to Operating Authorities-Climate Change Impacts[5].

[5] Flood and Coastal defence Appraisal Guidance, FCDPAG3 Economic Appraisal, Supplementary Note to Operating Authorities-Climate Change Impacts, October 2006

3 Extreme Tide Analysis

Water levels at Musselburgh are also significantly influenced by sea levels in the Firth of Forth. Tides are defined as the periodic rise and fall in the level of the water in oceans and seas; the result of gravitational attraction of the sun and moon.

Sea levels are also affected by storm surges which are weather dependent and difficult to predict in comparison to tides. Wind generated waves can also be a significant factor in assessing the risk of flooding due to wave overtopping. However this is usually considered separately and it is accepted practice to present the combined effects of astronomical tides and storm surges under the term “still water level”. The extreme water levels estimated in this section of the report for the Firth of Forth at Musselburgh are still water levels and do not included any wave effects. The extreme still water is of more concern than wave overtopping as the still water level could result in inundation over a longer period.

3.1 Extreme Water Level Analysis Methodology

Ideally, extreme water level prediction for a site of interest should be based on good quality records of observed sea water level at the site for a suitably long duration. In the absence of this data, estimates can be made using a number of sources of existing information and analysis. In order to assess water levels in the Firth of Forth at the mouth of the River Esk, an extreme water level analysis has been undertaken using the data and methodology detailed in the POL 112 Report (Section 5.2.1). In addition, the likely future impact of climate change on sea water levels at the mouth of the River Esk has been assessed for various climate change scenarios.

3.2 Extreme Water Level Analysis for Musselburgh

The analysis of extreme water levels at the mouth of the River Esk would normally be based on the ***Proudman Oceanographic Laboratory (POL) Internal Report 112 'Spatial Analysis for the UK Coast' by Dixon and Tawn 1997***[6]. POL Internal Report 112 presents the work undertaken to develop a spatial model of extreme water levels around the UK coast, based on records of observed levels at 41 sites. The resulting spatial model covering the coast has 89 nodes and the report presents the methodology and data to enable the calculation of a range of extreme probability tide event water levels for a coastal site between two adjacent nodes.

Extreme Water Levels (EWL) for 1% and 0.5% AEP (100 and 200year return period) tide events at the mouth of the River Esk were calculated,

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[6] Spatial Analysis for the UK Coast, Proudman Oceanographic Laboratory, Internal Document No.112, Dixon & Town, 1997.

using the predictions for Nodes 12 (Easting 352851, Northing 701072) and 13 (Easting 385631, Northing 670788) which are the closest to the area of interest.

In order to determine the change in EWL between Nodes 12 and 13 and the mouth of the River Esk, a relationship between the distances of these nodes to Wick was used to determine the EWL at these nodes, then a second relationship involving again the distance of the mouth of the River Esk to these nodes was used to determine the weighting of each node on the EWL at the mouth of River Esk. Based on this methodology 3.99mAOD and 4.07mAOD were calculated as representing the 1% and 0.5% AEP extreme event tide levels in the Firth of Forth at the mouth of the River Esk.

A review of work by others in the area of interest indicated that there is a range of estimates for the EWL using the same or similar methodologies. A study by Kaya (2008)[7] estimated the 1% AEP and 0.5% AEP tide event EWL at 4.01mAOD and 4.08mAOD respectively. Jeremy Benn Associates (JBA) indicated in their study[8] for Cockenzie Power Station that ***storm surges within East Lothian area tend to be small and relatively frequent, rather than experiencing large extreme events.*** JBA estimated EWL at Leith and translated these levels to Cockenzie using the correlation between Mean High Water Spring (MHWS) levels. Using a similar correlation, the levels at Cockenzie for 1% and 0.5% AEP tide events were translated to the mouth of the River Esk, yielding 3.62mAOD and 3.70mAOD for the 1% and 0.5% AEP tide events respectively.

A similar investigation carried out by HR Wallingford[9] as part of an assessment of joint probability of flows in the River Esk and the extreme tide levels at the mouth of the watercourse indicated that EWL for the 1% and 0.5% AEP events is likely to be 3.87mAOD and 3.94mAOD respectively.

The report by HR Wallingford indicates that SEPA adopted a still water level of 4.3mAOD for the 0.5% AEP tidal event in the Firth of Forth near Musselburgh to assess the indicative extent of tidal inundation for the Indicative River and Coastal Flood Map (Scotland). It was considered by HR Wallingford, that their estimated value of 3.94mAOD represents the best estimate of still water level for the 0.5% AEP tide event in the Firth of Forth at the mouth of the River Esk and 4.3mAOD as used by SEPA should only represent a conservative estimate of the still water level.

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7 Yusuf Kaya, Kaya Consulting Ltd "Taylor Wimpey, Proposed Development at Pinkie Mains, Musselburgh – Flood Risk Assessment, 14 January 2008

8 JBA, Sediment Transport Processes – Cockenzie Power Station Final Report, December 2009

9 HR Wallingford, Eskside House, Study of joint probability of river flow, sea level and waves for use in a flood risk study. Technical Note: DEM5791/01, May 2007

A detailed assessment of the extreme still water sea levels around the UK was carried out for Defra, SEPA, the Scottish Government and the Environment Agency and findings of the study were published in a report in February 2011.[10]

This study utilises tide-level data as recorded at 40 Class A and 5 other sites to undertake statistical analysis and to generate probabilities of predicted high tide and of skew surge. Combining these two elements is considered to provide the overall design level probabilities. It is understood that these results were further refined using predictions from a continental shelf tide surge model and other corrections to arrive at predictions for various % AEP tide events. Using the information provided in Table 4.1in the published report, and the detailed results provided in the GIS files[11], it is estimated that 1% AEP and 0.5% AEP tide events still water levels are 3.88mAOD and 3.96mAOD respectively.

Table 3 shows the comparison of EWL in the Firth of Forth at the mouth of the River Esk as estimated by the Defra approach and by the various other investigations.

AEP	Predicted Still Water level (mAOD)					
	Defra	POL112	Kaya	JBA	HR	SEPA
1%	3.88	3.99	4.01	3.62	3.87	-
0.5%	3.96	4.07	4.08	3.70	3.94	4.30

Table 3 - Comparison of EWL in the Firth of Forth at the mouth of the River Esk in various studies

Taking all the above comparisons into account, it is considered that the levels derived using the findings of the study for Defra, SEPA, the Scottish Government and the Environment Agency represents the best current estimate of extreme tide levels in the Firth of Forth at the mouth of the River Esk. The study is considered to provide the soundest estimates of extreme tide levels based on currently available data and the latest techniques. Table 4 shows the estimated extreme tide levels for all % AEP tide events.

[10] Defra, SEPA, Scottish Government, EA. Coastal flood boundary conditions for UK mainland and islands, Project : SC060064/TR2: Design sea levels, February 2011
[11] Defra, SEPA, Scottish Government, EA. Coastal flood boundary conditions for UK mainland and islands, Project : SC060064/TR4: Practical guidance design sea levels, February 2011

AEP	Return Period (year)	Estimated Extreme Still Water Level (mAOD)
100%	1	3.36
50%	2	3.43
20%	5	3.53
10%	10	3.60
4%	25	3.71
2%	50	3.79
1%	100	3.88
0.5%	200	3.96

Table 4 - Best Current Estimate of Extreme Still Water Level in the Firth of Forth at the mouth of the River Esk (based on Project : SC060064/TR4: Practical guidance design sea levels, February 2011[6]).

4 Joint Probability Analysis

4.1 Dependence between variables

Tidal parts of rivers such as the lower River Esk through Musselburgh are at risk of flooding from both fluvial and tidal events. The probability of both a high flow in the river and an extreme sea level occurring together is termed the joint probability. Joint probability analysis takes into account the dependence of one event upon the other. Even a small amount of dependence between extremes of river flow and sea levels (for example both may occur during the same weather event) can have a significant influence in determining the joint probability of the combined water level, or the water levels calculated for a range of annual exceedance probabilities (%AEP).

An understanding of the dependence between river flow and extreme sea level enables a more accurate estimate of their combined probability of occurrence, and greater confidence in assessment of any associated risk.

The mouth of the River Esk lies on the southern shores of the Firth of Forth. Svensson and Jones (2004)[12] stated that dependence between sea surge and river flow around the coasts of Britain occurs mainly in catchments with slopes exposed to south-westerly winds.

The areas with higher dependence mainly lie along the western part of English south coast and the south coast of Wales, but also include the Solway Firth area and the area to the north of the Firth of Forth in Scotland. Although the area to the north of Firth of Forth is on the east coast, it is the first hilly area that air in a south westerly flow will encounter. At the same time, the surges on the east coast are often associated with a depression moving eastwards between Scotland and Iceland. These surges are generated as the depression moves onto the continental shelf to the north west of Scotland and propagate into the North Sea in the form of a progressive long-wave. As the depression moves further east, the trailing northerly or north-westerly winds over the North Sea may act to raise the surge height[13].

Defra and the Environment Agency (2005a)[14] commissioned a study to analyse the dependence between river flow and surge based on long time-series flow and tide level data for 72 river gauging stations and 19 tide gauges. The study also included the analysis of dependence of flows and surges in the River Esk using flow records at Musselburgh Gauging Station and surge observations at Aberdeen and North Shields. A

[12] C Svensson, D A Jones, Sensitivity to storm track of the dependence between extreme sea surges and river flows around Britain, Hydrology: Science & Practice for the 21st Century: Volume 1, British Hydrological Society, 2004

[13] D T Pugh, Tides, Surges and Mean Sea-Level, John Wiley & Sons Ltd, 1987

[14] Defra/Environment Agency, Joint Probability: Dependence between extreme sea surge, river flow and precipitation: A study in South and West Britain, R&D Technical report FD2308/TR3, March 2005

dependence measure, X, especially suited for extremes was employed to estimate dependence between the river flow and the surge.

Based on the information provided in this study, dependence values between extreme daily mean flow and daily maximum sea surge and between extreme daily mean flow and daily maximum sea surge occurring at high tide at the River Esk based on the Aberdeen surge station were estimated at 0.02 and 0.04 respectively.

Figure 2 in the Defra/Environment Agency (2005)[15] report, an extract of which is shown in,Figure 4 indicates that for the River Esk in Musselburgh which is identified as Station No: 19007, the extremes of river flow the surge are ***independent*** with a X value of equal or less than 0.01.

It is recommended in the report that the dependence between two or more conditions, in this case, the river flow and the surge level, should be neither independent nor fully dependent. In view of this, it is considered that a dependence value, X, of 0.02 should be regarded as most representative of the situation in the River Esk.

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[15] Defra/Environment Agency, Use of Joint Probability Method in Flood management, A Guide to Best Practice R&D Technical Report FD2308/TR2, March 2005

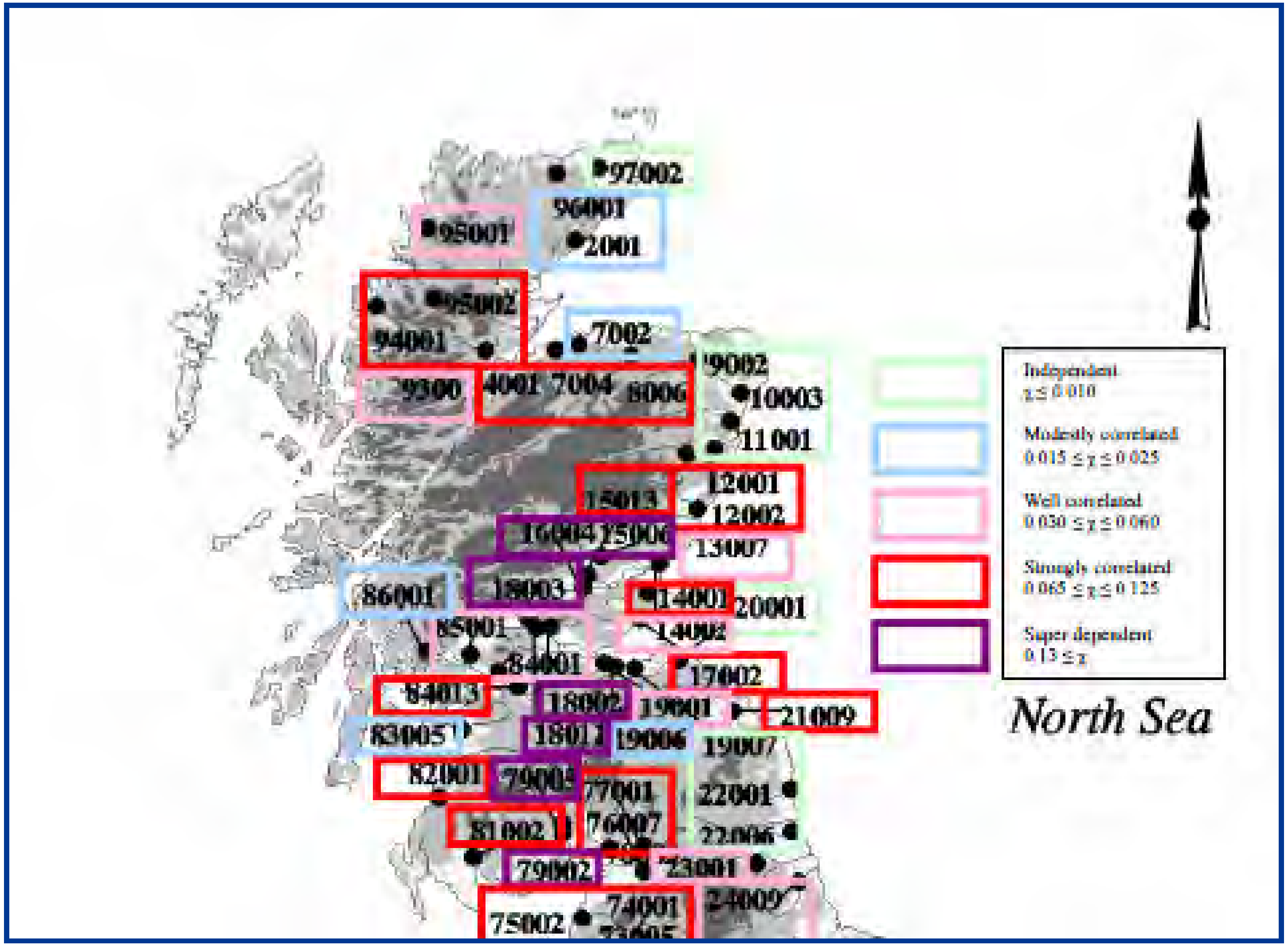


Figure 4 – Summary dependence information for river flow and surge[10]

4.2 Joint Probability of Exceedence Analysis

Joint probability is defined as the chance of two or more conditions occurring at the same time, in this particular case the simultaneous occurrence of an extreme river flow in the River Esk and an extreme surge in the Firth of Forth. Such a joint probability of occurrence could involve:-

- ***Extreme flow in the River Esk coincident with a high surge in the Firth of Forth.***
- ***Extreme surge in the Firth of Forth coincident with an extreme flow in the River Esk.***
- ***High but not extreme river flow and surge are coincident***

Extreme situations that are likely to test the suitability and durability of flood defence structures such as walls and embankments for fluvial and coastal flood defence schemes are often caused by a combination of environmental variables. In river engineering, the same joint probability can arise for different combinations of river flow and surge level. Hence a range of possible combinations should be assessed prior to making a decision on the water level appropriate for the construction of a flood defence. For this reason Joint Probability of Exceedence Analysis is necessary.

The desk study methodology described in A Guide to Best Practice, R&D Technical Report FD2308/TR2, March 2005 requires as input high and extreme values of each of two variables (river flow and surge level), together with a simple representation of the dependence between the two. The method provides a list of pre-computed combinations of river flow and surge level with the required joint return period.

Table 5 below shows the results of Joint Probability of Exceedence Analysis for river flow and surge level for the River Esk for 2% AEP and 0.5% AEP joint extreme events.

2% AEP Joint Probability		0.5% AEP Joint Probability		2% AEP Joint Probability		0.5% AEP Joint Probability	
River Flow (year)	Tide Level (year)	River Flow (m^3/s)	Tide Level (mAOD)	River Flow (year)	Tide Level (year)	River Flow (m^3/s)	Tide Level (mAOD)
50	0.01	185.4	2.82	200	0.01	257.9	2.82
50	0.02	185.4	2.91	200	0.02	257.9	2.91
20	0.05	148.4	3.01	200	0.05	257.9	3.01
10	0.1	123.4	3.09	160	0.1	245.3	3.09
5	0.2	101.1	3.17	80	0.2	208.1	3.17
2	0.5	71.3	3.27	32	0.5	166.7	3.27
1	1	52.0	3.36	16	1	140.3	3.36
0.5	2	38.0	3.43	8	2	116.2	3.43
0.2	5	22.0	3.53	3.2	5	86.6	3.53
0.1	10	15.0	3.60	1.6	10	65.1	3.60
0.04	25	5.7	3.71	0.64	25	43.0	3.71
0.02	50	1.3	3.79	0.32	50	30.2	3.79
				0.16	100	19.7	3.88
				0.08	200	12.7	3.96

Table 5 – Joint Probability Estimates of River Flow and Tide Level in the River Esk, Musselburgh

As can be seen in the table, a wide range of combinations of river flow in the River Esk in Musselburgh and the tide level in the Firth of Forth at the mouth of the river can produce water levels for a specific joint probability. Model simulations are able to demonstrate whether the flow, or the tide level, or a combination of both is the dominant factor in determining the water level at any specific location along the River Esk. This depends on the physical characteristics of the channel.

5 Mathematical Modelling

5.1 Extent of Mathematical Model

A mathematical model of the River Esk through Musselburgh was set up covering the reach between a location approximately 450m upstream of the A1 Road Bridge over the River Esk near Whitecraigs and the Firth of Forth, covering a total length of approximately 5.0km.

5.2 Model Construction

Version 3.5.1 of the ISIS river modelling software package was used for modelling the River Esk in Musselburgh. The software package is able to model complex looped and branched networks, and is designed to provide a comprehensive range of methods for simulating flood plain flows. ISIS Flow incorporates both unsteady and steady flow solvers, with options that include backwater representation, flow routing and full unsteady simulation. The simulation engine provides a direct steady-state solver and adaptive time-stepping methods to optimise run-time and to enhance model stability

The model requires the input of river cross sections to represent the main channel, input of floodplain data including bank levels to represent out of bank flows and physical geometry of man-made structures such as bridges, culverts and weirs.

A limited number of channel cross-sections in the River Esk were surveyed in 1993 as part of the original study to supplement the cross-section information provided by then the Forth River Purification Board at that time. The survey also included bank level and threshold level information to identify properties likely to be affected by flooding. As these channel cross-sections mainly represented a limited reach in Musselburgh, additional channel cross-section and bridge survey work was undertaken by East Lothian Council in the spring of 2011. In addition to these channel cross-sections the Council also provided survey information to supplement the available data.

The channel cross-sections representing the reach upstream of Inveresk Weir, up to Whitecraigs were extracted from LIDAR survey information. LIDAR survey data was originally provided by the Scottish Government; however review of the survey information indicated that filtered LIDAR data which was expected to represent the ‘bare-earth’ situation (where the Digital Surface Model is converted to a Digital Elevation Model by removing man-made structures and high vegetation) was not ideally suited for model use. Following the filtering process the definition of the river channel was not clear and there were high points in Musselburgh distorting the ground model. However, in the knowledge that this was the only survey information readily available for the area upstream of Inveresk

Weir at that time, best use of this information was made to define the channel cross-sections for the reach upstream of the weir.

A walkover inspection of the River Esk was undertaken in March 2011 by the Jacobs modelling team to familiarise the team with the watercourse and the flooding related issues in Musselburgh. The debris marks left on the vegetation over the right bank indicated that the area had been affected by a recent high flow event and flooded up to a depth of 0.5m in places upstream of Inveresk Weir.

Flow and water level data was therefore requested from the Scottish Environment Protection Agency (SEPA) for the River Esk at Musselburgh Gauging Station for the first three weeks of February 2011. Review of the data indicated that a high flow event occurred on 7^{th} February 2011 and the recorded peak flow was approximately 67.0m^3/s.

A model simulation was undertaken using this flow information to determine if the channel cross-sections were representative of the reach upstream of Inveresk Weir. The model predictions indicated that the right bank was unlikely to flood based on the cross-sections extracted from the LIDAR survey information unless an unrealistic amount of reduction was made to the ground levels.

In view of this, several inquires were made on any other sources of survey information to identify if there was any other suitable data was available. One lead indicated that the Environment Agency also holds LIDAR survey information for locations in Scotland. The Geomatics Group of the Environment Agency were approached to find out if they had any information in Musselburgh and if they could provide an example of the data held. Figure 4 below shows the comparison of the two sets of LIDAR survey information for Musselburgh.

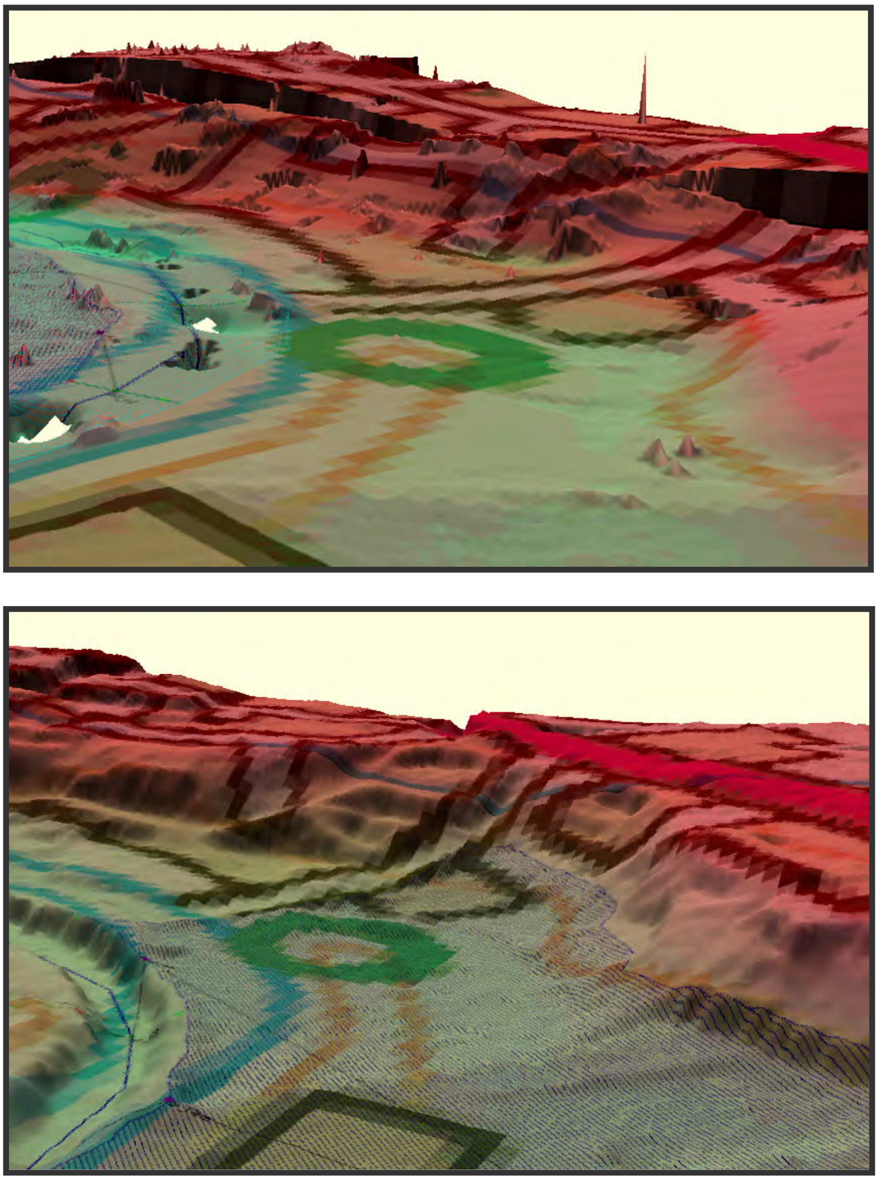
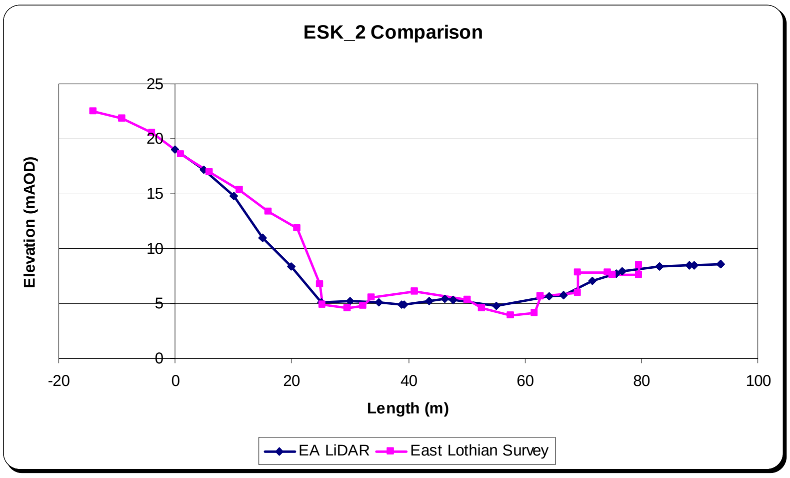


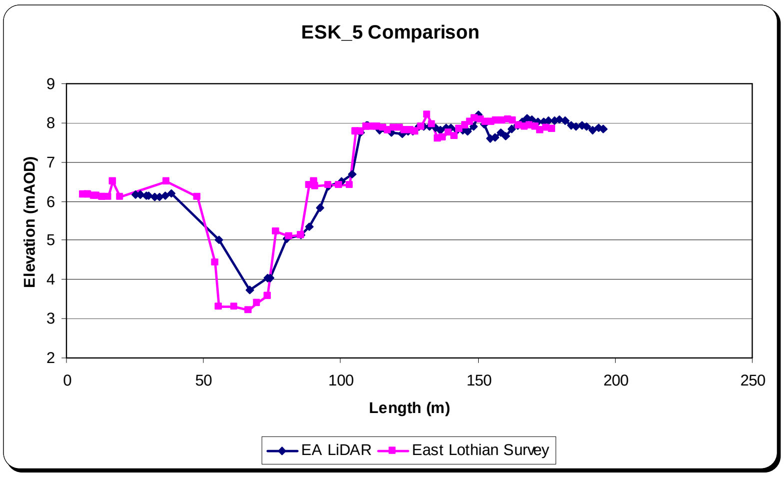
Figure 5 – Comparison of LIDAR data provided by the Scottish Government (SG), (above) and the Environment Agency (below). Note: Musselburgh Golf Course is inside the bend in the river. The lack of channel definition in the SG data is clearly visible

As can be seen in the comparison, the LIDAR data held by the Environment Agency was significantly better for model use due to the much clearer definition of the channel and other land features. This data was therefore requested from the Environment Agency and used in the derivation of channel cross-sections upstream of Inveresk Weir.

It is recognised that LIDAR survey of the river channel is affected by the water surface in the channel as the conventional LIDAR does not penetrate the water surface. In order to determine the effect of water in the channel on the LIDAR survey level, a comparison of the LIDAR derived channel cross-sections was carried out at locations where conventional channel cross-section survey information was available.

Figure 6 shows the comparison of the conventional and LIDAR survey channel cross-sections in the River Esk downstream of Inveresk Weir. Comparison shows that the bed level in the conventionally surveyed channel cross-sections is approximately 1.0m lower than the bed level for cross-sections extracted from the LIDAR survey information. Based on this information, the river bed part of the channel cross-sections extracted from the LIDAR survey information for locations upstream of Inveresk Weir were reduced by 1.0m. Subsequent model simulation using the 7 February 2011flow information indicated that the right hand bank upstream of Inveresk Weir would be affected by flooding with depths of up to 0.5m. This exercise increased the level of confidence in the representation of the reach upstream of Inveresk Weir with cross sections based on the adjusted Environment Agency data.





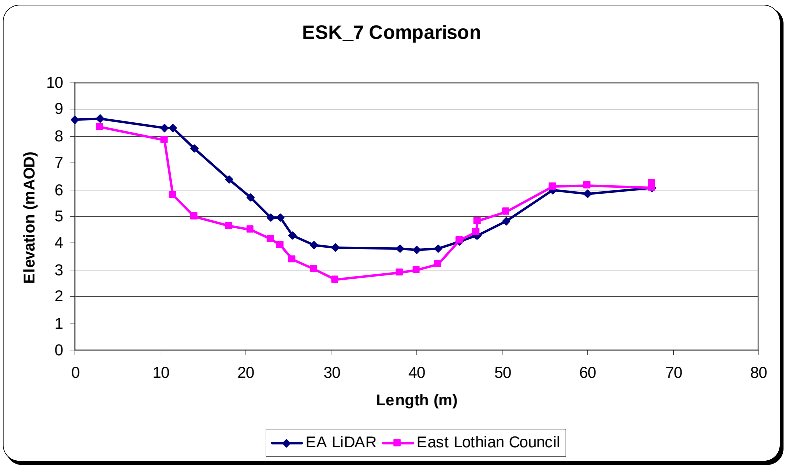


Figure 6 – Comparison of conventional and LIDAR survey channel cross-sections in the River Esk

Identification of the floodplain storage areas upstream of Inveresk Weir was based on the indicative extent of 0.5% AEP flood event as shown on the SEPA Indicative River and Coastal Flood Map (Scotland).

Musselburgh Golf Course and the fields opposite were represented as flood storage reservoirs using LIDAR survey information obtained from the Environment Agency. The likely flow interaction between the main river channel and the flood storage reservoirs during a high flow event were maintained by spill units which represent the high points between the channel and the floodplain.

The narrow strip of land over the right bank upstream of Inveresk Weir was represented as an extended channel cross-section following observations made during the site walkover inspection of March 2011. The field which is located between the River Esk and Inveresk Industrial Estate was represented as a flood storage reservoir due its enclosed nature.

The reach between Inveresk Weir and High Street in Musselburgh was represented as channel cross-sections as this section of the river is either confined between high natural banks or masonry training walls.

Flood storage reservoirs were used to represent the large low lying areas on both sides of the River Esk downstream of High Street. Eskside East and Eskside West are noted in the East Lothian Council severe Weather Response Plan as areas considered for sandbag distribution, indicating likelihood of flooding. With the exception of the banks along the River Esk there is no other higher ground in these areas which could be used for delineation of storage reservoirs; hence roadways and boundary walls were used as spill units to maintain flow of floodwaters between various flood storage reservoirs.

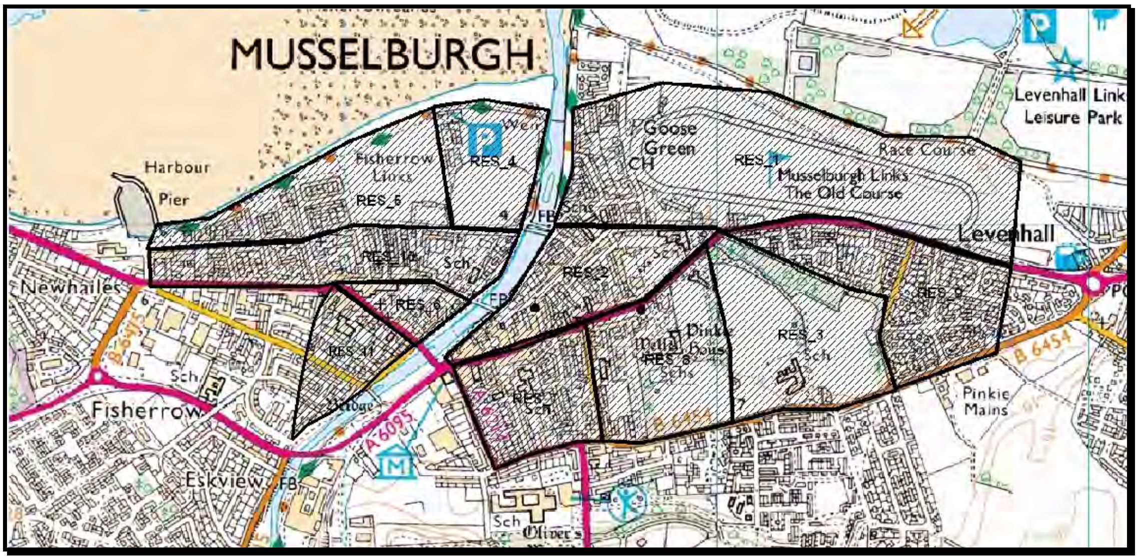


Figure 7 – Flood Storage Reservoirs used in the model

Figure 7 shows the location of each storage reservoir.

There are 5 and 7 flood storage reservoirs modelled along the left and right hand banks respectively. Table 6 shows the area covered by each flood storage reservoir used in the model representation of the river system.

Flood Storage Reservoir	Location	Coverage
RES_1	RHB	Musselburgh Race Course and Goose Green
RES_2	RHB	Eskside East, Loretto School
RES_3	RHB	Pinkie St Peters Primary School
RES_4	LHB	Newfield Sports Ground
RES_5	LHB	Fisherrow Links and Promenade
RES_6	LHB	Area between North High Street and Bridge Street
RES_7	RHB	Area between High Street and Inveresk Road
RES_8	RHB	Loretto Primary School and Pinkie House
RES_9	RHB	Pinkie Braes
RES_10	LHB	Area between New Street and North High Street
RES_11	LHB	Area between Campie Road and Market Street
-	RHB	Station Road and Eskmill

Table 6 – Flood Storage Reservoirs used in the model

The spill units linking flood storage reservoirs and the River Esk were derived using the top of bank level and centre of the road level information provided by the Council and the LIDAR survey information obtained from the Environment Agency.

The remaining reach of the River Esk downstream of the weir at Goose Green was represented as extended channel cross-sections and the sections were extended to the Fisherrow Sands and the Firth of Forth to properly represent tidal influence on water levels.

The channel roughness coefficients for the large extended cross-sections where storage of tidal water, rather than conveyance of floodwaters is likely to take place were set to a value of zero to represent quiescent storage of tide/floodwater.

Photographs of all key structures represented in the mathematical model of the River Esk are presented in Appendix B,

Initial test runs were carried out using the model of the main channel and the weir structures. Following these tests, any difficulties which were apparent in model operation and conditions that might give rise to unrealistic model results were identified and resolved. Following the inclusion of all major structures further model test runs were carried out as before to identify and resolve any potential anomalies in model operation and model predictions.

Once the initial model results were considered reasonable for conditions representing in-bank flows, the banks representing engineered and natural high ground between the river and the floodplain areas where ponding is likely to occur and storage compartments representing areas in Musselburgh were included in the model.

5.3 Model Calibration

Mathematical river models require to be calibrated against historical flood events to increase confidence in model predictions. The degree of model calibration that can be carried out depends on the quantity and quality of recorded water level and flow data for a number of historical events. Ideally, these events should cover a range from moderate in-bank flood events to out-of-bank events. Model calibration is carried out by adjusting some of the model parameters including channel roughness coefficient and weir coefficient that are not precisely known until a reasonable agreement is obtained with recorded water levels and flows.

The accuracy of prediction of water levels for design events depends on the accuracy with which the main channel and floodplains are represented in the model. In-bank flow events are used to adjust the channel roughness and weir coefficients within the main channel and out-of-bank flow events are used to adjust the coefficients representing overflow to and from floodplains and also head-loss coefficients at bridges and other hydraulic structures.

A good calibration event is one where there are observed water levels (normally in the form of peak levels) at all critical locations within the model area and where the corresponding flows are known. With the exception of Musselburgh Flow Gauging Station which is located approximately 50m upstream Olive Bank Road Bridge and the water level recorder at Goose Green, there is little other reliable historical water level data available in Musselburgh. In order to increase the level of confidence in the model predictions through Musselburgh, water level observations in the River Esk along the reach between Inveresk Weir and the Goose Green level recorder would be required during, and in the days following, significant tidal and fluvial events.

In view of the absence of historical water level information in the River Esk, the observations made during the walkover inspection in March 2011 and the information available in the national press were used to achieve a degree of calibration of the model parameters to increase the level of confidence in the fluvial and tidal water level predictions.

As indicated earlier, the walkover inspection of March 2011 identified a recent high flow event. Data requested from SEPA indicated that, a high flow event with a peak flow of $67.05m^3/s$ took place on 7th February 2011. The corresponding peak level recorded at Musselburgh Gauging Station was 4.84mAOD. The level recorded at Musselburgh Gauging Station was used to calibrate the channel in the vicinity. Model prediction using a flow of $67.05m^3/s$ indicated that the predicted peak water level would be 4.83mAOD which is 10mm lower than the recorded level and considered to be a good correlation.

Review of national press articles indicated that high water levels were experienced in the River Esk during 30 March 2010. A photograph showing Council operatives placing sandbags on the footpath leading to the entrance of Newfield Sports Ground on Eskside West was also available. The photograph, although not very clear, indicated that the left hand bank downstream of the entrance was under water and the water level was near the crest of the footpath in line with the bollards. Topographical survey information provided by the Council indicated that the ground level at the gate was around 3.40mAOD.

The water level information at Goose Green recorder and the flow at Musselburgh Gauging station were requested from SEPA. Information indicated that the peak tide level and the river flow recorded on 30 March 2010 were 3.44mAOD and $69.28m^3/s$ respectively. Model simulation using time-series tide level and flow data indicated that, the channel roughness coefficient (Manning's n) for the tidally dominated reaches downstream of Goose Green Weir should be reduced to 0.017 in order to achieve an agreement between the recorded and predicted peak water levels at the monitoring site for the recorded high tide conditions. Figure 8 shows the comparison of observed and predicted peak water levels at Goose Green Level Recorder on 30 March 2010. The difference in predicted peak water levels at the lower peak, which is estimated to be around 100mm, is due to the water level recorded at the level recorder located upstream of the weir being used as a downstream boundary without a correction. As the effect of the weir becomes negligible at a high tide situation, it is considered that this difference is not significant for the outcome of the investigation.

It should be noted that due to lack of observed historical water level and flow information the model has been calibrated to the extent possible at this stage and this level of calibration is considered reasonable for the assessment of flood risk for the purposes of this study. However the calibration of the model should be further refined as further recorded data becomes available.

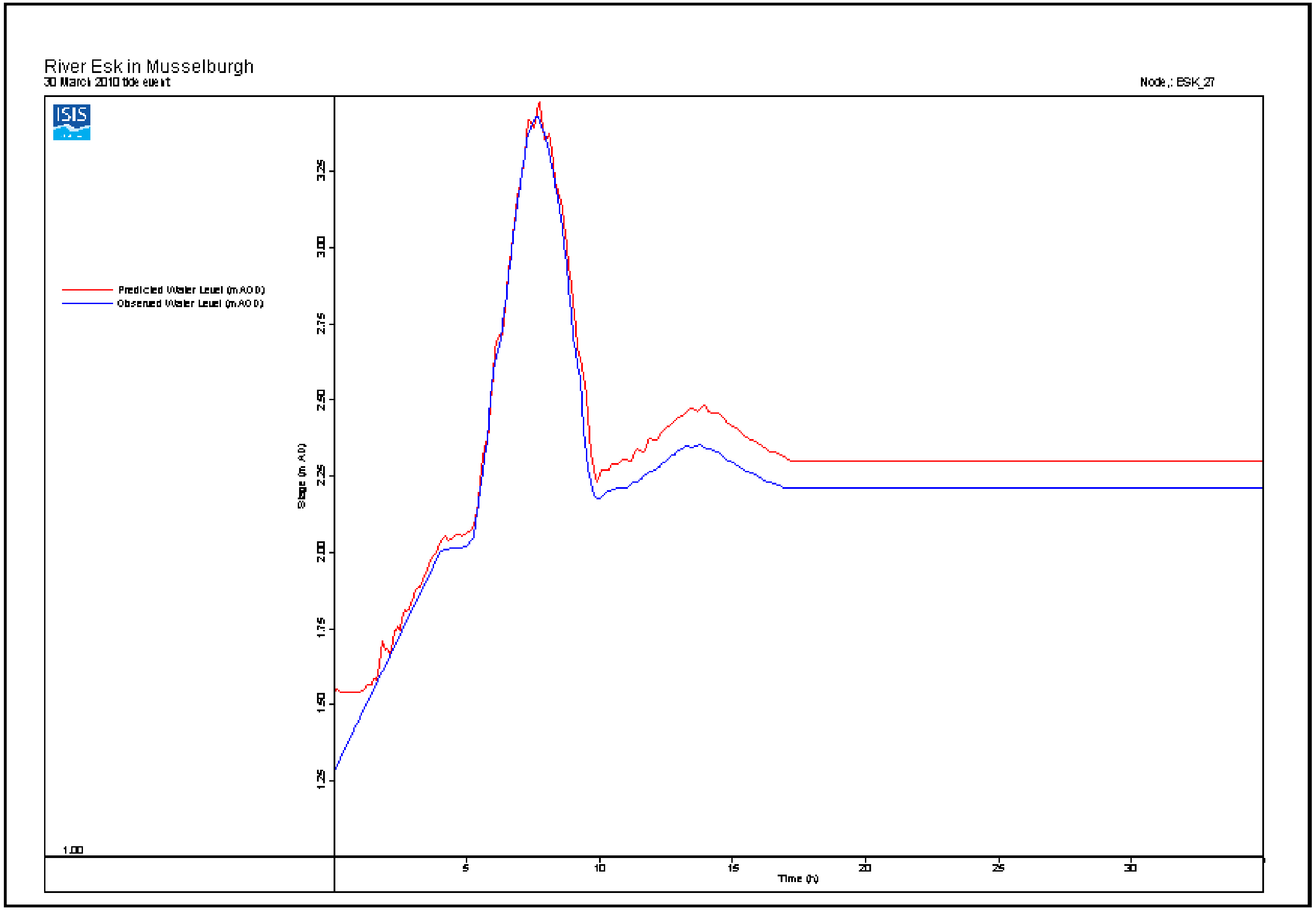


Figure 8 - Comparison of predicted and observed water levels at Goose Green Level Recorder

5.4 Model Simulations

The partially calibrated model of the River Esk was used to predict the peak water levels in order to asses the risk of flooding and identify the indicative extent of flooding due to high tidal and fluvial conditions and combinations of both along the modelled reach of the River Esk between Whitecraigs and its confluence with the Firth of Forth. 62 model simulations, corresponding to the 20%, 10%, 4%, 2%, 1%, and 0.5% AEP joint probability flood events were carried out.

A summary of the peak water levels and flows at key locations along the river is presented in Table 7. The table also indicates whether the dominant influence on peak water level is fluvial or tidal or a combination of both.

A full set of model results with the peak water levels for all above % AEP joint probability fluvial/tidal flood events are presented in Appendix C.

Model Node		Location	Predicted Peak Water Level (mAOD)				
			20% AEP	10% AEP	2% AEP	1% AEP	0.5% AEP
Fluvial	ESK_7	Gauging Station	4.60	5.17	6.02	6.24	6.47
Fluvial	ESK_15	u/s Old Bridge	4.21	4.68	5.38	5.57	5.79
Fluvial	ESK_17	u/s New Bridge	3.88	4.23	4.75	4.87	5.04
Both	ESK_19	Shorthope Street Footbridge	3.21	3.44	4.31	4.53	4.77
Tidal	ESK_24	Electricity Footbridge	3.20	3.37	3.81	3.89	4.14
Tidal	ESK_27	Weir at Goose Green	3.19	3.37	3.80	3.88	3.97

Table 7 – Comparison of predicted peak water levels in the River Esk

Model simulations were carried out for all joint probability combinations. However the comparison of results indicated that for each joint probability event, the extreme fluvial and tidal events coincident with a very small flow or tide appear to produce the highest water levels in the River Esk. An extreme fluvial event in the River Esk is likely to influence the water levels in the reach approximately down to Goose Green Footbridge (ESK_24) depending on the rarity of the event. Similarly the influence of an extreme tidal event could extend as far upstream as Shorthope Street footbridge (ESK_19). The water levels in the locations between Shorthope Street and Goose Green Footbridges are likely to be determined by a combination of both tidal and fluvial events. Figure 9 below shows the effect of tide level and fluvial flows on the resultant water levels in the River Esk at the Goose Green area in Musselburgh.

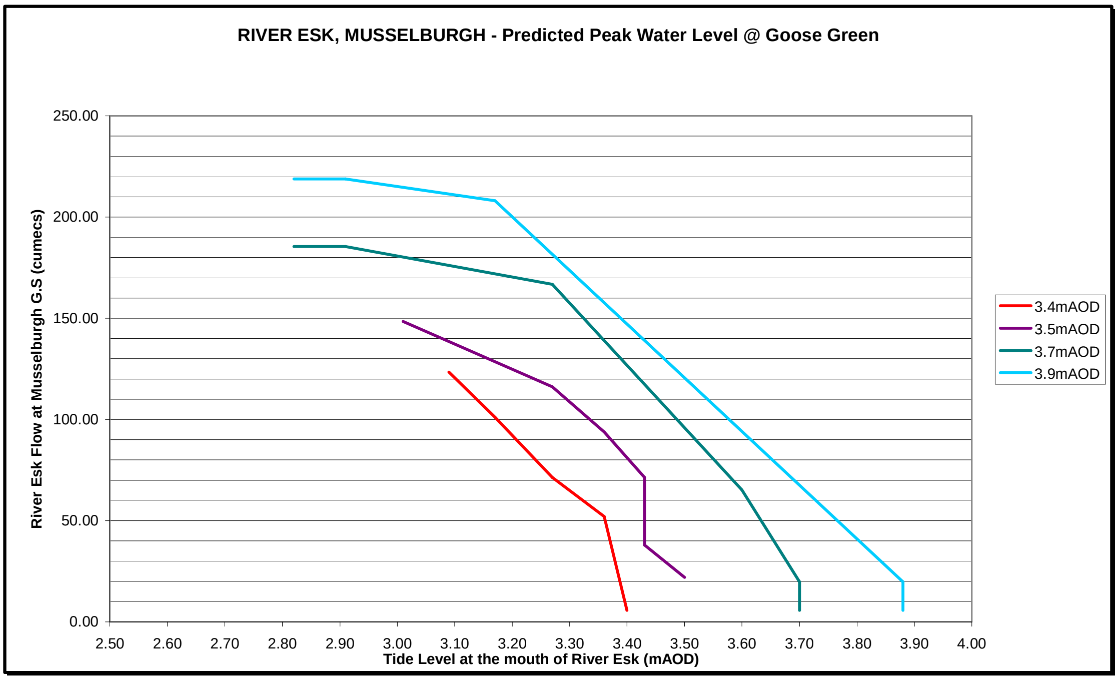


Figure 9 – Effect of Tide and Fluvial Flows on the Water Levels in the River Esk at Goose Green area in Musselburgh

Sensitivity to Climate Change

The Flood and Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities – Climate Change Impacts (October 2006) by DEFRA supports applicability of a 20% allowance up to 2080 for peak river flow. This applicability of this allowance was also confirmed by the findings of a joint Defra/Environment Agency study of Regionalised Impacts of Climate Change on Flood Flows[16] in 2009.

The updated Defra allowances use only the IPCC High Emissions 'highest estimate' of projected sea-level rise. The guidance suggests these allowances are appropriate for detailed flood and coastal risk management and planning, and should be used for these purposes until further updates are provided by Defra. However, there remain significant uncertainties associated with climate change scenarios and the resulting projections of future sea-level rise.

Table 8 below shows the net sea-level rise for Scotland up to 2115 as indicated by the Defra guidance.

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[16] Defra/EA, Regionalised impacts of climate change on flood flows, R&D Technical report FD2020/TR, November 2009

Administrative or Devolved Region	Assumed Vertical Land Movement (mm/yr)	Net Sea-Level Rise (mm/yr)			
		1990-2025	2025-2055	2055-2085	2085-2115
NW England, NE England, Scotland (north of Flamborough Head)	+0.8	2.5	7.0	10.0	13.0

Table 8 – Defra regional net sea-level allowances

Based on the above allowances it is estimated that by 2080, the sea-level rise in coastal waters near Musselburgh could be around 550mm.

UK Climate Projections, UKCP09, provide the latest predictions for the effect of climate change on a range of parameters including sea-level. Table 9 below provides a summary of predictions for sea-level rise for the period between 2012 and 2080 for a range of probability and emission scenarios at site 12612 which represents the grid cell in UKCP09 User Interface, where Musselburgh is located.

Emission Scenario	Net Sea-Level Rise (m)		
	5%ile	50%ile	95%ile[17]
Low	0.04	0.16	0.28
Medium	0.05	0.21	0.37
High	0.06	0.27	0.47

Table 9 – UKCP09 sea-level predictions at Musselburgh up to 2080

Based on the above predictions, it is considered that a value of 0.27m is likely to provide the best estimate of sea-level rise in the Firth of Forth near Musselburgh up to 2080.

As the model simulations indicated that the flooding in Musselburgh is predominantly fluvially dominated, in order to predict the effect of a 20% increase in the fluvial flow in the River Esk on the water levels, an additional model simulation was undertaken using a flow of 0.5% AEP flood event with 20% increase in the flows coincident with a tide level of 2.82mAOD (0.01 year return period tide level) to represent the effect of climate change on fluvial flows only. Model simulation shows that significant increases of around 300mm could be experienced in the water levels of the River Esk increasing the depth and possibly extent of flooding in Musselburgh.

[17] The 95th percentile means that 95% of the time, the value is below this amount.

	Model Node	Location	Predicted Peak Water Level (mAOD) 0.5% AEP	0.5% AEP+20% increase in flow	Difference (mm)
Fluvial	ESK_7	Gauging Station	6.58	6.91	+330
	ESK_15	u/s Old Bridge	5.81	6.07	+260
	ESK_17	u/s New Bridge	5.05	5.24	+190
Both	ESK_19	Shorthope Street Footbridge	4.73	4.97	+240
Tidal	ESK_24	Electricity Footbridge	4.14	4.47	+330
	ESK_27	Weir at Goose Green	3.50	3.72	+220

Table 10– Comparison of the effect of 20% increase in flows due to Climate Change on peak water levels in the River Esk

Other Sensitivity Checks

In addition to assessing the sensitivity of water levels to changes in the fluvial flows due to climate change, the sensitivity against the changes in the channel roughness was also investigated. A model simulation for the 0.5% AEP fluvial flood event coincident with 2.82mAOD tide level was carried out by increasing the channel roughness coefficient by 20%. Model simulations indicate that the predicted peak water level in the River Esk could increase by as much as 300mm for a 20% increase in the channel roughness coefficient. The largest increase occurs in the fluvially dominated upstream reaches of the River Esk.

It is emphasised that the water level values quoted in this report are predictions from a one –dimensional mathematical model of the River Esk which does not include effects such as variation of water surface across the channel cross-section, local effects, and fluctuations or elevation of water surface due to wind induced or other turbulence etc.

5.5 Inundation Mapping

Although the model simulations were undertaken using the ISIS river modelling software based mathematical model of the River Esk, due to ease of data manipulation and faster model simulation times, the indicative extents of inundation for various % AEP flood events were generated using a one-dimensional InfoWorks RS river modelling software package which combines the ISIS Flow simulation engine with geographical analysis and a relational database within a single model environment. Geographical analysis and the relational database allows instantaneous flood-mapping of any simulated event, including full dynamic replay and display of peak indicative extent of flooding. This method was also selected due to the availability of LIDAR survey information as the basis for mapping.

It should be noted that due to the one-dimensional nature of the modelling software, the lines showing the extent of flooding for various % AEP flood events are indicative only and should not be used for assessing the risk of flooding to individual properties.

The inundation maps have been plotted for the 4% AEP, 2% AEP, 1% AEP, 0.5% AEP fluvial and tidal joint probability flood events are provided in Appendix D.

For a 0.5% AEP joint probability flood event the modelling indicates that the likely areas that would be flooded in Musselburgh town are as shown in the table below.

Areas likely to be flooded	Flooding Mechanism
Both banks between Whitecraigs and railway bridge	Narrow strip of land over both banks would be affected by high water levels in the River Esk. The source of the flooding is fluvial.
Right hand bank between Wedderburn House and Inveresk Lounge	Low-lying agricultural fields between Wedderburn Terrace and the River Esk to the north of railway embankment would be affected by flooding due to overtopping of natural banks along the watercourse. The source of flooding is fluvial
Musselburgh Golf Course	Golf course would be inundated by flood flows overtopping the banks downstream of the railway embankment. Flood flows would traverse the golf course grounds in a north-westerly direction and rejoin the River Esk over the bank upstream of Inveresk Weir. Although it is understood that there are informal flood embankments around the golf course, the mathematical model uses information provided in the LIDAR survey information.
Right hand bank upstream of Inveresk Weir	A narrow strip of land including the foot and cycle path between Inveresk Lodge and Inveresk Weir would be affected by flooding. The vacant land to the south of Inveresk Mills Industrial Park would also be inundated by floodwaters overtopping the informal flood embankment separating the field from the foot and cycle path.
Right hand bank between Eskmills and Olive Bank Road bridge	The low-lying area currently occupied by Eskmills Industrial Business Park, Eskmill Villas, Jobcentre Plus and Eskmill Bowling Club would be affected floodwaters entering the site along the low bank downstream of the footbridge. Floodwaters would return the channel over the bank upstream of the Gauging Station.
Haugh Park over left hand bank	Haugh Park on the bank opposite to Inveresk Industrial Business Park would be affected by flooding as it forms part of the natural floodplain. It is expected that the flooding of Haugh Park is likely to occur for a flood event with 2% AEP or rarer.
Left hand bank between Olive Bank Road bridge and New Bridge	The left bank from a point half-way between Campie Road and West Holmes Gardens and Market Street would be overtopped by floodwaters during 2% AEP or rarer flood events. Floodwater entering Eskside West is likely to flow towards Bridge Street and join larger ponding further downstream
Left hand bank between Bridge Street and North High Street	Eskside West and residential properties along Eskside West would be affected by floodwaters overtopping the bank for

Areas likely to be flooded	Flooding Mechanism
	flood events rarer than 4%AEP. Although extent of inundation would largely be limited to Eskside West and properties in the immediate vicinity, the extent would move further inland towards North High Street. And the floodwater would flow further downstream over North High Street.
Left hand bank between North High Street and New Street	The flooding would be the result of floodwaters flowing downstream over North High Street and floodwaters overtopping the left bank immediately downstream of Shorthope Street footbridge and spreading inland. Floodwaters would spread further north and enter New Street and some would spill back into the River Esk over the banks upstream of Goose Green footbridges.
New Street, Newfield Sports Grounds and Fisherrow Links	Flow entering New Street from Eskside West is likely to spread westwards along New Street. While the floodwaters are moving west, the openings on either side of New Street are likely to act as conduits allowing the land on both sides of New Street to become affected by floodwaters. Current predictions indicate that for a 0.5% AEP flood event, Newfield Sports Grounds and Fisherrow Links are likely to be affected by floodwaters entering these areas through openings along continuous walls. The level information separating New Street and land on either side originated from the available LIDAR survey information; hence it is likely that the walls were not represented. Therefore it is considered that extent of flooding shown for Fisherrow Links and Newfield Sports Ground could be viewed as conservative.
Right hand bank between New Bridge and Shorthope Street footbridge	The area is likely to be affected by flooding by floodwaters overtopping the banks downstream of New bridge and upstream of Shorthope Street footbridge. The floodwater entering the area is likely to use the roadways to spread eastwards into Pinkie, Goose Green and Musselburgh Race Course. Depending on the magnitude of the flood events, varying amount of floodwater would return to the River Esk over the banks upstream of Goose Green footbridges.

Table 11 - Summary of Areas Affected by Flooding and Mechanism of Flooding

When interpreting the indicative flood maps the following must be taken into account:

- ***The flood maps provide an indicative estimate of the extent of flooding, based upon the predicted levels of a one-dimensional mathematical model.***
- ***It should be noted that certain locations may be at risk of flooding from other sources such as pluvial flooding (surface flooding associated with very intense rainfall), sewer flooding, road drainage, field ditches, water mains etc; also from other watercourses not modelled in this study.***
- ***The inundation outlines are based upon water levels predicted at discrete points along the main channel and on floodplains where appropriate. The inundation at all other locations is based on interpolation and therefore the flood outlines need to be considered as broadly indicative.***

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- ***Transfer of floodwaters between various floodplain storage reservoirs is based on the level information obtained form the current LIDAR survey information, which does not represent boundary walls and openings on these walls. Hence in general, the inundation outlines shown on the indicative extent of inundation plans could represent an area larger than might actually be affected in reality.***
- ***Channel roughness used in the model represents average conditions and would not necessarily reflect conditions if heavy weed growth, or debris were allowed to build up in the channel.***
- ***The modelling cannot predict the potential occurrence of transitory debris dams and the associated consequences.***

6 Conclusions and Recommendations

In order to assess the risk of flooding in Musselburgh from the River Esk a mathematical model of the River Esk between Whitecraigs and the Firth of Forth has been constructed. Channel cross-sections used for the model construction were either provided by East Lothian Council or extracted from the LIDAR survey information obtained from the Environment Agency by the Council. The Council also provided survey information for significant hydraulic structures over the River Esk and spot level information along the banks between New Bridge and Goose Green footbridges. A walking survey was carried out to assess current conditions along the river.

The model has been partially calibrated using information gathered during the walkover inspection and information available in the press in relation to recent high flow events. Flow and water level information for these events was provided by the Scottish Environment Protection Agency. The close agreement between the model results and the recorded flood event data provides confidence in model predictions for the design events. The predicted flood pattern in Musselburgh town confirmed the existing understanding of the mechanism of flooding.

The current investigation sets a benchmark in terms of flows and indicative extent of inundation in Musselburgh town and areas in the vicinity for a range of % AEP flood events. The current modelling indicates that extensive areas are likely to be at significant risk of flooding. These areas are indicated in the flood inundation mapping and summarised in Table 11

In order to consider further the viability of flood mitigation measures for Musselburgh and, if necessary, surrounding areas, we would recommend that the following be undertaken:

- ***Undertake observations of water levels and survey of wrack marks during and in the days following significant future flow and/or tidal events.***
- ***Further refine the mathematical model using detailed topographical survey information and observations made during future significant flow/tidal events and refine the assessment of flood risk based on this information.***
- ***Assess in outline possible flood mitigation options. This may involve further application of the mathematical model.***
- ***Undertake an assessment of the outline costs for technically viable options and undertake a benefit/cost appraisal of these options to assess economical viability.***
- ***Assess the risk of flooding from other sources including surface water flooding. This would involve a preliminary assessment of***

pluvial flood risk; also liaison with Scottish Water to determine the risk of flooding through sewers and surface water drains.

- ***Assess the potential impact of possible flood mitigation measures on the sewerage and drainage system and local watercourses.***
- ***Determine ownership of areas of land likely to be affected directly by likely flood mitigation options.***
- ***Collate information on the condition of existing masonry walls and river retaining walls and undertake further structural inspection and condition assessment where necessary to determine the areas where existing walls might need repair or replacement. Carry out an initial assessment of stability under design flood conditions.***
- ***Enter into discussions with SEPA and other relevant organisations to determine their views on possible flood mitigation options and in particular the impact on amenity, habitat, groundwater and water quality and likely CAR (Controlled Activities Regulations) issues.***
- ***Consider the public acceptability of proposals through initial consultation, possibly via elected members.***
- ***Obtain information on water, sewerage, electricity, gas, cable networks and any other utilities and make contact with authorities to identify 'sensitive' apparatus and obtain preliminary estimates for diversion works.***
- ***Undertake a geotechnical desk study to determine availability of site investigation (SI) data and requirements for subsequent ground investigation.***
- ***Undertake a preliminary environmental scoping study to identify key issues to be addressed.***

Appendix A Audit Trail

Jacobs flood study audit trail
FEH pooling group analysis

RIVER ESK@ MUSSELBURGH (NT 33850 72350)

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Tel 0121 700 1250   Fax 0121 700 1251

Project details

Project title: Musselburgh Flood Study

Project number: B1592000
Work Stage:
Client: East Lothian Council
Flood study site: RIVER ESK@ MUSSELBURGH

Jacobs flood study audit trail
FEH pooling group analysis

Contents

Jacobs flood study audit trail

FEH pooling group analysis

1 General

The following analysis was undertaken using the FEH CD-ROM Version 3.0 (2009) and Winfap-FEH Version 3.0.003 (2009). The Jacobs Winfap-FEH database uses the HiFlows-UK database v 3.02 dated November 2009, published on Environment Agency website.

2 Catchment description

Grid Reference of the outflow**: NT 33850 72350**

2.1 FEH catchment descriptors:

AREA	322.54
FARL	0.944
PROPWET	0.49
ALTBAR	239
ASPBAR	27
ASPVAR	0.23
BFIHOST	0.567
DPLBAR	24.8
DPSBAR	94.8
LDP	44.55
RMED-1H	8.6
RMED-1D	35.9
RMED-2D	49.9
SAAR	837
SAAR4170	853
SPRHOST	34.09
URBEXT1990	0.0236
URBEXT2000	0.0326

2.2 Presence of significant land-use or catchment factors:

Factors	Comment	Potential Significance
Reservoir\lake	There is minimal attenuation due to rivers or lakes FARL = 0.944	NIL
Urban	URBEXT2000 = 0.0326 updated using the national model of urban growth to URBEXT2010 = 0.0334. The catchment is slightly urbanised.	NIL
Land use	The catchment is slightly urbanised encompassing the urbanised areas of Musselburgh, Gorebridge and many other small villages.	Possible increased Tp due to impermeable urban surfaces.
Soils\Geology	Topography ranges from approximately 480m upstream, to 3m downstream. BFIHOST = 0.567, SPRHOST = 34.09	NIL

2.3 Flow record:

Target site: Gauged

3 Estimation of QMED

3.1 Approach used

Used	Condition	Approach followed
✓	N >=30	Estimate QMED using annual maxima
	14=< N =<29	Estimate QMED from annual maxima & optionally adjust for climatic variation
	2=< N= <13	Estimate QMED from POT data & adjust for climatic variation
	N <2 & suitable donor site with 20 years or more of record	Ignore record at subject site; transfer QMED from donor site
	N <2 & suitable donor with 10 to 19 years of record & 12 month overlap between records	Estimate QMED using procedure based on flood peak regression
	N <2 & suitable donor with 10 to 19 years of record but no 12 month overlap	Ignore record at subject site; transfer QMED from donor site
	N <2 & no long-record site nearby	Estimate QMED from very short POT record
	N <2 & no long-record site nearby	Treat site as ungauged catchment
	N <2 & no long-record site nearby	Defer analysis until longer flow record available
	N <2 & no long-record site nearby	(Abstract flood event information and apply the UH rainfall-runoff model as an alternative, to the pooling group procedure. Particularly recommended when site is urbanised)
	Ungauged catchment	Estimate QMED from catchment descriptors
	Ungauged catchment	Estimate QMED by data transfer from donor catchment
	Ungauged catchment	Estimate QMED by data transfer from analogue catchment
	Ungauged catchment	Estimate QMED from channel dimensions
	Ungauged catchment	Compare to regional pattern of mapped QMED adjustment factors

* preferred method

QMED Calculation

Two annual maximum datasets are available for the River Esk at Musselburgh. One is held and maintained by the gauging authority SEPA, the other was collated as part of the Environment Agency / SEPA HiFlows-UK project, originally to provide data for the Flood Estimation Handbook statistical method, and available on the Environment Agency's HiFlows-UK website. The two datasets are provided in Appendix 4.

No comments have been received either from SEPA or within HiFlows as to the reliability of the high flow record at this station. The station is decribed in HiFlows as being a ***velocity-area station in a section with steep banks. Low flow control is a rock bar, high flow control formed by bridge buttresses. In extreme flows, control of bridge diminishes and control becomes the downstream channel and a Roman footbridge. All flows to date have been contained. Rating derived from current meter gaugings up to 2.5m (about 1.8 QMED), simple extrapolation beyond. High rating appears to oscillate with periodic dredging and accretion of a bar on the right bank.***

It was felt that since the SEPA gauging authority maintain the gauging station the records held by them would be the most up to date. The HiFlows-UK dataset is updated only every few years due to the size of the data collection task.

The SEPA record runs from 1962 – 2009, a period of 48 years. The information was provided in calendar years. Checks were made and there are no events within the record which run over the end of the calendar year and therefore it was thought appropriate to use the list to provide the median annual maximum flood.

QMED taken from AMAX is 69.0m^3/s.

4 Steps involved in construction and analysis of a pooling group – standard method

4.1 Pooling group construction

Site of interest

(a) Station Number	N/A	(b) Name	Esk@Musselburgh
Name of saved **.feh** group file		**River Esk@Musselburgh_rev2.feh**	
Target return period (years) for 5T rule		100	

4.2 Initial Pooling group details

Total number of sites	17	Total number of years	674

Total number of initial high discordancy sites	0
List them: N/A	
Total number of short records (< 7 years) removed	0
List them: N/A	
Number of pooled years after sites removed	674

4.3 Subject Site Details

Is subject site included as Rank 1 in pooled group: ~~yes~~ no

If no state reason why: The subject site is not included in the pooling group as the catchment is ***slightly urbanised.***

4.4 Test statistics on validity of pooling group for flood frequency analysis

Heterogeneity test H2 value = 1.53

Status			
	Review not necessary		H2 < 1
	Review optional	✓	1 < H2 < 2
	Review desirable		2 < H2 < 4
	Review essential		H2 > 4

Goodness-of-fit test	Z values			Value
		GL	acceptable / ~~not acceptable~~	1.06
		GEV	acceptable / ~~not acceptable~~	1.25
		PT3	~~acceptable~~ / not acceptable	1.72
	other			

(Note: in the FEH the GL is the generally favoured distribution for use)

ACTION is construction of flood frequency curve valid?

No ~~Yes~~ Check suitability of sites in the pooling group

4.5 Revision of Pooling Group

Revision No. 1

Station Number	Reason for changes in pooling group
43005, 43008, 42010	Removed SPRHOST<15%

Since the subject site has a FARL value below 0.95 – the threshold was reduced to 0.9.

Number of sites 14 Years 544

Heterogeneity test H2 value = 2.12

Status			
	Review not necessary		H2 < 1
	Review optional		1 < H2 < 2
	Review desirable	✓	2 < H2 < 4
	Review essential		H2 > 4

Note: FEH Vol.3, chapter 16.3.2: "The ideal pooling-group is homogeneous. However, a representative but heterogeneous pooling-group gives better flood frequency estimates than either single-site data or a pooling-group that has been made homogeneous by inappropriately removing sites. In general, it is anticipated that a significant proportion of pooling-groups will remain heterogeneous, even after review."

				Value
Goodness-of-fit test	Z values	GL	~~acceptable~~ / not acceptable	1.66
		GEV	acceptable / ~~not acceptable~~	-0.29
		PT3	~~acceptable~~ / not acceptable	-1.75
	other			

ACTION is construction of flood frequency curve valid?
~~No~~ Yes
Comment?

4.6 Flood frequency analysis of pooling group

Distributions selected	GL	✓	PT3	
	GEV	✓	other	

Standardisation method selected: Median ~~Mean~~ (this acts as a check as median is the only method allowed within the pooling group method)

Construct flood frequency curve

URBEXT updated	yes	~~no~~	If yes from	0.0326	to	0.0334
Urban adjustment*	~~yes~~	no				
Value of QMED =		**69.0**	m^3/s			

GL		
Return period (yrs)	Growth factors	**Design flows (m^3/s)**
2	1.000	69.0
5	1.377	95.0
10	1.653	114.0
25	2.053	141.7
50	2.400	165.6
75	2.624	181.0
100	2.794	192.8
200	3.246	224.0
500	3.948	272.4

GEV	***for comparison***	
Return Period (yrs)	Growth factors	Design flows (m^3/s)
2	1.000	69.0
5	1.415	97.6
10	1.704	117.6
25	2.086	143.9
50	2.381	164.3
75	2.558	176.5
100	2.686	185.3
200	3.001	207.1
500	3.435	237.0

4.7 Pooling group including site gauge

A revised pooling group was developed to include the local gauge. This is because the catchment descriptors suggest that the catchment is only slightly urbanised, though the long Musselburgh record quite possibly samples a period when the urbanisation in the catchment was less and might have been classed as essentially rural. Such a subtle reason for exclusion is likely to be out weighed by the local information brought to the analysis by the inclusion of the gauged record. Therefore this pooling is considered to be stronger than the pooling without the inclusion of the gauge at the site.

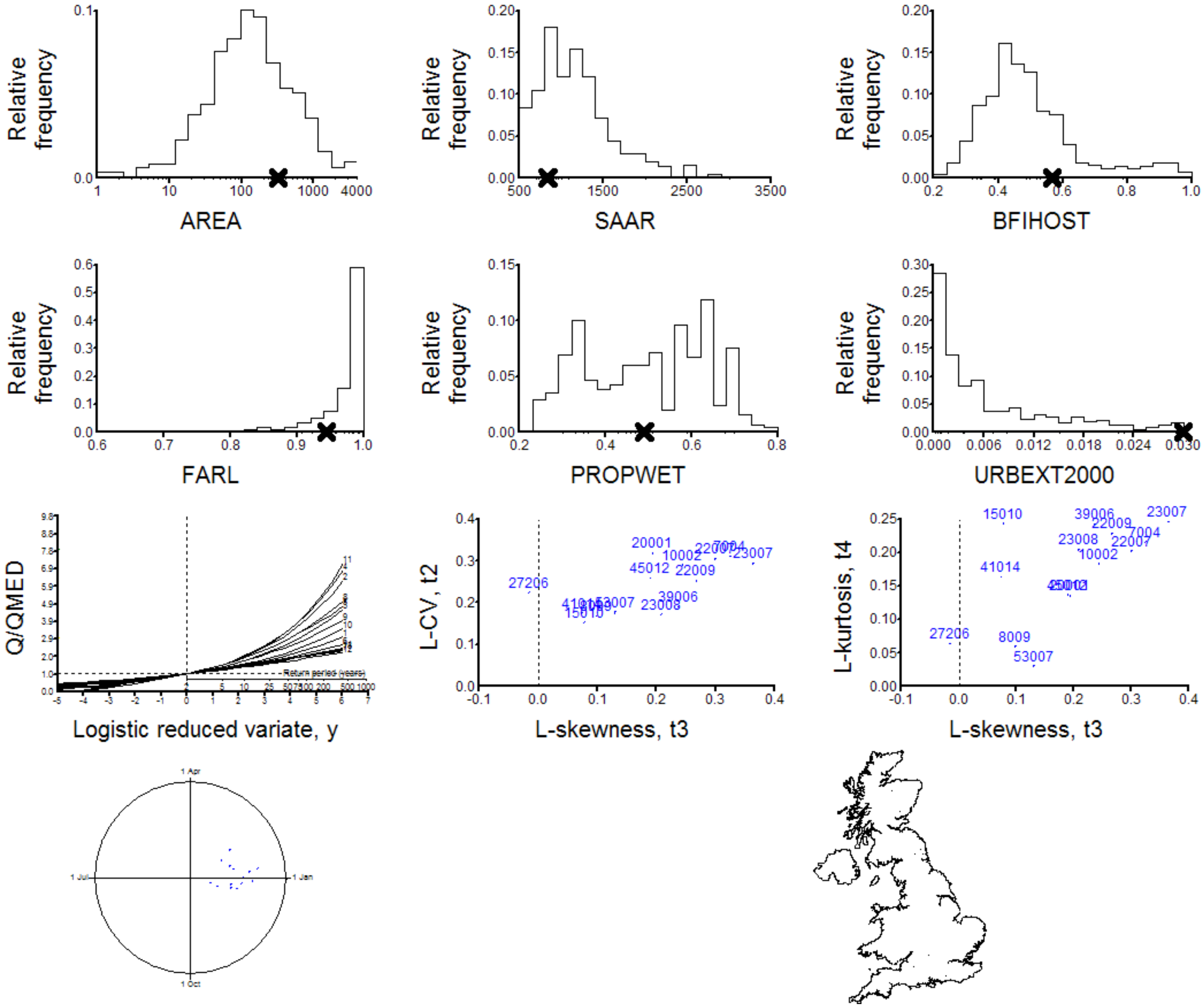
This could not be done as a simple exercise of inserting the station to the pooling group, as WINFAP v.3 does not allow any gauges not suitable for pooling to be inserted in a pooling group.It is possible to derive this result by inserting gauge 19011 instead of 19007 (site gauge), changing all catchment descriptors and AMAX to reflect the 19007 information provided by SEPA and run the growth curve. This cannot be saved on WINFAP (limitation of the model).
The growth curve factors derived by pooling group within the site gauge are shown below.

Return period	Growth Factor	Design flows (m^3/s)
2	1	69
5	1.412	97.4
10	1.707	117.8
25	2.138	147.5
50	2.515	173.5
75	2.759	190.4
100	2.946	203.2
200	3.443	237.6
500	4.222	291.3

Jacobs flood study audit trail
FEH pooling group analysis

Appendix 1 Location of catchment

Appendix 2 Pooling Group Details – Graphs



Appendix 3 Pooling Group Details – Table

Standard Pooling Group

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy
23008 (Rede @ Rede Bridge)	0.326	40	134.549	0.173	0.208	0.809
22007 (Wansbeck @ Mitford)	0.332	46	100.859	0.305	0.300	0.496
22009 (Coquet @ Rothbury)	0.373	33	129.967	0.254	0.266	0.262
7004 (Nairn @ Firhall)	0.390	25	95.830	0.312	0.325	0.655
20001 (Tyne @ East Linton)	0.419	47	57.803	0.320	0.193	1.175
53007 (Frome(somerset) @ Tellisford)	0.423	47	57.750	0.177	0.130	2.261
27206 (Esk @ Briggswath)	0.425	15	140.325	0.225	-0.016	2.110
10002 (Ugie @ Inverugie)	0.440	35	45.871	0.291	0.243	0.301
45012 (Creedy @ Cowley)	0.449	44	72.632	0.260	0.189	0.161
39006 (Windrush @ Newbridge)	0.451	58	11.300	0.191	0.237	0.821
23007 (Derwent @ Rowlands Gill)	0.491	44	40.910	0.294	0.364	0.912
15010 (Isla @ Wester Cardean)	0.528	22	85.020	0.154	0.077	2.127
41014 (Arun @ Pallingham Quay)	0.536	34	76.299	0.177	0.073	0.671
8009 (Dulnain @ Balnaan Bridge)	0.543	54	94.451	0.169	0.097	1.240
Total		544				
Weighted means				0.237	0.199	

Appendix 4 Single Site Analysis

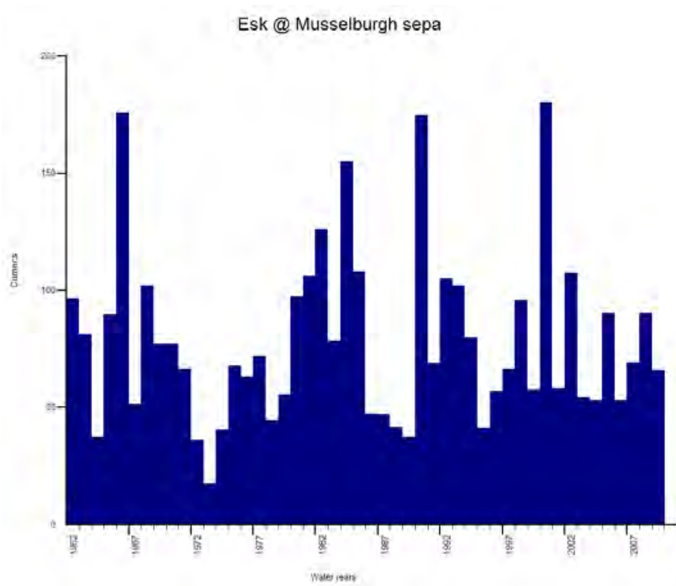
Gauge name and number: Esk at Musselburgh (19007)

Two annual maximum datasets are available for the gauging station at Musselburgh. One is held by the gauging authority, SEPA, the other was collated as part of the HiFlows programme and is available via the Environment Agency's web site. A single-site analysis has been undertaken on both of these sets of data and a comparison made.

SEPA 1962 – 2009 (48 station years)

Data is held by SEPA in calendar years. The data was checked and there was no double counting of events at the end of the year and therefore a standard single-site analysis on the dataset was deemed appropriate. The AMAX data are provided below.

Calendar Year	Date	Flow (m^3/s)
1962	12SEP1962	96.7
1963	23NOV1963	81.3
1964	11OCT1964	37.4
1965	26SEP1965	89.8
1966	14AUG1966	176.0
1967	16MAY1967	51.5
1968	5MAY1968	102.0
1969	22NOV1969	77.1
1970	31OCT1970	77.1
1971	24MAR1971	66.4
1972	17FEB1972	36.1
1973	22DEC1973	17.6
1974	17DEC1974	40.5
1975	18SEP1975	67.9
1976	15OCT1976	63.2
1977	25JAN1977	71.9
1978	15NOV1978	44.6
1979	8DEC1979	55.3
1980	25NOV1980	97.1
1981	2OCT1981	106.0
1982	3JAN1982	126.0
1983	1JUN1983	78.6
1984	3NOV1984	155.0
1985	21SEP1985	108.0
1986	30DEC1986	47.4
1987	18JUL1987	46.9
1988	2JAN1988	41.6
1989	11JAN1989	37.4
1990	6OCT1990	175.0



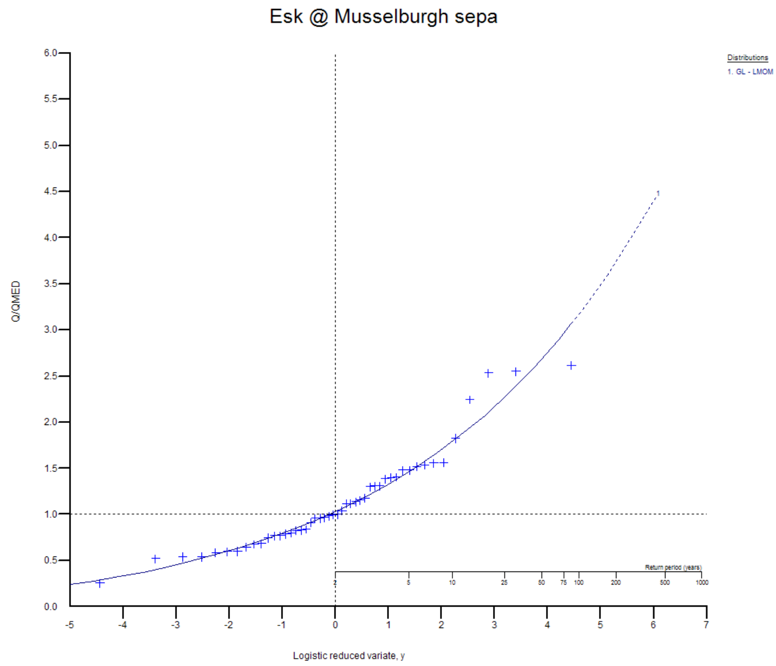
1991	23FEB1991	68.9
1992	8JAN1992	105.0
1993	9OCT1993	102.0
1994	11DEC1994	79.8
1995	31JAN1995	41.4
1996	18DEC1996	57.0
1997	20FEB1997	66.7
1998	2NOV1998	95.6
1999	12DEC1999	57.4
2000	26APR2000	180.5
2001	19AUG2001	58.1
2002	22OCT2002	107.4
2003	22JAN2003	54.7
2004	2FEB2004	53.1
2005	8JAN2005	90.3
2006	16NOV2006	53.1
2007	21NOV2007	69.1
2008	7AUG2008	90.2
2009	4SEP2009	66.1

QMED: 69.0 m^3/s

The WINFAP-FEH software was used to run the single site analysis and the results were as follows:

GL		
Return period (years)	Growth factors	Design flows (m^3/s)
2	1.033	71.3
5	1.465	101.1
10	1.788	123.4
25	2.266	156.4
50*	2.687	185.4
75*	2.962	204.4
100*	3.173	218.9
200*	3.738	257.9
500*	4.632	319.6

* return period > record length

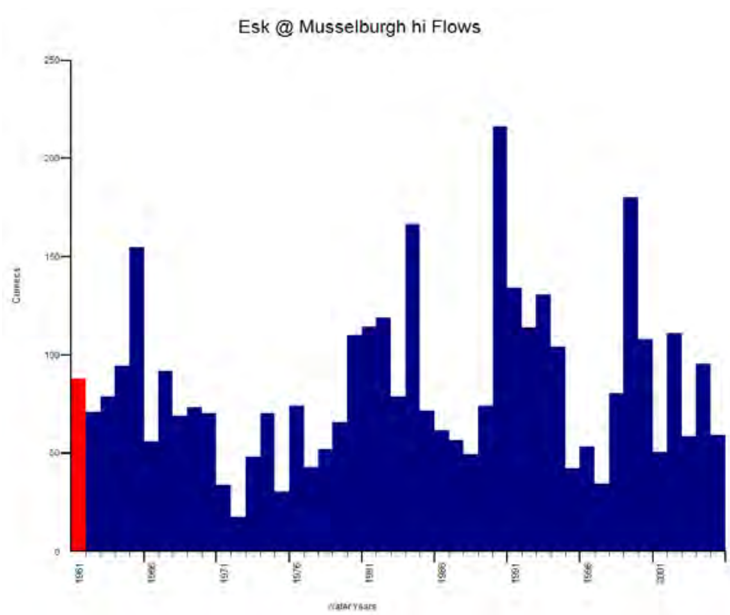


HiFlows-UK Dataset dated Nov 09 1961-2005 (44 years)

(1961 was rejected as an incomplete water year)

QMED: 72.6 m^3/s

Water year	Date	Flow (m^3/s)
1961	11Sep1962	87.8
1962	05Mar1963	71.0
1963	23Nov1963	78.9
1964	26Sep1965	94.5
1965	13Aug1966	154.6
1966	19Dec1966	56.1
1967	05May1968	92.0
1968	01Nov1968	69.5
1969	22Nov1969	73.4
1970	31Oct1970	70.3
1971	17Feb1972	33.8
1972	11Dec1972	17.8
1973	17Mar1974	48.3
1974	18Sep1975	70.3
1975	03Apr1976	30.8
1976	25Jan1977	74.1



1977	30Oct1977	42.8
1978	15Nov1978	52.5
1979	08Dec1979	65.7
1980	25Nov1980	110.0
1981	03Jan1982	114.4
1982	23Nov1982	118.9
1983	04Feb1984	79.0
1984	03Nov1984	166.7
1985	21Dec1985	71.8
1986	30Dec1986	61.9
1987	02Jan1988	56.8
1988	11Jan1989	49.7
1989	17Feb1990	74.1
1990	06Oct1990	216.4
1991	08Jan1992	134.2
1992	15May1993	113.9
1993	10Oct1993	130.6
1994	12Dec1994	104.3
1995	16Nov1995	42.4
1996	21Feb1997	53.3
1997	11Dec1997	34.6
1998	03Nov1998	80.3
1999	27Apr2000	180.4
2000	07Nov2000	108.1
2001	24Jan2002	50.6
2002	22Oct2002	111.0
2003	02Feb2004	58.9
2004	08Jan2005	95.3
2005	12Oct2005	59.3

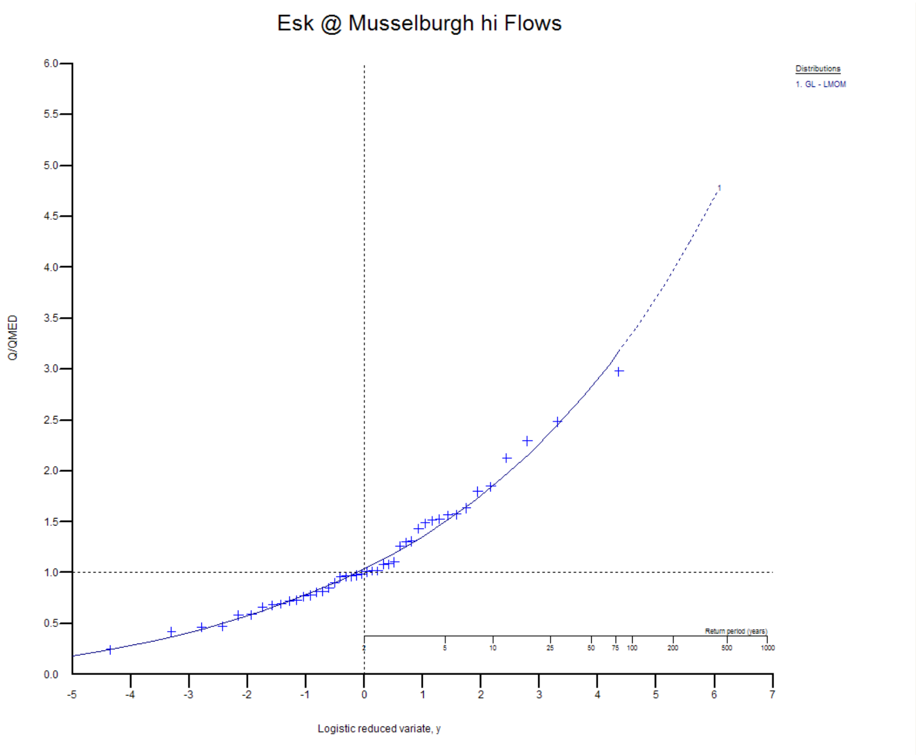
The WINFAP-FEH software was used to run the single site analysis and the results were as follows:

GL		
Return period (years)	Growth factors	Design flows (m^3/s)
2	1.036	75.2
5	1.502	109.0
10	1.852	134.5
25	2.370	172.1
50*	2.827	205.2
75*	3.127	227.0
100*	3.356	243.6
200*	3.972	288.4
500*	4.948	359.2

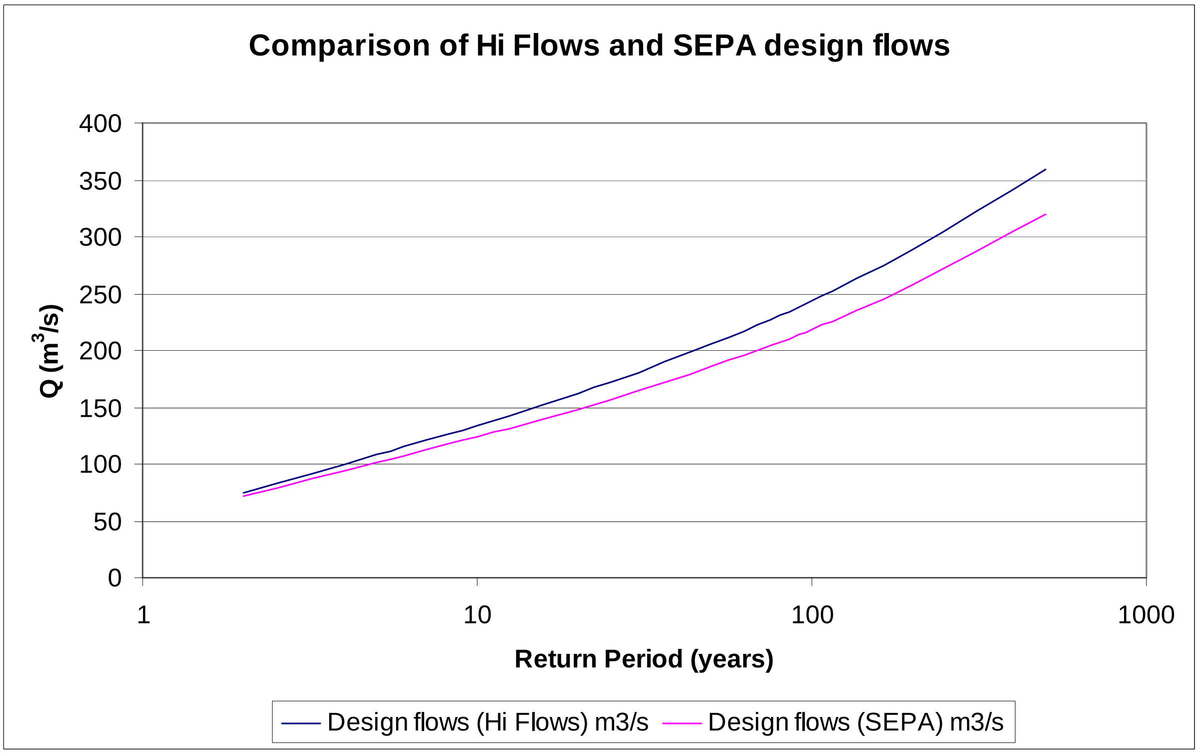
* return period > record length

Jacobs flood study audit trail

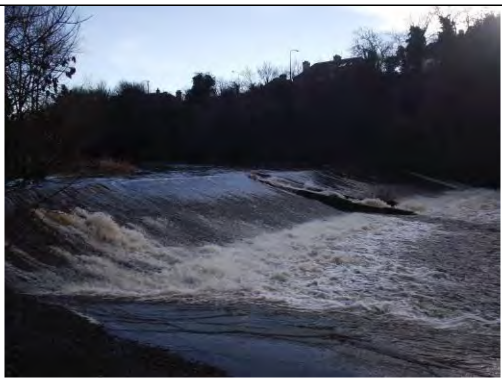
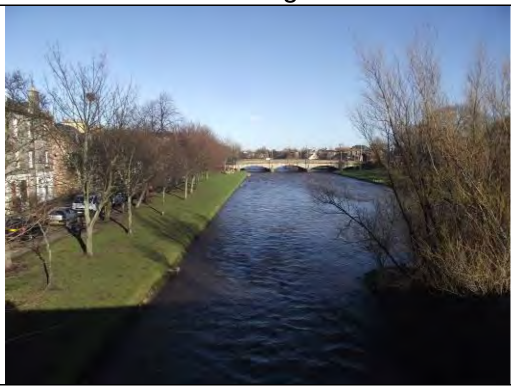
FEH pooling group analysis



The HiFlows-UK data analysis provides higher flows at all return periods.



Appendix B Photographs

	
Inveresk Weir	Olive Bank Road bridge
	
Old Bridge	New Bridge
	
Shorthope Street footbridge	Goose Green Footbridges

Appendix C Water Level Predictions

Node	Predicted Peak Water Level (mAOD) for Joint probability Events						Location
	20%AEP	10%AEP	4%AEP	2%AEP	1%AEP	0.5%AEP	
SEC_1	12.88	13.47	14.17	14.46	14.82	15.21	
SEC_2	12.36	13.09	13.89	14.28	14.70	15.34	
SEC_3	12.23	13.01	13.81	14.16	14.55	15.31	
SEC_4	12.17	12.97	13.83	14.24	14.65	15.33	
SEC_5	12.10	12.93	13.81	14.20	14.59	15.28	A1 Road Bridge
SEC_6	11.44	12.11	12.66	12.88	13.03	13.54	
SEC_7	11.35	12.03	12.58	12.82	12.96	13.29	
SEC_8	10.77	11.39	11.97	12.23	12.56	12.85	
SEC_9	10.71	11.40	11.86	12.06	12.25	12.49	LHB - Musselburgh Golf Course RHB – Wedderhouse Terrace
SEC_10	10.48	11.19	11.58	11.70	11.78	11.82	
SEC_11	10.41	11.12	11.59	11.78	11.94	12.10	
SEC_12	10.27	10.97	11.43	11.61	11.78	11.91	
SEC_13	10.11	10.76	11.20	11.38	11.54	11.62	
SEC_14	9.62	10.19	10.58	10.75	10.90	11.21	
SEC_15	9.22	9.74	10.11	10.27	10.39	10.80	
SEC_16	9.18	9.76	10.14	10.24	10.33	10.47	
SEC_17	9.06	9.63	10.03	10.14	10.24	10.40	
SEC_18	8.95	9.49	9.89	9.99	10.08	10.20	
SEC_19	8.89	9.41	9.80	9.88	9.96	10.08	
SEC_20	8.86	9.41	9.81	9.90	9.99	10.12	
SEC_21	8.64	9.07	9.58	9.69	9.81	9.99	
SEC_22	8.33	8.74	9.23	9.37	9.50	9.65	
SEC_23	7.93	8.24	8.49	8.61	8.72	8.85	
WEIR_US	8.07	8.34	8.61	8.71	8.80	8.92	u/s Inveresk Weir
WEIR_DS	6.05	6.60	7.23	7.51	7.78	8.06	d/s Inveresk Weir
ESK_1	6.04	6.59	7.22	7.51	7.78	8.05	
ESK_2	5.75	6.33	7.00	7.30	7.58	7.85	
ESK_3	5.46	6.09	6.83	7.14	7.44	7.71	
ESK_4	5.05	5.63	6.22	6.46	6.67	7.19	
ESK_5	4.85	5.47	6.12	6.46	6.79	7.19	

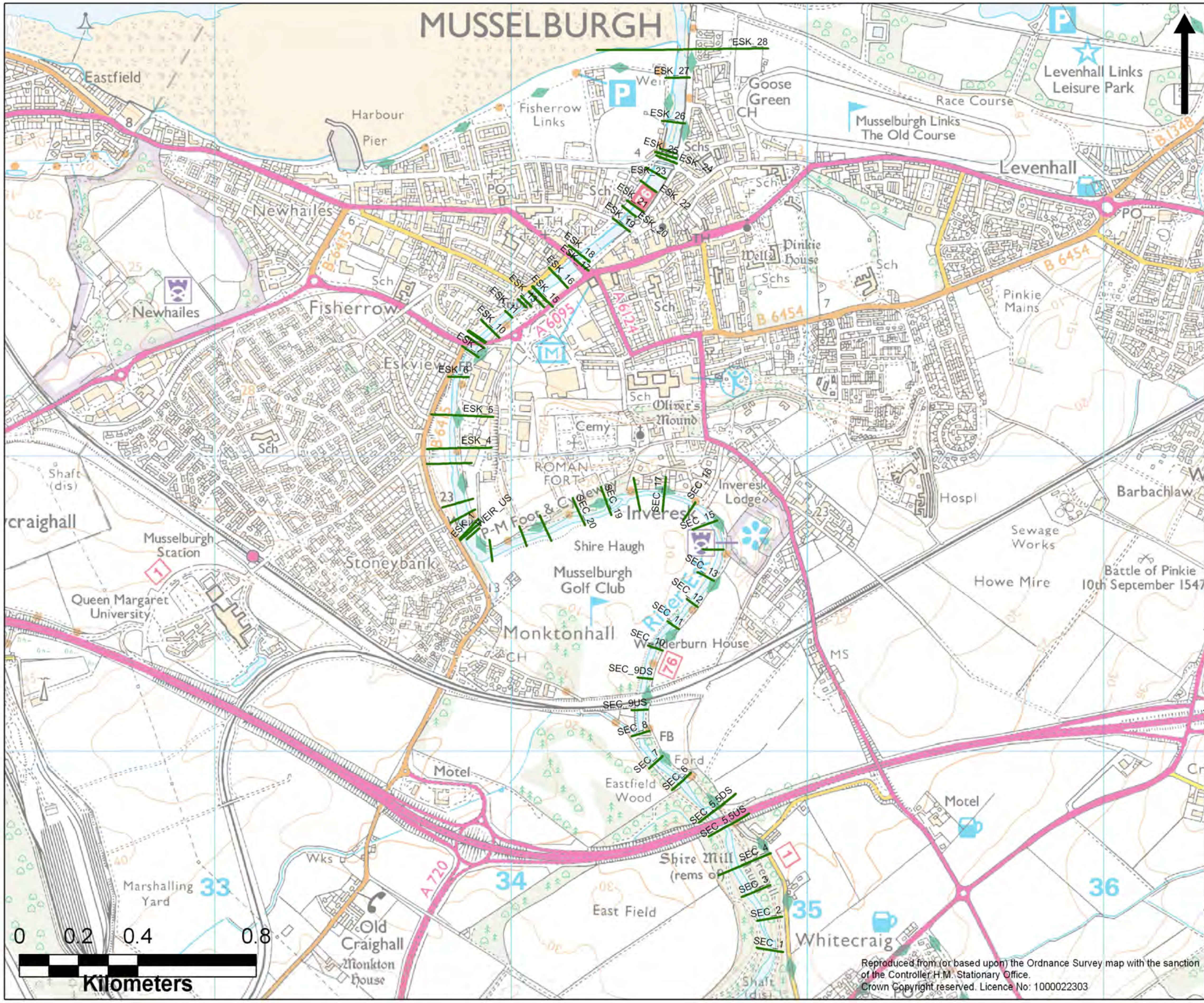
Node	Predicted Peak Water Level (mAOD) for Joint probability Events						Location
	20%AEP	10%AEP	4%AEP	2%AEP	1%AEP	0.5%AEP	
ESK_6	4.74	5.27	5.81	6.02	6.21	6.45	
ESK_7	4.60	5.17	5.77	6.02	6.24	6.47	Gauging Station
ESK_8	4.59	5.18	5.83	6.10	6.34	6.64	Olive Bank Road Bridge
ESK_9	4.57	5.15	5.77	6.02	6.25	6.52	
ESK_10	4.45	4.97	5.50	5.70	5.88	6.08	
ESK_11	4.36	4.84	5.32	5.50	5.62	5.73	
ESK_12	4.26	4.73	5.22	5.39	5.53	5.70	
ESK_13	4.26	4.74	5.26	5.46	5.62	5.83	
ESK_14	4.25	4.72	5.23	5.43	5.60	5.82	Old Bridge
ESK_15	4.21	4.68	5.19	5.38	5.57	5.79	
ESK_16	3.92	4.28	4.65	4.78	4.90	5.06	
ESK_17	3.88	4.23	4.61	4.75	4.87	5.04	New Bridge
ESK_18	3.86	4.19	4.54	4.64	4.73	4.84	
ESK_19	3.21	3.47	4.08	4.31	4.50	4.73	Shorthope Road footbridge
ESK_20	3.21	3.37	3.74	3.82	4.03	4.30	
ESK_21	3.20	3.37	3.73	3.81	3.99	4.29	
ESK_22	3.20	3.37	3.73	3.81	3.96	4.29	
ESK_23	3.20	3.37	3.73	3.81	3.92	4.26	
ESK_24	3.20	3.37	3.73	3.81	3.89	4.14	Goose Green footbridges
ESK_25	3.20	3.37	3.73	3.81	3.89	3.97	
ESK_26	3.20	3.37	3.73	3.81	3.89	3.97	
ESK_27	3.19	3.37	3.72	3.80	3.88	3.97	Weir
ESK_28	3.19	3.37	3.72	3.80	3.88	3.97	
ESK_29	3.19	3.37	3.72	3.80	3.88	3.96	
ESK_30	3.19	3.37	3.72	3.80	3.88	3.96	
ESK_31	3.19	3.36	3.72	3.80	3.88	3.96	
ESK_32	3.18	3.36	3.71	3.79	3.88	3.96	
ESK_32!	3.17	3.36	3.71	3.79	3.88	3.96	

<table>
<tr><th colspan="7">Predicted Peak Water Level (mAOD)</th><th>Location</th></tr>
<tr><td></td><td>20%AEP</td><td>10%AEP</td><td>4%AEP</td><td>2%AEP</td><td>1%AEP</td><td>0.5%AEP</td><td></td></tr>
<tr><td colspan="8">LEFT BANK</td></tr>
<tr><td>PNL_9</td><td rowspan="6">No flooding</td><td>8.98</td><td>9.57</td><td>9.74</td><td>9.88</td><td>10.04</td><td>Musselburgh Golf Course</td></tr>
<tr><td>RES_11</td><td rowspan="5">No flooding</td><td>No flooding</td><td>4.34</td><td>5.13</td><td>5.33</td><td>South Eskside West</td></tr>
<tr><td>RES_6</td><td>4.07</td><td>4.31</td><td>3.82/4.49</td><td>3.98/4.67</td><td>North High Street-Bridge Street</td></tr>
<tr><td>RES_10</td><td>3.35/3.59</td><td>3.56/3.86</td><td>3.82/3.98</td><td>3.98/4.29</td><td>New Street-North High Street</td></tr>
<tr><td>RES_4</td><td>3.35/3.59</td><td>3.56/3.86</td><td>3.82/3.98</td><td>3.98/4.28</td><td>Newfield Sports Ground</td></tr>
<tr><td>RES_5</td><td></td><td>3.27</td><td>3.02/3.98</td><td>3.48/4.29</td><td>Fisherrow Links & Promenade</td></tr>
<tr><td colspan="7">RIGHT BANK</td><td></td></tr>
<tr><td>PNR_6</td><td rowspan="10">No flooding</td><td rowspan="10">No flooding</td><td colspan="4">No flooding</td><td></td></tr>
<tr><td>PNR_9</td><td>No flooding</td><td>10.19</td><td>10.89</td><td>11.17</td><td>A1 Road bridge - Railway bridge</td></tr>
<tr><td>PNR_22</td><td>8.62</td><td>8.70</td><td>8.79</td><td>8.89</td><td>west of Wedderhouse Terrace</td></tr>
<tr><td>PNR_ESK_6</td><td>5.32</td><td>6.07</td><td>6.29</td><td>6.52</td><td>Upstream of Inveresk Weir</td></tr>
<tr><td>RES_1</td><td>3.67</td><td>2.03/3.96</td><td>3.10/4.14</td><td>3.47/4.29</td><td>Station Road/Eskmill Bowling Club</td></tr>
<tr><td>RES_2</td><td>3.67</td><td>2.60/3.96</td><td>3.15/4.14</td><td>3.47/4.29</td><td>Musselburgh Race Course</td></tr>
<tr><td>RES_3</td><td>3.62</td><td>3.96</td><td>4.14</td><td>4.29</td><td>Eskside East/Loretto School</td></tr>
<tr><td>RES_7</td><td rowspan="3">No flooding</td><td>3.96</td><td>4.14</td><td>4.29</td><td>Pinkie/St Peters Primary School</td></tr>
<tr><td>RES_8</td><td>3.96</td><td>4.14</td><td>4.29</td><td>Loretto Primary School & Pinkie House</td></tr>
<tr><td>RES_9</td><td>3.96</td><td>4.14</td><td>4.29</td><td>Pinkie Braes</td></tr>
</table>

KEY

	Fluvial
	Tidal
2.03/3.96	Tidal/Fluvial

Appendix D Plans showing Indicative Extent of Inundation and Location of Channel Cross-Sections



Reproduced from (or based upon) the Ordnance Survey map with the sanction of the Controller H.M. Stationary Office.

KEY

Cross Section

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Approved
A	06/06/12	Original	RH	BS	BS

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Drawing Title
Cross Section Location Plan

Drawing Status

Scale	NTS
Jacobs no.	B1592000
Client no.	
Drawing no.	B1592000_Fig3
Rev	A

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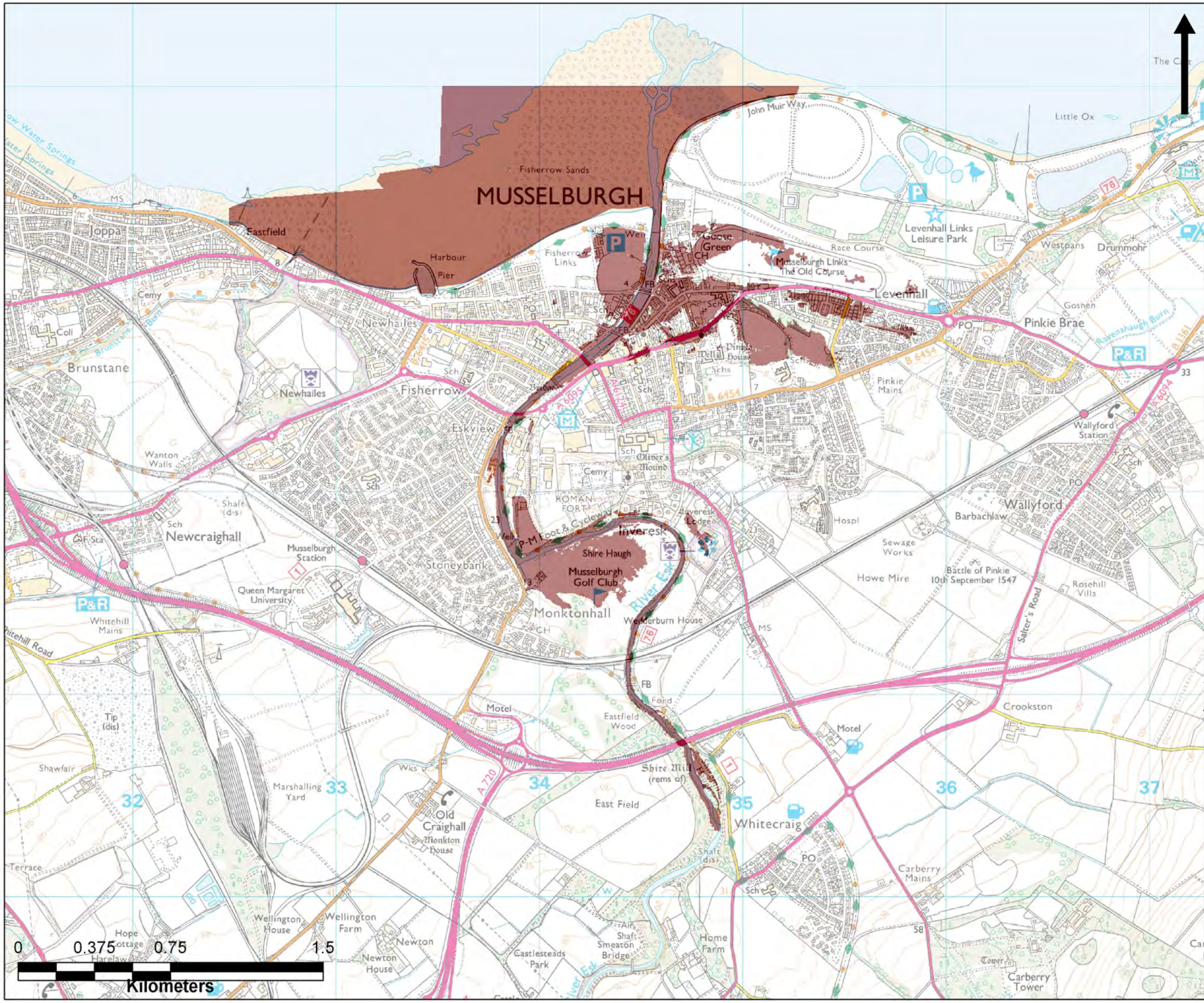

KEY

2% AEP (Fluvial) Indicative Extent of Inundation

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Approved
A	05/04/12	Original	RH	BS	BS

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Project

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Drawing Title

2% AEP (FLUVIAL) INDICATIVE EXTENT OF INUNDATION

Drawing Status

Scale	NTS
Jacobs no.	B1592000
Client no.	
Drawing no.	B1592000_Fig2
Rev	A

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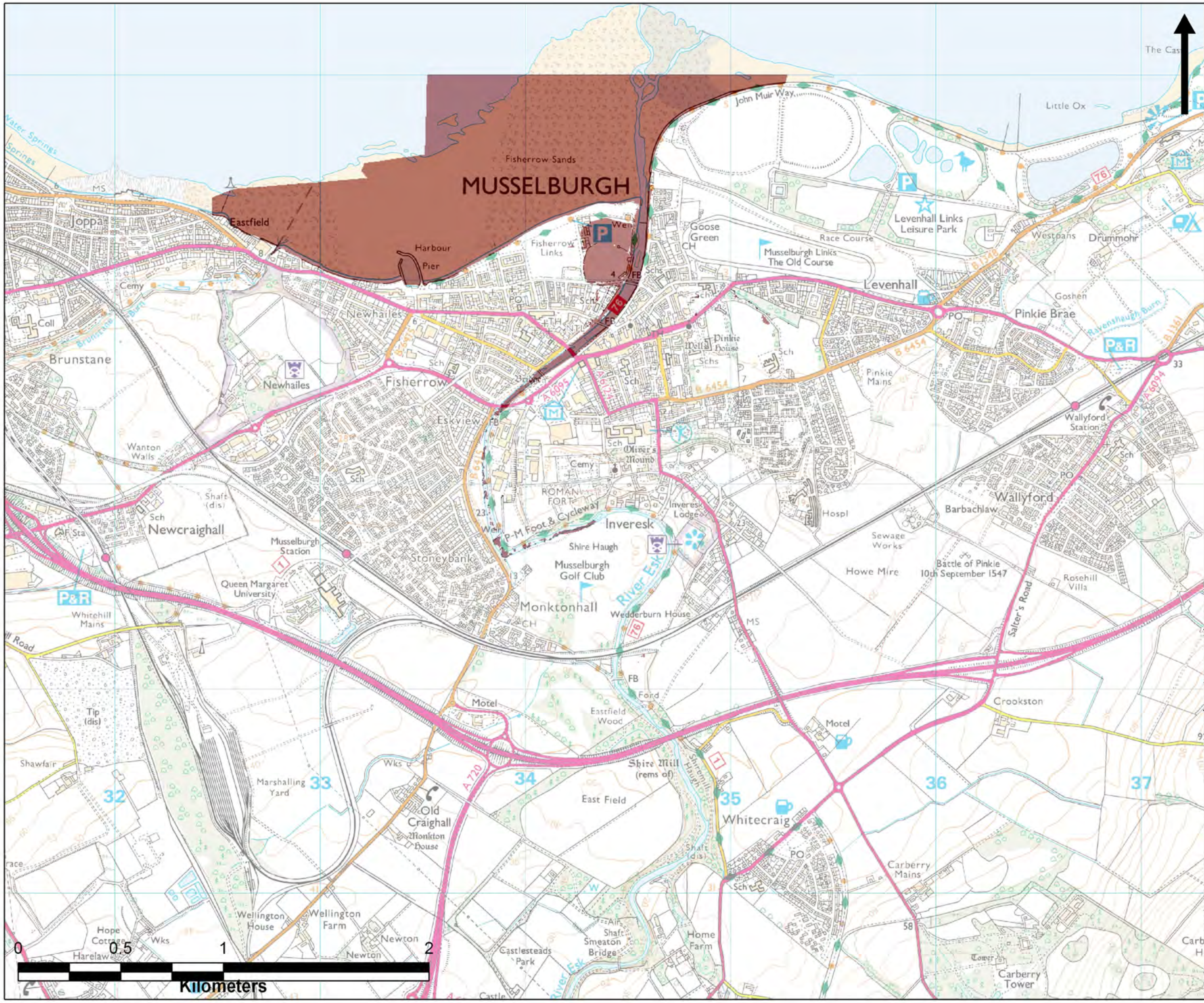

KEY

2% AEP (Tidal) Indicative Extent of Inundation

A	05/04/12	Original	RH	BS	BS
Rev	Rev. Date	Purpose of revision	Drawn	Checked	Approved

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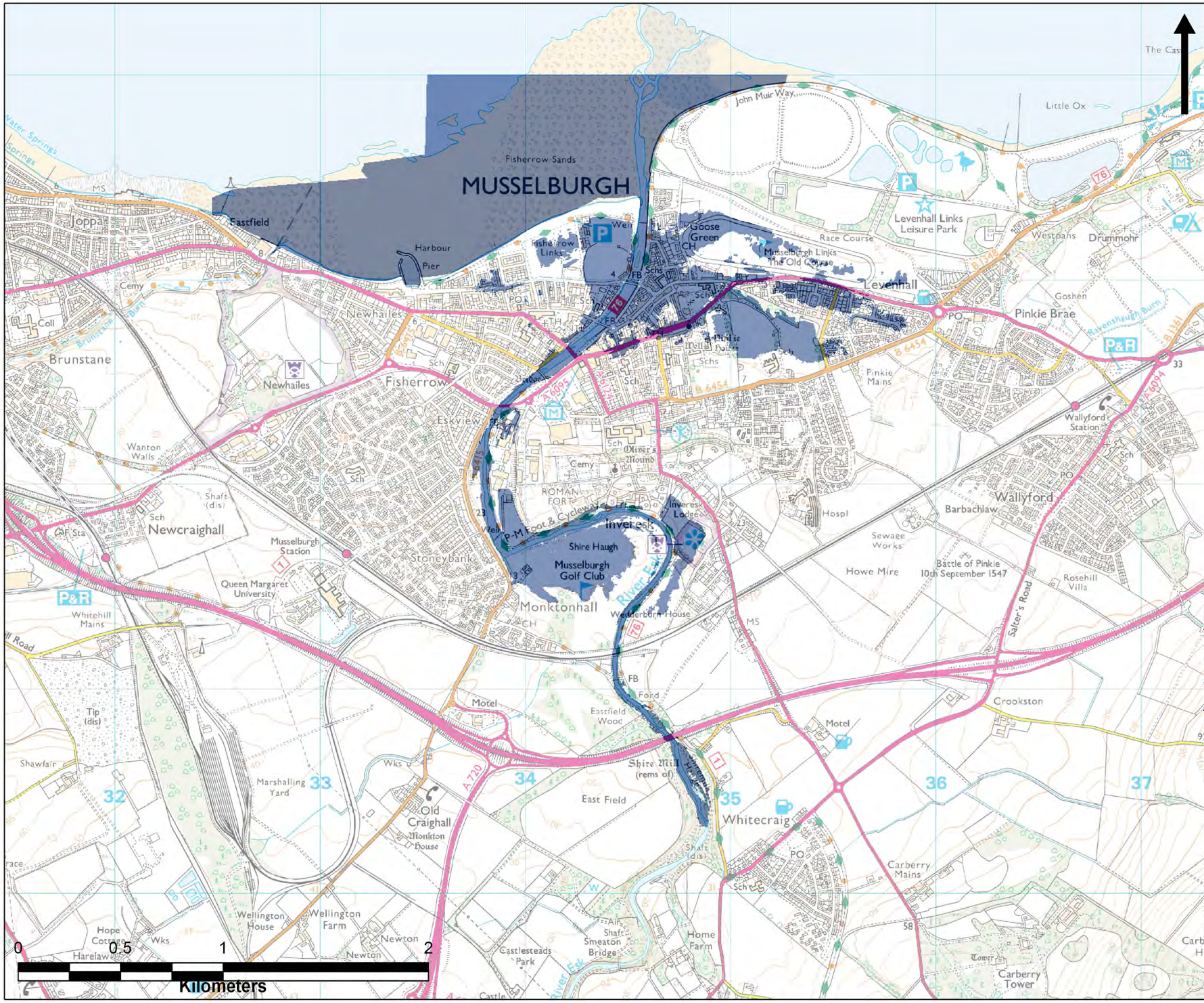
Drawing Title
2% AEP (TIDAL) INDICATIVE EXTENT OF INUNDATION

Drawing Status

Scale	NTS
Jacobs no.	B1592000
Client no.	
Drawing no.	B1592000_Fig1
Rev	A



KEY

1% AEP (Fluvial) Indicative Extent of Inundation

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Approved
A	05/04/12	Original	RH	BS	BS

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Drawing Status

Scale	NTS
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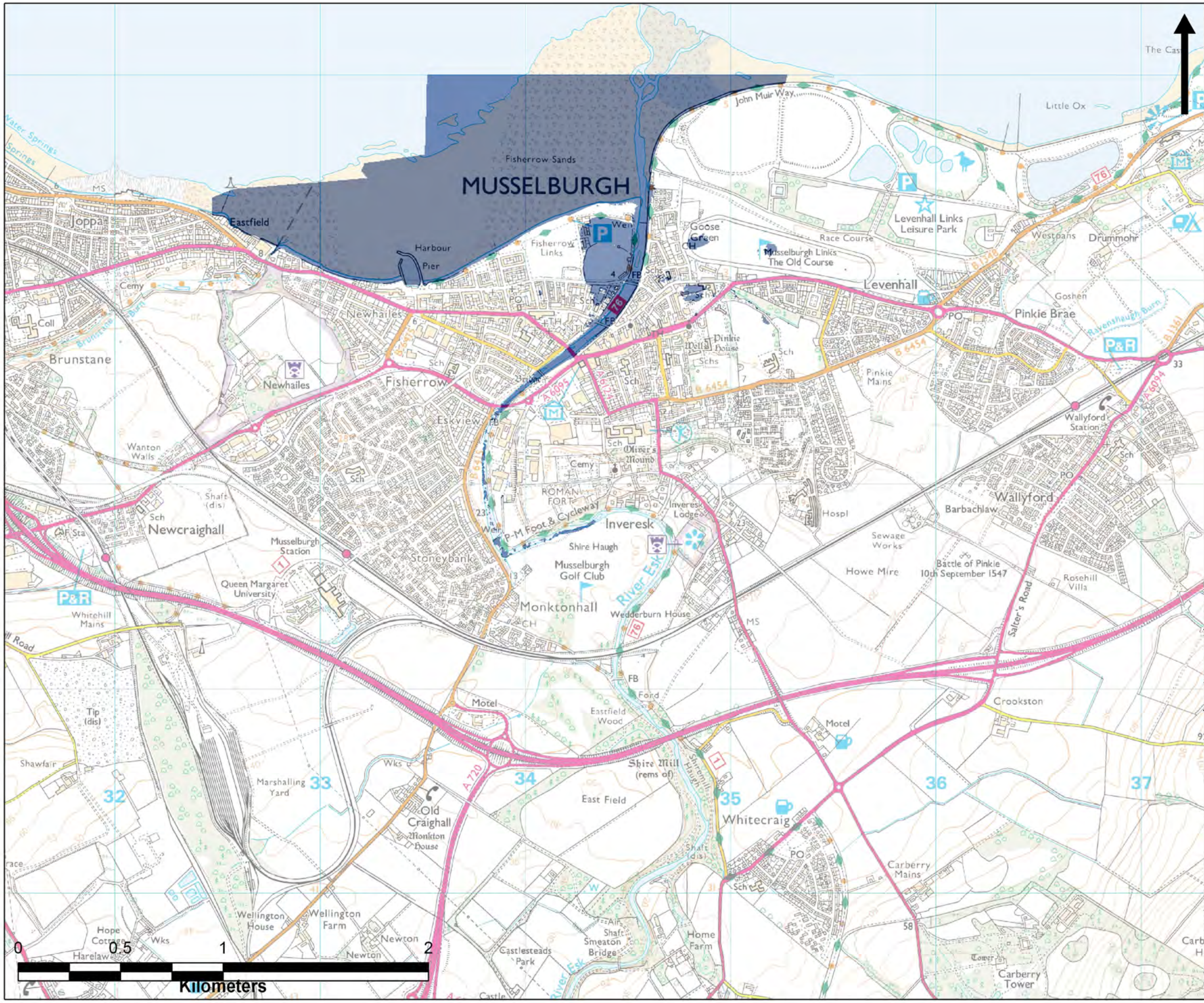
Client no.	
Drawing no.	B1592000_Fig4
Rev	A



KEY

1% AEP (Tidal) Indicative Extent of Inundation

Rev	Rev. Date	Purpose of revision	Drawn	Checked	Approved
A	05/04/12	Original	RH	BS	BS

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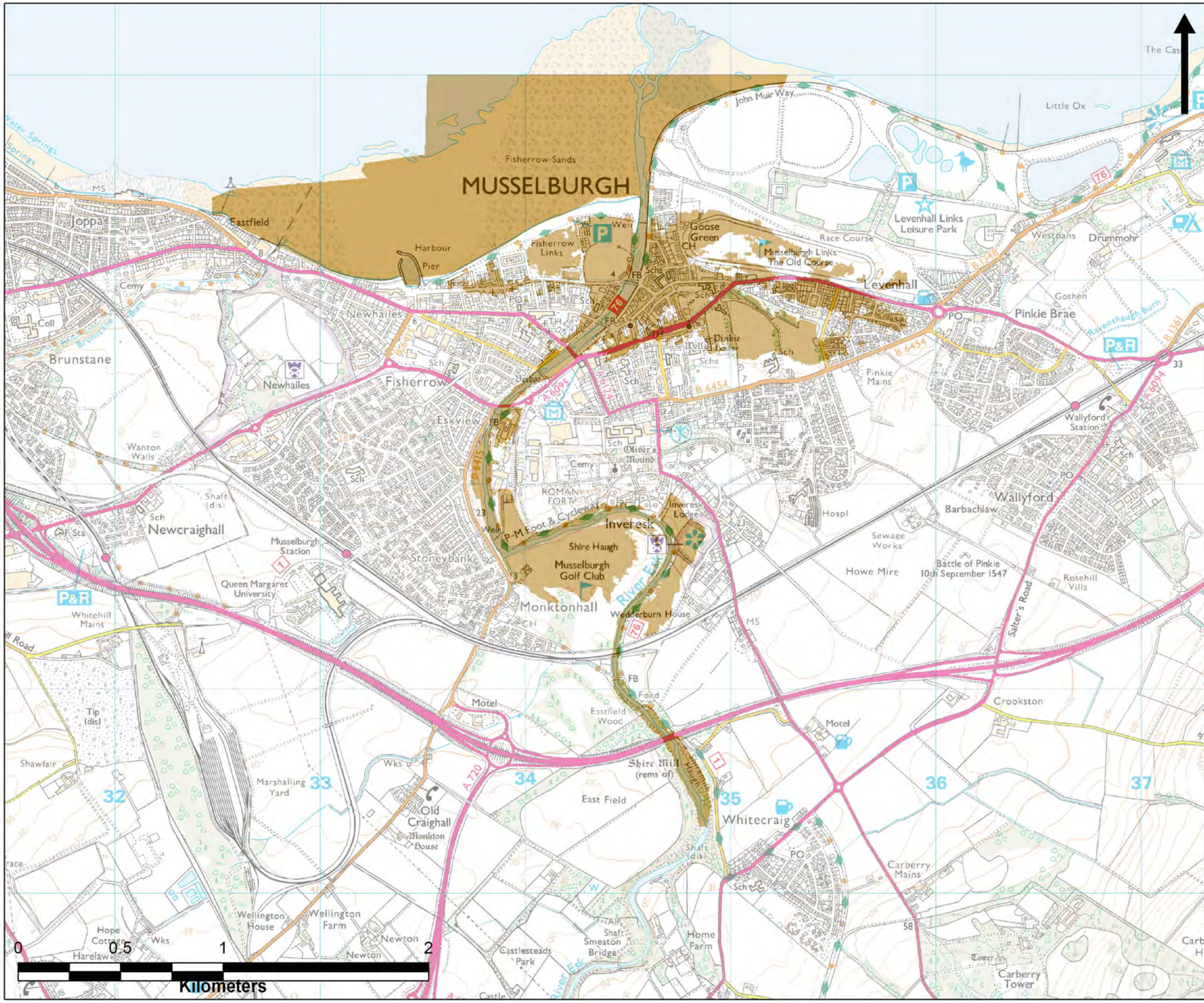
Drawing Status

Scale	NTS
Jacobs no.	B1592000
Client no.	
Drawing no.	B1592000_Fig3
Rev	A



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0.5% AEP (Fluvial) Indicative Extent of Inundation

A	05/04/12	Original	RH	BS	BS
Rev	Rev. Date	Purpose of revision	Drawn	Checked	Approved

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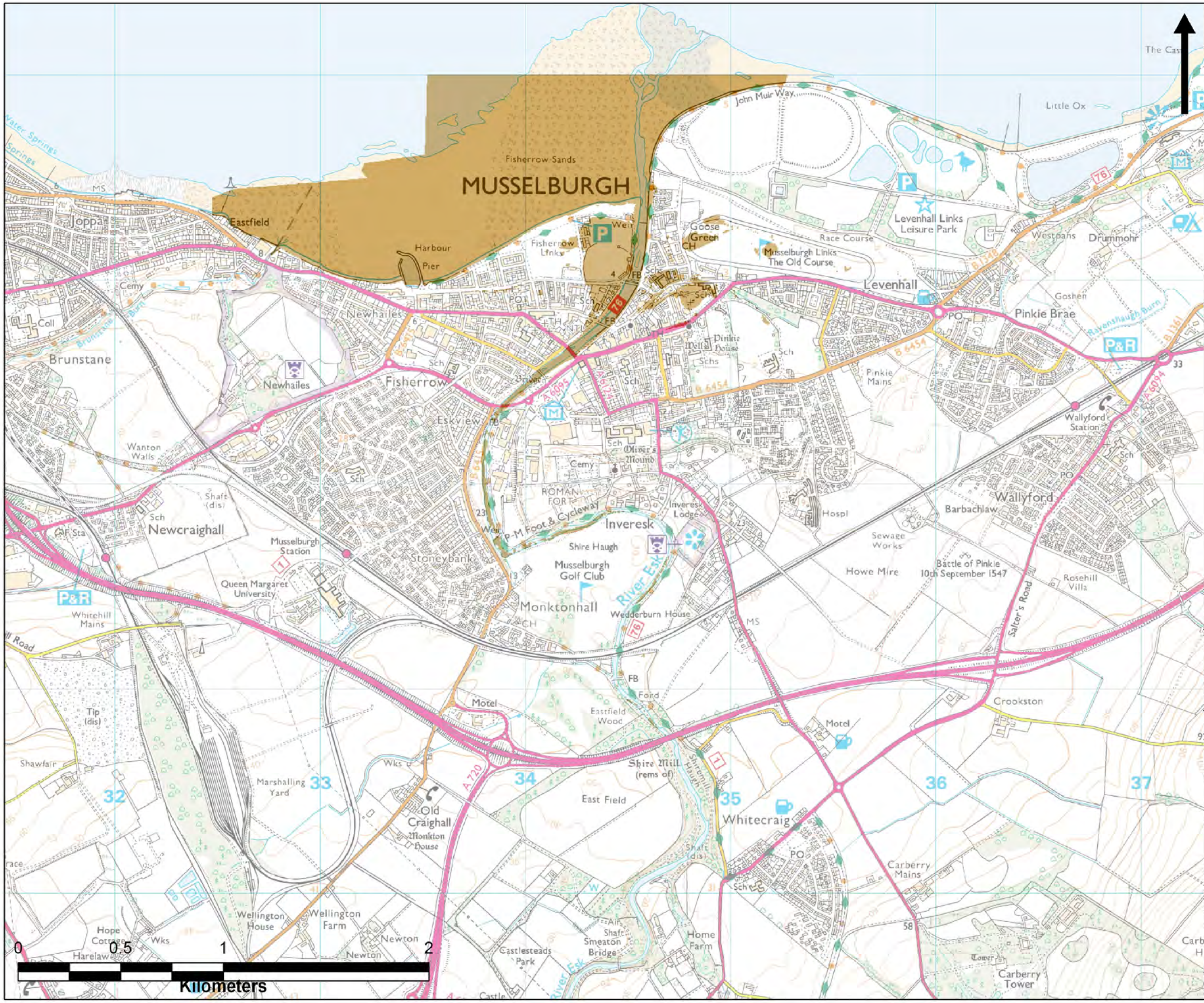
Drawing Title
0.5% AEP (FLUVIAL) INDICATIVE EXTENT OF INUNDATION

Drawing Status

Scale	NTS	
Jacobs no.	B1592000	
Client no.		
Drawing no.	B1592000_Fig6	Rev A



KEY

0.5% AEP (Tidal) Indicative Extent of Inundation

A	05/04/12	Original	RH	BS	BS
Rev	Rev. Date	Purpose of revision	Drawn	Checked	Approved

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Drawing Title
0.5% AEP (TIDAL) INDICATIVE EXTENT OF INUNDATION

Drawing Status

Scale	NTS
Jacobs no.	B1592000
Client no.	
Drawing no.	B1592000_Fig5
Rev	A