Flood Risk Assessment

Lowestoft Flood Walls and Barrier

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Document history

This document has been issued and amended as follows:

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Contents

Introduction

1.1. Purpose of Study

JACOBS have been commissioned by Balfour Beatty (on behalf of East Suffolk Council) to prepare a flood risk assessment (FRA) in support of the planning application for tidal flood walls in Lowestoft. Additionally, planning permission for a tidal flood barrier will be sought as part of the Transport and Works Act Order (TWAO) process. The tidal flood barrier will be built after the completion of the flood walls (the construction is envisaged to start in 2021 and will take three years approximately). Therefore, the tidal flood barrier has been included into the FRA as an additional element to address how flood risk will change in the area; a) when the flood walls are being built, b) when the flood walls are fully built and c) when the tidal flood barrier is in place in addition to the built walls. The FRA also includes additional testing to evaluate the consequences of the walls breaching and the effect of waves overtopping the crest of the walls and seepage underneath the walls.

The policy guidance for development and flood risk, National Planning Policy Framework (NPPF), was first published in March 2012. This FRA considers the development proposal with regard to NPPF and addresses any flood risk concerns raised by the Environment Agency and concerned councils.

1.2. Supporting Documents and Data used

The aim of this report is primarily to consider flood risk and satisfy requirements under NPPF. This assessment has also been undertaken in accordance with CIRIA C624 'Development and Flood Risk – Guidance for the Construction Industry' (2004) and 'Development and Flood Risk: Practice Guide' (2008).

Data and information have been obtained from online desk-based studies and from the following sources:

- 2017 CH2M Lowestoft Flood and Coastal Erosion Risk Management Outline Business Case hydraulic model and outline design,
- 2017/18 JBA Lowestoft Flood Risk Management Strategy (including surface water hydraulic model results),
- 2017 CH2M Lowestoft Flood Risk Management Strategic Outline Case,
- 2014 Broadlands Environmental System Ltd (BESL) model (including hydraulic model, related results and report),
- Suffolk County Council Flood Incident Record,
- Environment Agency Data Catalogue,
- Section 19 (Flood Incident Record),
- Anglian Water Incident Enquiry,
- 2007 Broadlands Strategic Flood Risk Assessment,
- 2009 Broadlands Catchment Flood Management Plan,
- 2013 indicative flood data supplied by the EA.

1.3. Ordnance Survey Base Mapping

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2. Background Information

2.1. Purpose of Development

Following the 2013 December tidal surge, in which 158 residential properties and 233 commercial properties in Lowestoft and Oulton Broad area were flooded, a group formed by East Suffolk Council partnering with Suffolk County Council, the Environment Agency, Anglian Water, New Anglia and Suffolk Chamber of Commerce, formed the Lowestoft Flood Risk Management Project (LFRMP). The LFRMP was established to reduce the risk of flooding from the sea, rivers and extreme rainfall to ensure the support of economic growth and regeneration in Lowestoft.

Lowestoft faces a risk from tidal flooding from the North Sea (and indirectly via the Broads at Mutford Lock), fluvial flooding from Kirkley Stream and River Waveney (part of the Broadlands system), and surface water flooding from the local Anglian Water sewage network, Suffolk County Council drainage network and from rainfall-runoff in the urbanised environment. Groundwater flooding is assumed to be a secondary risk in the catchment (Broadlands Rivers Catchment Flood Management Plan, 2009) but has also been considered as a potential source of flooding in this document. The predominant risk to flooding in Lowestoft is tidal.

At current there are no formal permanent defences in place to protect against tidal flooding/ surges.

The proposed Lowestoft Flood Risk Management Scheme comprises the construction of a tidal flood barrier and adjoining flood walls to tie-in with high grounds and existing coastal defences. The delivery plan includes construction of the flood walls ahead of the proposed tidal flood barrier. Therefore, there will be a period of time (completion planned 2024), where the walls will be in place without the barrier. This period may be longer depending on partnership funding availability.

Once built the proposed scheme; tidal flood barrier and walls, will provide a minimum of 0.5% AEP Standard of Protection (SoP). An adaptive approach to climate change is proposed.

2.2. Development Area

Lowestoft is situated on the east coast of England, approximately 35 km south east of Norwich, and is part of East Suffolk Council and Lowestoft Town Council. Suffolk County Council is also responsible for certain elements e.g. highways maintenance. The scheme is situated around the outer harbour and Bascule Bridge area (east Lowestoft). The wall alignment is shown in Figure 1. The FRA will consider both the walls only scenario and the finished works which is walls and barrier. It is currently understood that the temporary works will involve limited amount of ground excavation and no material will be left on the floodplain, therefore permanent works will be the focus of this document.

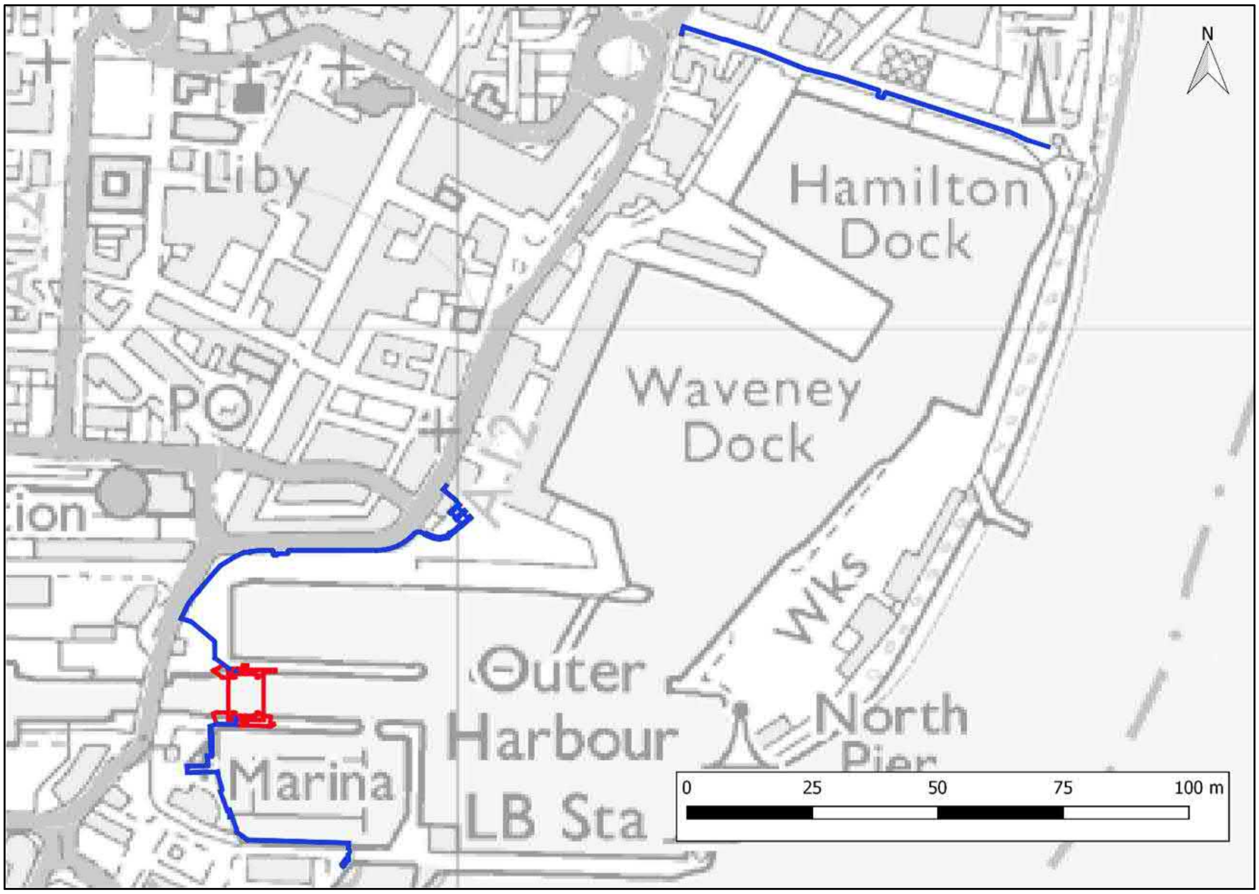


Figure 1: Location of the proposed flood walls/ gates/ demountable barriers and permanent tidal flood barrier (barrier location in red) in 2117.

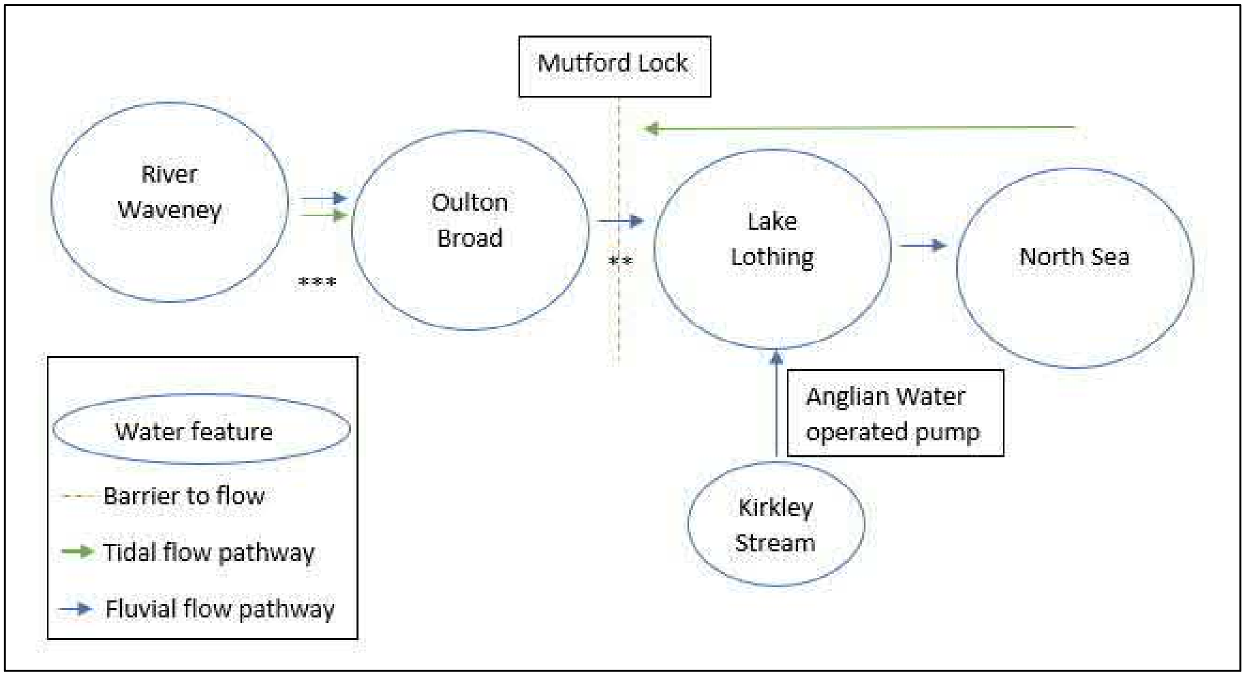
2.3 Overview of Water Features

The River Waveney flows into Oulton Broad. Oulton Broad is linked hydrologically to Lake Lothing through Mutford Lock. Mutford Lock is manually operated and is normally closed. The flow from Oulton Broad is predominantly tidal as the lock would not be open in fluvial events. Oulton Broad is hydraulically connected to Great Yarmouth through the River Waveney, Breydon Water and the River Yare, meaning that tidal events at Great Yarmouth can influence water levels at Oulton Broard.

Lake Lothing is freely connected downstream to the North Sea; through Lowestoft Harbour. There is no hydrological boundary after Mutford Lock as the lock is typically closed unless navigation is required , therefore the volume of water that passes through the lock is considered to be negligible.

Kirkley stream is a watercourse running from south west to north east into Kirkley Ham (part of Lake Lothing; approximately 680 m west of Bascule Bridge). There is a pumping station that pumps water, during periods of high tide, into Lake Lothing. The maximum capacity of the pumping station is 1.2 m^3/s (JBA, 2017/18). The pumping station is operated by Anglian Water. Additionally, there is a flood storage area that takes excess flow from Kirkley Stream before it reaches the pumping station. In normal conditions, Kirkley Stream discharges in Lake Lothing through a gravity outfall. The Kirkley Stream is classified as a 'main river' by the Environment Agency upstream of Bloodmoor Roundabout at Carlton Colville.

The schematic in Figure 2 summarises the water features listed above.



*The above summary of water features for Lowestoft is not to scale or position.

** If gravity discharge is possible

*** Hydrologically connected to Great Yarmouth so can be tidally influenced from Great Yarmouth

Figure 2: Key water features in Lowestoft

3. Definition of Flood Hazard

3.1 Combined fluvial and tidal flooding

Tide locking is when high tide levels prevent river flows from discharging and draining away. This can lead to flooding. The joint probability of tidal and fluvial flood events in the east of England is low according to Joint probability: Dependence mapping and best practice" (project code: FD2308), Defra, 2005. According to the Broadland Rivers Catchment Flood Management Plan (2009) Lowestoft is not a town that is affected by tide locking. However, during high tides, the existing drainage system could become tide locked (although this may not result in flooding). Kirkley Stream would also be tide locked if the existing pumping station was not in operation.

3.2 Strategies already in place

3.2.1 Broadlands SFRA (2007)

Lowestoft is covered within the Strategic Flood Risk Assessment (SFRA) for Broadland District Council area (report reference: 7293C/21/CW/06-07/1775). On page 18 it describes Lowestoft as a:

"Large urban area with harbour. Risk from tidal surges overtopping or breaching harbour walls. May also be at risk from surface water or sewer flooding. High risk to properties from tidal surges from Lake Lothing and Oulton Broad and from sewer flooding."

It also notes Lowestoft as being Policy 5. Policy 5 is "Take further action to reduce flood risk". The reasoning in the report is due to the large number of properties at risk from flooding in Lowestoft.

It suggests implementation of the following to reduce flood risk:

- Undertake flood risk strategy
- Work with 1st East urban regeneration company to reduce flood risk to new development
- Work with Anglian Water to reduce sewer flooding
- Encourage householders to use flood protection measures

3.2.2 Broadland Rivers Catchment Flood Management Plan (2009)

Lowestoft is covered within the Broadland Rivers Catchment Flood Management Plan (BRCFMP) (2009). CFMPs cover inland flood risk and there are 77 that cover England and Wales. Coastal flooding is covered within Shoreline Management Plans (SMP). The role of CFMPs is to establish flood risk management policies which will deliver sustainable flood risk management for the long term.

The BRCFMP identifies risk at Lowestoft as being tidal flooding. In addition, it references Lowestoft as being a location where past flooding has been caused by surface water and sewer flooding caused by inadequate capacity of the sewage system.

Based on modelling undertaken at the time, approximately 941 properties, and 1,808 people, were identified to be at risk in the 0.5% AEP tidal event. There is no agricultural land at risk, but there are some A-roads, five electricity sub-stations and one railway station at risk in the 0.5% AEP tidal flood..

Lowestoft is not listed as having properties at risk from a combined river and tidal flood event.

Around 85% of the people at risk from the 0.5% tidal flood are located in Lowestoft. They are at risk from flooding via Lowestoft Harbour and Oulton Broad. Thus, highlighting the scale of risk from tidal events proportionally in the region to be predominantly located at Lowestoft.

3.2.3 Shoreline Management Plans

Lowestoft is covered within two Shore Management Plans (SMPs). The two SMPs that cover Lowestoft are; Kelling to Lowestoft Ness (2012) and Lowestoft Ness to Felixstowe Landguard Point (2015).

A SMP provides an assessment of coastal flood risk and present policy framework to try to address and reduce the risks identified.

Ness Point in Lowestoft is described as having a highly pronounced promontory with little volume of beach left due to exposure to the sea. However, this material does not feed beaches to the south. The recommended approach is to allow the cliffs and beaches between Gorleston and Lowestoft to erode naturally with the premise that this supply of material will protect other areas. The SMP realises that this will inevitably lead to loss of land and potentially some property but claims that the benefits elsewhere will outweigh these losses. Therefore, from Corton to Lowestoft the approach is managed realignment. However, Lowestoft North (to Ness Point) is hold the line to ensure protection of the town frontage.

The coast between Lowestoft Ness and Kessingland is made of soft geology; waves are deemed the main cause of change in sediment distribution. Sediments generally move from north to south along the shoreline. The degree of movement/ erosion varies along the coast. Policy Development Zone 1 covers the area of Lowestoft. The proposed flood scheme crosses the following sub- areas: Lowestoft Ness and Outer Harbour (LOW 01), the inner harbour (LOW 02) and South beach (LOW 03). The recommended policy for all the sub-areas is hold the line up to 2105 as it recognises that there is increasing pressure on defences with potential threat to the population and urban regeneration of Lowestoft.

3.2.4 Lowestoft Flood Risk Management Strategy (2017/18) (DRAFT) dated April 2018

JBA Consulting produced a Flood Risk Management Strategy (FRMS) to reduce pluvial and fluvial flood risk in Lowestoft on behalf of East Suffolk Council (ESC). The FRMS forms part of the Lowestoft FRMP described in section 2.1. The FRMS explored multiple ways to reduce flood risk in Lowestoft and shortlisted the following options after modelling and economic review:

- Direct defences at Velda Close/ Aldwyck Way with a pumping station;
- Property Level Protection for 288 properties.

Note that at the time of writing this report, the FRMS was under development. The modelled outputs for combined fluvial and pluvial flood extents are shown in Figure 3. Hotspots can be noted in the vicinity of the tidal flood barrier along Hamilton Road and Wilde Street in a 5% AEP. Please refer to the updated FRMS for more up-to-date information.

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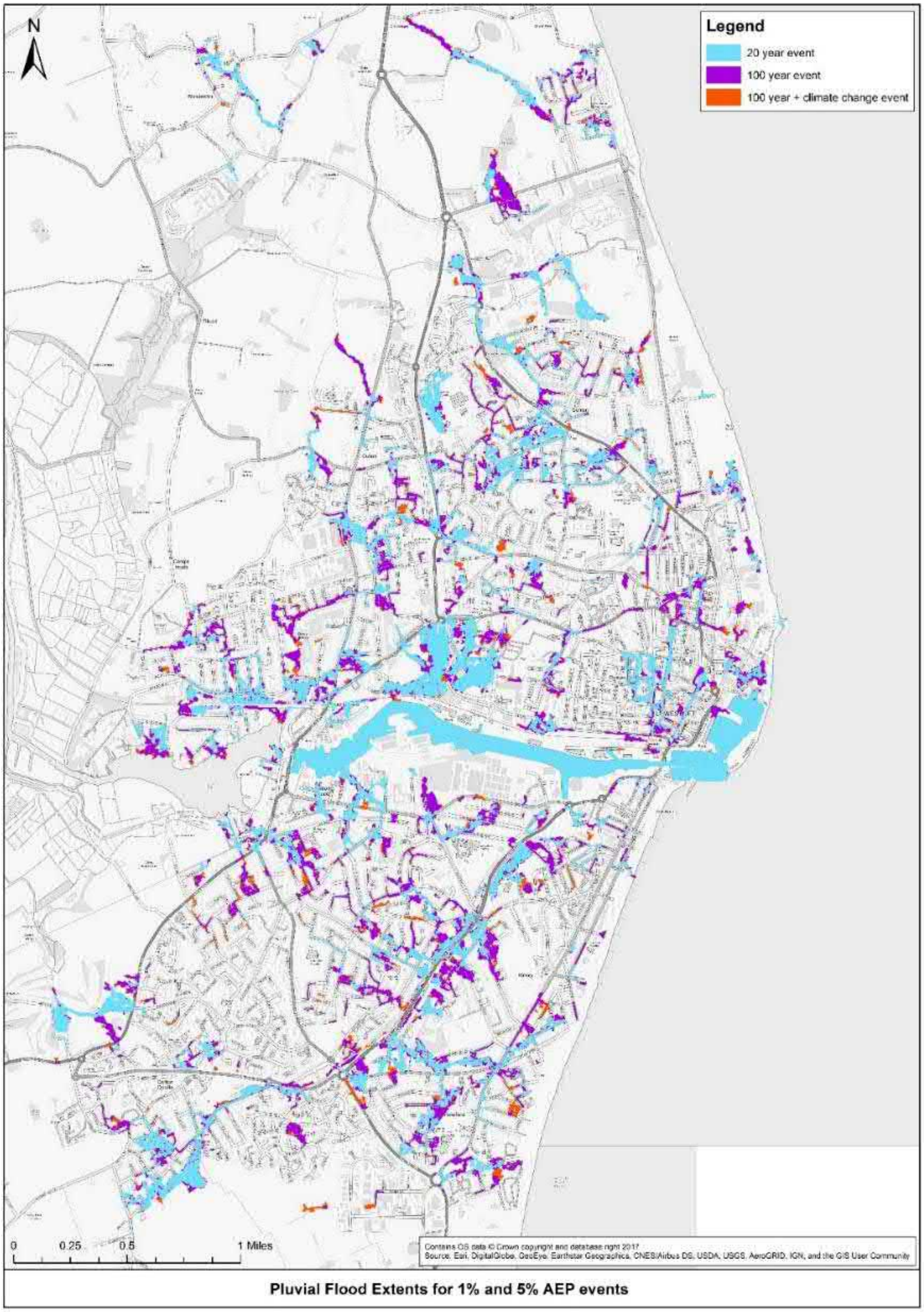

Figure 3. Pluvial flood extent map taken from JBA Consulting FRMP, 2017/18. DRAFT version.

3.2.5 Suffolk Coastal and East Suffolk Council Level 2 Strategic Flood Risk Assessment (2018)

Lowestoft is covered within the Level 2 Strategic Flood Risk Assessment (SFRA), prepared by East Suffolk Council (ESC)/ AECOM.

ESC identified five allocated development sites during the formulation of the East Suffolk Council Local Plan, and all are in the centre of Lowestoft or surrounding area. These five sites were the focus of the Assessment.

The primary flood risk to the area is deemed to be, for the purpose of the SFRA, tidal surge from the North Sea.

However, "Lowestoft is additionally vulnerable to surface water flooding, particularly around Kirkley Stream, Aldwick Way and Velda Close, as demonstrated by the significant flooding in July 2015. Within the local area, there is a close interaction between tidal and surface water flooding as many local drainage systems discharge into the tidal watercourse, which has historically led to surcharge of the surface water system during high tidal events."

It documents that the EA Surface Water Flood Mapping indicates that there is a localised area of high flood risk (3.3% AEP) between Wilde Street and Hamilton Road, as well as along Newcombe Road.

It cites that there is limited potential for groundwater flooding at all sites.

It notes that without future investment in flood defences Lowestoft will remain at risk.

The SFRA is based upon a similar option explored in this FRA; construction of flood walls and barrier. If implemented, at the stage the SFRA was conducted, the modelling undertaken revealed that the scheme would entirely remove the sites Peto Square, Kirkley Waterfront and Sustainable Urban Neighbourhood and the Western End of Lake Lothing from the current 1 in 200 year/ 0.5% AEP flood event. The majority of the last site remaining; PowerPark, would also be protected.

3.3 Flood risk by source

This section summarises flood risk at Lowestoft divided by source and referencing historical flooding where relevant. For a full review of the flood history at the site please refer to Appendix A.

3.3.1 Fluvial and tidal

The predominant flood risk is tidal flooding from the North Sea (BRCFMP, 2009). The Environment Agency map shows the proposed permanent development (Tidal Flood Barrier and flood walls) is located in Flood Zone 3 (Figure 4).

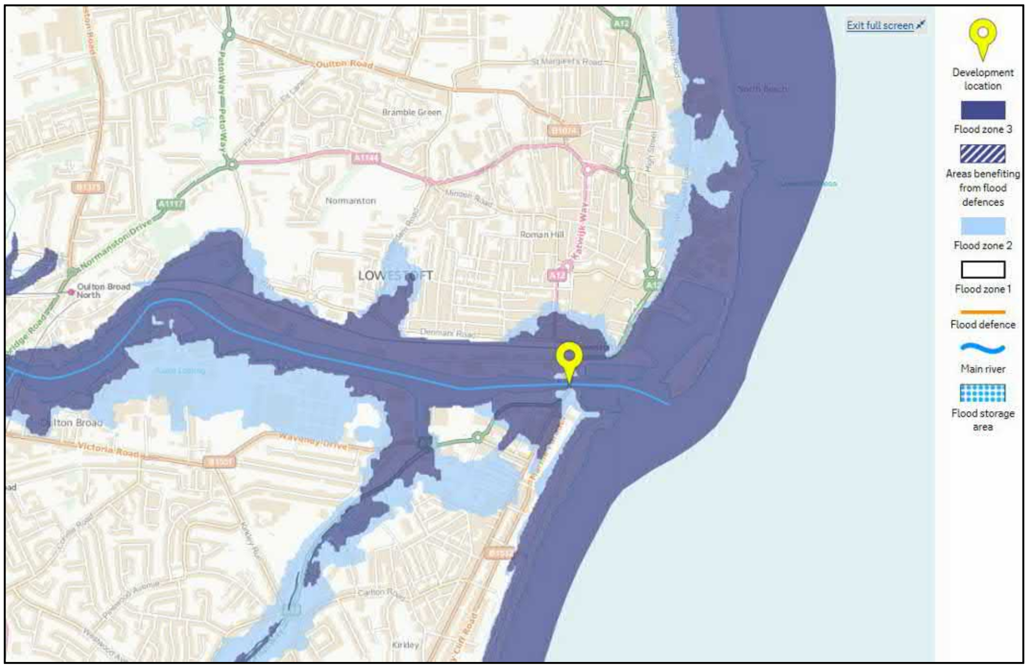

Figure 4: Flood zones in the study area (from https://flood-map-for-planning.service.gov.uk/, accessed 2nd of March 2018).

There is historical flooding from tidal surges in Lowestoft; most notably 1953 and 2013. Tidal surges have widespread receptors that are not localised to one area. Tidal surges can form when a significant low-pressure system (depression) moves across the Atlantic towards the British Isles. As the depression moves it draws up the sea beneath it causing localised raised water levels which move easterly with the depression. If this area of raised water passes Scotland and heads south into the North Sea, the sudden change in bed level from deep to shallow causes the raised water to rise even further, creating a surge. This surge may then travel down the east coast of England, potentially increasing in height if combined with strong northerly winds. If a high surge coincides with a high spring tide there could be a significant flood danger along most of the Lowestoft coast and areas beside Lake Lothing.

On the 31st January 1953, a severe storm surge created in the North Sea was further raised by an exceptional northerly gale. The combined effect of the storm surge and the extremely strong northerly winds resulted in sea level of 3.35 mAOD at Lowestoft. The surge lead to disastrous flooding and considerable loss of life in the UK.

On December 5th 2013, a tidal surge flooded 158 residential properties and 233 commercial properties in Lowestoft and Oulton Broad area, with many houses losing electricity and power. Telecommunications were also severely impacted as was the operation of the Bascule Bridge (electrical and hydraulic systems of the bridge were severely damaged). Coastal defences and infrastructure at the port also suffered from structural damage. The A12/ A47 and a number of roads were closed due to flooding; train services were also suspended.

Outlon Broad, which is west of Lowestoft, is linked to the River Waveney and water flows from Oulton Broad into Lake Lothing before flowing into the North Sea. However, during fluvial events; Mutford Lock remains closed. No observed records of fluvial flooding were identified from Oulton Broad in this study.

The Kirkley Stream drains into Lake Lothing, via a pumping station at Kirkley Ham, and is another source of fluvial flooding.

3.3.2 Pluvial and sewer flood risk

There is further risk from pluvial flooding owing to the urbanised nature of Lowestoft. Blockages and overloading of the drainage/ sewer system can occur, leading to surface water flooding. Historical incidents of pluvial risk and fluvial risk exist (from Kirkley Stream) to the surrounding area – specifically Velda Close and Aldwyck Way. It can be seen from Figure 5 and Figure 6 that the low-lying area in the vicinity of Kirkley Stream is at combined risk from both river and sea and surface water flooding. This is corroborated by the historical flood events that have been recorded at this location including a Section 19 report.

The pluvial 0.1% AEP map correlates in terms of spatial trend to the pattern showed by JBA (2017/18); shown in Figure 3.

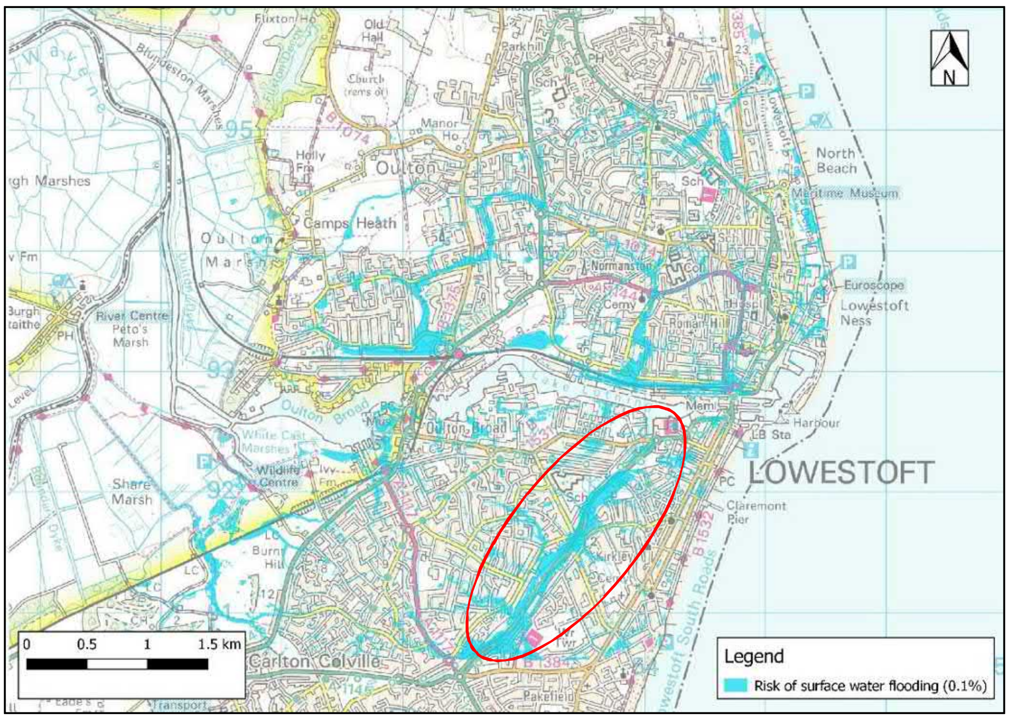

Figure 5. Surface water flood risk in the Lowestoft area (0.1% AEP). The red circled area is the approximate location of Kirkley Stream.

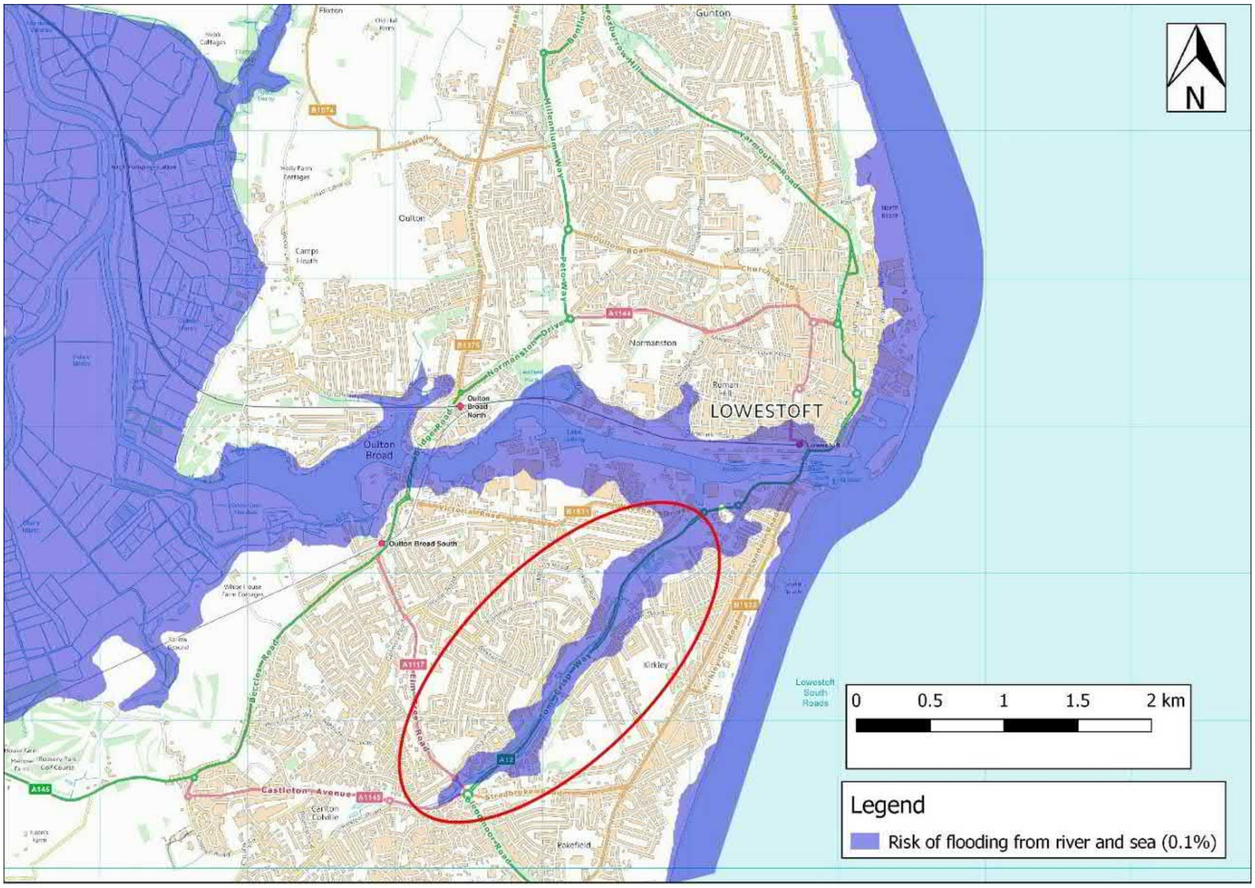

Figure 6. Risk of flooding from river and sea in the Lowestoft area (0.1% AEP). The red circled area is the approximate location of Kirkley Stream.

Suffolk County Council (SCC) provided incident records for Lowestoft. The incident record covered the period 01/10/2009 to 06/06/2018. There are 327 incidents recorded.

The record contains a postcode, easting and northing, a date of the incident, unique incident numbers, priority levels, description and event type. Crucially, not every incident has a description and the event type does not always specify a cause.

According to the event type listed:

- 98 out of 327 events are due to blockages;
- 3 out of 327 events are due to drainage capacity issues.

However, sometimes the description gives more information and a cause of flooding can be inferred. Inferring from the description highlights that there are a larger number of incidents for drainage capacity and blockage than the event type would suggest:

- Potentially 130 out of 327 events due to blockage;
- Potentially 87 out of 327 events due to capacity issues;
- Potentially 15 out of 327 events due to design inefficiencies e.g. resurfacing of road without consideration of drainage;
- 95 out of 327 are too ambiguous from the description to be allocated to a cause.

It is important to note that many of the events could be a combination of causes. For example, partial blockage paired with a drainage network designed for a lower Standard of Protection (SoP) than a given rainfall event.

In addition, in regard to drainage network capacity, increasing urbanisation and therefore introduction of impermeable surfaces like tarmac, are likely to lead to increase frequency of drainage capacity being exceeded. This is perhaps reflected in the number of incidents per year being higher more recently (see Table 1). However, another possible explanation of the trend of increasing incidents is that the reporting increased; as the years 2010 and 2011 have no records at all.

Table 1: Incidents recorded by Suffolk County Council per year.

Year	Number of incidents recorded
2009	3
2012	5
2013	4
2014	4
2015	77
2016	93
2017	73
2018	68

In terms of spatial trends, the postcode areas beginning NR33 8 and NR33 9 have the largest number of incidents recorded (see Table 2). See Figure 7 for locations of postcode (note NR33 1 is not recorded on this data set). It should be noted that the peripheral postcodes may have more incidents, but the data requested for the incident record covered Lowestoft only.

Table 2. Incidents recorded by Suffolk County Council per first 5 characters and numbers of postcode.

Postcode area	Number of incidents recorded
NR32 1	20
NR32 2	37
NR32 3	34
NR32 4	55
NR32 5	7
NR33 0	17
NR33 1	1
NR33 7	20
NR33 8	71
NR33 9	65

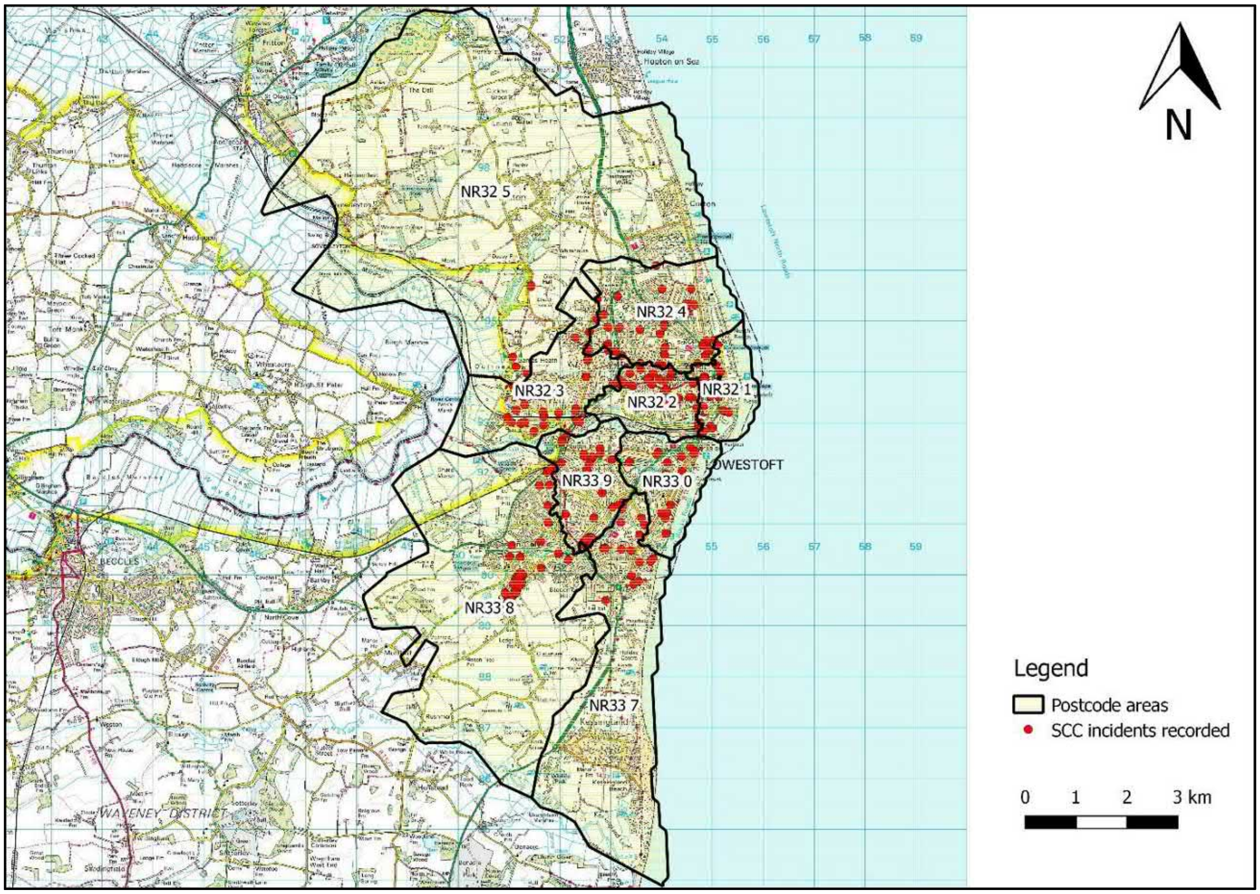

Figure 7. Postcode areas of SCC flood incidents.

The walls and barrier are not likely to have a large spatial effect on pluvial flood risk. Therefore, only incidents close to the scheme were looked at in more detail;

- There are 13 incidents within 400m of the scheme (see Figure 8).
- Six out of the 13 are recorded in event type as blockage and upon review a further three also appear to be blockage from the description. The scheme is unlikely to increase the rate of blockage or the delivery/ volume of debris reaching the surface water network. One of the incidents has no description. Two are ambiguous in description.

Anglian Water were also consulted in regard to flooding due to the sewer network in Lowestoft. They confirmed that they had no records of flooding in the vicinity of the proposed works due to capacity limitations in the public sewerage system. See Appendix B.

Figure 8. 13 incidents within 400 m of the proposed scheme (circled in red). Areas beyond this not envisioned to be affected by the proposed works in terms of pluvial risk.

3.3.3 Reservoir

According to the Environment Agency flood risk maps Lowestoft is unlikely to face risk from reservoir flooding. A google aerial map search of the area further corroborates that the risk from reservoir flooding is low.

3.3.4 Groundwater

The bedrock for Lowestoft is Crag Group Sand which, according to the British Geological Survey, consists of sands, gravels, silts and clays. Therefore, some areas may be susceptible to groundwater flooding if the bedrock has high sand/ silt/ gravel content. Furthermore, the superficial deposit that is most common across Lowestoft is Happisburgh Glaciogenic Formation- Sand.

There are no flood events documented online for groundwater flooding in Lowestoft. This is corroborated by the 2008 Suffolk Coastal and Waveney District Strategic Flood Risk Assessment which also assumed groundwater to be a secondary risk in the catchment.

A separate groundwater assessment was carried out to support this FRA which concludes that the risk of groundwater flooding post construction will remain low and be unaffected by the proposed works. See Technical Note CRM72114-JAC-00-ZZZ-TN-GT-0002 for further details (Appendix L).

3.4 Consequences of flooding at the site

In the present-day situation without the proposed flood defences in place, the main impacts are likely to be as follows:

- Disruption to access of the harbourside and marina with consequent loss of recreational benefits and negative impact on commercial activities;
- Flooding and damage of residential properties;
- Flooding and damage of industrial buildings and businesses; with knock on effects on revenue during and post flood event;
- Flooding and damage of the Railway Station and roads with consequent transport disruption, including damages at the Bascule Bridge and associated electric/ operating system;
- Potential disruption and damages to water infrastructure (e.g. local surface water pumps and water-supply);
- Damages and disruption to schools and other public services;
- Increased burden to hospital and health-care services, including post-event trauma of local residents;
- Potential evacuation of local residents; and
- Potential danger to life.

As mentioned previously, the timescales for the implementation of the flood wall project and tidal flood barrier scheme are different and largely dependent on funding availability. The hydraulic model shows that the implementation of the flood walls only does not provide flood attenuation benefit to Lowestoft except for the independent flood cell protected by the flood defences along Hamilton Road.

The full benefits of the Lowestoft Tidal Flood Defences scheme will only be fully realized once the tidal flood barrier is in operation.

As anticipated, the hydraulic model also shows that on completion of the tidal flood barrier works, the area surrounding the proposed development will be protected from tidal flooding for events up to 0.5% AEP.

4. Model Development and Justification

4.1. Model schematisation

The model of Lowestoft harbour is 1D/2D model built in FloodModeller/ TUFLOW (Figure 9). The model was built by CH2M in 2014 and was used to derive damages from tidal sources for the strategic outline case (SOC) and outline business case (OBC) for Lowestoft.

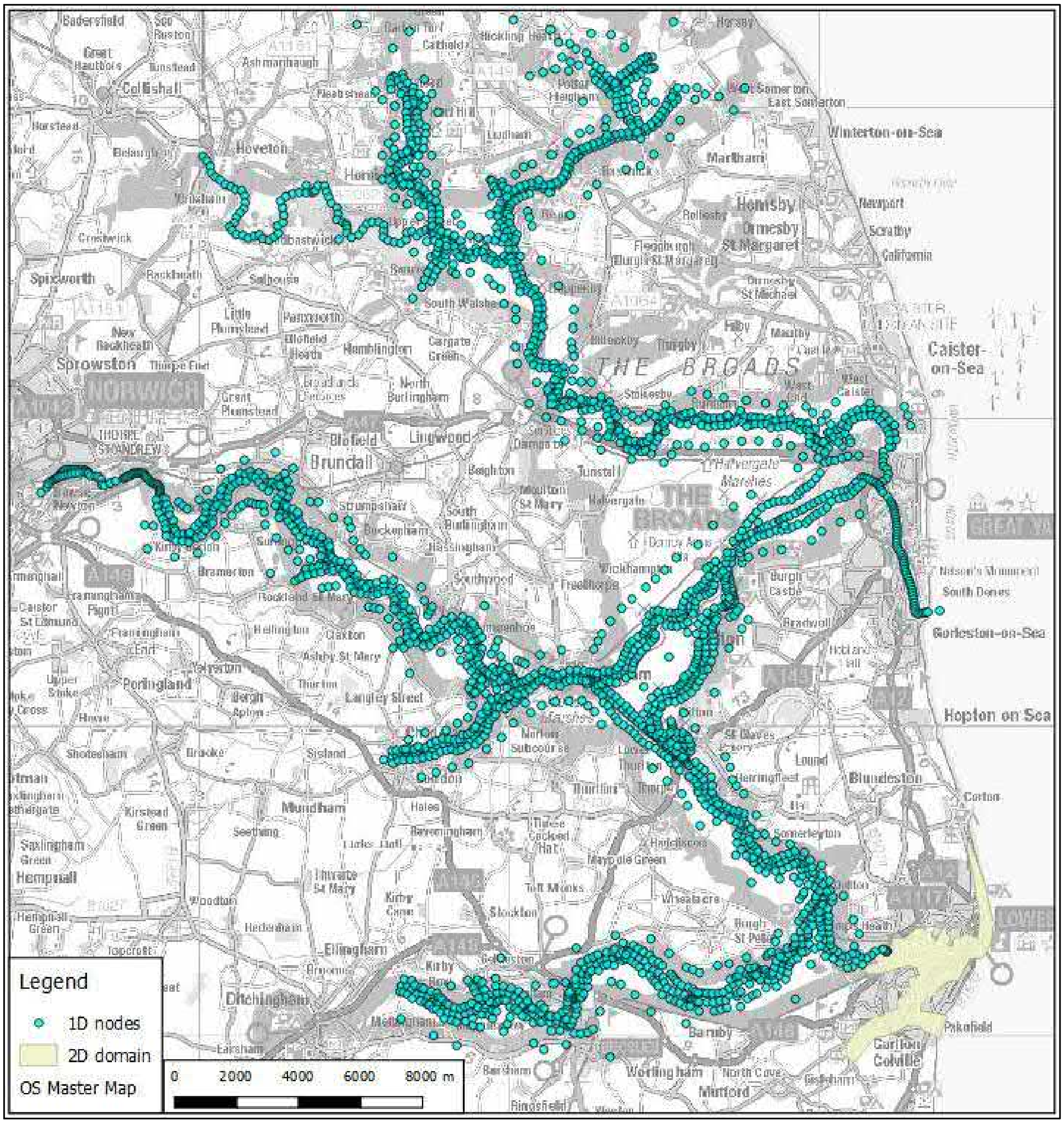

Figure 9. Extent of 1D and 2D domains

The 1D model domain covers the whole extent of the Broadlands system. The model is hydro-dynamically linked at Mutford Lock to a 2D domain at Lowestoft. Model boundaries consist of tidal head-time boundaries at Lowestoft and Great Yarmouth, and fluvial baseflows at numerous locations within the Broads.

A 2D grid resolution of 10 m (2015) was used for the urban area of Lowestoft; this allows a reasonable level of detail whilst keeping run times practical.

See Appendix C for a full review of the modelling files provided and for the set-up of the FRA modelling files. See Appendix I for model log example files.

4.2. Tidal Boundaries and Hydrology

4.2.1 Tidal Boundaries

The extreme water levels were taken from the JBA East Coast model (started in 2015 and still in development). Relative sea level rise data for Lowestoft was taken from the National Planning Policy Framework (NPPF) website- see Table 3. The obtained Sea Level Rises (SLR) were used to update water levels obtained from the JBA modelling work (2015) for future years.

The present day and climate change hydrographs used for this FRA are included in Appendix D.

Table 3. NPPF rate of sea level rise (m/year) for East, east midlands, London and South East.

	Beginning/ end year			
	1990	2026	2056	2086
	2025	2055	2085	2115*
Rise per year (m/ year)	0.004	0.0085	0.012	0.015

*2115 to 2117 was taken to also be 0.015 m per year.

4.2.2 Fluvial Inflows

Inflows from Kirkley Stream to Lake Lothing were extracted from the 2017/18 JBA Study. For the purpose of this FRA, it was assumed that a 10% AEP fluvial event would take place concurrently with the considered tidal surges. This is deemed to be a conservative assumption as FD2308 suggests that the probability of combined fluvial and tidal events is shown to be low.

Climate change for river flow allowances were applied to fluvial inflows (Kirkley Stream). Allowances were extracted from the relevant NPPF guidance (https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances) for the Anglian Region.

4.2.2 Wave Overtopping

Following consultation of FD2308, the correlation between tidal surges and wind-generated waves has been assessed along the East Coast near Lowestoft.

The overtopping discharge rates were estimated as part of the detailed review of the residual uncertainty allowance during the ongoing detailed design of the tidal flood walls. The wave overtopping rates have been assessed in accordance with the EurOtop Manual 2016 – see document referenced CRM72114-JAC-DZ-300-MO-HY-0001 in Appendix G for further details.

The assessment considered overtopping of the flood walls along Yacht Basin, Trawler Dock. Owing to the predominant wind direction, the flood wall along Hamilton Road are not likely to experience waves overtopping during an extreme surge event. Wave overtopping was not considered for the present day scenario, as no overtopping of the flood walls could occur in 2019.

See Figure 10 for location.

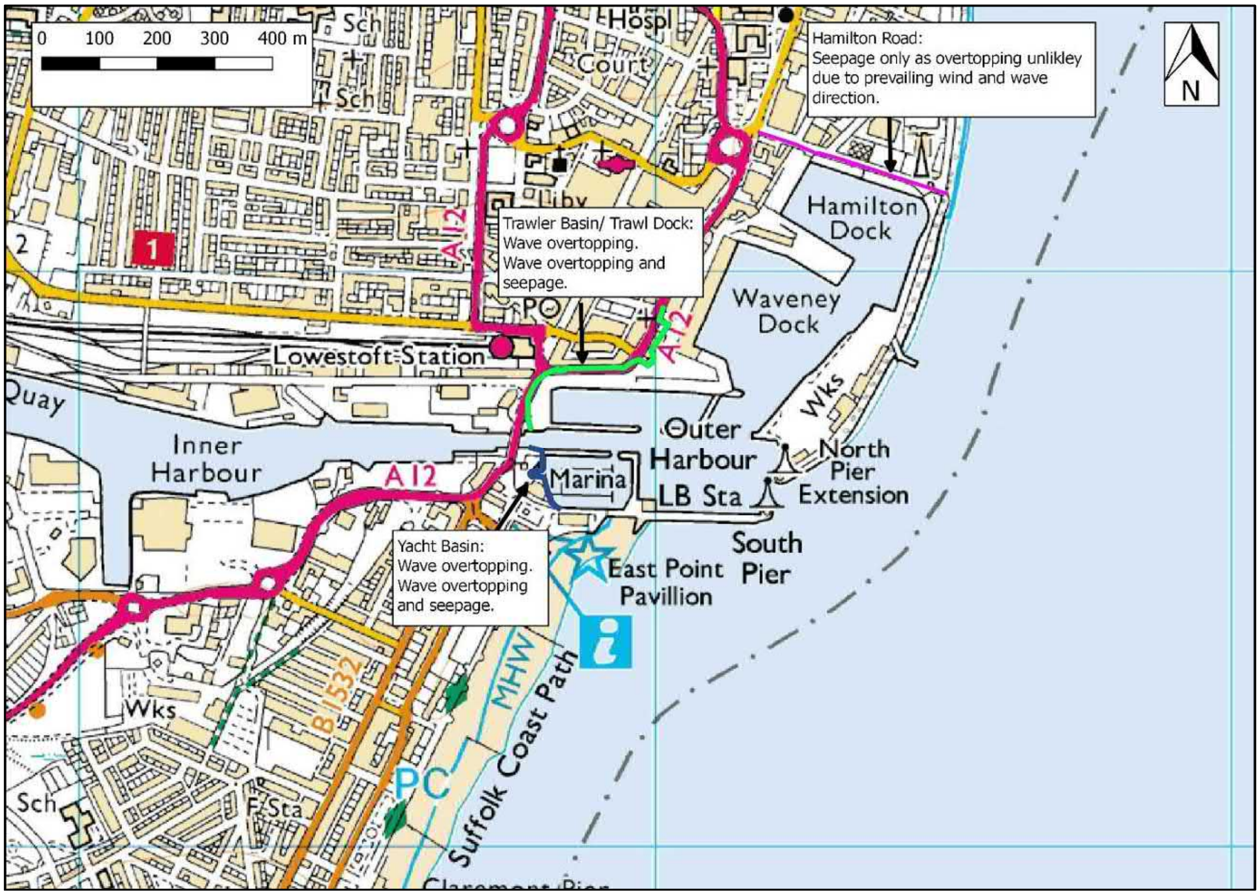

Figure 10. Location of wave overtopping and seepage.

For the purpose of FRA modelling, wave overtopping has only been applied as a sensitivity test to the combined ‘walls and tidal flood barrier’ scenario to determine the potential risk associated with the overtopping discharge from wind-generated waves.

The document referenced CRM72114-JAC-DZ-300-MO-HY-0001 provides both ultimate limit state (ULS) condition and serviceability limit state (SLS) thresholds. ULS overtopping rates represent the maximum rate of overtopping which could impair the stability of the walls. However, for the purpose of the FRA, the overtopping need to be representative of more characteristic conditions (more frequent AEP event) rather than an ultimate value typically used for a safety in design assessment. This gives a more practical consideration of the likely impact on people/ infrastructure from overtopping and in turn informs the need for any design mitigation measures.

The EurOtop guidance provides the following discharge threshold:

- SLS (Pedestrians) – For people at the seawall and a wave height of <0.5m There is no limit for overtopping. i.e. not a risk to people.
- SLS (Vehicles) – For vehicles at the seawall and a wave height of = 1.0m Limit overtopping to 75l/s/m and/or 2000l/m for overtopping.
- SLS (Buildings) – Building structure elements for a wave height of 1.0m limit overtopping to 1l/s/m and/or 1000l/m.

Overtopping rates, associated with 0.5% AEP still water levels are summarised in Table 4 (2117) and Table 5 (2070). It can be noted that overtopping rates in 2070 are more severe than the 2117 equivalent due to a difference in freeboard allowance made for each epoch as a result of the confidence level in sealevel forecasts with less certainty in sealevel rise forecasts for 2117 resulting in more conservative allowances being made. Despite the change in alignment, the overtopping rate is conservatively assumed to remain constant over the entire length of defences. The resulting wave overtopping volumes are included in Table 6.

Table 4: 2117 overtopping rates

FRA still water levels (mAOD)	ULS condition		SLS condition	
	Yacht Basin rate (l/s/m)	Trawl Dock (l/s/m)	Yacht Basin rate (l/s/m)	Trawl Dock (l/s/m)
4.35	0.36	0.02	0.04	0.00
4.57	0.78	0.06	0.39	0.02

Table 5. 2070 overtopping rates.

FRA still water levels (mAOD)	ULS condition		SLS condition	
	Yacht Basin rate (l/s/m)	Trawl Dock (l/s/m)	Yacht Basin rate (l/s/m)	Trawl Dock (l/s/m)
3.69	0.57	0.21	0.08	0.10
3.91	1.70	0.50	0.99	0.26

Table 6: Wave overtopping volume for the 0.5% AEP event divided per epoch and location using SLS overtopping rates

Location	Volume of wave-overtopping in 2070 (m^3)	Volume of wave-overtopping in 2117 (m^3)
Yacht Basin	624 (in 3hrs)	258 (in 2.25hrs)
Trawl Dock	262 (in 2.25hrs)	23 (in 1.5hrs)

4.2.3 Seepage

Similar to the wave overtopping, the volume of water from seepage beneath the walls in a surge event was estimated for the detailed design of the scheme.

Seepage rates were provided for Hamilton Road, Yacht Basin and Trawl Dock from the detailed design assessment. The flow rates for each are summarised in Table 7. The flow rates provided have been derived using the characteristics and upper bound permeability of the underlying ground and were only assessed for the 2117 water levels. For the purpose of the FRA, the 2070 seepage rates are conservatively assumed to be equivalent to the 2117 ones, however the surge duration will be reduced for the 2070 scenario, hence the reduction in the total volume of the water shown in table 8 below.

The seepage analysis also considers steady state conditions (i.e. immediate ground water response with no tidal lag). This is a conservative assumption albeit consistent with the groundwater monitoring undertaken as part of the stage 1 ground investigation during which a small tidal lag response was observed.

The seepage volumes shown in Table 8 were only calculated for the 'walls and tidal' barrier scenario for the same reasons reported in section 4.2.2. Seepage volumes were found to be smaller than wave overtopping volumes but not insignificant.

Table 7: Seepage rates for stretches considered

FRA still water levels (mAOD)	Upper bound permeability			Characteristic permeability		
	Rate at Hamilton Road (l/s/m)	Rate at Yacht Basin (l/s/m)	Rate at Trawl Dock (l/s/m)	Rate at Hamilton Road (l/s/m)	Rate at Yacht Basin (l/s/m)	Rate at Trawl Dock (l/s/m)
3.10*	0.02	0.03	0.02	0.002	0.003	0.002
4.57	0.06	0.09	0.07	0.006	0.009	0.007

*average ground level behind the walls

Table 8: Seepage volume and combined seepage/ wave overtopping volumes using characteristic permeability

	Hamilton Road		Yacht Basin		Trawl Dock	
	2070	2117	2070	2117	2070	2117
Seepage volume (m^3)	14	32	10	22	15	34

4.2.4 Combined Overtopping and Seepage

The combined seepage and overtopping volumes are presented in Table 9 below.

Table 9: Seepage volume and combined seepage/ wave overtopping volumes using SLS overtopping rates and characteristic permeability

	Hamilton Road		Yacht Basin		Trawl Dock	
	2070	2117	2070	2117	2070	2117
Combined seepage and wave overtopping (m^3)	14	32	634	280	277	57

During a surge event with combined overtopping and seepage discharge, the water will migrate towards low lying areas.

Along the Trawl Basin, water will generally run off along the A47 towards Station Square. Although the area is shown to be at high risk of surface water flooding (3.3% AEP - reported on the Environment Agency website), according to section 3.1, the joint probability of tidal and rainfall flood events in the Lowestoft is deemed to be low. Therefore, it anticipated that during a surge event, the existing surface water network will have sufficient capacity to accommodate the volume of water shown in the above table or at least some of it. Therefore, given the level of conservatism built into the above assessment, the risk of localised flooding at this location is considered to be minimal.

Any potential localised flooding from seepage at Hamilton Road is likely to result in small puddles developing along the carriageway. The existing surface water network should have some capacity to alleviate the impact of seepage in a surge event. The relatively small volume of seepage water at this location should have no impact on services or residential properties. Therefore, localised flood mitigation measures at this location are not deemed to be required.

Overtopping along the Yacht Basin could result in some localised flooding. The area is currently shown to be at low risk of surface water flooding from the Environment Agency website, as water can freely gravity discharge into the sea. Following the scheme implementation, water could be ponding behind the walls during a tidal surge if no mitigation measures are taken. Therefore, a gravity drainage system discharging immediately behind the proposed tidal flood barrier will be implemented to mitigate the potential flood risk. The drainage system will be designed to cope with both seepage infiltration and wave overtopping combined. Additional investigation will also be carried out to ensure that the drainage system can also cope with rainfall runoff.

A sensitivity analysis was carried out to compare the wave overtopping and seepage volumes to a typical rainfall event at the Yacht Basin and Trawl Dock. The analysis was based on FEH based rainfall parameter values/ depths and outline catchment area levels from LiDAR. The analysis estimated that the comparative rainfall event, to the volume of wave overtopping and seepage, at the Yacht Basin was approximately equivalent to a 10% AEP rainfall event and a 100% AEP rainfall event at the Trawl Dock. This appears to be reasonable given the high risk of surface water flooding at Trawl Dock.

4.3 Model runs undertaken

4.3.1 Scenarios Modelled

This FRA considered the following scenarios:

- Do nothing/ do minimum: representative of the current status of the defences in Lowestoft.
- Walls only: flood walls next to the barrier being completely built, but tidal flood barrier not in place. Please refer to Section 2.2 of this FRA for extent of the flood walls.
- Walls and tidal flood barrier: full scheme completed.
- Breaching: three breach locations selected along different areas of the walls. The effect of breaches of each breach was quantified separately. Each breach scenario was designed following National Breach Guidance/ Modelling and Forecasting Technical Guidance Note, 2017 (EA).

Sensitivity runs were undertaken to better understand the impact of wave overtopping and seepage beneath the proposed tidal flood walls.

Please refer to Appendix D for more details on how each individual scenario was set-up.

Table 10: Full set of model simulations run for this FRA

	Present day				2070	2117			
	5% AEP (1:20)	1.33% AEP (1:75)	0.5% AEP (1:200)	0.1% AEP (1:1000)	0.5% AEP (1:200)	5% AEP (1:20)	1.33% AEP (1:75)	0.5% AEP (1:200)	0.1% AEP (1:1000)
Do nothing/ minimum	√	√	√	√		√	√	√	√
Walls only	√	√	√	√		√	√	√	√
Walls and tidal flood barrier (no wave overtopping/ seepage)	√	√	√	√		√	√	√	√
Walls and tidal flood barrier- Breaching (x3)			√	√				√	√
Walls and tidal flood barrier (wave overtopping/ seepage sensitivity) *					√			√	

*GIS exercise only

The AEPs were selected to cover a range of event severity. Furthermore, for tidal events the 0.5% and 0.1% AEP events must be included from a planning perspective; as agreed with the Environment Agency at the beginning of this FRA (see the agreed scope in Appendix E).

4.4 Model results

4.4.1 Do nothing/ minimum

Figure 11 and Figure 12 shows the do nothing/ do minimum flood extents in 2018 and 2117.

After a visual inspection of the flood maps, the following observations were made:

- The extent of the area flooding east of Oulton Broad is largely similar for all the AEPs considered. Extent of flooding remains similar in 2117, suggesting that flooding in the area is mainly driven from high water levels in the Broadlands.
- Properties to the North of the outer harbour do not flood until the 0.1% AEP flood event (present day). Flooding south of Lake Lothing commences in the 5% AEP event, whilst the area to the north starts flooding in the 1.33% AEP event. Flooding around Lake Lothing and the outer harbour will notably worsen with climate change.

- In the present day runs, flooding that would cause disruption to travel begins in the 5% AEP with flooding of Belvedere Road and adjoining roads. The railway station and track are flooded from 1.33% AEP onwards. Severe long-term disruption would occur to central Lowestoft business and properties in the 0.5% AEP and 0.1% AEP.

The do nothing/ minimum 0.1% AEP flood extent, in general, matches well to the EA risk of flooding from river and sea map (downloadable from the EA data catalogue). See Figure 15 in Appendix D. This also includes a comparison to indicative 2013 flood data. Furthermore, the flood history could be argued to corroborate the flooding shown in small magnitude flood events shown by the model owing to the high frequency of past flooding events.

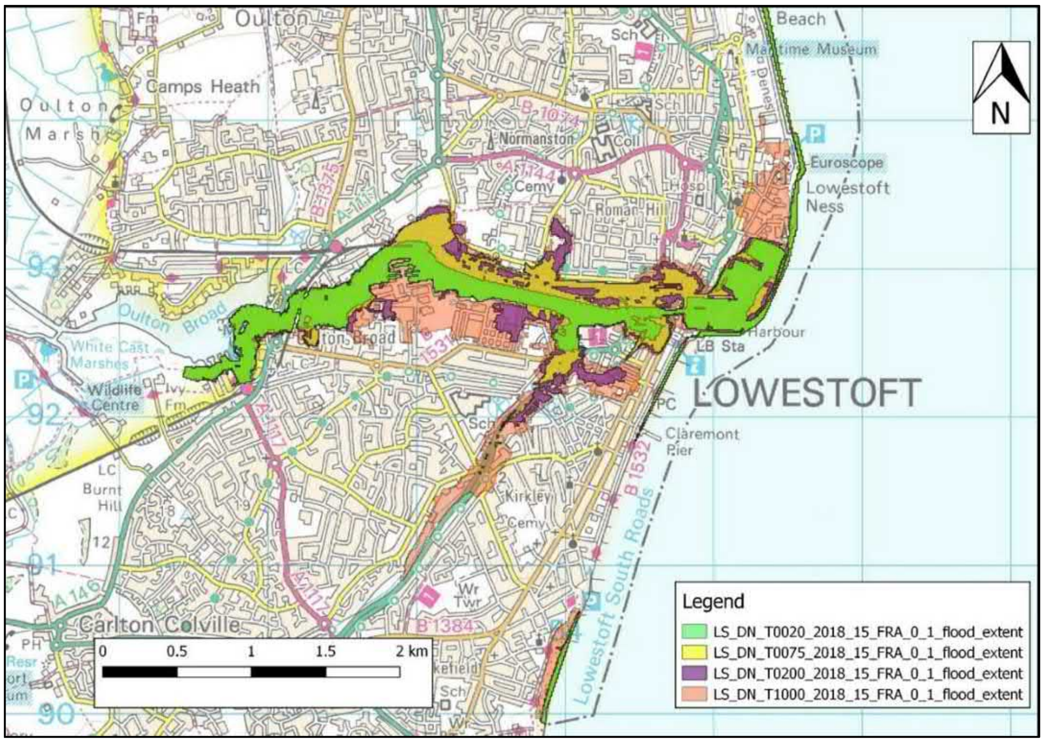

Figure 11. Do nothing/ Minimum flood extents.

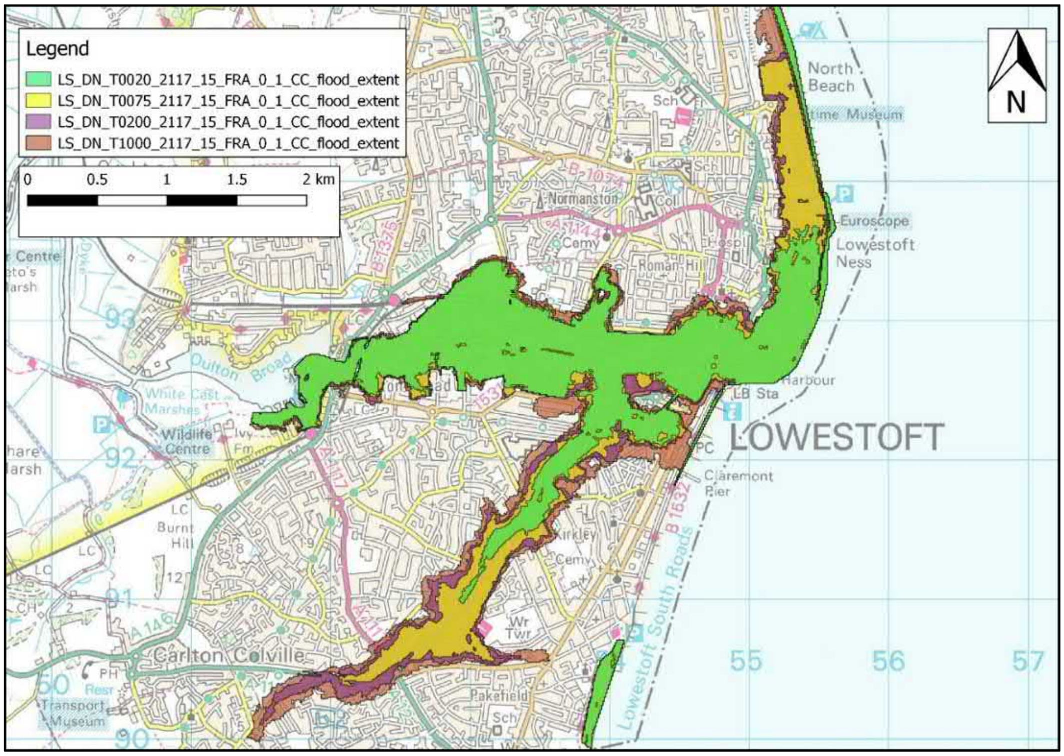

Figure 12. Do nothing/ Minimum flood extents in 2117.

4.4.2 Walls only scenario

Figure 13 and Figure 14 show the 'walls only' maximum flood extents in 2018 and 2117.

In general, the flood extents are very similar to the do nothing/ minimum but with a slight decrease in flood extent in the harbourside area (from a 1.33% AEP and higher) in present day and with significant reduction in flooding in the area north of Hamilton Road (as expected). Defences along Hamilton Road offer protection to properties up to and including the 0.1% AEP event in 2018 and 0.5% AEP in 2117.

The pattern of flooding found confirms that the majority of the flooding in Lowestoft is caused by tidal ingress through Bascule Bridge (in this scenario), and that flooding along Hamilton Road will be independent from the barrier operation (assuming the flood walls are in place).

The wall only scenario does not have any adverse impact on flood risk to local communities. There are no additional areas (compared with the do nothing/ minimum) flooded as a consequence of the walls being in place.

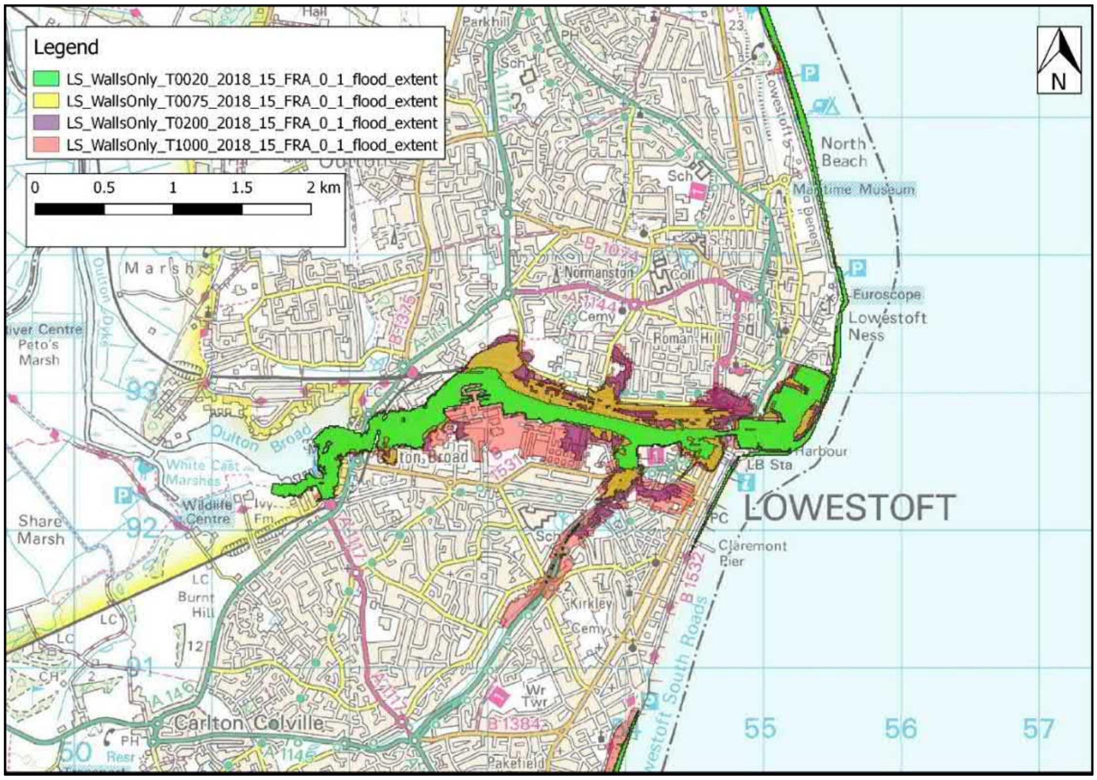

Figure 13. Walls only flood extents in 2018.

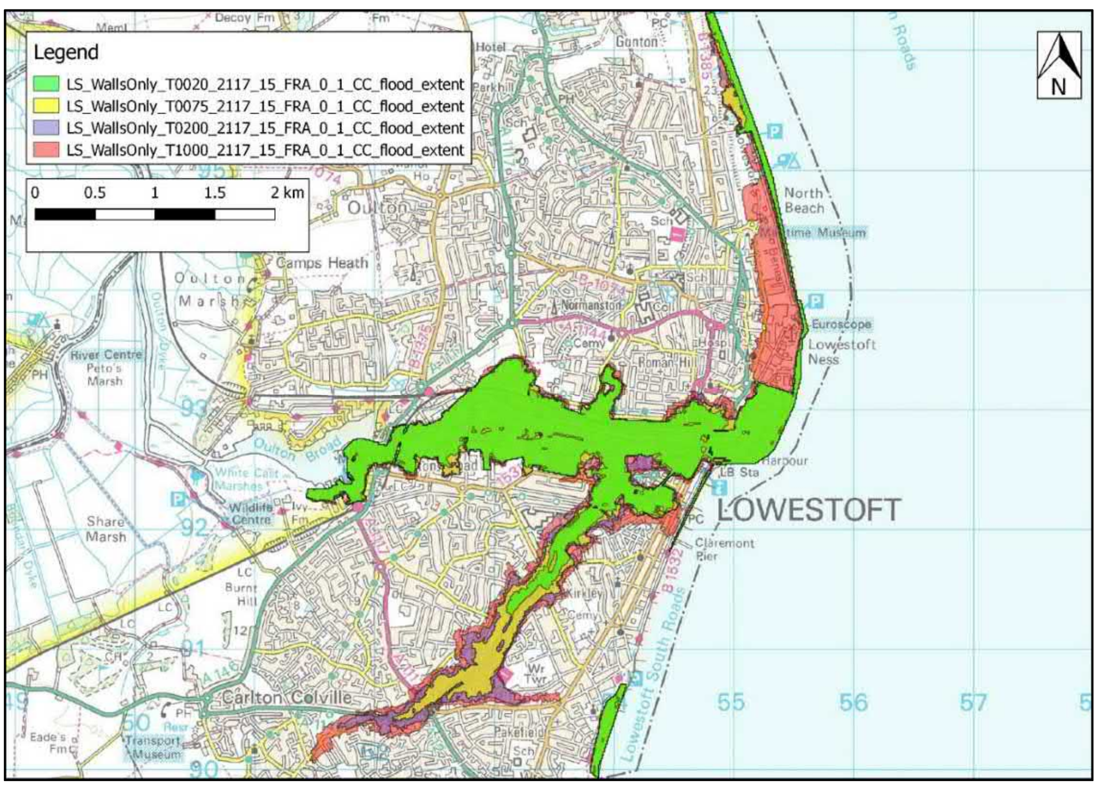

Figure 14. Walls only flood extents in 2117.

4.4.3 Walls and Tidal Flood Barrier

Figure 15 and Figure 16 show the 'walls and tidal flood barrier' maximum flood extents in 2018 and 2117.

Comparison of the 'walls and tidal flood barrier' flood maps with the equivalent do nothing/ minimum shows a significant reduction of flooding around Lake Lothing (as expected) and a slight reduction in flooding in the Oulton Broad area. Reduced flooding at Oulton Broad is assumed to be due to lower water levels in Lake Lothing and increased gravity discharge through Mutford Lock, whilst reduction of flooding elsewhere is linked to the operation of the tidal flood barrier. There is no increase in flood extent in any AEP event; when compared with do nothing/ minimum, as a result of the proposed scheme.

Model results suggest that the proposed scheme will provide protection up to and including the 0.1% AEP present day and 0.5% AEP in 2117.

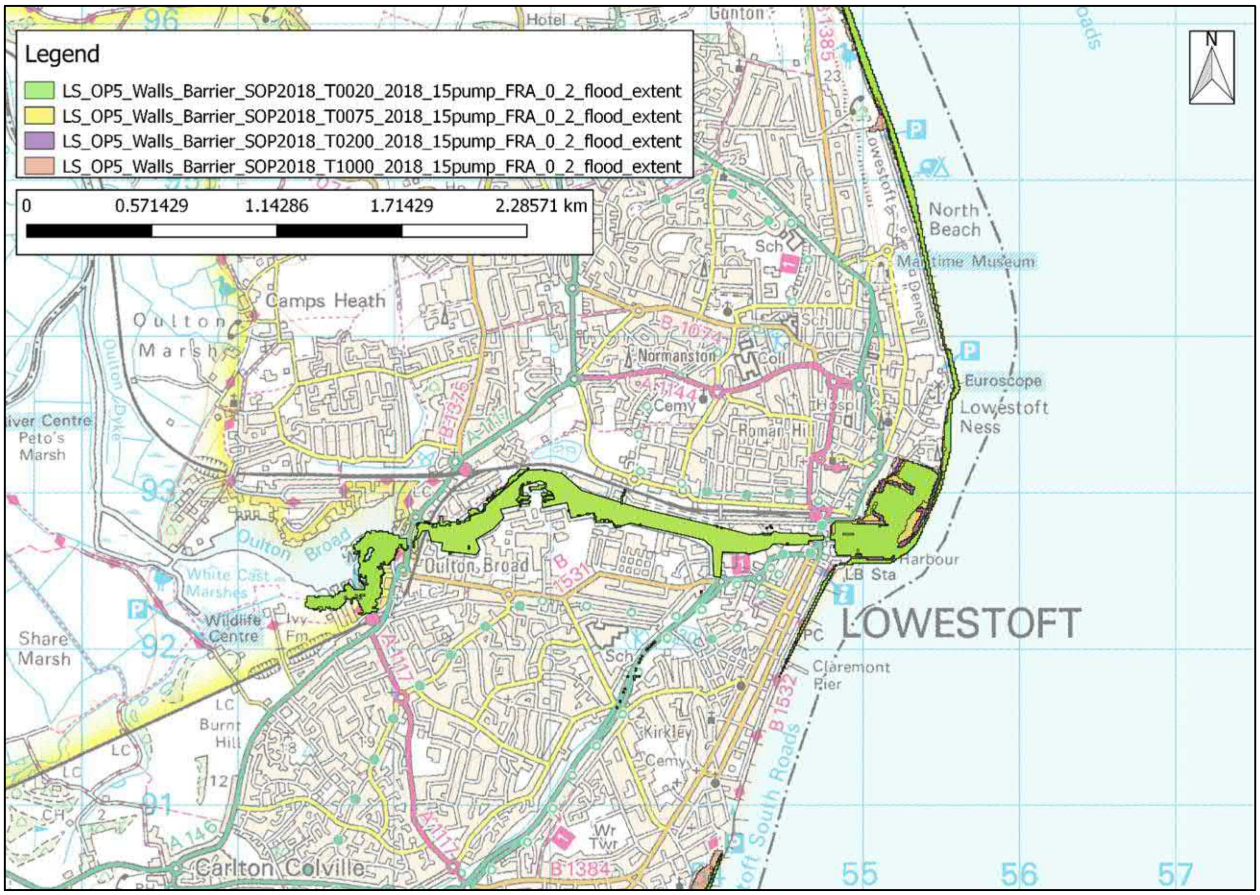

Figure 15. Walls and barrier flood extents in 2018 (no wave overtopping/ seepage considered).

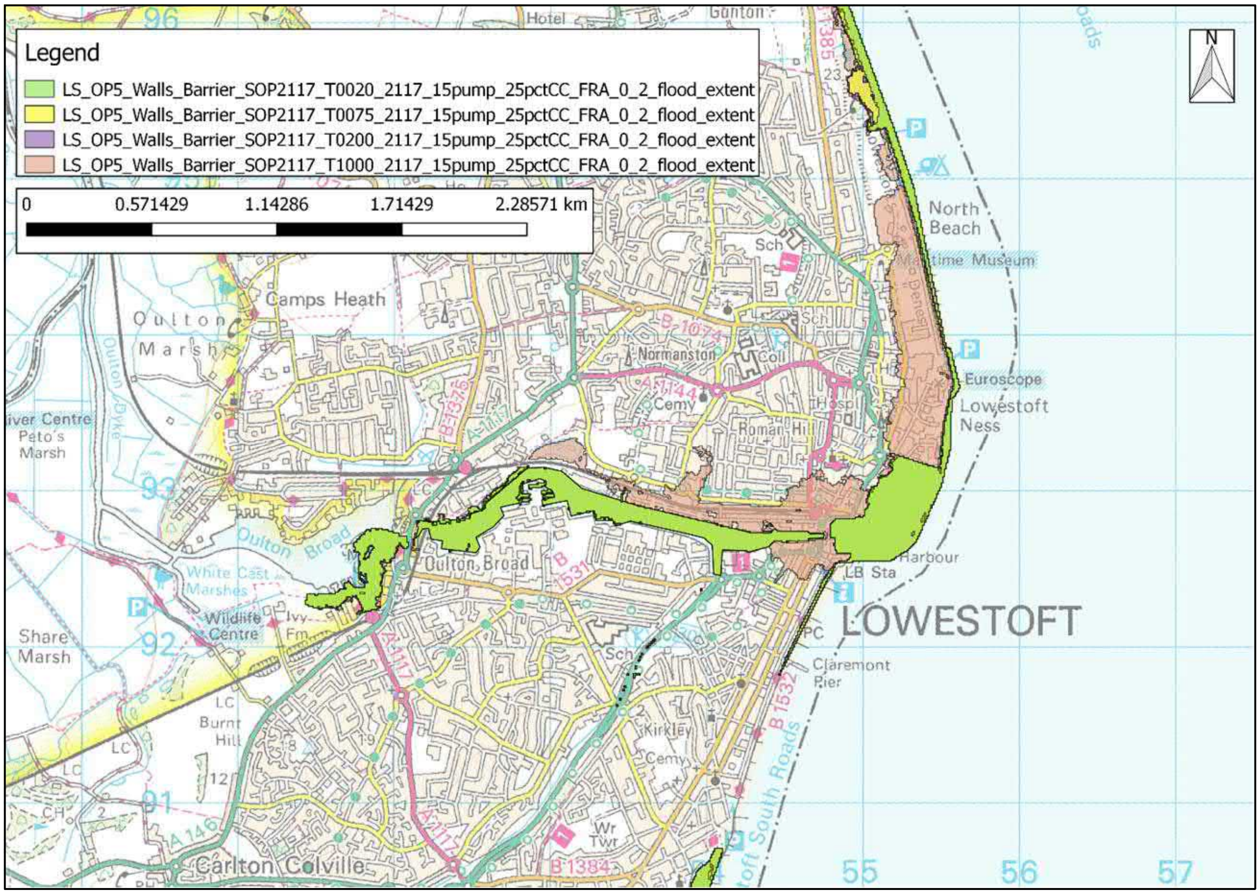

Figure 16. Walls and barrier flood extents in 2117 (no wave overtopping/ seepage considered).

4.3.1 Breach Modelling

Figure 18 to Figure 23 show the maximum flood extent should a breach occur. The effect of each breach was considered independently, and three breach locations were chosen (see Figure 17). For more information see appendix D.

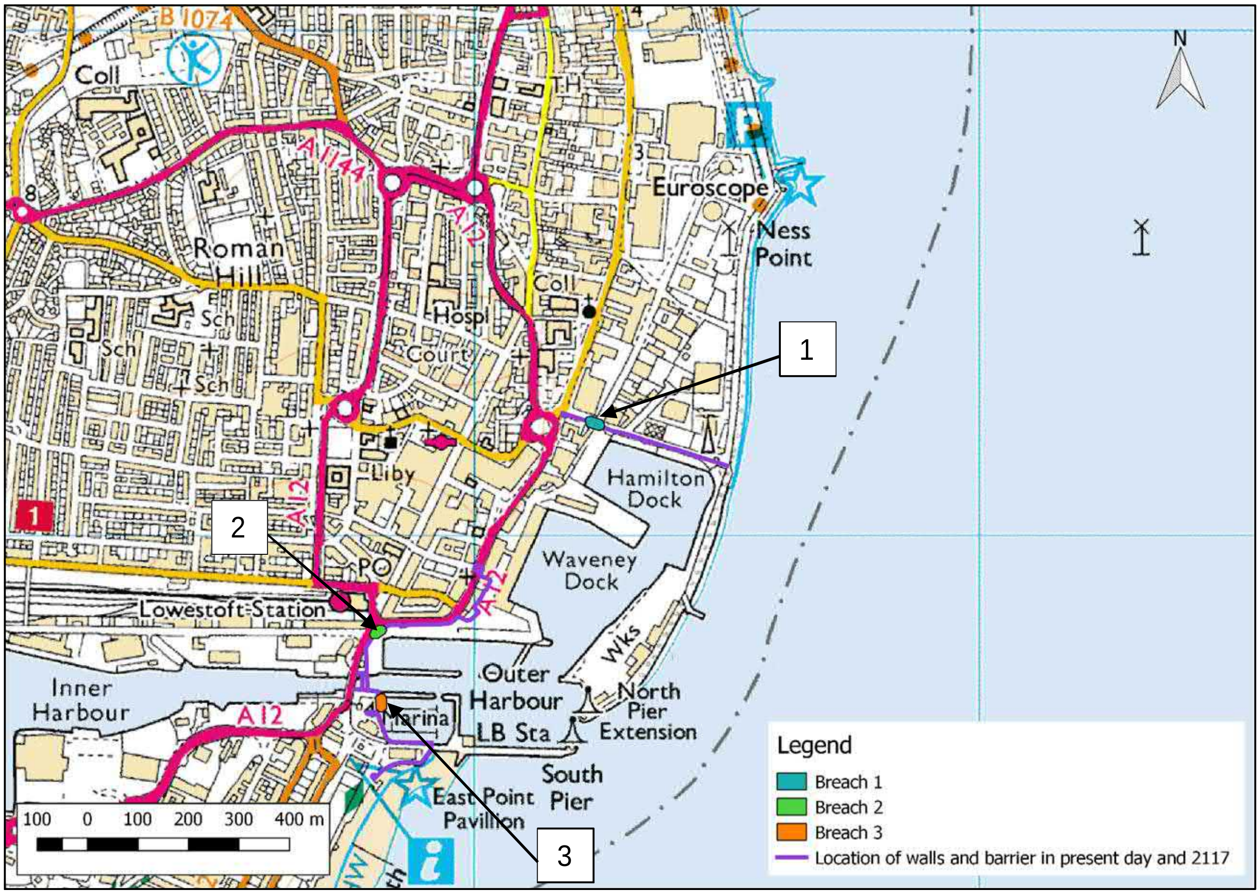

Figure 17. Locations of the three independent breaches tested.

Visual observation of the breach flood maps showed that flood extents were smaller in extent than the equivalent do nothing/ minimum. This was anticipated owing to the barrier and non-breached wall sections providing protection.

Interpretation of the do minimum/ nothing water levels shows that breach 1 would not occur in the 0.5% AEP present day, as the water level does not reach half of the wall height (recommended condition for walls breaching in National Breach Guidance/ Modelling and Forecasting Technical Guidance Note, 2017 (EA)). This is corroborated by the lack of flooding in this area in the do minimum/ nothing present day 0.5% AEP event. The 0.1% AEP breach 1 results show flooding north of Hamilton Dock. Flood water extends half way up Newcombe Road. The furthest flood water from the breach is 350m north east- on Wilde Street. In 2117, the 0.5% AEP event extensively floods north of Hamilton Dock. The flood extent is smaller than the do nothing/ minimum equivalent.

Interpretation of the breach 2 flood extents shows that flooding extends as north as Bevan Street West and as far west as the southern roundabout of Rotterdam Road in the 0.5% AEP event. This therefore means the railway station is flooded. The 0.1% AEP in breach 2 flooding occurs extensively along the north of Lake Lothing. However, this is much smaller in extent than the do nothing equivalent.

In 2117, the 0.5% AEP breach 2 flood extent is similar to the 0.1% AEP present day. The 0.1% 2117 AEP breach 2 is smaller than the equivalent do nothing/ minimum. The difference between flood extents for the walls and barrier and the equivalent run with the breach 2 is larger than the breach 1 change.

Interpretation of the 0.5% AEP breach 3 flood maps show that there is no flooding of property. The water level reaches the toe of the wall but flooding is limited to only approximately 40 m west of the breach. This is corroborated by the do nothing/ minimum equivalent run also having a small flood extent in this area. In the 0.1% AEP there is flooding along the A12/ A47 (south of Bascule Bridge) and B1532 and between the two roads. In 2117, both the 0.5% AEP and 0.1% AEP flood extent are largely similar to the equivalent 0.1% AEP flood extent. Flood extents are much smaller than the do nothing equivalent runs.

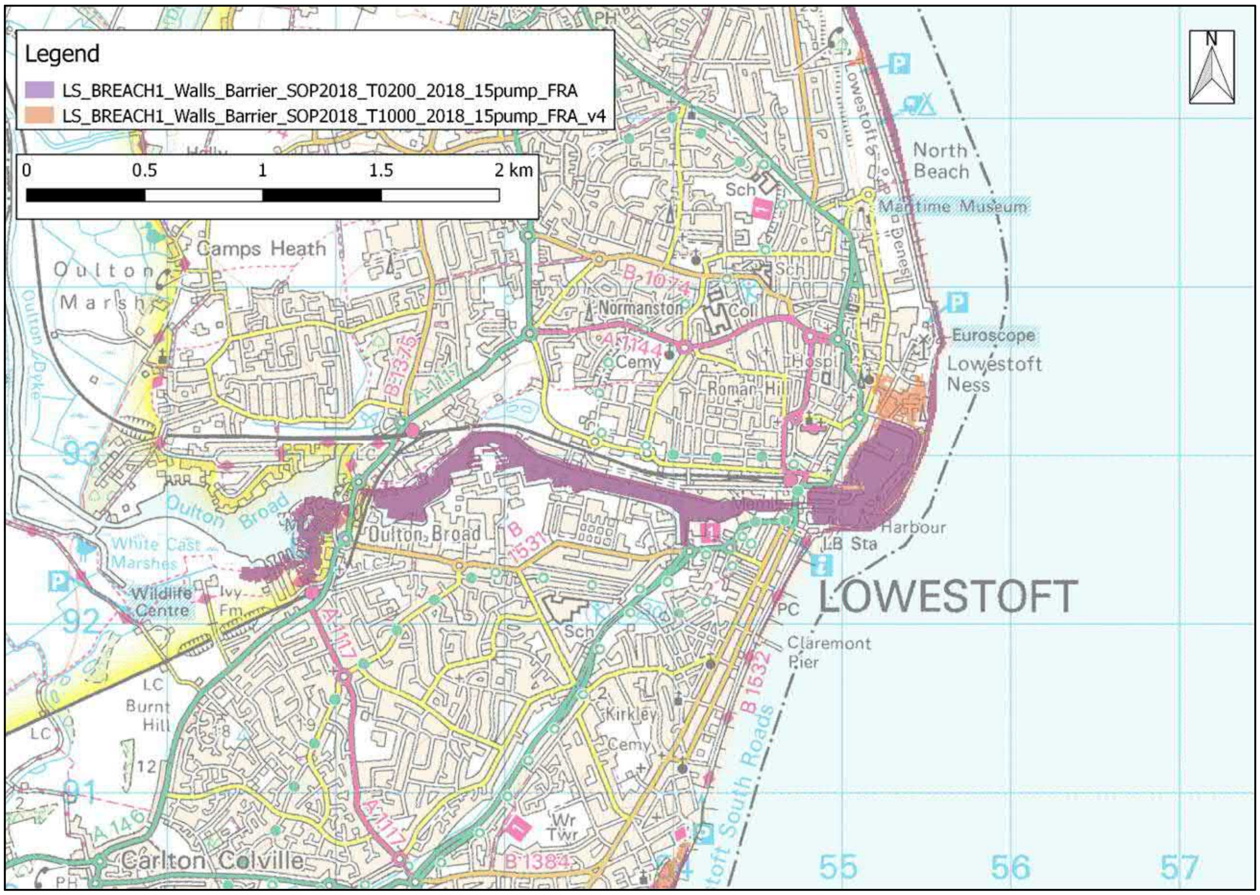

Figure 18. Breach 1 in 2018 applied to the walls and barrier scenario.

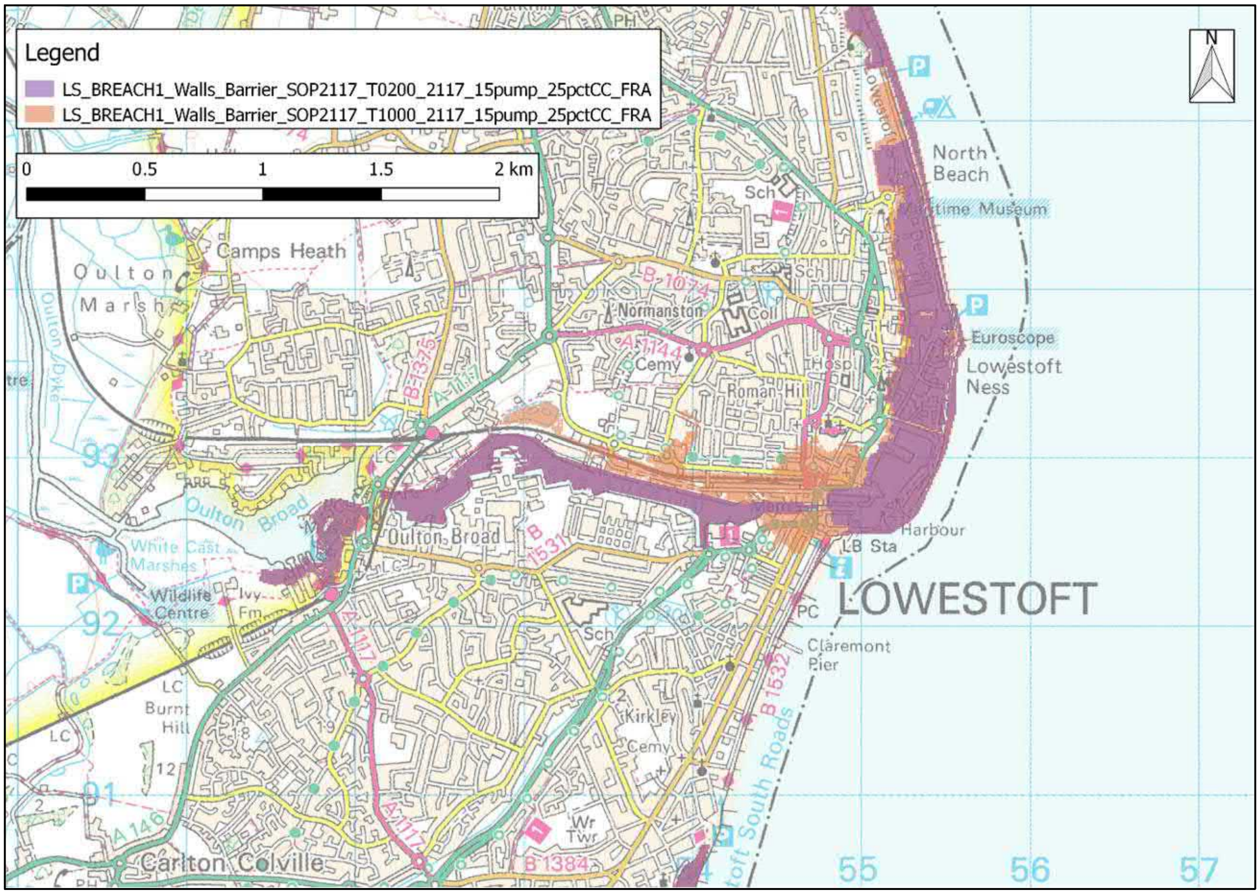

Figure 19. Breach 1 in 2117 applied to the walls and barrier scenario.

Figure 20. Breach 2 in 2018 applied to the walls and barrier scenario.

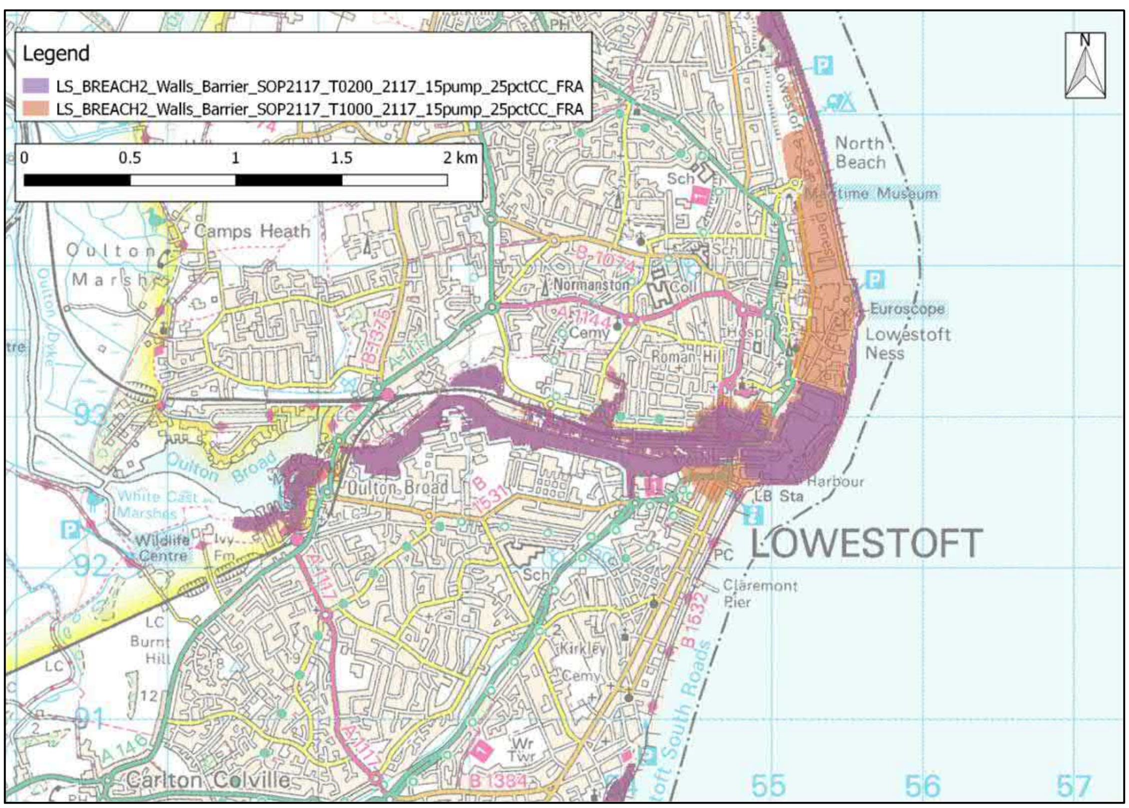

Figure 21. Breach 2 in 2117 applied to the walls and barrier scenario.

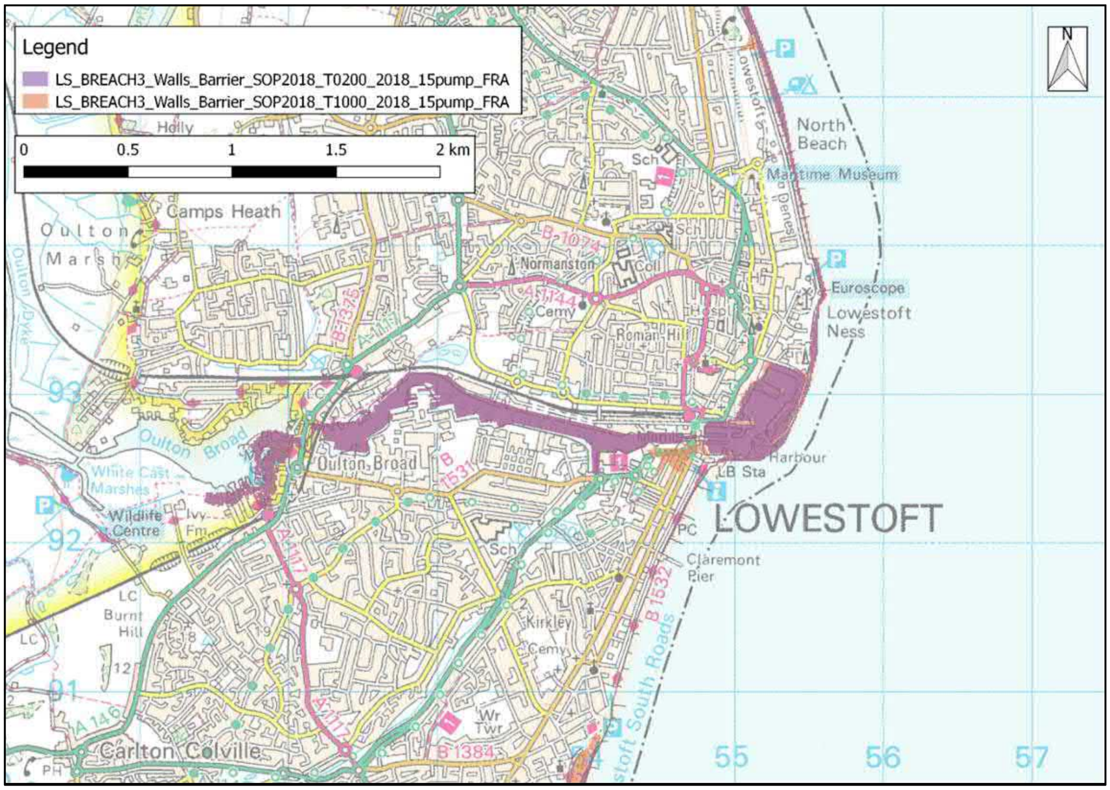

Figure 22. Breach 3 in 2018 applied to the walls and barrier scenario.

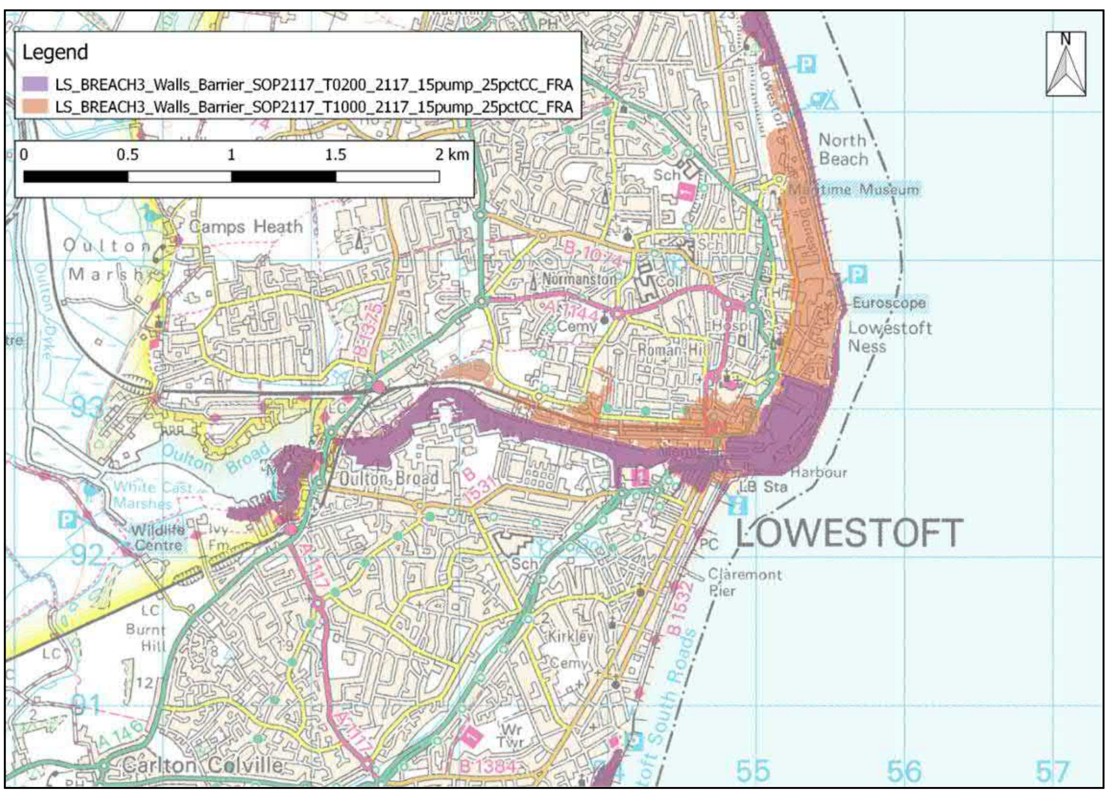

Figure 23. Breach 3 in 2117 applied to the walls and barrier scenario.

5 Consultation

The Environment Agency was consulted on the return periods/ AEP events and scenarios to model and approved the study approach undertaken for this FRA. The Environment Agency has also been involved throughout the business case production and is supportive of the proposed scheme.

Suffolk County Council provided flood incidents records for the Lowestoft area. This is outlined in section 3.3.2. Suffolk County Council was also consulted about flow pathways and whether any would be affected by the proposed works. This was done following guidance from the EA. However, no response was provided.

Anglian Water was asked for DG5 incident records. They replied that, due to data protection laws, they cannot provide specific details. Therefore, the site figure plan was sent to them to confirm whether flooding incidents due to sewer overload had occurred in close proximity to the proposed site. See Appendix B for response; they confirmed there had not been.

6 Flood risk vulnerability classification and Sequential/ Exception Tests

NPPF aims to ensure inappropriate development is avoided in areas at risk of flooding. The Sequential Test, required under NPPF, is a tool for determining land uses that are compatible with the level of flood risk at each development site within a Local Authority area.

The Environment Agency produces flood zones that are the starting point for the Sequential Test. Flood Zones 2 and 3 indicate the land at medium to high risk of flooding during extreme events, and Flood Zone 1 is the low-risk zone, which is all land outside Zones 2 and 3. These flood zones refer to the probability of sea and river flooding only, excluding any existing defences.

The proposed development of the tidal flood barrier and tidal flood defence walls in Lowestoft is within Flood Zone 3 of the Environment Agency flood maps. In accordance with Table 2 of NPPF, the proposed development will fall into the 'water compatible' vulnerability class, under the classification 'flood control infrastructure'. This development is an opportunity to reduce the overall level of flood risk in the area through its layout and form.

This development would, therefore, be deemed suitable under NPPF and assessment of other sites would not be required.

See Appendix F for flood zone summary with appropriate land uses (sequential test).

7 Flood Risk Management

The proposed development in this FRA is part of the Lowestoft Flood Risk Management Project (Lowestoft FRMP), which aims at reducing flood risk at residential properties and the business in the urban area of Lowestoft from tidal, fluvial and surface water sources.

This FRA deals with the elements of the scheme mitigating against tidal flooding. Schemes mitigating against fluvial and pluvial flood risk will go through a separate planning application and process as necessary.

8 Access and Egress

The tidal flood barrier will be closed manually (by pushing a button in the control building) with East Suffolk Council being responsible for its operation. This will likely be controlled from the existing Bascule Bridge control building adjacent to the proposed barrier location. The tidal flood barrier will always be manned throughout the duration of the surge event. The operating and control equipment of the tidal flood barrier will, as reasonably practicable, be designed to achieve the highest level of resilience to minimise the repair time subsequent to a breach event or surge event greater than 0.5%AEP.

The walls will require flood gates to be closed and demountable barriers to be put in place in case of a flood event. An Operational Protocol detailing the triggers for the closure of the tidal flood barrier, closure of flood gates and deployment of the demountable defences along the tidal wall alignment will be developed in consultation with key stakeholders, including the Environment Agency and the Suffolk Resilience Forum. It is envisaged that the Environment Agency flood warning system will be the key trigger for the deployment of the tidal defences. East Suffolk Council will be responsible for the deployment and closure of the tidal defences.

9 Mitigation measures

The barrier and flood walls will reduce the risk from tidal flooding; see section 4.

The barrier will not increase the impermeable surface area and is therefore unlikely to increase the risk from pluvial flooding from rainfall runoff.

Water from seepage infiltration and wave overtopping could result in localised ponding behind the Yacht Basin walls if no appropriate drainage infrastructure is in place. The construction of flood walls will also interrupt existing surface water drainage pathways. This will be mitigated against through the adaptation of existing / design of additional surface water drainage systems.

As the proposed defences are located within an urban environment, the rear of the defences are heavily paved hence mitigating the risk of erosion during an overtopping event and in turn preventing the structure to be destabilise for all the possible combinations in water levels and waves for a 0.5% AEP.

Sewer flood risk is not deemed to be affected by the walls or barrier proposed; during both the temporary works and on completion/ the permanent works. Flap valve or penstocks will be added to the sewer network where appropriate to avoid backflow, therefore it could be argued that the scheme will have a positive impact on the sewer and surface water system.

Groundwater flood risk is not deemed to be affected by the walls or barrier proposed; during both the temporary works and on completion/ the permanent works.

10 Residual risks

Following completion of the proposed development Lowestoft will remain at risk from tidal flooding for events above the design SoP (0.5% AEP).

11 Conclusions

The proposed development at Lowestoft comprises a tidal flood barrier just downstream of the Bascule Bridge and adjoining tidal walls. The purpose of the proposed development is to provide a 0.5% AEP SoP against tidal flooding at Lowestoft. The proposed development will be built in two phases with the tidal walls will be built first and the tidal flood barrier in a second phase (assumed to start in 2021 and be completed in three years). The aim of this report is primarily to consider flood risk and satisfy requirements under National PPF.

The proposed development in this FRA is part of the LFRMP, which aims at reducing flood risk at residential properties and the business in the urban area of Lowestoft from tidal, fluvial and surface water sources. Whilst surface and fluvial flood risk are recognised to be a problem and are being dealt as part of the Lowestoft LFRMP, the focus of this FRA is tidal flood risk.

A number of strategies/ documents have been reviewed. A review of tidal, fluvial, pluvial, groundwater and reservoir flood risk was undertaken (including a review of observed flood events). The literature review showed that the predominant risk of flooding at Lowestoft is from tidal sources and the proposed development aligns with all the relevant management plans. Pluvial flooding is also a considerable source of risk but deemed to be a secondary source in the area near the proposed development. The findings were corroborated by the flood history research undertaken. Risk from reservoir flooding and groundwater flooding was found to be negligible.

A hydraulic model was built to test the effectiveness of the scheme, identify any potential receptor dis-benefitting from the scheme and understand the consequences of the scheme failure. The model evaluated the effect of extreme tidal events during present day conditions and in the future (2117). A full range of scenarios (agreed with the Environment Agency) were tested including:

- Do nothing/ do minimum: representative of the current status of the defences in Lowestoft.
- Walls only: flood walls next to the barrier being completely built, but tidal flood barrier not in place.
- Walls and tidal flood barrier: full scheme completed.
- Breaching: three breach locations selected along different areas of the walls. The effect of breaches of each breach was quantified separately.

A review of the model results found the followings:

- <u>Do nothing/ do minimum</u>: flooding south of Lake Lothing commences in the 5% AEP event, whilst the area to the north starts flooding in the 1.33% AEP event. Flooding that would cause disruption to travel begins in the 5% AEP with flooding of Belvedere Road and adjoining roads. The railway station and track are flooded from 1.33% AEP onwards. Severe long-term disruption would occur to central Lowestoft business and properties in the 0.5% AEP and 0.1% AEP. Flooding disruption would worsen with climate change.

- Walls only: flood extents are very similar to the do nothing/ minimum but with a slight decrease in flood extent in the harbourside area and with significant reduction in flooding in the area north of Hamilton Road (as expected). Defences along Hamilton Road offer protection to properties up to and including the 0.1% AEP event in 2018 and 0.5% AEP in 2117. The wall only scenario does not have any adverse impact on flood risk to local communities. There are no additional areas (compared with the do nothing/ minimum) flooded as a consequence of the walls being in place.
- Walls and Tidal Flood Barrier: comparison with the equivalent do nothing/ minimum shows a significant reduction of flooding around Lake Lothing and a slight reduction in flooding in the Oulton Broad area. Reduced flooding at Oulton Broad is assumed to be due to lower water levels in Lake Lothing and increased gravity discharge through Mutford Lock, whilst reduction of flooding elsewhere is linked to the operation of the tidal flood barrier. There is no increase in flood extent in any AEP event; when compared with do nothing/ minimum, as a result of the proposed scheme. Model results suggest that the proposed scheme will provide protection up to and including the 0.1% AEP present day and 0.5% AEP in 2117.
- Breach modelling: flood extents were found to be smaller in extent than the equivalent do nothing/ minimum. The 0.1% AEP breach 1 (near Hamilton Road) results show flooding north of Hamilton Dock with flood water extending half way up Newcombe Road. Consultation of the breach 2 (Trawl Dock) flood extents shows that flooding extends as north as Bevan Street West and as far west as the southern roundabout of Rotterdam Road in the 0.5% AEP event (including the railway station). The 0.1% AEP in breach 2 flooding occurs extensively along the north of Lake Lothing. However, this is much smaller in extent than the do nothing equivalent. Consultation of the 0.5% AEP breach 3 (Yacht Basin) flood maps show that there is no flooding of property. All flood extents are much smaller than the do nothing equivalent runs.

The effect of wave overtopping (over the crest of the walls) and seepage was also tested. The analysis found that the combined effect of both seepage and wave overtopping have negligible consequences at Trawl Dock and Hamilton Road. Water was found to be ponding behind the walls at Yacht Basin (whilst could freely discharge into the sea in the do nothing/ minimum). An appropriate drainage system will therefore be designed to ensure wave overtopping discharge and surface water are appropriately discharged.

No other mitigation measures are proposed as the barrier will not increase the impermeable surface area and is therefore unlikely to increase the risk from pluvial flooding from rainfall runoff. Similarly, sewer flood risk and groundwater flood risk are deemed to be unaffected.

Following completion of the proposed development Lowestoft will remain at risk from tidal flooding for events above the design SoP.

12 References

"Broads Authority SFRA Final Report", Millard, 2007.

Broadlands Environmental System Ltd (BESL) model update (including hydraulic model, related results and report), CH2M; 2014; (updated 2014).

“Broadland Rivers Catchment Flood Management Plan – Summary report”, EA, 2009.

“East Coast model” JBA, 2015; (started in 2015 and still in development).

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“Joint probability: Dependence mapping and best practice” (project code: FD2308), Defra, 2005.

“Kelling to Lowestoft Ness – Shoreline Management Plan”, AECOM, 2012.

“Lowestoft Flood Risk Management Project Outline Business Case”, CH2M, 2018.

“Lowestoft Flood Risk Management Project Strategic Outline Case”, CH2M, 2017.

“Lowestoft Flood Risk Management Strategy- Options report”, JBA, 2018.

“National Breach Guidance/ Modelling and Forecasting Technical Guidance Note”, EA, 2017.

“Section 19 Flood Investigation Report – Velda Close and Aldwyck Way Lowestoft” (report references: FW2015-0019 to 0025, FW2015-0028 to 0023).

13 Appendices

Appendix A – Flood history

Appendix B – Anglian Water sewer network flooding email correspondence

Appendix C –Lowestoft Modelling Validation Note_V3_SG

Appendix D – FRA Modelling TN_2018-11-07SG

Appendix E – Scope of project and EA response

Appendix F – Sequential test

Appendix G – CRM72114-JAC-DZ-300-MO-HY-0001 - Overtopping Technical Note

Appendix H – Not Used

Appendix I – Model Log

Appendix J – Lowestoft tidal barrier and flood walls technical memorandum (2017)

Appendix K – Lowestoft_Tidal_Defences_final_draft_03.pdf; which contains historic modelling details

Appendix L – CRM72114-JAC-00-ZZZ-TN-GT-0002; Groundwater Technical Note

Appendix A- Flood history

See Table: 1 for summary record of desk based historical flood history in Lowestoft.

Table: 1. Online desk based collation of historic flood incidents in Lowestoft.

Event	Source of flooding	Comment/ description	Area affected	Reference
January 31st- February 1st 1953.	Tidal.	400 homes flooded according to BBC. Broadland SFRA (2007) cites over 3, 500 for Great Yarmouth, Lowestoft and the Broads area and also cite 10 deaths. This document cites the surge as having a 1.33% AEP. Railway line forced to close between Lowestoft and Norwich.	Wide spread.	BBC. Broadland SFRA 2007 (report reference: 7293C/21/CW/06-07/1775).
February 21st 1993.	Assumed tidal.	12 properties and a holiday park flooded at Outlon Broad. Regional repair costs in excess of £1 million. £100 k damages to Oulton Broad defences. 1.91 m surge recorded.	Oulton Broad.	Lowestoft Estuary Inception Study (Halcrow, 2013). Report_Final Report_Feb2013_rev2.doc
September 2002.	Fluvial and pluvial.	Section 19 report mentions previous flooding history at the location that the report is focused on (Velda Close and Aldwyck Way). This date is listed as flooding historically. See July 2015 for the event the section 19 report focuses upon.	Velda Close and Aldwyck Way.	Section 19 report.
December 16th – 17th 2005.	Assumed tidal.	Reported by police that flooding is occurring on Caldecott Road and Bridge Road with water levels reaching the sills of parked cars. Wherry Hotel car park flooded. 0.9 m surge recorded.	Caldecott Road and Bridge Road.	Lowestoft Estuary Inception Study (Halcrow, 2013). Report_Final Report_Feb2013_rev2.doc

Event	Source of flooding	Comment/ description	Area affected	Reference
September/ October 2006.	Fluvial and pluvial.	Section 19 report mentions previous flooding history at the location that the report is focused on (Velda Close and Aldwyck Way). This date is listed as flooding historically. See July 2015 for the event the section 19 report focuses upon. In addition, the Great Yarmouth Borough Surface Water Management Plan says that more than 90 properties in Great Yarmouth and Lowestoft were affected.	Velda Close and Aldwyck Way.	Section 19 report. Great Yarmouth Borough Surface Water Management Plan.
November 9th 2007.	Tidal.	Highest observed level was 0.71 m above the Environment Agency alert level. Online news articles are dated before the tidal surge event happened and very few after suggesting damage was minimal and less than expected. No explicit reports of flooding.	N/A.	Suffolk Police Website. Met Office. The Eastern Daily Press.
September/ October 2013.	Fluvial and pluvial.	Section 19 report mentions previous flooding history at the location that the report is focused on (Velda Close and Aldwyck Way). This date is listed as flooding historically. See July 2015 for the event the section 19 report focuses upon.	Velda Close and Aldwyck Way.	Section 19 report.
December 5th 2013.	Tidal.	158 residential properties and 233 commercial properties in Lowestoft and Oulton Broad area were flooded	Wide spread.	WDC, Overview and Scrutiny Committee- East Coast Tidal Surge, Sept 2014.
July 24th-25th 2015.	Fluvial and pluvial.	On the night of 24/25 July 2015, 82mm rainfall fell. Section 19 report details that flooding occurred on 24th and 25th July 2015 due to surface water drainage, highway	Velda Close and Aldwyck Way.	Section 19 report and Kirkley Stream progress update reports.

Event	Source of flooding	Comment/ description	Area affected	Reference
		drainage, public sewer and Kirkley Stream capacity being exceeded. 33 properties documented as flooding internally with further reports of gardens and outbuildings. The public highway was flooded to 450 mm.		
January 13th 2017.	Tidal.	Suffolk Constabulary close bridges as a pre-cautionary measure and state that flooding has been reported around Oulton broad. However, the tidal surge is lower than predicted.	Oulton Broad- particularly the Caldecott Road area.	Suffolk Police Website.

[redacted]

From:	Anglian Water <planningliaison@anglianwater.co.uk>
Sent:	13 July 2018 15:29
To:	[redacted]
Subject:	Jacobs Lowestoft Site, LOWESTOFT - Harbour Flood Risk Query Response

[redacted]

Thank you for your Flood Risk Query you submitted for Jacobs Lowestoft Site, LOWESTOFT - Harbour.

Our response to this is: Anglian Water is able to confirm that we have no records of flooding in the vicinity that can be attributed to capacity limitations in the public sewerage system. It is possible that other flooding may have occurred that we do not have records of, other organisations such as the Local Authority, Internal Drainage Board or the Environment Agency may have records.

Should you have any questions relating to this please contact 0345 606 6087 Option 1. Your reference for this enquiry is 00029249.

Kind Regards
Growth and Planning Services Team

Lowestoft Modelling Validation Note- Hydraulic Modelling

PREPARED BY:	Libby Bush
DATE:	June 22nd, 2018
PROJECT NUMBER:	676284
REVISION NO.:	1.0
CHECKED BY:	Silvia Garattini
APPROVED BY:	

1.0 Introduction

CH2M (now JACOBS) have been commissioned by Balfour Beatty to develop an Outline Business Case (OBC) on behalf of the Waveney District Council for the Lowestoft Flood Risk Management Project (LFMRP). The proposed scheme includes construction of a tidal barrier at Bascule Bridge and walls on both sides of the barrier tying into high-ground. As part of the OBC, a model was developed for the existing scenario (Do-minimum) and for the proposed scheme. The hydraulic model and related results have been used to derive tidal flood damages and benefits of the proposed scheme.

Alongside the OBC, CH2M (now JACOBS) is also preparing a planning application for the proposed walls. A Flood Risk Assessment (FRA) is included in the aforementioned planning application. The FRA will use both a do-minimum model, a model of the proposed scheme and a model with 'walls only' (without the tidal barrier). Breach scenarios will also be considered as appropriate together with the combined effect of wave overtopping and seepage.

This technical note describes the methodology/ tests undertaken to develop the appropriate Do-minimum model for the FRA. The note also comments on the impact of any suggested changes of the OBC economics.

2.0 Available Data and Quality Review

2.1 Available Models

Available models for the FRA exercise are listed below:

- 2014 Lowestoft Model – feasibility study: this is a 1D-2D model developed in ISIS- TUFLOW. The 2D model domain covers the urban area of Lowestoft, whilst the 1D element includes the whole Broadlands system. The model was used to evaluate risk of flooding from tidal sources as part of a high level feasibility study.
- 2016 Lowestoft Model- strategic outline case: the model was developed using the 2014 files as a baseline. Key modifications include:
  - Use of 2015 LiDAR,

    - Tidal boundaries updated based on UKCP09 medium emission scenario (95 percentile) sea level additions (for the change factor),
- 2017 Lowestoft Model- OBC: the model was developed using the 2016 files as a baseline. Key modifications include:
    - improvements to Mutford Lock representation,
    - adoption of most recent extreme water levels for the East Coast (JBA, 2015),
    - sea bed level lowered from 0.0 mAOD to -1.5 mAOD at the entrance to the outer harbor,
    - 2D grid resolution of 10 m was used for the urban area of Lowestoft,
    - on the west end of the 2D domain, near Oulton Broad, a HQ boundary was applied to ensure no "glasswalling" within the area of interest,
    - Mutford Lock was modeled as a flapped orifice unit and was assumed to be closed during tidal conditions in Lowestoft. The lock was assumed to open only when gravity discharge is possible between Oulton Broad and Lake Lothing,
    - Please consult the technical memorandum as part of the OBC; 'Lowestoft tidal barrier and flood walls' (2017); Appendix J of the main FRA report, for a full description of the modifications undertaken to the model files previously.

2.2 Quality Review

The 2017 OBC model constitutes the most up-to-date version of the Lowestoft model.

A quality review of the model files was undertaken and the following points are noted:

- The model methodology used (1D-2D) is considered suitable for representing the Lowestoft system.
- Bed levels in Lake Lothing were modelled as -1.5mAOD (this being lowest astronomical tide level at Lowestoft) instead of -6.2mAOD (level maintained by ABP). The reason behind this change is unknown but assumed to be to increase model numerical stability.
- No allowance was made for Kirkley Stream pumping station

Owing to the tidal nature of the events, it is believed that bed levels and pumped inflows should have a negligible impact on the extreme water levels in Lake Lothing. However, as part of the current exercise, sensitivity of modelled water levels and flood extents to these two parameters was evaluated.

3.0 Outline method

Model modifications were made prior to the FRA for the proposed flood walls and barrier following receipt of new/ additional information. The changes made to the model (which was used for the OBC) were:

- Bed level changed from -1.5 mAOD to -6.2 mAOD,
- Pump added at Kirkley Ham with a 1 in 10 year/ 10% AEP inflow applied to represent inflows from Kirkley Stream,
- Introduction of level changes around a dry dock in the north west of Lake Lothing.

The pumped inflow from Kirkley stream was extracted from the JBA 2017 Lowestoft FRMS study "2017s6113 - Lowestoft FRMS - Options Appraisal Report (Draft Rev 1)". It was assumed that peak flow would coincide with peak tide adopting therefore a conservative approach. A 1 in 10 year event/ 10% AEP was selected on the basis of low correlation between fluvial and tidal events on the East Coast according to FD2308 (Defra, 2005). The location of the pump is shown in Figure 1.

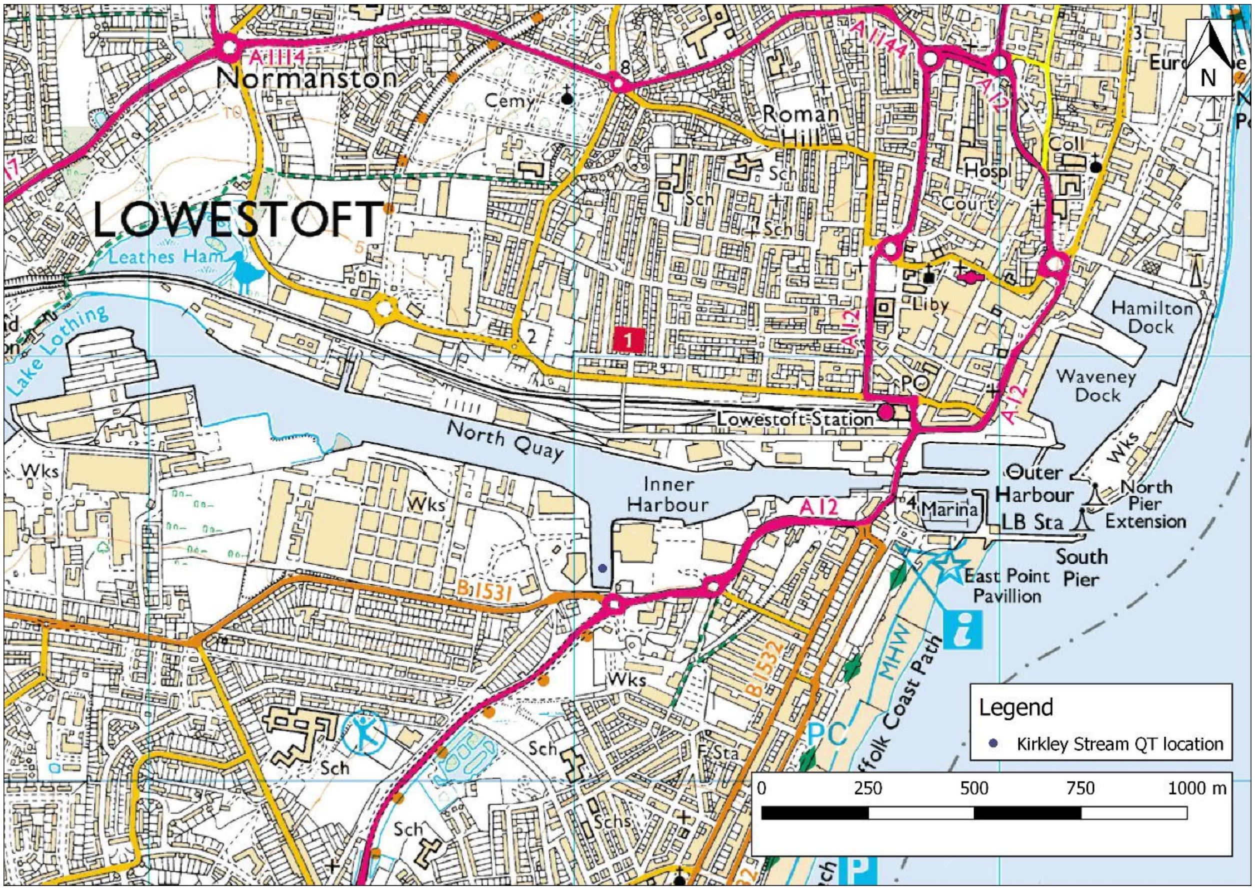

Figure 1: Location of Kirkley pump inflow.

Level from Dry Dock were extracted from level plan survey taken by ABP (Associated British Ports) (2014). See Figure 2 for location.

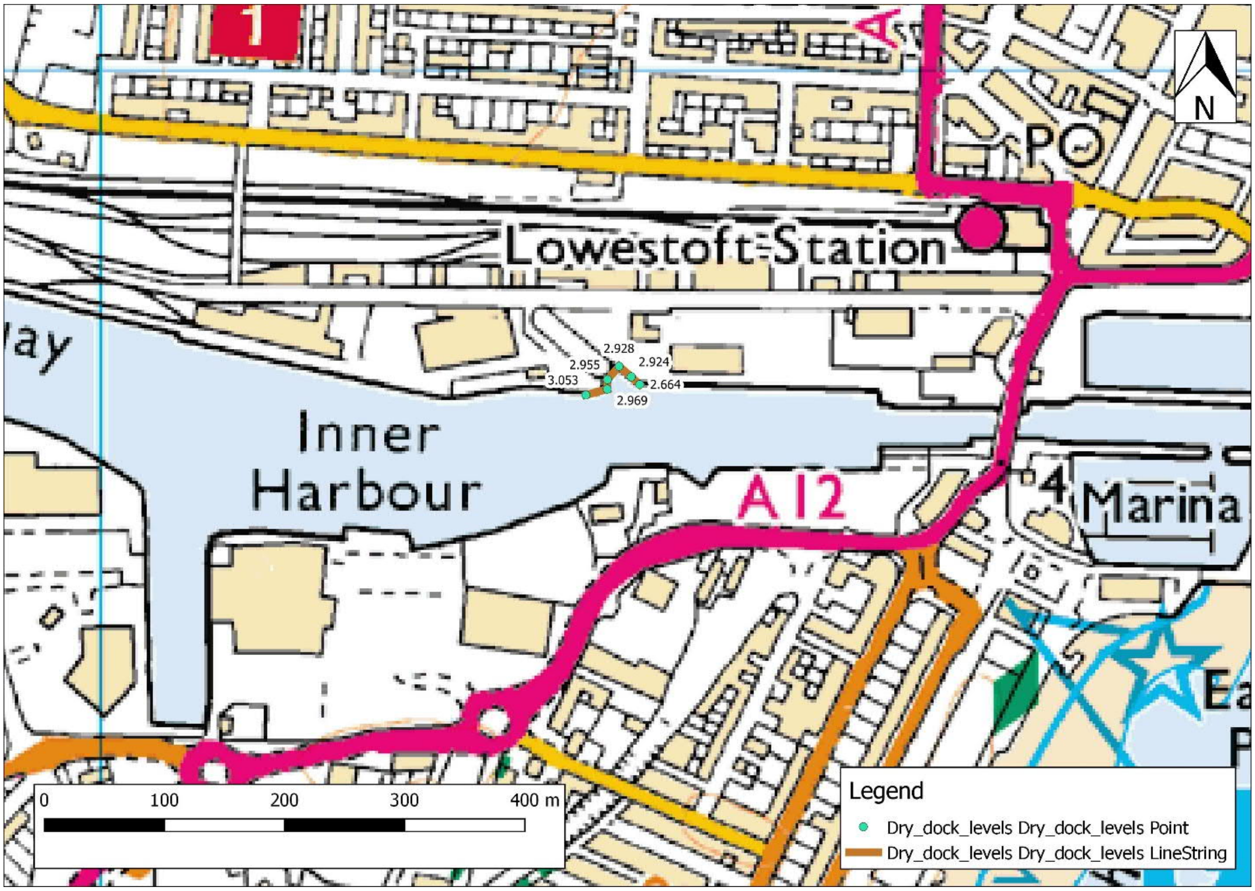

Figure 2: Z line added to the model to raise the elevation around a dry dock. This was done as survey data, provided by ABP, had a higher level (mAOD) than the LiDAR was representing the dry dock to have.

The following runs were tested with the Kirkley Stream pump and dry dock levels with the original bed level of -1.5 mAOD:

- Do nothing/minimum for 1 in 20 year/ 5% AEP,
- Option 5 with an SoP at 1 in 75 year/ 1.33% AEP in 2117 and a tidal event of 1 in 200 year/0.5% AEP in 2117.

Following the amendments to the model summarised above; the following model runs were chosen for comparison to the original model (detailed in the main model note).

- Return periods: 1 in 20/ 75/ 200 year (5%/1.33%/0.5% AEP),
- Climate change scenarios: Present day and 2117,
- Options: Do nothing/ minimum, Option 5 with the SoP at 1 in 75 and 1 in 200 year (1.33% and 0.5% AEP).

The runs were chosen so that a range of both scenarios and flood events were covered to capture any changes in results following the model amendments. In addition, the events were chosen on the basis of the Partnership Funding (PF) risk bands.

The 1 in 10 year/ 10% AEP Kirkley Stream pump inflow-time series is shown below in Figure 3. For the proposed works scenarios' the Kirkley Stream pump inflows were added into the Lake Lothing reservoir unit as a QT boundary.

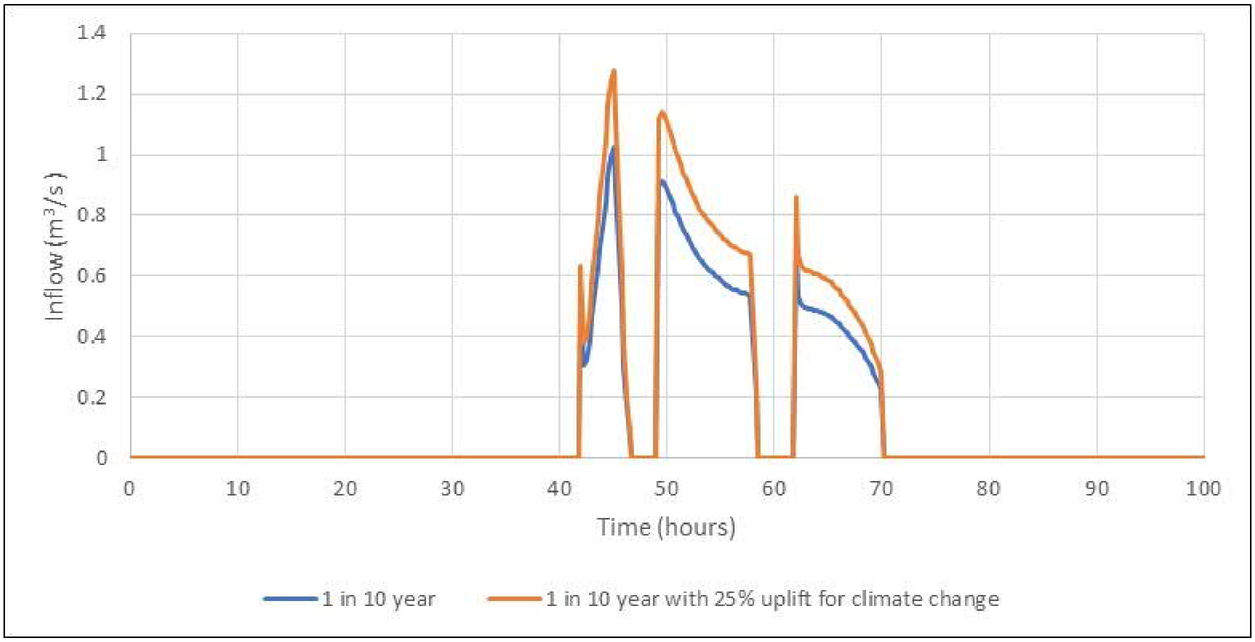

Figure 3. Inflows for the 1 in 10 year/ 10% AEP Kirkley Stream pump taken from JBA (2017). Timing of onset has been modified to match the peak of the tidal events in the model.

4.0 Model Results

4.1 Sensitivity to bed levels

Following the amendments described in section 3.0, the do nothing/ minimum model initially presented numerical instability issues which prevented it from completing successfully the simulations. To increase computational solving to allow the model to run; the time step was changed from 2.5 (s) to 1.25 (s) for 1D and 5 (s) to 2.5 (s) for 2D.

Following changes to the bed level and the time step being halved, the model showed instability with unrealistic and large changes in water level over a short distance (see Figure 4-which did not have the Kirkley pump inflows added at that point).

To obtain realistic results, a roughness patch was added in the area with the largest changes in water level; the harbor. The location of the roughness patch is shown in Figure 5. This was set to have a Manning's n value of 0.3. This is a modelling expedient to slow water down and therefore increase stability. It is therefore not physically realistic. The stage results, following the addition of the roughness patch, were consistent and did not show unrealistic jumps in water level (see Figure 6).

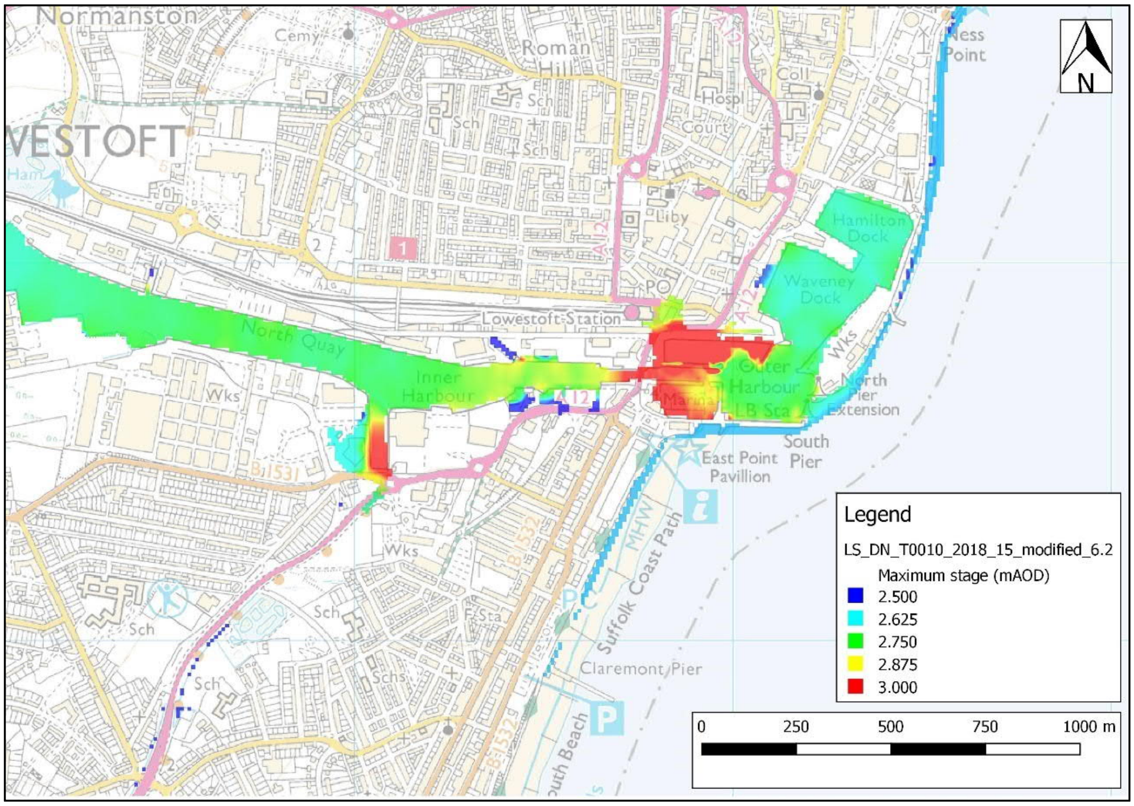

Figure 4: The stage results (mAOD) (graduated to visually show different stages) for Do nothing/ Do minimum in a 1 in 10 year/ 10% AEP tidal event in 2018. The model amendments at this time were the bed level set to -6.2 mAOD and a pump (of a fixed rate of 1.2 m^3/s as it was before the inflow data for the 1 in 10 year/ 10% AEP was received).

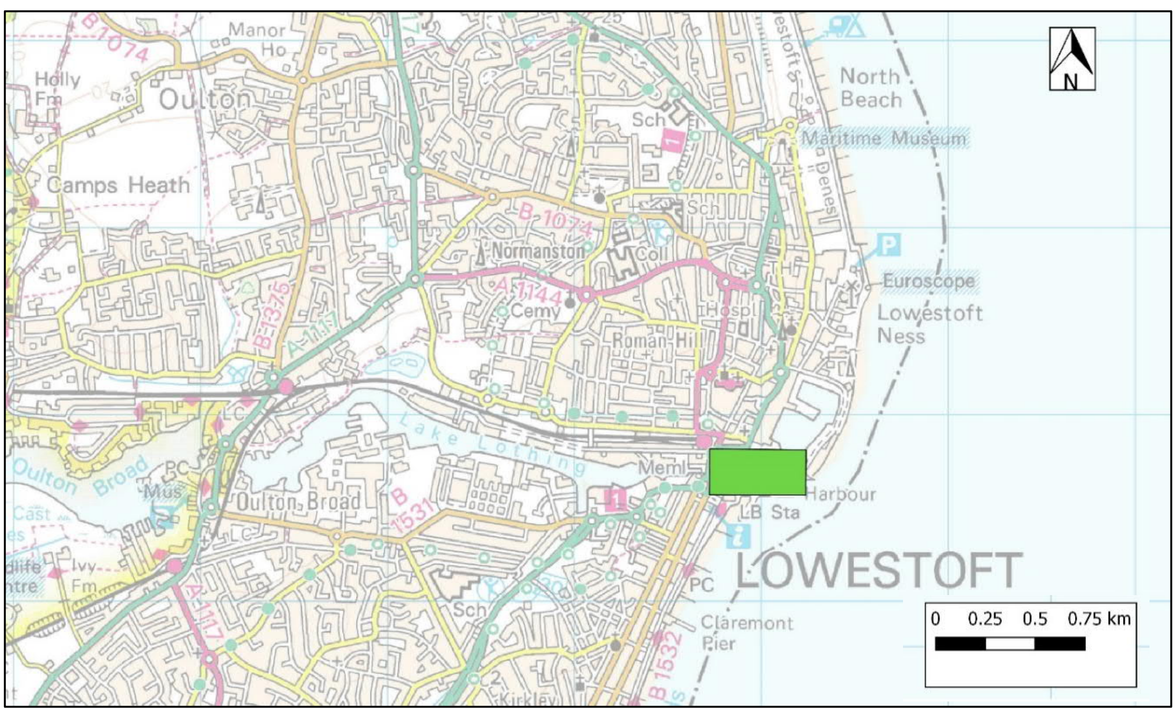

Figure 5: Location or roughness patch used in the model to increase stability (green rectangle).

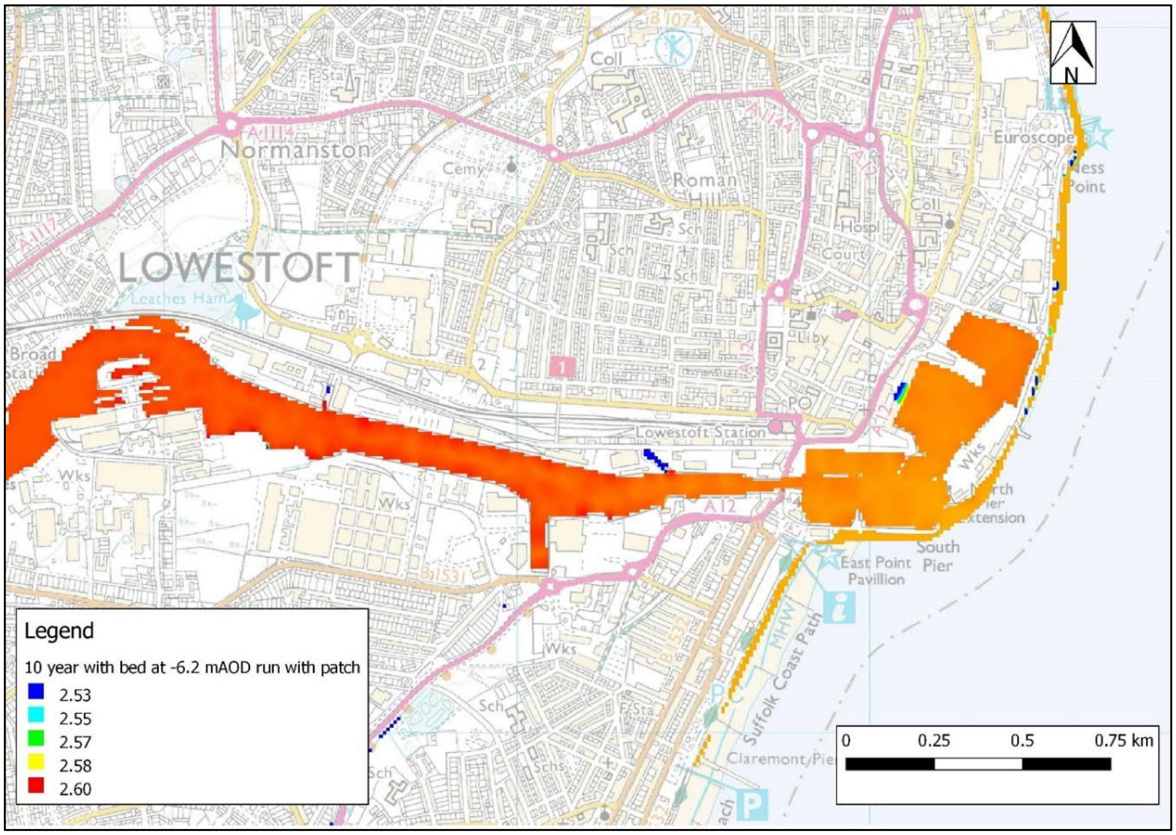

Figure 6: Stage results (mAOD) for the 1 in 10 year/ 10 AEP event and Do nothing/ minimum scenario and the model with the modification of Lake Lothing bed level to -6.2 mAOD with the roughness patch added to the model. See Figure 5 for location of roughness patch. Note: the pump was not in this run to reduce variables that the results were due to. Therefore, the only amendment to this model was bed level and roughness patch to enable the stability problems to be addressed.

4.2 Sensitivity to Kirkley Stream pumped inflows

The model was run for two events with the bed level at -1.5 mAOD. This therefore did not need the time step to be halved for stability and the time step of 2.5 (s) for 1D and 5 (s) for 2D was retained from the original model.

Do nothing/ minimum for a 1 in 20 year/ 5% AEP present day tidal event was similar with two areas showing an increase in flood extent due to the pump.

The spatial extent of change is not large and localised to near the pump location. See Figure 7Error! Reference source not found.. The brown colour is where both match. Purple is the model with the pump and dry dock level added. Adjacent to Kirkley Ham itself; there is a larger flood extent but only 1 building extra is flooded and it is associated with the building which was already being flooded in this return period (1 in 20 year/ 5% AEP) in the equivalent model without the pump. In addition, south east of the Bascule Bridge there is again a slightly larger extent. This appears to result in the flooding of approximately 2 extra properties.

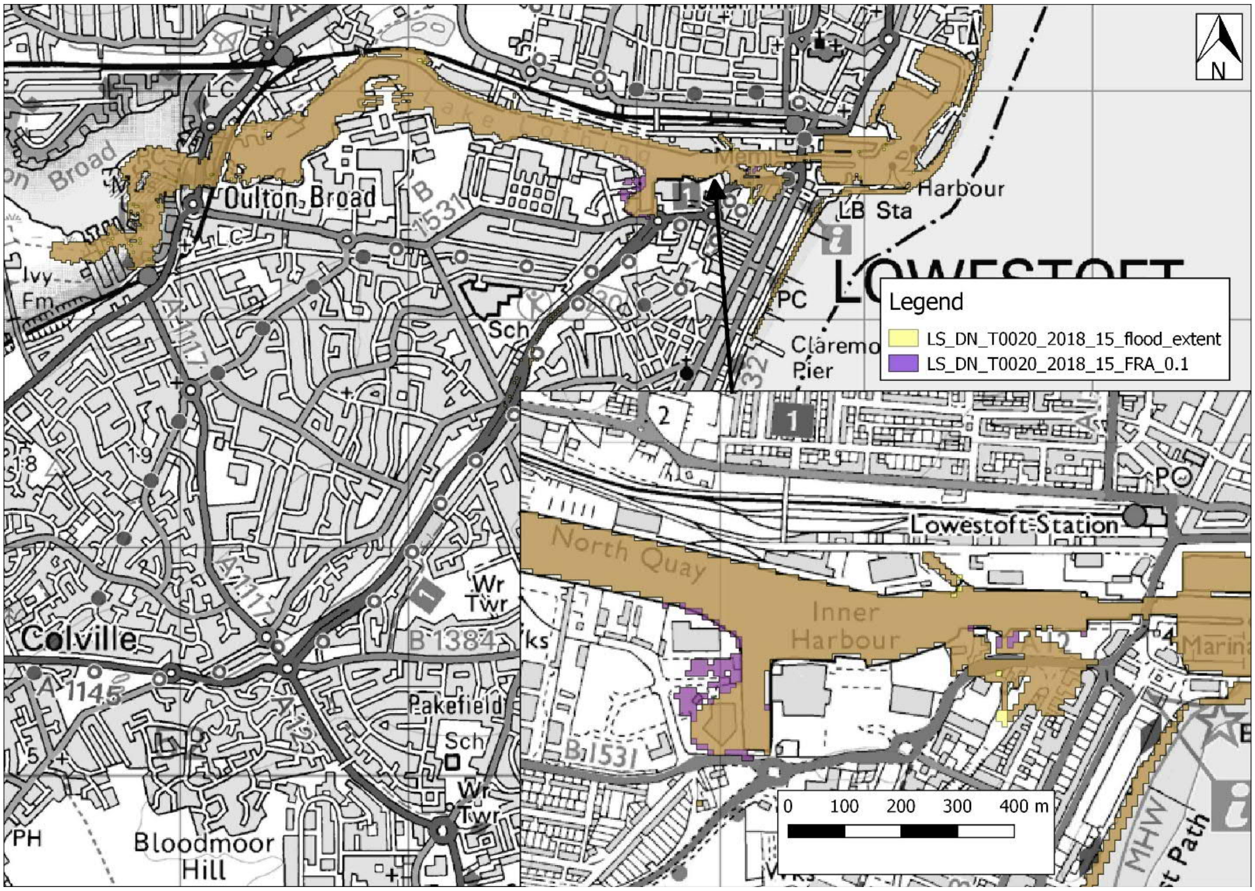

Figure 7: Stage results (mAOD) for Do nothing/ minimum 1 in 20 year/ 5% AEP in the model with bed level at -1.5 mAOD and model with bed level at -1.5 mAOD, 1 in 10 year/ 10% AEP pump and dry dock levels.

The model was also run for option 5 with a SoP of 1 in 75 year/ 1.33% AEP in 2117 and a tidal event of 1 in 200 year/ 0.5% AEP in 2117. The flood extent output matched well with minimal difference in flood extent. See Figure 8Error! Reference source not found..

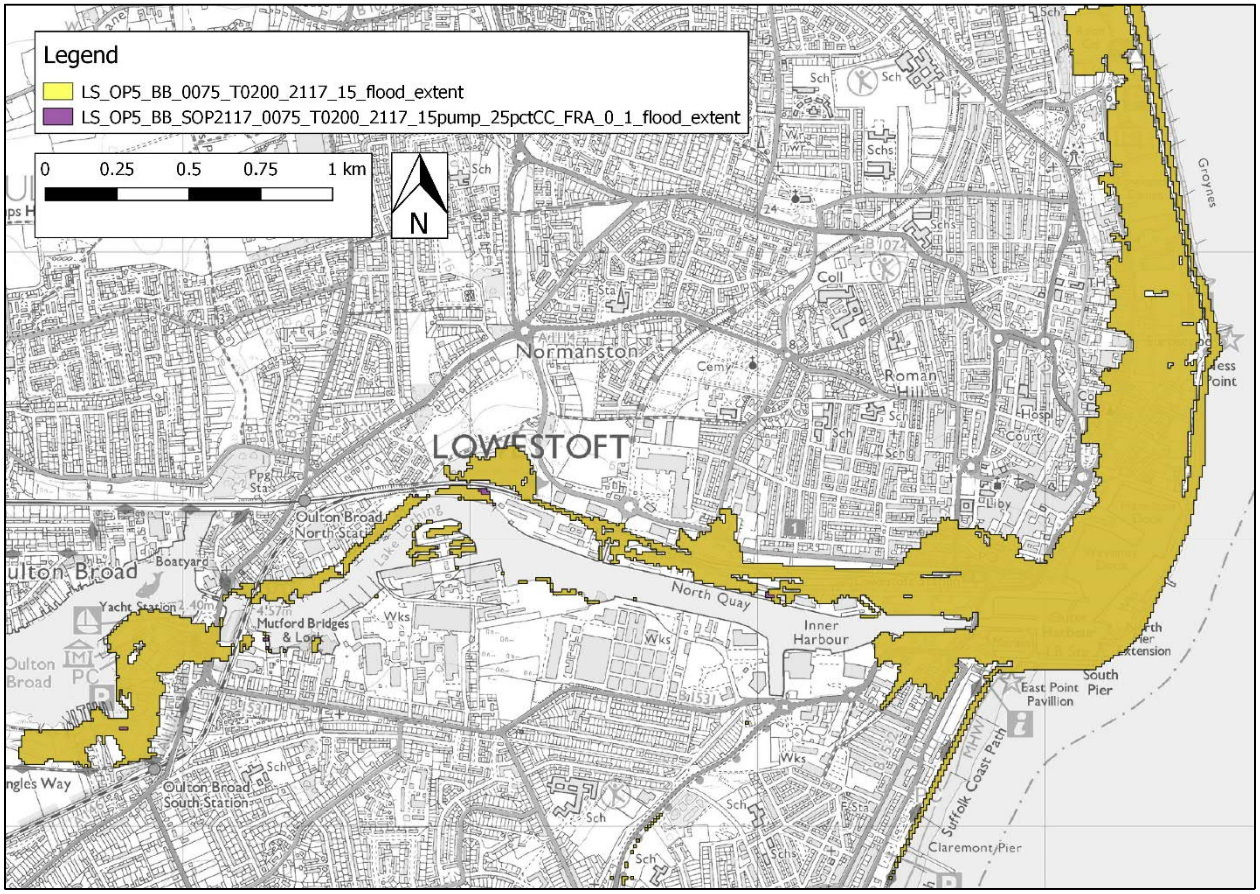

Figure 8: Stage results (mAOD) for Option 5 with an SoP of 1 in 75 year/ 1.33% AEP in 2117 and a tidal event of 1 in 200 year/ 0.5% AEP in 2117 in the model with bed level at -1.5 mAOD and model with bed level at -1.5 mAOD, 1 in 10 year pump (10% AEP) (plus 25% climate change) and dry dock levels.

The addition of a pump and dry dock levels therefore does not change the results of the model to the point of requiring the economics of the options to be re-done.

The Do nothing/ minimum 1 in 20 year/ 5% AEP results showed oscillations in the maximum stage results near to the pump. This was in the order of 2 cm (see Figure 9) and therefore deemed acceptable/ within modeling tolerance considering that the flood extents correlated well (see above) to the OBC model. The water colour gradient was manually picked and therefore the levels specified on the legend do not represent the water level across the model.

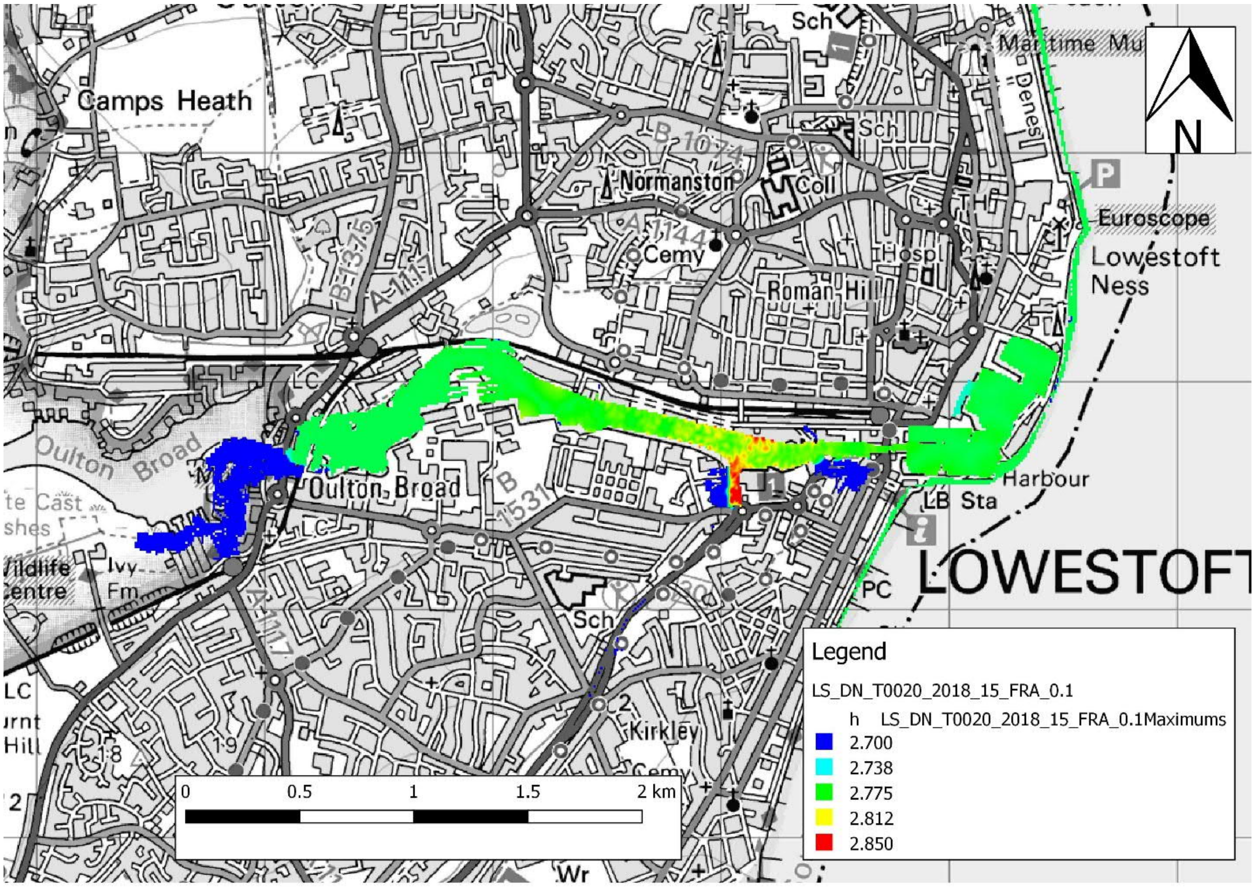

Figure 9. Stage results(mAOD) for the Do nothing/ minimum 1 in 20 year/ 5% AEP event with the 1 in 10 year/ 10% AEP pump, dry dock levels and bed level set at -1.5 mAOD.

4.3 Comparison with OBC results

Option results

A comparison between the OBC flood extents and flood extents derived using the newly developed model was undertaken. Results were found to be largely similar, especially for the proposed option scenario the largest change from the original in terms of flood extent in area being +0.03 km^2. See

Table: 1 and

Table: 2.

Table: 1. Area difference between original model set at a bed level of -1.5 mAOD and the model modified as per section 1 of this document for option 5 with an SoP of 1 in 75 year/ 1.33% AEP. A – sign indicates that the model with the bed level set at -6.2 mAOD was smaller in flood extent. A + sign indicates that the modified model with bed level at 6.2 mAOD was larger in flood extent.

	Option 5 SoP 1 in 75 year/ 1.33% AEP with a tidal event of 1 in 20 year/ 5% AEP present day.	Option 5 SoP 1 in 75 year/ 1.33% AEP with a tidal event of 1 in 75 year/ 1.33% AEP present day.	Option 5 SoP 1 in 75 year/ 1.33% AEP with a tidal event of 1 in 200 year/ 0.5% AEP present day.	Option 5 SoP 1 in 75 year/ 1.33% AEP with a tidal event of 1 in 20 year/ 5% AEP in 2117.	Option 5 SoP 1 in 75 year/ 1.33% AEP with a tidal event of 1 in 75 year/ 1.33% AEP in 2117.	Option 5 SoP 1 in 75 year/ 1.33% AEP with a tidal event of 1 in 200 year/ 0.5% AEP in 2117.
Area difference (km^2)	-0.001	-0.001	-0.002	+0.001	+0.002	+0.031

Table: 2. Area difference between original model set at a bed level of -1.5 mAOD and the model modified as per section 1 of this document for Option 5 with an SoP of 1 in 200 year/ 0.5% AEP. A – sign indicates that the model with the bed level set at -6.2 mAOD was smaller in flood extent. A + sign indicates that the modified model with bed level at 6.2 mAOD was larger in flood extent.

	Option 5 SoP 1 in 200 year/ 0.5% AEP with a tidal event of 1 in 20 year/ 5% AEP present day.	Option 5 SoP 1 in 200 year/ 0.5% AEP with a tidal event of 75 year/ 1.33% AEP present day.	Option 5 SoP 1 in 200 year/ 0.5% AEP with a tidal event of 1 in 200/ 0.5% AEP year present day.	Option 5 SoP 1 in 200/ 0.5% AEP year with a tidal event of 1 in 20/ 5% AEP year in 2117.	Option 5 SoP 1 in 200 year/ 0.5% AEP with a tidal event of 1 in 75 year/ 1.33% AEP in 2117.	Option 5 SoP 1 in 200 year/ 0.5% AEP with a tidal event of 1 in 200 year/ 0.5 % AEP in 2117.
Area difference (km^2)	-0.001	+0.001	0	+0.006	+0.002	+0.002

<u>Do minimum Results</u>

The Do minimum change was larger than when compared to the OBC flood extents. The largest change was -0.219 km^2. Therefore, the bed level and patch in the do minimum was resulting in a smaller flood extent. This was investigated further.

National Receptors Database (NRD) data was cleaned to remove upper floors. All Multi Coloured Manual (MCM) codes were left in. This resulted in fewer properties (although this would include MCM codes not counted in the economics) in the model with the lowered bed level and roughness patch. See Table: 3. In addition, property depth thresholds were not taken into account and therefore the difference may be smaller than reported in this note.

Table: 3. Property difference between model set at bed level -1.5 mAOD and model with modifications as listed in section 1. All properties are less in the model with the bed level set to -6.2 mAOD.

	Do nothing/ minimum tidal event of 1 in 20 year/ 5% AEP present day.	Do nothing/ minimum tidal event of 1 in 75 year/ 1.33% AEP present day.	Do nothing/ minimum tidal event of 1 in 200 year/ 0.5% AEP present day.	Do nothing/ minimum tidal event of 1 in 20 year/ 5% AEP 2117.	Do nothing/ minimum tidal event of 1 in 75 year/ 1.33% AEP 2117.	Do nothing/ minimum tidal event of 1 in 200 year/ 0.5% AEP 2117.
Difference in properties	-1	-113	-57	-34	-118	-330

The modified model with the bed level at -6.2 mAOD showed a decrease in properties flooding. This was due to an increase in head loss through Bascule Bridge of approximately 10 cm (compared to the equivalent -1.5 mAOD model run). This decreased level was leading to less flooding north of the Lowestoft Railway Station and in the Kirkley Stream area.

Therefore, the model with the bed level lowered and the roughness patch (which was necessary to run the model), was resulting in fewer properties being flooded in the do nothing/ minimum scenario. This is can be attributed to the roughness patch slowing water down in the Harborside which is increasing head loss through Bascule Bridge and thus lowering water level in the east Lake Lothing.

On the whole (as there were differences through Bascule Bridge as discussed above), the water levels between the model at -1.5 mAOD and -6.2 mAOD were similar. A point to the east of Bascule Bridge; approximately at 654767.9, 292708.7, was used to spot check water level results. The maximum difference was 3 cm. This was deemed to be within modelling tolerance and also showed that a bed level change of 4.7 m did not result in a large change of modelled water level output. See Table: 4.

Table: 4. Water level comparison between the model set at bed level of -1.5 mAOD and model with the modifications in section 1. Water levels (mAOD) were taken at the approximate co-ordinates of 654767.9, 292708.7. Water levels were rounded to 2 decimal places. + indicates the model with -6.2 mAOD has higher water levels. – indicates lower levels.

Scenario	Modified model (-6.2 mAOD) water level (mAOD). Note this also contained the Kirkley pump inflow.	Original model (-1.5 mAOD bed level) water level (mAOD).	Difference in water level (m).
Do nothing/ minimum present day 1 in 20 year/ 5% AEP.	2.76	2.76	0.00
Do nothing/ minimum present day 1 in 75 year/ 1.33% AEP.	3.08	3.08	0.00
Do nothing/ minimum present day 1 in 200 year/ 0.5% AEP.	3.31	3.32	-0.01
Do nothing/ minimum, 2117, 1 in 20 year/ 5% AEP.	3.41	3.44	-0.03
Do nothing/ minimum, 2117, 1 in 75 year/ 1.33% AEP..	3.70	3.72	-0.02
Do nothing/ minimum, 2117, 1 in 200 year/ 0.5% AEP.	3.93	3.94	-0.01
Option 5 present day with SoP of 1 in 200 year/ 0.5% AEP, with a 1 in 20 year/ 5% AEP tidal event.	2.77	2.78	-0.01
Option 5 2117 with SoP of 1 in 200 year/ 0.5% AEP, with a 1 in 200 year/ 0.5% AEP tidal event.	4.19	4.19	0.00
Option 5 2117 with SoP of 1 in 75 year/ 1.33% AEP, with a 1 in 200 year/ 0.5% AEP tidal event.	3.91	3.90	+0.01

5.0 Conclusions

The amendments kept are as follows:

- Pump added at Kirkley Ham with a 1 in 10 year/ 10% AEP inflow applied to represent inflows from Kirkley Stream (for present day; an uplift for climate change runs of 25% will be applied),
- Introduction of level changes around a dry dock in the north west of Lake Lothing.

It was found that the model would not run and required further modifications to get results that were consistent for the bed level lowering. These modifications were halving the time step and including a roughness patch that covered the entire harbor area. A smaller roughness patch was tested and this did not produce realistic stage results.

The Option 5 scenario with the roughness patch added and bed level lowered produced realistic spatial trends and matched the model with bed level at -1.5 mAOD in terms of which return period the walls were overtopped in.

Do nothing/ minimum resulted in less properties as a result of the roughness patch; which was a necessity to be able to run the bed level at -6.2 mAOD. This was due to the water being slowed in the harbor which increased the head loss through Bascule Bridge by 10 cm (compared to an equivalent model run with -1.5 mAOD). This resulted in a smaller flood extent especially around the Kirkley Stream area and north of the rail way station. Both head loss values for the models with different bed levels were not unfeasible. The head loss change of 30 cm, for the model with the bed level set at -1.5 mAOD, through Bascule Bridge with a Do nothing/ minimum 1 in 200 year/ 0.5% AEP event in 2117, however, seemed more realistic than 40 cm, which was the head loss of the model with the bed at -6.2 mAOD. The property differences calculated may not reflect the values found in the economics as depth thresholds and mcm codes were not taken into account for this investigation owing to the high-level nature of this document.

The water levels spot checked increased confidence that changing the model bed level did not significantly alter the water levels that were output from both models.

The model being set at -6.2 mAOD did not produce physically realistic results without the addition of a roughness patch; which in itself is not physically realistic as it was a large area set to a mannings n roughness of 0.3. Therefore, the reality trying to be achieved by setting the bed level to -6.2 mAOD was negated through the need of a large roughness patch which slowed the water/ flood wave. Furthermore, flood models are mathematical models and not physical models; there have to be approximations for the model to run. TUFLOW uses shallow water equations. These equations do not work over large depths. By reducing the bed level to -6.2 mAOD the model could not solve these equations. This was seen in the TUFLOW instability error messages and the fact that the model required a smaller time step to run. As the model is tidally dominated (which is set at a water level) and underwater currents or advection is not being taken into account for this project; the bed level is more an arbitrary number than a number that needs to reflect the actual bed level conditions. The water levels on land are more important than the bed level and the model with the bed level set to -1.5 mAOD produced more spatially realistic trends in water level.

Therefore, owing to the fact that the model with the bed level set at -1.5 mAOD correlated well with 2013 indicative flood data (see 2014 Lowestoft modeling note; Appendix K of the main FRA); it was decided that this model should be taken forward for the FRA with the amendment of the 1 in 10 year/ 10% AEP pump (with 25% uplift for any climate change runs).

TECHNICAL MEMORANDUM

Lowestoft FRA – Modelling Technical Note

PREPARED BY:	Libby Bush
DATE:	October 1, 2018
REVISION NO.:	1
APPROVED BY:	Silvia Garattini

1.0 Introduction

1.1 Study Background

JACOBS have been commissioned by Balfour Beatty to prepare a Flood Risk Assessment (FRA) in support of the planning application of flood walls in Lowestoft. Additionally, planning permission for a flood barrier will be sought as part of the Transportation Works Act Order application. The flood barrier will be built after the completion of the flood walls and therefore the flood barrier will be added into the FRA as an additional element to address how flood risk will change in the area; a) when the flood walls are being built, b) when the flood walls are fully built and c) when the flood barrier is in place in addition to the built walls.

The exercise includes an investigation on the current tidal flood risk and in the proposed. This analysis was undertaken via the creation of several ISIS-TuFLOW 1D-2D models to compare pre- and post- development flood risk for various AEPs.

The model used for this FRA was inherited from the model used in the business case development. A review of the business case model is reported in Appendix C of the accompanying FRA.

1.2 Study Objectives

The primary study objectives of the FRA are as follows:

i. Produce flood extents for do nothing/ minimum scenario (pre-scheme)
ii. Produce flood extents for walls only scenario
iii. Produce flood extents for walls and barrier scenario (post scheme).
iv. Assess the impacts of
   - breach scenarios,
   - wave overtopping,
   - wave overtopping and seepage combined.

2.0 Hydrology

2.1 Overview of water features

The River Waveney flows into Oulton Broad. Oulton Broad is linked hydrologically to Lake Lothing through Mutford Lock. Mutford Lock is manually operated by Environment Agency staff and is normally closed. The flow from Oulton Broad is predominantly tidal as the lock would not be open in fluvial events. Oulton Broad is hydraulically connected to Great Yarmouth through the River Waveney, Breydon Water and the River Yare, meaning that tidal events at Great Yarmouth can influence water levels at Oulton.

Lake Lothing is connected downstream to the North Sea; through Lowestoft Harbour. At current there is no hydrological boundary after Mutford Lock and water in Lake Lothing and the North Sea flow freely.
Kirkley stream is a river running from south west to north east into Kirkley Ham (part of Lake Lothing; approximately 680 m west of Bascule Bridge). There is a pumping station that pumps water, during periods of high tide, into Lake Lothing. The maximum capacity of the pump is 1.2 m^3/s (JBA, 2017/18). The pumping station is operated by Anglian Water. Additionally, there is a flood storage area that takes excess flow from Kirkley Stream before it reaches the pumping station. In normal conditions, Kirkley stream discharges in Lake Lothing through a gravity outfall. Kirkley stream is classified as a 'main river' by the Environment Agency upstream of Bloodmoor Roundabout at Carlton Colville.
The schematic in Figure 1 summarises the water features listed above.

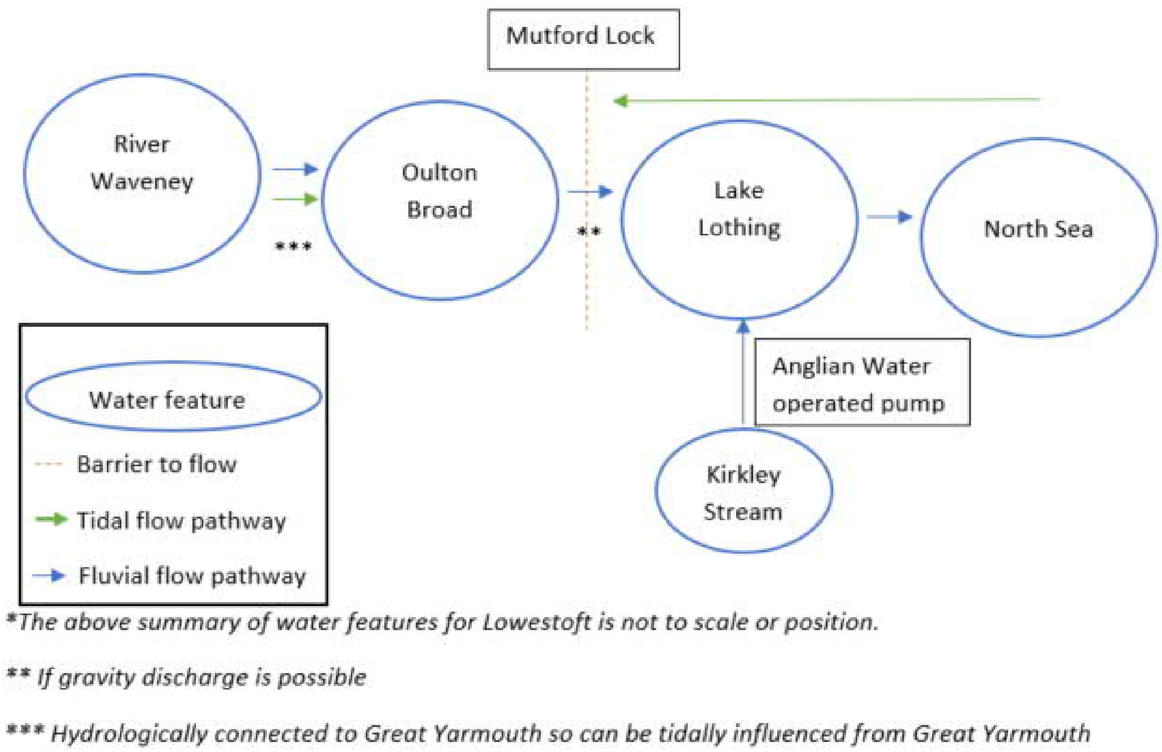

Figure 1: Key water features in Lowestoft

2.2 Fluvial inflows

During a tidal event, the only fluvial inflow to Lake Lothing is the pumped inflow from Kirkley Stream. Due to tide locking, it was assumed that there would be now flow through Mutford Lock.

The pumped inflow from Kirkley stream was extracted from the JBA 2017 Lowestoft FRMS study "2017s6113 - Lowestoft FRMS - Options Appraisal Report (Draft Rev 1)".

For the purpose of FRA modelling, it was assumed that peak flow would coincide with peak tide adopting therefore a conservative approach. A 10% AEP (1 in 10 year) event was selected on the basis of low correlation between fluvial and tidal events on the East Coast according to FD2308 (Defra, 2005). The location of the pump is shown in Figure 2.

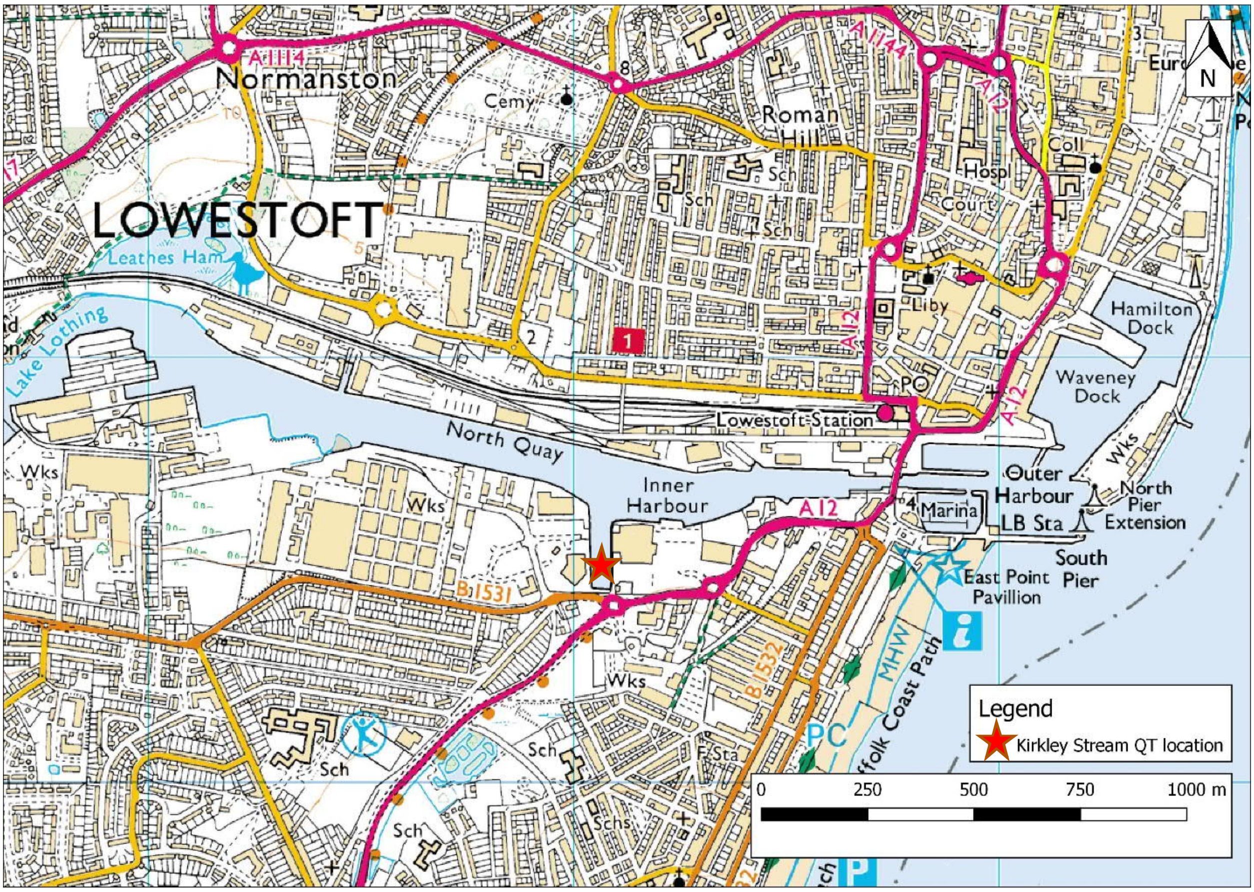

Figure 2: Location of Kirkley pump inflow.

The 10% AEP Kirkley Stream pump inflow-time series is shown below in Figure 3. This was added in all scenarios both pre- and post- scheme. For the walls and barrier scenario, breach and wave overtopping.

Please note that the Kirkley Stream pump inflows were added into the Lake Lothing reservoir unit as a flow-time boundary in ISIS, owing to the different schematization of Lake Lothing.

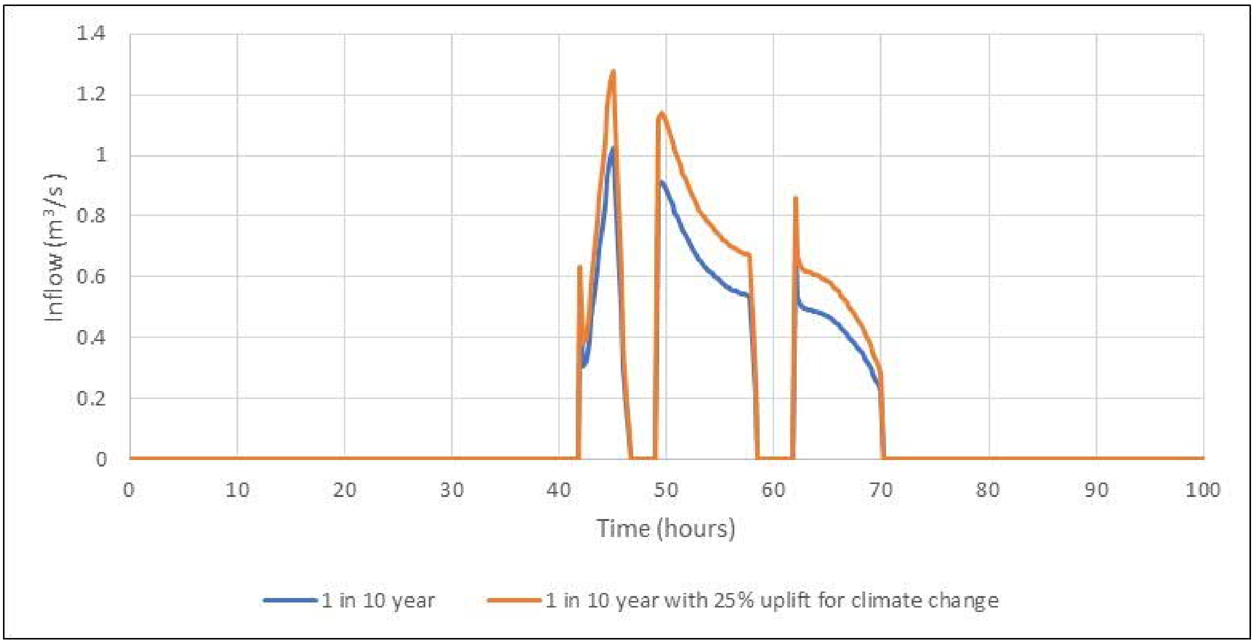

Figure 3: Inflows for the 10% AEP Kirkley Stream pump taken from JBA (2017). Timing of onset has been modified to match the peak of the tidal events in the model.

2.3 Fluvial climate change allowances

For fluvial inflow from Kirkley Stream a 25% uplift was applied for the epoch 2117 to account for climate change. This was applied to every model run/ scenario. Allowances were extracted from the relevant National Planning Policy Framework (NPPF) guidance (https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances) for the Anglian Region.

3.0 Tidal boundaries and overtopping

3.1 Tidal boundaries

The extreme water levels for Lowestoft and Great Yarmouth were taken from the latest East Coast tidal modelling (JBA, 2015- still under development). Relative sea level rise data for Lowestoft was taken from the NPPF website- see Table 1. The obtained Sea Level Rises (SLR) were used to update water levels obtained from the JBA modelling work (2015) for future years.

Table 1: NPPF rate of sea level rise (m/year) for East, east midlands, London and South East.

	Beginning/ end year			
	1990	2026	2056	2086
	2025	2055	2085	2115*
Rise per year (m/ year)	0.004	0.0085	0.012	0.015

*2115 to 2117 was taken to also be 0.015 m per year.

The peak tidal stages are as summarized in Table 2. The applied hydrographs are displayed in Figure 4 to Figure 7.

Table 2: Peak tidal stages for the 2018 and 2117 epochs at Great Yarmouth and Lowestoft.

	Peak stage (mAOD)

	T0020 2018	T0020 2117	T0075 2018	T0075 2117	T0200 2018	T0200 2117	T1000 2018	T1000 2117
Great Yarmouth	2.87	4.01	3.24	4.38	3.54	4.67	4.07	5.21
Lowestoft	2.76	3.90	3.13	4.27	3.43	4.57	3.93	5.07

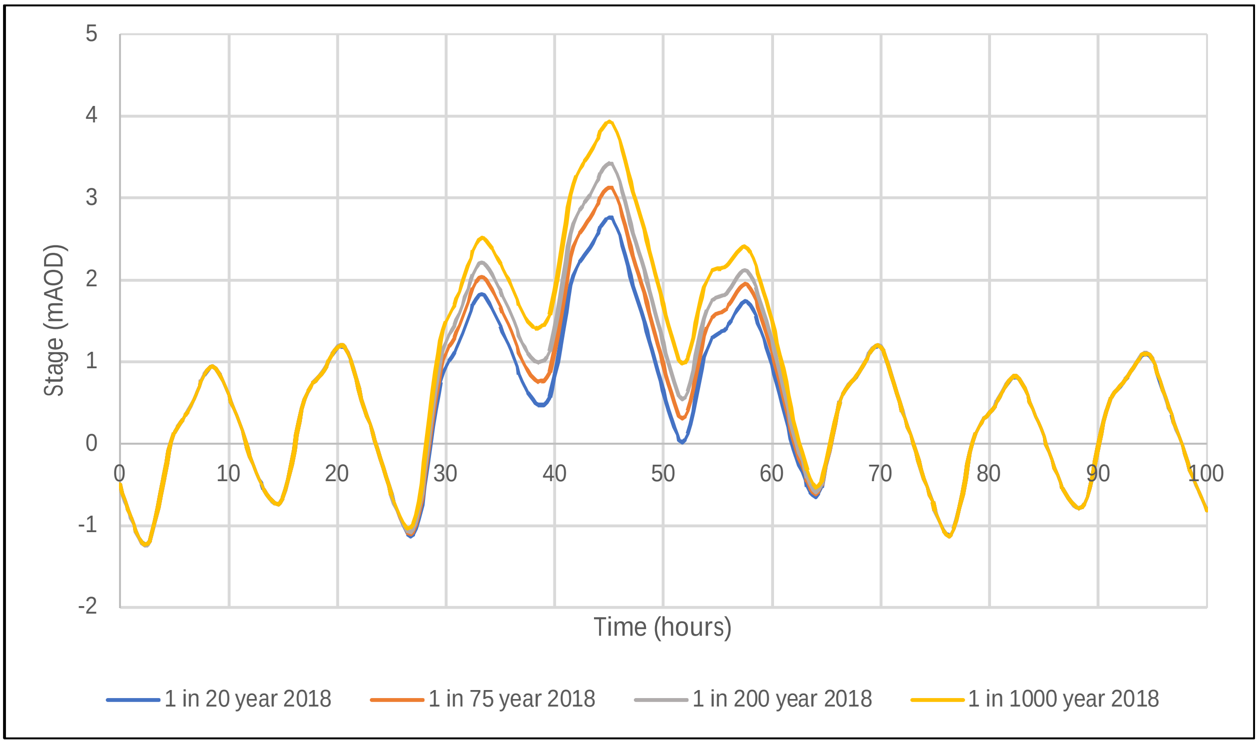

Figure 4. Tidal water level time series for Lowestoft in 2018.

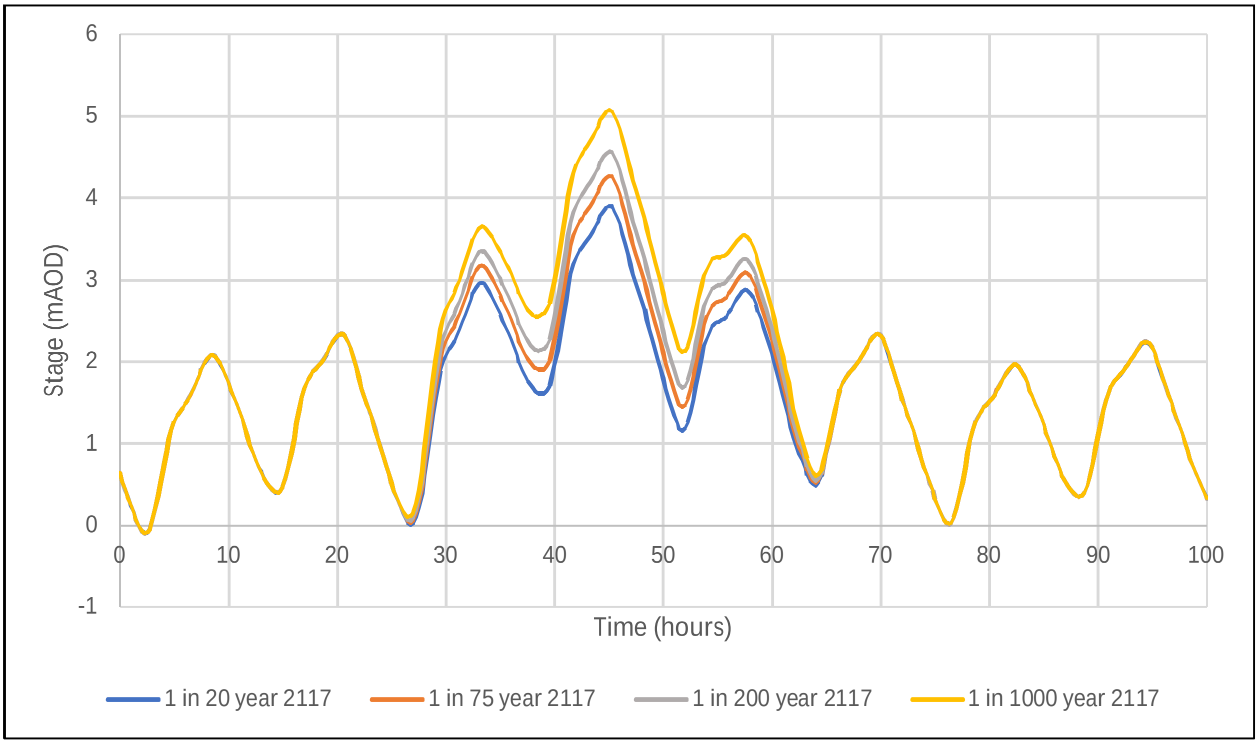

Figure 5. Tidal water level time series for Lowestoft in 2117.

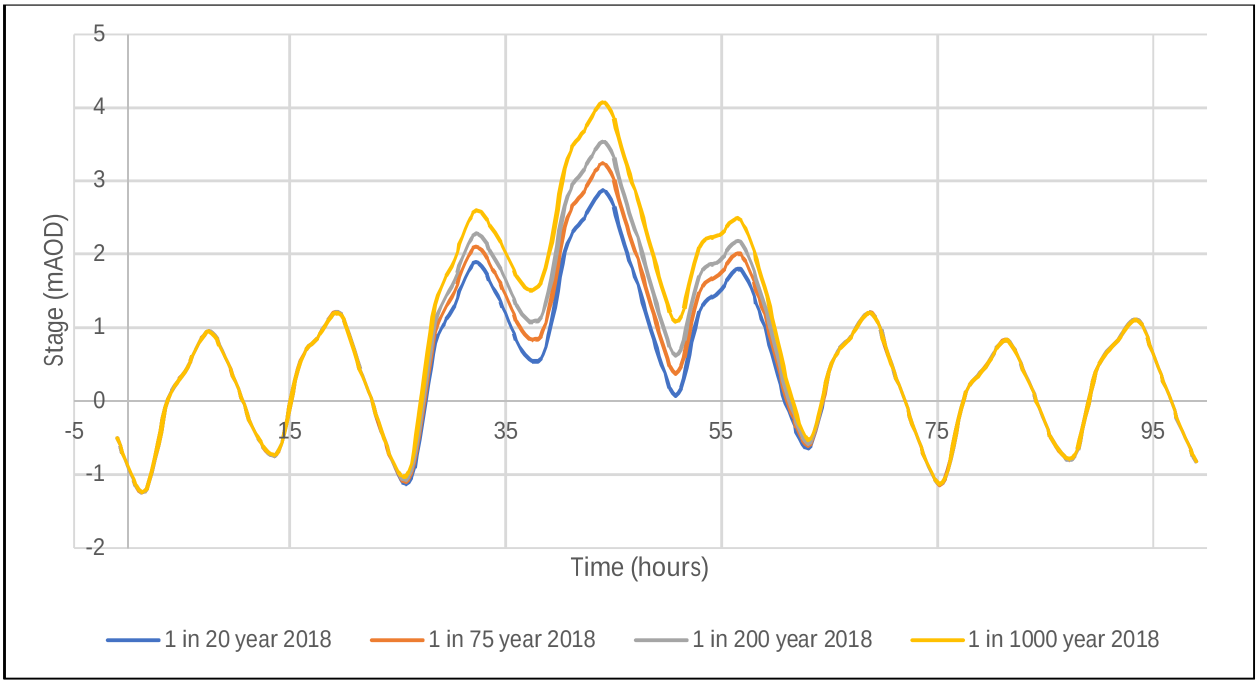

Figure 6. Tidal water level time series for Great Yarmouth in 2018.

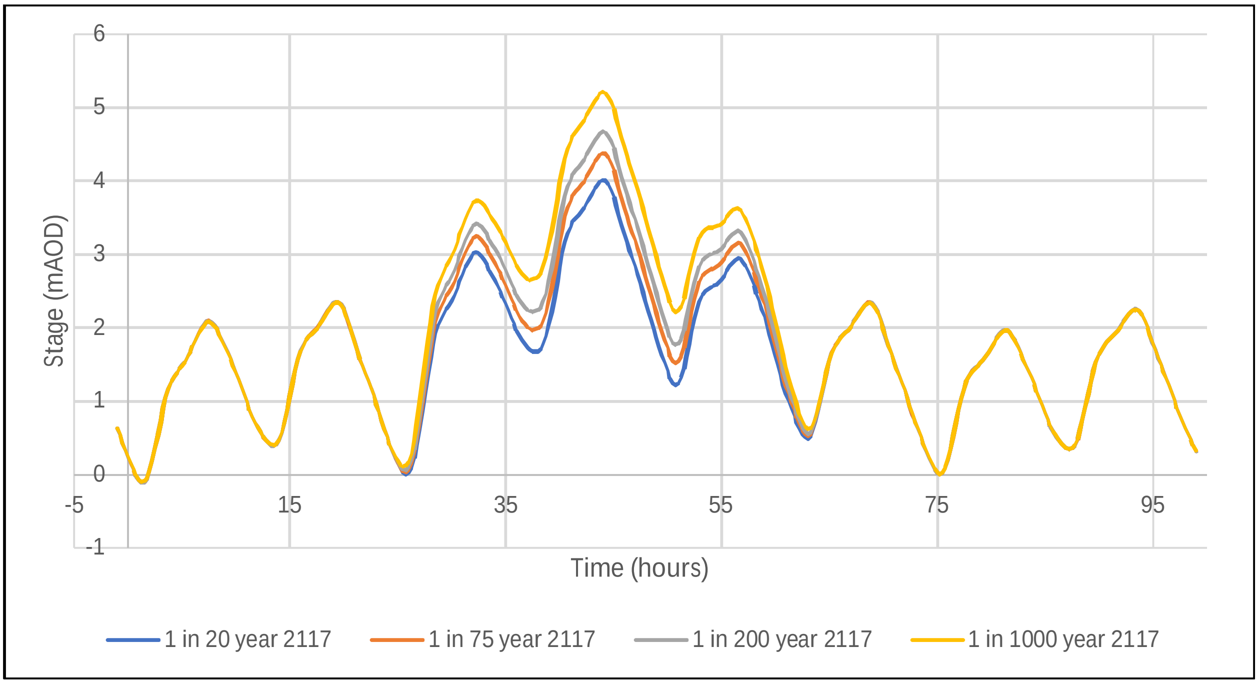

Figure 7. Tidal water level time series for Great Yarmouth in 2117.

3.2 Wave overtopping

Following consultation of FD2308, it was assessed that there is a high correlation between tidal surges and wind-generated waves along the East Coast near Lowestoft. Wave overtopping rates for the flood walls were estimated using the appropriate 2016 EurOtop guidance for the entire life of the structure (see accompanying 676284-CH2-DZ-300-MO-HY-0001, part of the detailed design package). The analysis considered overtopping of the flood walls along Yacht Basin, Trawler Dock and Hamilton Road. See Figure 8 for location. It was concluded that no overtopping of the flood walls would occur in 2018. Owing to the predominant wind direction, the flood wall along Hamilton Road would also not experience any overtopping.

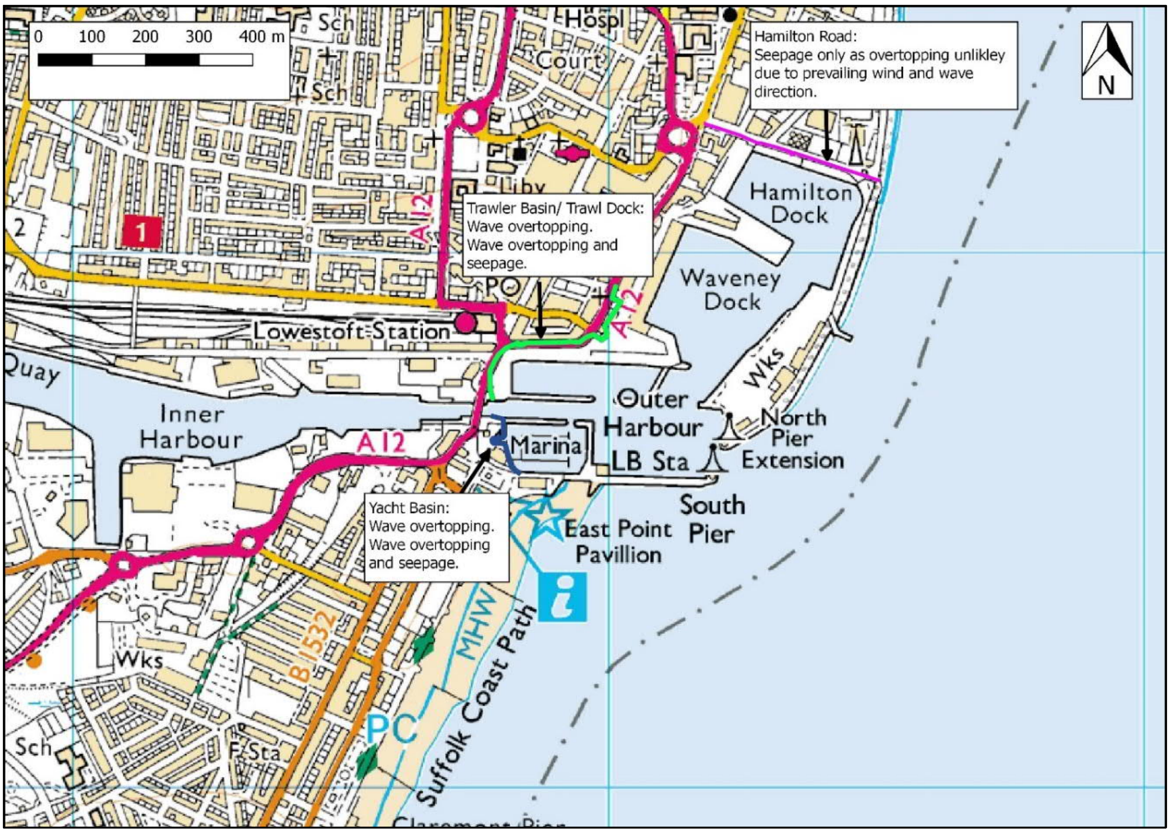

Figure 8. Location of wave overtopping and seepage.

For the purpose of FRA modelling, wave overtopping was applied as a sensitivity test to the 'walls and tidal barrier' scenario only to evaluate the extent of flooding due to wind-generated waves. Inclusion of overtopping in the 'walls only' scenario was deemed too conservative and unnecessary as flooding associated with wave overtopping would be far smaller than flooding associated with the tidal surge. Similarly, wave overtopping for the 'walls and tidal barrier' scenario was applied only if the walls were not being overtopped by still water levels.

Overtopping rates, associated still water levels are summarised in Table 3 (2070) and Table 4 (2117). It can be noted that overtopping rates in 2070 are more severe than the 2117 equivalent; this is due to level of the walls being lower than the 2117 epoch. The resulting overtopping volumes for the FRA modelling are included in Table 5. Please note that the volumes refer to the 0.5% AEP event (in 2070 and 2117), as the 0.1% AEP event water level was already causing overtopping of the walls.

Please note that the following assumptions were made for this FRA and differ from 676284-CH2-DZ-300-MO-HY-0001 assumptions:

- Still water levels considered for wave overtopping were amended to reflect different SLR allowances being used for planning. This was implemented by increasing the design still water levels with the difference between the appraisal and planning allowances. Note, this should not affect the amount of water overtopping the defences.
- minimum overtopping rates for Yacht Basin and Trawl Dock were increased to be an average between the minimum and max rates reported in 676284-CH2-DZ-300-MO-HY-0001; this is a conservative assumption deemed more representative of wave overtopping for the 'intermediate water levels' not explicitly accounted in 676284-CH2-DZ-300-MO-HY-0001.
- Overtopping of Yacht Basin was assumed to happen only for 165m of the proposed flood walls as the southern section will be raised to avoid wave overtopping.
- The existing drainage system was assumed to be completely full and have no available capacity.

The assumptions above were discussed and agreed with the design team and are considered a worst-case scenario for this FRA. It should therefore be noted that flood extents associated with wave overtopping are likely to be a conservative estimate.

Table 3: 2070 overtopping rates.

FRA still water levels (mAOD)	Yacht Basin rate (l/s/m)	Trawl Dock (l/s/m)
4.35	0.36	0.02
4.57	0.78	0.06

Table 4: 2117 overtopping rates.

FRA still water levels (mAOD)	Yacht Basin rate (l/s/m)	Trawl Dock (l/s/m)
3.69	0.57	0.21
3.91	0.70	0.50

Table 5: Wave overtopping volume for the 0.5% AEP event divided per epoch and location.

Location	Volume of wave-overtopping in 2070 (m^3)	Volume of wave-overtopping in 2117 (m^3)
Yacht Basin	848	490
Trawl Dock	574	58

4.0 Seepage

Similarly, to what was done for the wave overtopping, the volume of water from seepage beneath the walls was estimated for the detailed design of the scheme (ref. 676284-CH2-ZZ-ZZZ-TN-GT-0001-S1-P01, currently under development).

Seepage rates were provided for Hamilton Road, Yacht Basin and Trawl Dock. The rates for each of the considered stretches are summarised in Table 6. Rates provided refer to the upper bound permeability value and were calculated using 2117 water levels. 2070 rates were not provided but these will be lower than 2117 rates. Similarly, if characteristic permeability values were considered (rather than upper bound), seepage rates would be reduced by a factor of 0.1. At Hamilton Road the seepage analysis was also undertaken with the characteristic permeability values taken into consideration to highlight the difference in comparison to using upper bound. The analysis considers steady state conditions (i.e. ground water response is immediate – no tidal lag considered). This is consistent with what was observed in groundwater monitoring undertaken as part of the stage 1 ground investigation during which minimal lag observed.

For the FRA modelling, seepage volumes (Table 7) were calculated only for the ‘walls and tidal’ barrier scenario for the same reasons reported in section 4.2.2. Seepage volumes were generally found to be smaller than wave overtopping volumes but within the same order of magnitude. The combined volume of seepage and wave overtopping was also estimated as a worst case scenario.

As per the wave overtopping, seepage volumes estimated in this paragraph are likely to be a conservative estimate of what would actually occur.

Table 6: Seepage rates for stretches considered.

FRA still water levels (mAOD)	Rate at Hamilton Road (l/s/m)	Rate at Yacht Basin (l/s/m)	Rate at Trawl Dock (l/s/m)
3.10*	0.02	0.03	0.02
4.65	0.06	0.09	0.07

*average ground level behind the walls

Table 7: Seepage volume and combined seepage/ wave overtopping volumes.

	Hamilton Road		Yacht Basin		Trawl Dock	
	2070	2117	2070	2117	2070	2117
Seepage volume (m^3)	139	315	98	223	148	336
Combined seepage and wave overtopping (m^3)	139	315	946	713	722	394

4.1 Seepage and wave overtopping

The seepage and wave overtopping resulted in a total volume of water. These were added together in the case of Yacht and Trawler Basin.

The 0.5% event was chosen as the event to analyse flood extent of seepage and wave overtopping combined. Analysis of wave overtopping and seepage for lower AEPs (e.g. 0.1% AEP) was not considered necessary, as the volume flood water from the tidal event would be much higher than the overtopped/ seepage volume. For lower severity events (e.g. 5% AEP), wave overtopping of the walls was also not occurring. The final volumes (net total) are shown in Table 8.

Table 8: total volumes of water from wave overtopping and seepage.

	Hamilton Road		Yacht Basin		Trawl Dock	
	2070	2117	2070	2117	2070	2117
Seepage volume (m^3)	139	315	98	223	148	336
Combined seepage and wave overtopping (m^3)	139	315	946	713	722	394

5.0 Hydraulic model

The model of Lowestoft harbor is 1D/2D model built in FloodModeller/ TUFLOW (Figure 9). The model was built by CH2M in 2014 and was used to derive damages from tidal sources for the strategic outline case (SOC) and outline business case (OBC) for Lowestoft.

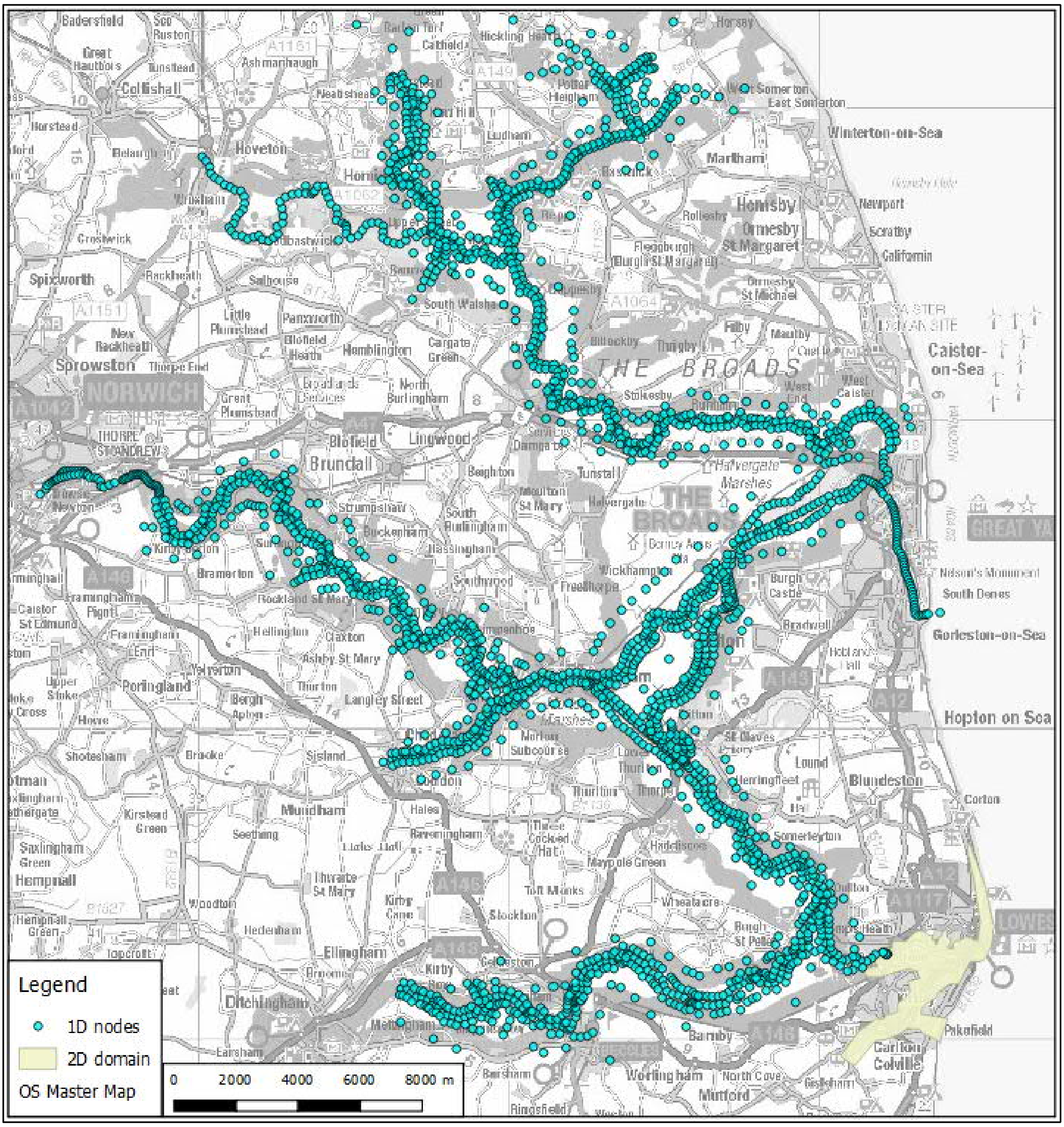

Figure 9. Extent of 1D and 2D domains.

The 1D model domain covers the whole extent of the Broadlands system. The model is hydro-dynamically linked at Mutford Lock to a 2D domain at Lowestoft.
Model boundaries consist of tidal head-time boundaries at Lowestoft and Great Yarmouth, and fluvial baseflows at numerous locations within the Broads.
A 2D grid resolution of 10m (2015) was used for the urban area of Lowestoft; this allows a reasonable level of detail whilst keeping run times practical.

See model log (Appendix I of this FRA) for list of dat file, tgc and tbc used for each scenario.

5.1 Do nothing/ minimum

To represent the do nothing/ minimum scenario, the business case pre-scheme model was modified as described in Section 5.0 of the 'Lowestoft Modelling Validation Note' (Appendix C of this FRA).

No formal defences were included in the model as no formal defences are currently in place in Lowestoft. Do nothing is a baseline comparison to the scheme and represents the situation if it were left as it currently is. In text it may sometimes be referred to as Do minimum as the Do minimum scenario is considered the same owing to the lack of formal defences and therefore there are no defences to maintain.

5.2 Walls only

The walls only models used the same representation of the do nothing/ minimum with the difference being the walls included in the model as a z-line in the following locations:

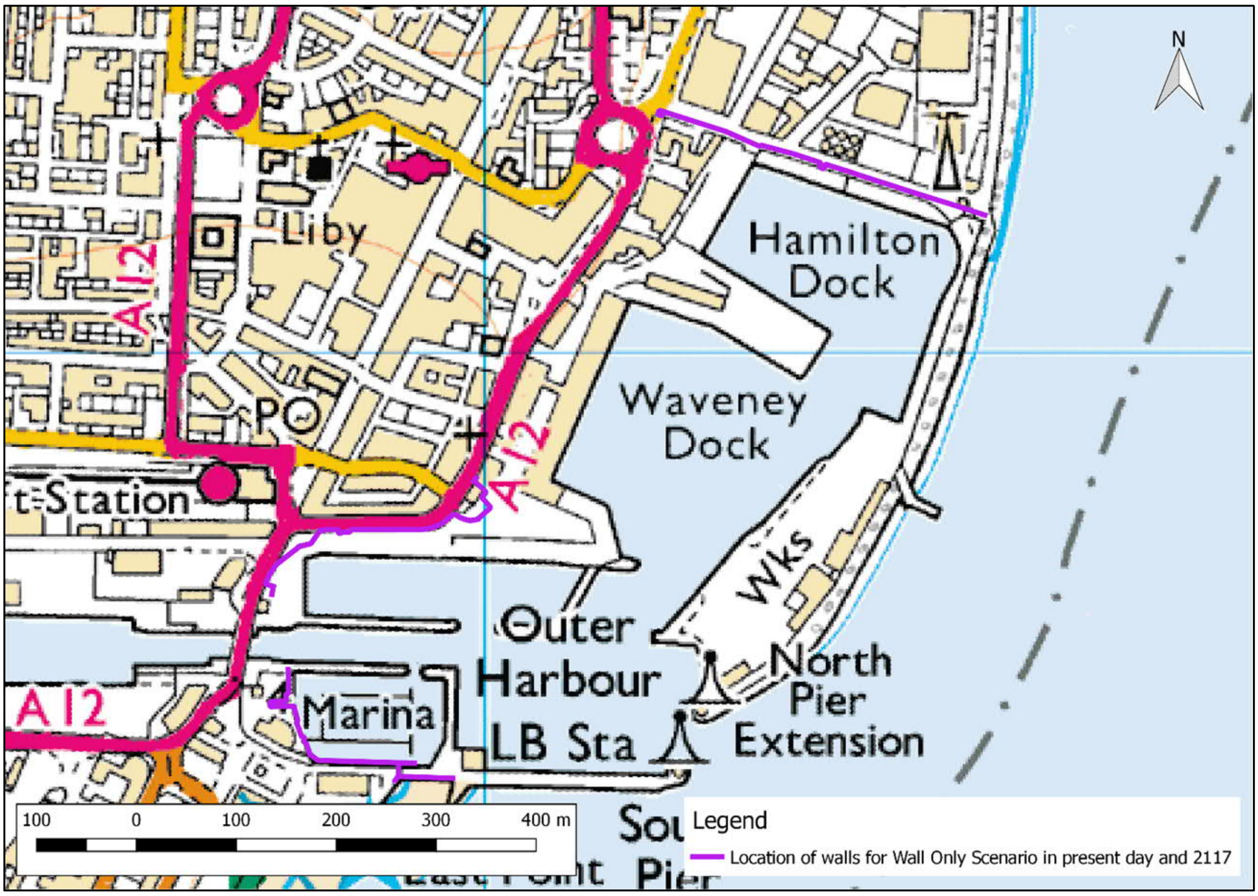

Figure 10. Location of walls in the walls only scenario.

The height of the walls were different in 2018 than 2117 as the walls will be raised to account for climate change. The wall height in 2018 is to provide a SoP of 0.5% in 2070 and the wall height in 2117 is set to provide a SoP of 0.5% in 2117. See Table 9 for level of wall in present day and 2117. The level of the walls provided include freeboard allowances.

Table 9: Level the walls are set to in 2018 and 2117.

Wall height (mAOD)	
2018	2117
4.10	4.65

5.3 Walls and tidal barrier

The 'walls and tidal barrier' scenario (full scheme) used a different schematization of Lake Lothing to the 'do nothing' and 'walls only' model. To ensure the rule of opening/ closing the tidal barrier could be fully represented in the model, Lake Lothing was represented in 1D only and not 2D.

The walls and barrier were located as shown in Figure 11. The barrier was set to the height of the walls as per Table 9.

Figure 11. Location of walls and barrier in the walls and barrier scenario.

5.4 Breach

The breach model was created using the 'walls and barrier' model as a starting point.

Breach locations were selected following consultation with the design team to understand the most likely locations for a breach. See Figure 12 for wall breach locations.

The walls were assumed to be breaching in the 40th hour of the model run. This was chosen as the breach time as the water level reached half that of the height of the wall at this time, as per breach guidance (National Breach Guidance/ Modelling and Forecasting Technical Guidance Note, 2017 (EA)).

The breach was set to the toe of the wall and it was assumed it would remain open for the remainder of the model run (up until 100 hours model time). The breach was not repaired using a conservative approach and also assuming that, once the peak tide had occurred, access could be difficult.

The breaches were 20-40 m wide; following breach guidance (National Breach Guidance/ Modelling and Forecasting Technical Guidance Note, 2017 (EA)). The width was chosen to not be under the category open coast; owing to the harbor providing protection. Therefore, the estuary/ tidal river was followed category was followed.

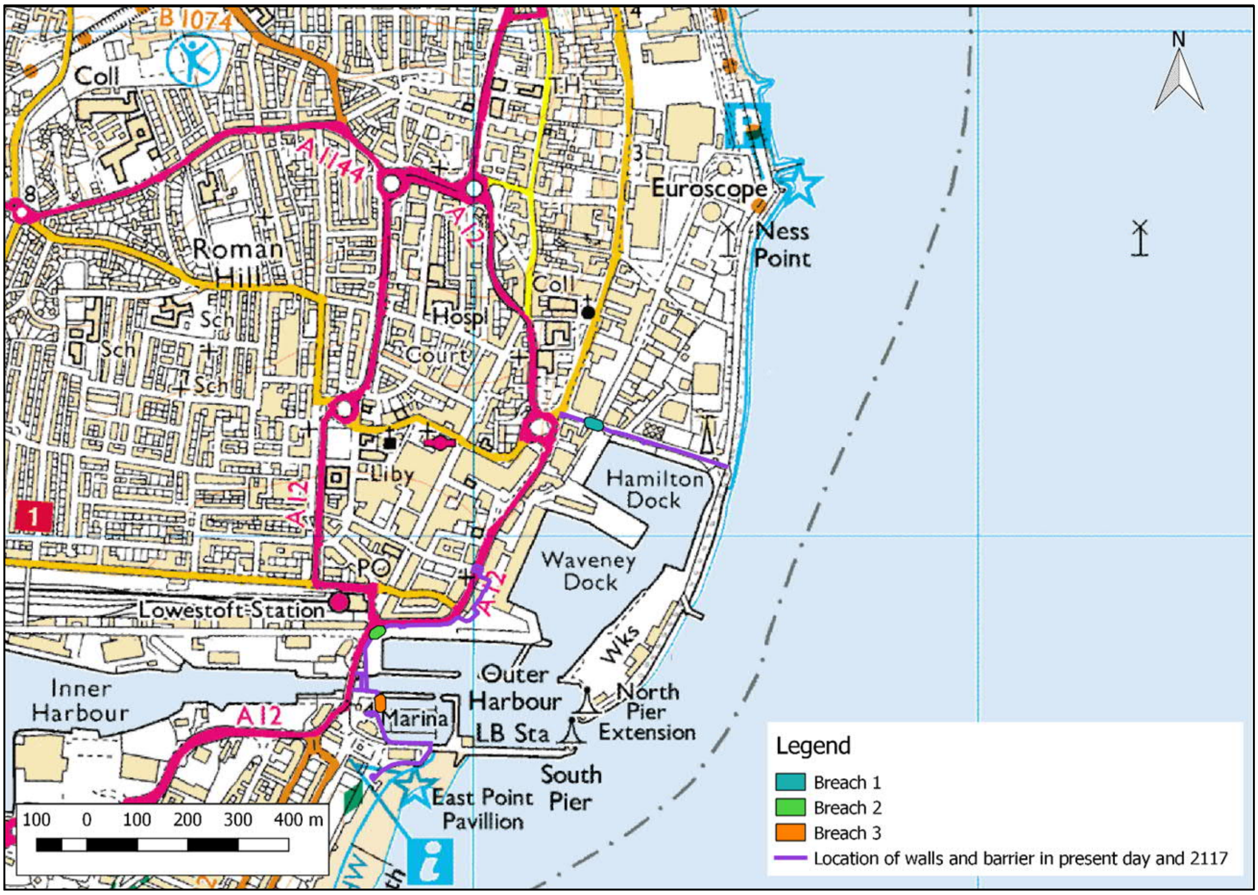

Figure 12. Location of the three breaches that were run independently.

5.5 Wave overtopping and seepage

For two events: 0.5% AEP in 2070 and 0.5% in 2117, wave overtopping and seepage were added to the 'walls and barrier' scenario as per section 3.2.

The extent of flooding due to wave overtopping/ seepage was determined through a GIS exercise (inspection of 1m LiDAR behind the defences) rather than modelling. The GIS exercise was preferred over hydro-dynamic simulations due to the grid resolution of the model (10m).

5.6 Model runs undertaken

The full set of model runs for this FRA is reported in Table 10.

Table 10: Full set of model simulations run for this FRA.

	Present day				2070	2117			
	5% AEP	1.33% AEP	0.5% AEP	0.1% AEP	0.5% AEP	5% AEP	1.33% AEP	0.5% AEP	0.1% AEP
Do minimum/ do nothing	√	√	√	√		√	√	√	√
Walls only	√	√	√	√		√	√	√	√

Walls and tidal barrier (no wave overtopping/ seepage)	√	√	√	√		√	√	√	√
Walls and tidal barrier- Breaching (x3)			√	√				√	√
Walls and tidal barrier (wave overtopping/ seepage sensitivity) *					√			√	

*GIS exercise only

5.7 Naming convention of model runs

Listed in Table 11 is first the name of present day model runs for each scenario and then in the same box listed underneath is the equivalent climate change run name.

Table 11: Naming convention for the model runs set up.

Scenario	Naming example	Key
do nothing	LS_DN_TXXXX_OOOO_15_FRA_0_1 and LS_DN_TXXXX_OOOO_15_FRA_0_1_CC	TXXXX is the tidal event run. OOOO is the epoch.
Walls only	LS_WallsOnly_TXXXX_OOOO_15_FRA_0_1 and LS_WallsOnly_TXXXX_OOOO_15_FRA_0_1_CC	TXXXX is the tidal event run. OOOO is the epoch.
Walls and barrier	LS_OP5_Walls_Barrier_SOPYYYY_TXXXX_OOOO_15pump_FRA_0_2* and LS_OP5_Walls_Barrier_SOPYYYY_TXXXX_OOOO_15pump_25pctCC_FRA_0_2*	YYYY is the SOP defence. TXXXX is the tidal event run. OOOO is the epoch.
Breach	LS_BREACHX_Walls_Barrier_SOPYYYY_TXXXX_ OOOO _15pump_FRA* and LS_BREACHX_Walls_Barrier_SOPYYYY_TXXXX_ OOOO _15pump_25pctCC_FRA*	Breach X is the breach location corresponding to 1, 2 and 3 in Figure X.

*Note that the pump added to the name refers to the Kirkley pump (see the technical note Appendix C for more details on this pump) and the _25pctCC added to the name refers to the 25% uplift on the Kirkley pump to account for climate change. However, the other model scenarios at present day all include the Kirkley pump and all other scenario climate change include the Kirkley pump with 25% uplift to account for CC as well. The only reason the other scenario model runs do not have this appended in the naming convention, like the walls and barrier and breach runs, is difference in personal naming style.

6.0 Model proving

6.1 Model Run Parameters

All models were run for 100 hours using a 2.5 (s) timestep in the 1D element and 5 (s) in the 2D element. Theta value was changed from 0.7 to 0.55 to improve model stability/ convergence. The number of maximum iteration was also increased to 19. No other modifications were made to the default parameters.

For the 0.1% AEP 2117 event the model parameters were changed for the model to run owing to the higher water levels. In addition to model parameters the time step was also halved for 1D and 2D: 2.5 (s) to 1.25 (s) for 1D and 5 (s) to 2.5 (s) for 2D.

The changes were deemed within acceptable tolerances to ensure the model ran stably without detrimentally affecting accuracy of model results. See Table 12Error! Reference source not found. for parameters modified and the values they were modified to.

Table 12: Parameters modified for the 2117 0.1% AEP events.

Parameter	Value for all events except 0.1% AEP 2117	Values for 0.1% AEP 2117
dflood	3	5
minitr	2	5
theta	0.55	0.90
alpha	0.7	0.4*

*0.5 is normally the lower bound recommended for alpha; however due to the increased minitr the results were not affected. A test to ensure results were not affected was carried out and running alpha at 0.5 did not change the depth results/outputs of the model. The mass balance increased slightly; 0.04% in 2D.

6.2 Convergence Plot and Mass balance

The convergence plot for each scenario for the 0.5% 2117 event has been reported. All showed reasonable stability.

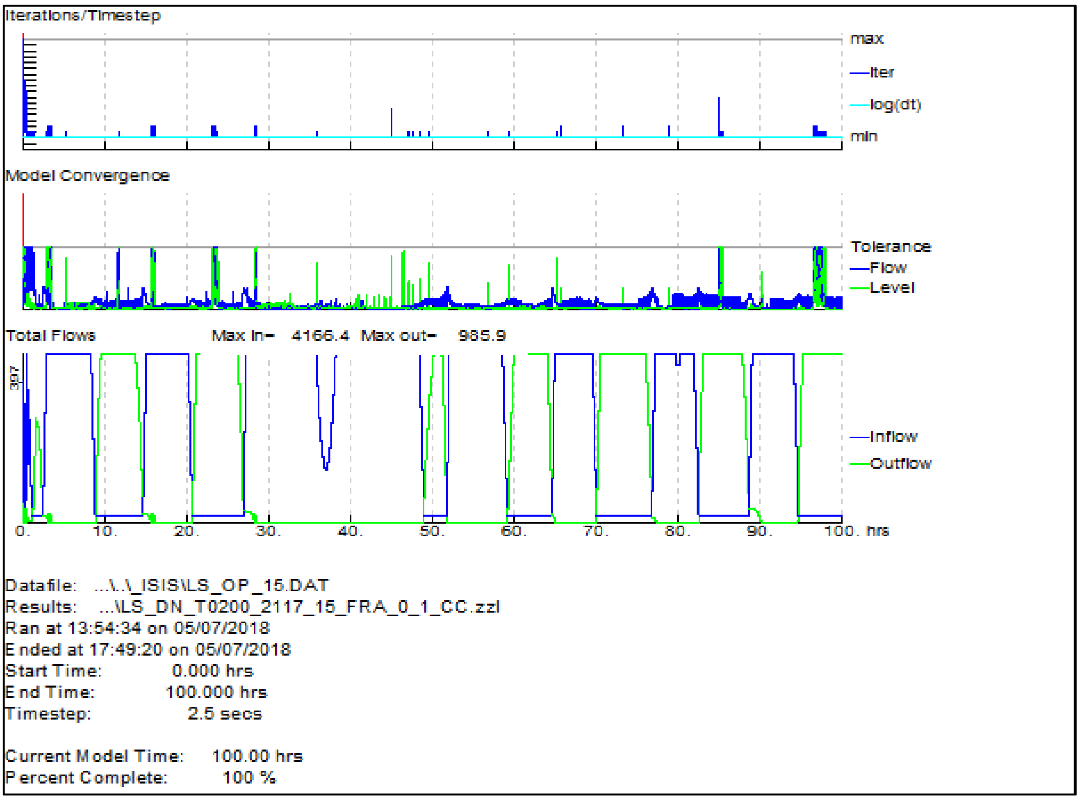

Figure 13: Do nothing/ minimum convergence plot, 0.5% AEP, 2117.

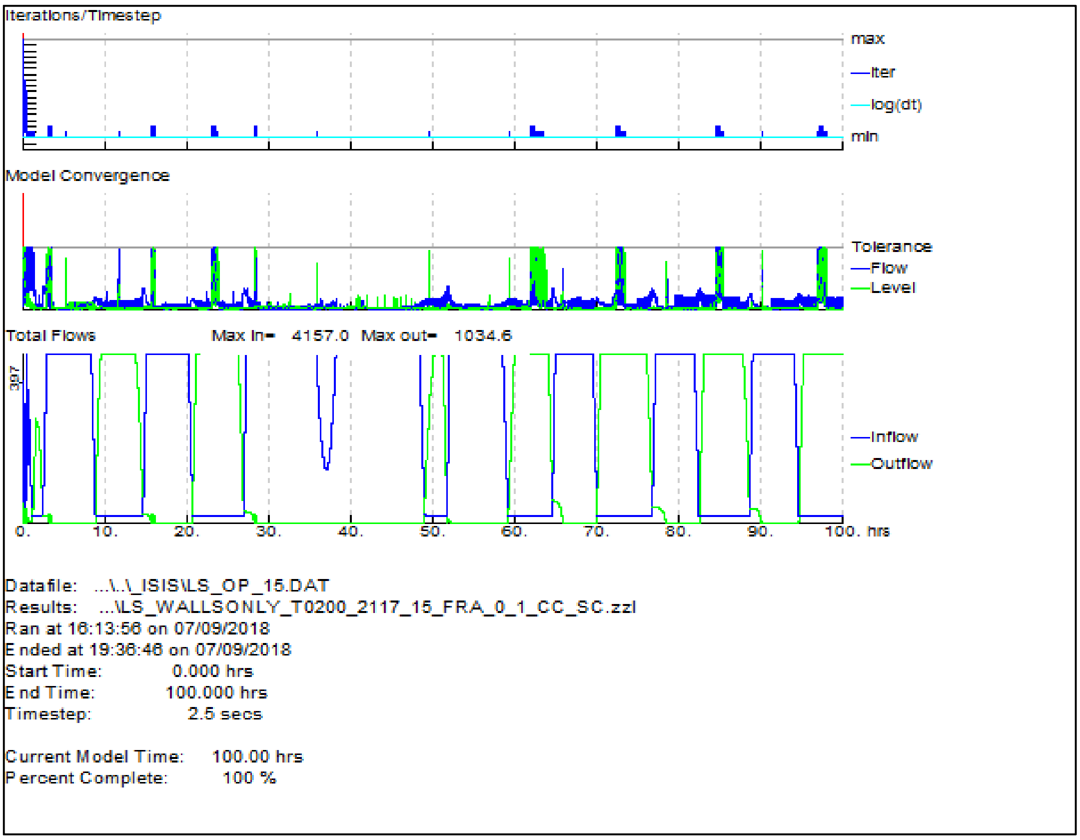

Figure 14: ‘Walls only’ convergence plot, 0.5% AEP, 2117.

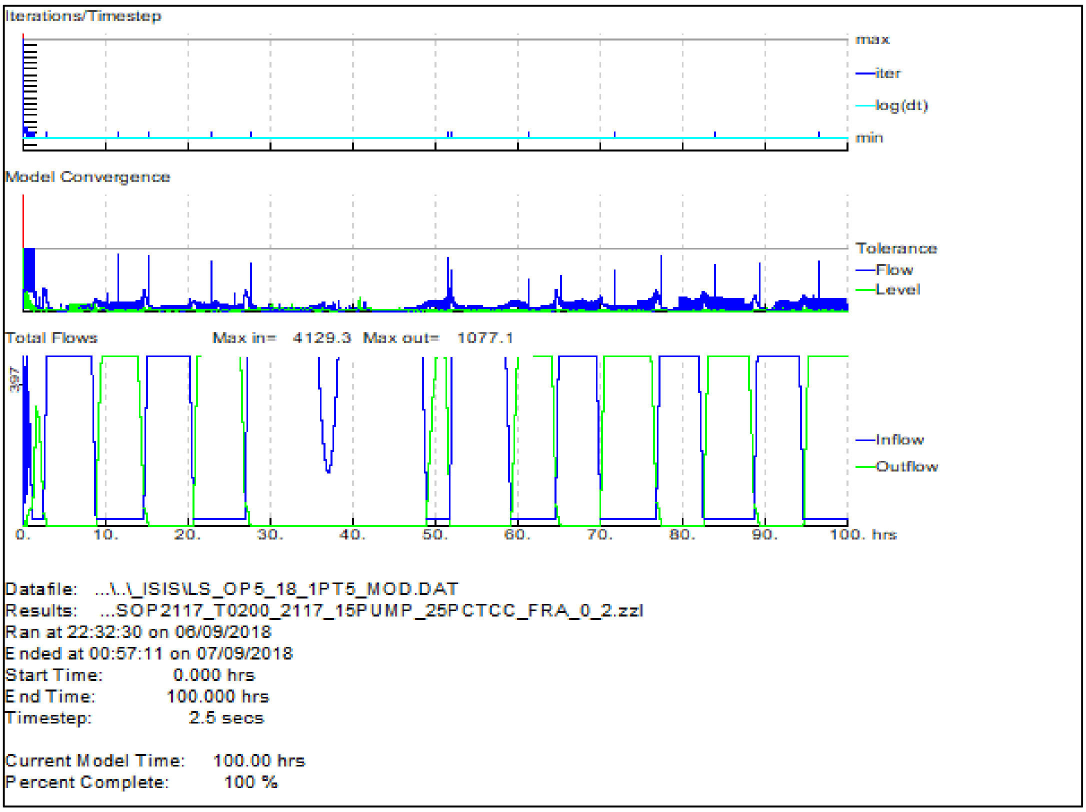

Figure 15: ‘Walls and tidal barrier’ convergence plot, 0.5% AEP, 2117.

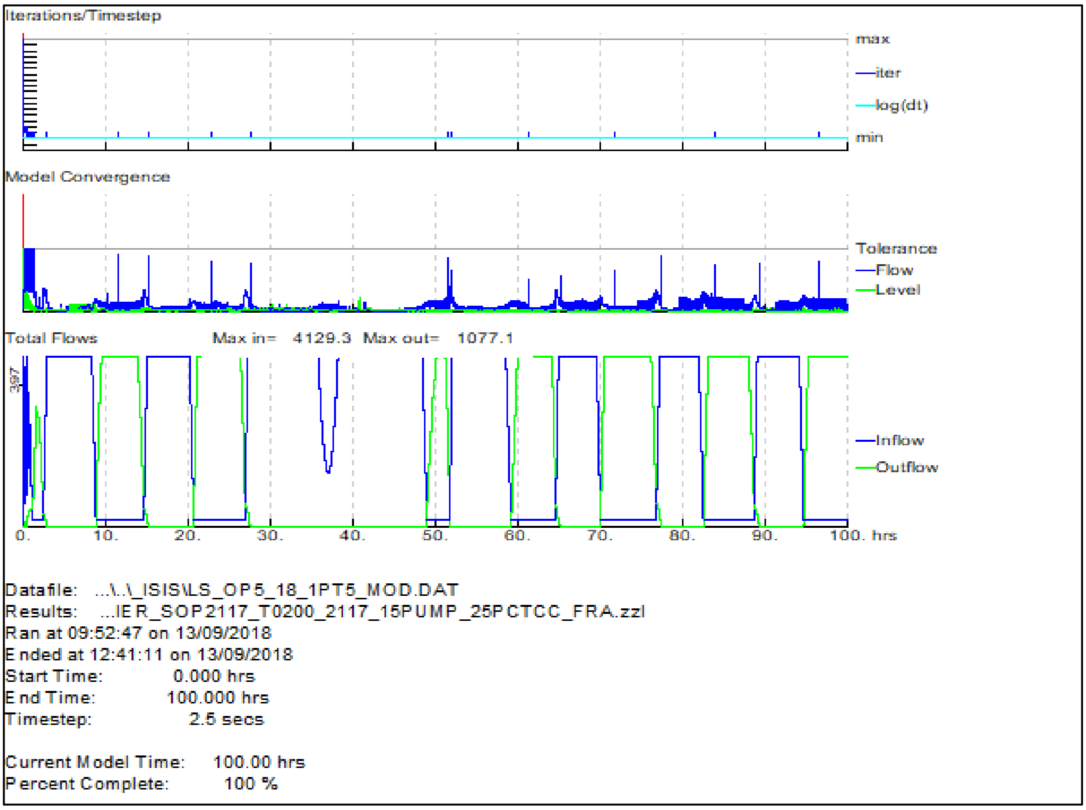

Figure 16: Breach 1, convergence plot, 0.5% AEP, 2117.

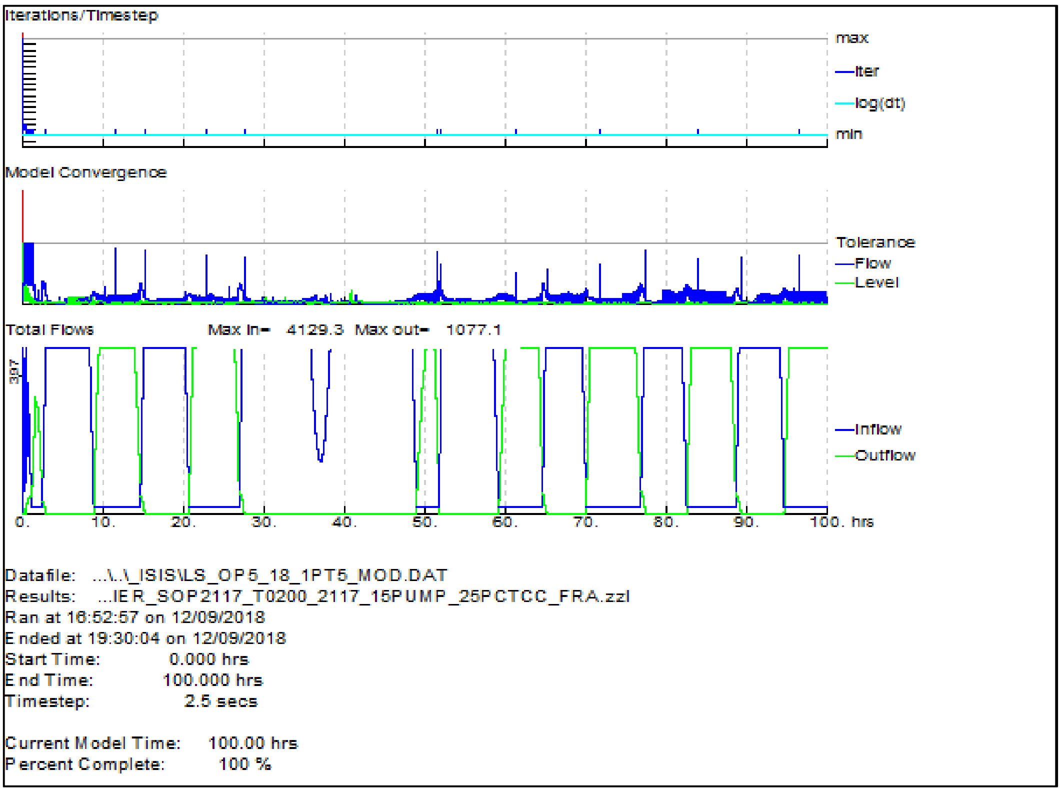

Figure 17: Breach 2, convergence plot, 0.5% AEP, 2117.

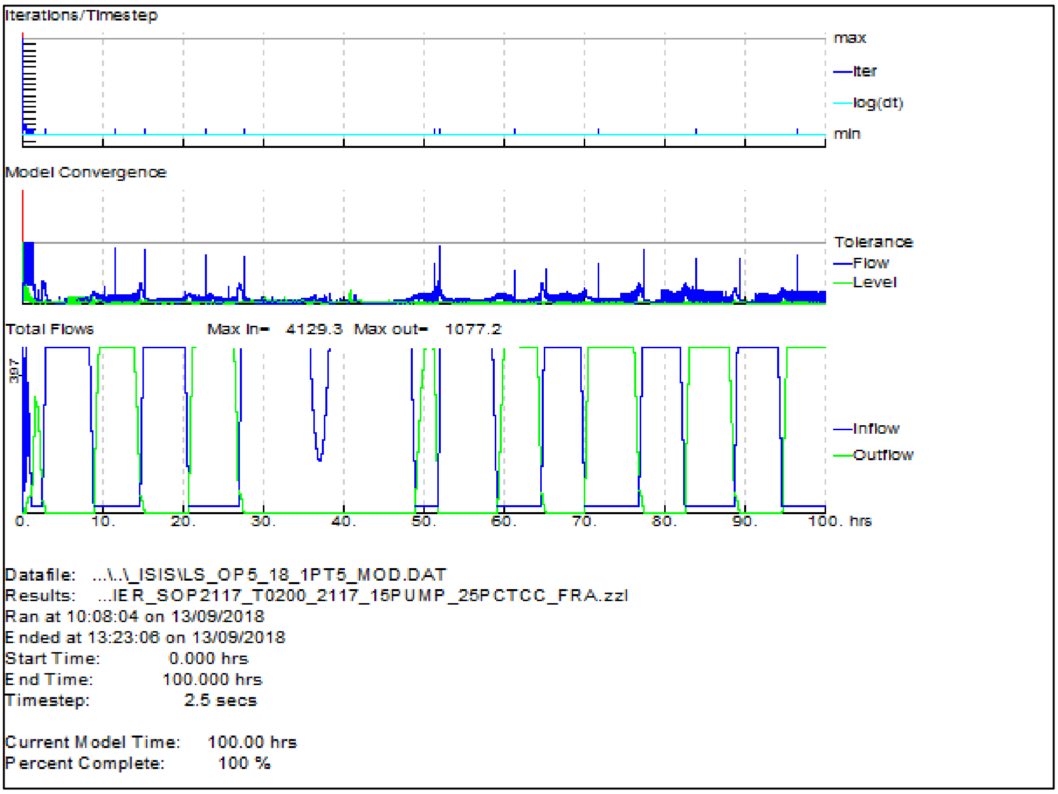

Figure 18: Breach 3, convergence plot, 0.5% AEP, 2117.

For 2D elements see Table 13 summary below for 0.5% AEP events in each scenario.

Table 13: Mass balance in 2D for the 0.5% event for each scenario.

Scenario	2D maximum cumulative ME (%)
LS_BREACH1_Walls_Barrier_SOP2018_T0200_2117_15pump_FRA	-0.17
LS_BREACH2_Walls_Barrier_SOP2018_T0200_2117_15pump_FRA	-0.17
LS_BREACH3_Walls_Barrier_SOP2018_T0200_2117_15pump_FRA	-0.17
LS_DN_T0200_2117_15_FRA_0_1_CC	0.42
LS_OP5_Walls_Barrier_SOP2117_T0200_2117_15pump_25pctCC_FRA_0_2	-0.17
LS_WallsOnly_T0200_2117_15_FRA_0_1_CC	0.40

6.3 Roughness patches

There were roughness patches that were inherited with the models and used for stability purposes. See Figure 19 for location and size. The patch circled in blue is set to a manning's n roughness value of 0.3. All other roughness patches are set to 0.1 manning's n roughness which is considered Natural Environment in the material coding.

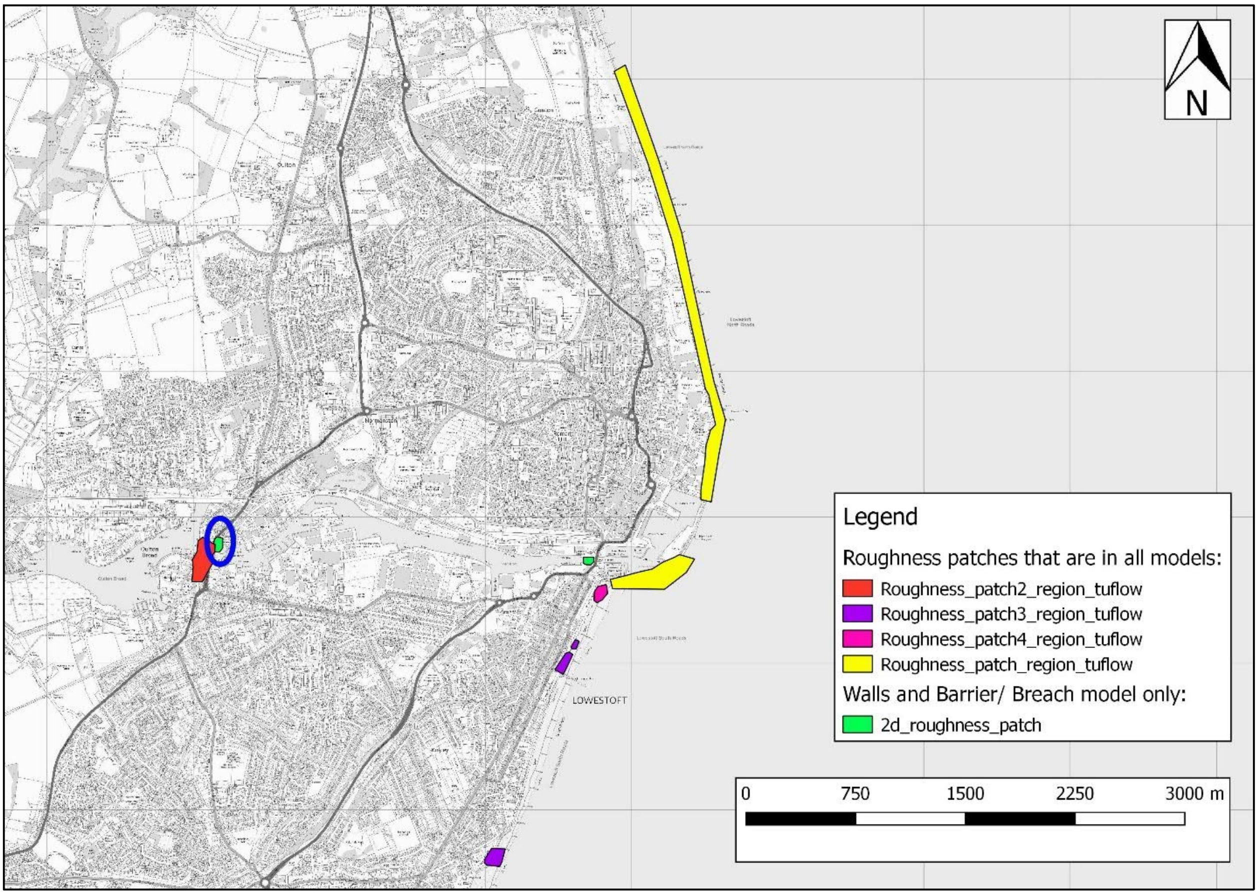

Figure 19: Location of roughness patches that were inherited in the model and used for model stability purposes. All roughness patches were set to 0.1 manning's n roughness apart from the patch circled in blue; this was set to 0.3 manning's n roughness.

6.4 Comparison to 2013 flood data

The EA provided indicative maps with approximations of properties/ complexes flooded in the 2013 storm surge. These can be seen in Figure 20 and Figure 21. Unfortunately, the quality of this data is relatively low with properties not being marked as flooding despite being between/ surrounded by numerous flooded properties. Furthermore, the orange shapes denoting flooding do not always appear to be over a property with some seeming to just be over undeveloped land. Therefore, this data is not very accurate.

The data provided was turned into approximate points to compare to the do nothing/ minimum flood extents. The level of the 2013 storm surge was estimated to be approximately a 0.5% AEP event.

The flood extent of 0.5% AEP do nothing/ minimum appears to match the clustered properties in the north of the harbourside area with the flood extent covering most of the properties. See Figure 22. Likewise, the properties densely packed to the south of the harbourside are predominantly within the flood extents for 1.33% AEP and 0.5% AEP. There are a few that extend further south than the flood extents predict.

The Oulton Broad properties are flooded in both the 1.33% AEP and 0.5% AEP. Note the red property north of Oulton Broad is out of the modeling extent.

There are two properties (see red circle on Figure 22) being shown as flooded in the 2013 indicative flood plan that the model shows as being dry (even in the 0.1% AEP present day tidal event). The LiDAR shows this area to be elevated in comparison to the surroundings. Additionally, the EA risk from river and sea does not flood this area in 0.1% AEP event. This would suggest that this area was not flooded due to the tidal event but potentially from other causes e.g. surface water.

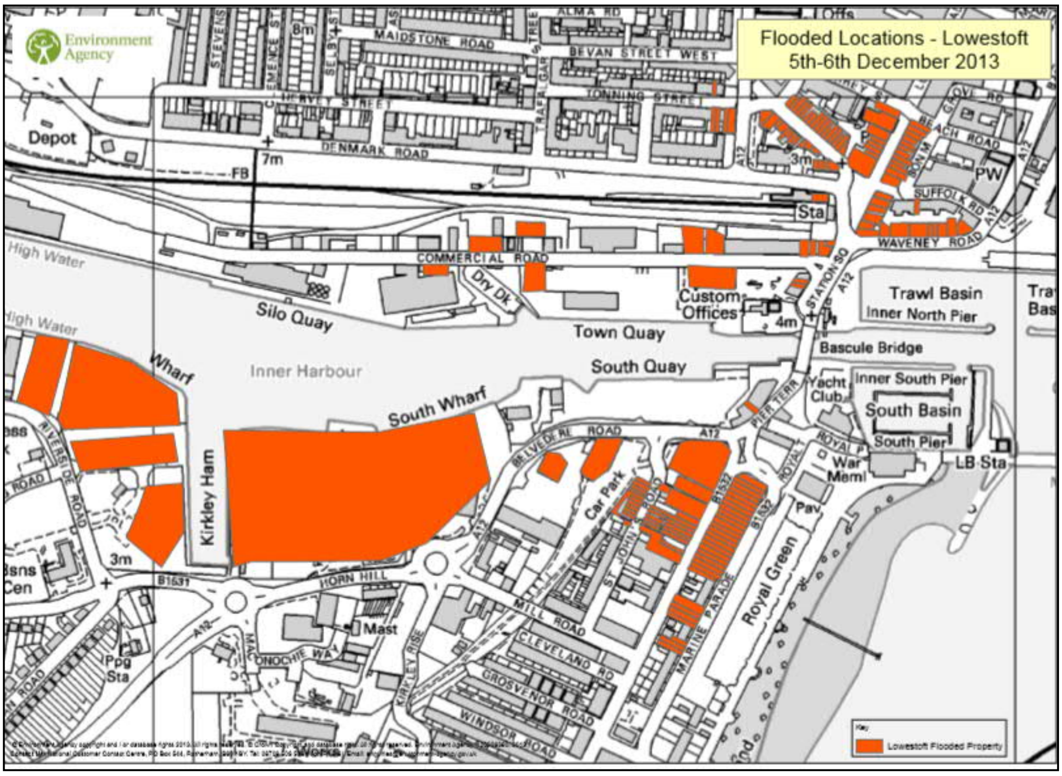

Figure 20. Approximate indicative data on flooding in the 2013 storm surge.

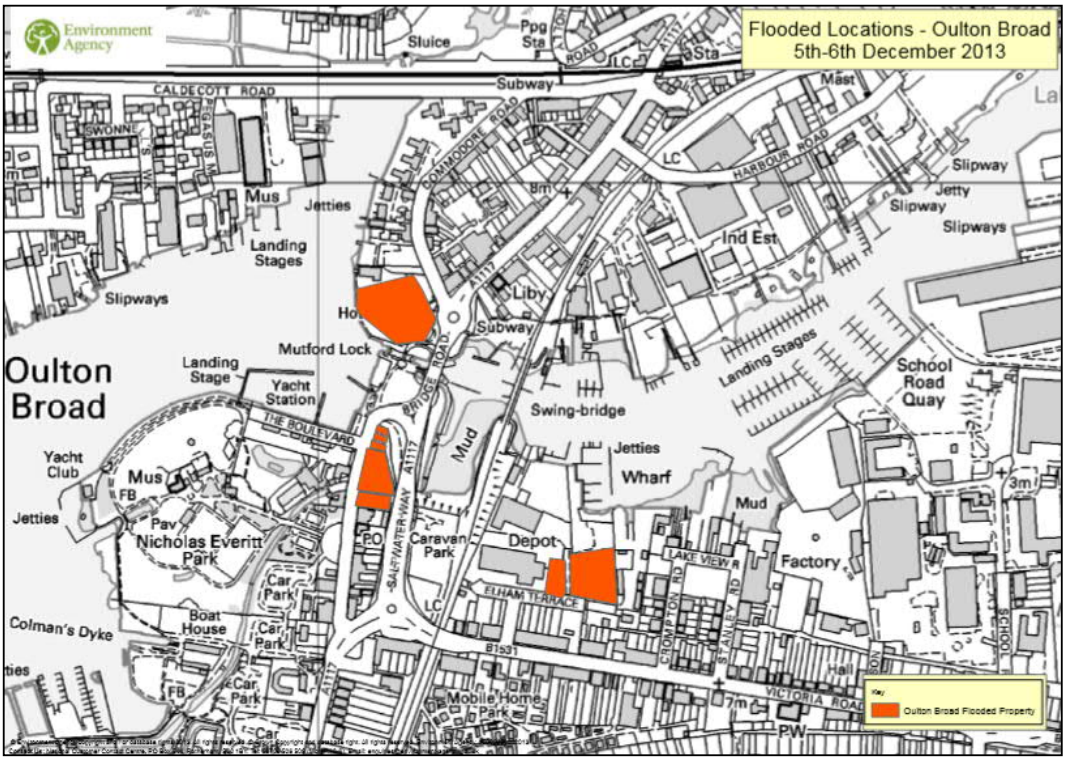

Figure 21. Approximate indicative data on flooding in the 2013 storm surge. Note the most northern orange polygon is out of the study area/ model extent.

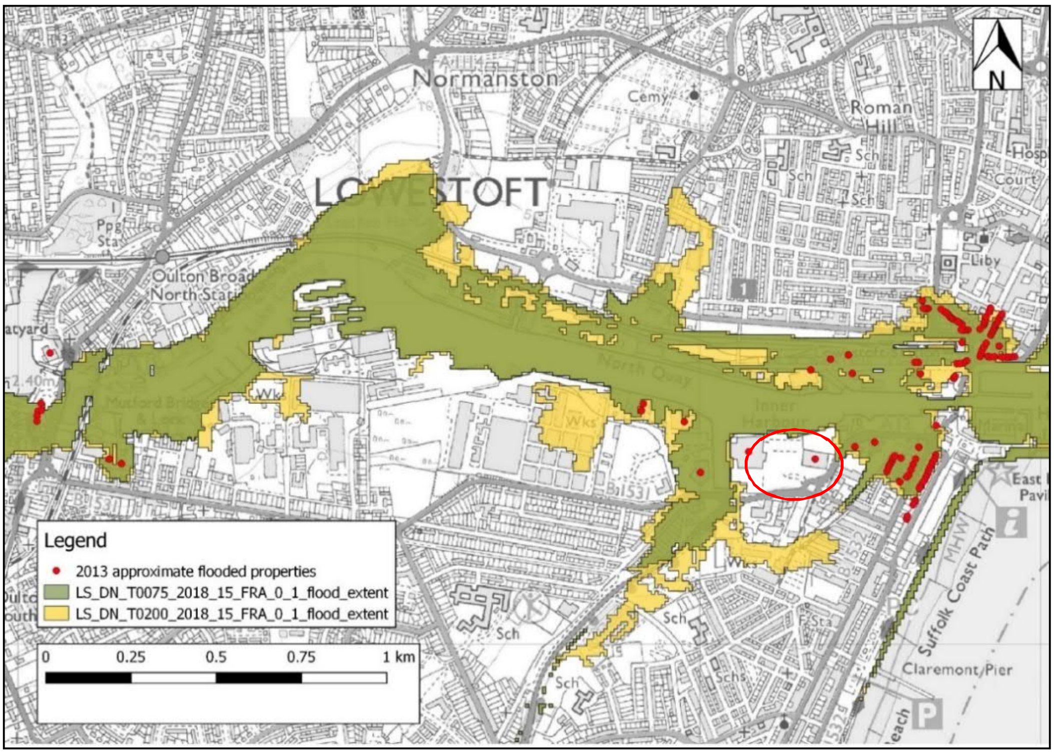

Figure 22. 1.33% AEP and 0.5% AEP do nothing/ minimum 2018 from the model and 2013 flooded properties (approximate and from indicative data). Red circle indicates area of difference between model and 2013 indicative flood data (see text for discussion).

7.0 Model results and discussion

See FRA for figures and further detail on results.

7.1 Do nothing/ minimum

Following a visual inspection of the flood maps the following observations were made:

- The extent of the area flooding east of Oulton Broad is largely similar for all the AEPs considered. Extent of flooding remains similar in 2117, suggesting that flooding is mainly driven from high water levels in the Broadlands.
- Properties to the North of the harbourside do not flood until the 0.1% AEP flood event (present day). Flooding south of Lake Lothing commences in the 5% AEP event and north commences flooding in the 1.33% AEP event. Flooding south of Lake Lothing and north of the harbourside will notably worsen with climate change.
- In the present day, flooding causing disruption to travel beings in the 5% AEP with flooding of Belvedere Road and adjoining roads. The railway station and track are flooded from 1.33% AEP onwards. Severe long-term disruption would occur to central Lowestoft business and properties in the 0.5% AEP and 0.1% AEP.

The do nothing/ minimum 0.1% AEP flood extent, in general, matches well to the EA risk of flooding from river and sea map (downloadable from the EA data catalogue). Furthermore, the flood history (included in main FRA) could be argued to corroborate the low return period flooding shown by the model owing to the high frequency of past flooding events.

7.2 Walls only

In general, the flood extents are very similar to the do nothing/ minimum but with a decrease in flood extent in the harbourside area from a 1.33% AEP and higher for present day. 0.5% 2117 AEP is similar to the do nothing with a marginal decrease in flood extent surrounding Kirkley Stream. Defences along Hamilton Road offer protection to properties up to and including the 0.1% AEP event in 2018 and 0.5% AEP in 2117.

The 0.1% AEP 2117 Walls only is a close match to the do nothing minimum equivalent with a marginal decrease in flood extent in the central and eastern harbourside area and Kirkley Stream. North of Hamilton Road is flooding in this event and is extensive; it is similar in extent to the do nothing/ minimum with a marginal decrease in extent north of Lowestoft Denes.
The above makes empirical sense in the fact that the majority of flooding occurs when tidal water escapes onto the floodplain from Lake Lothing. However, the walls provide protection locally around the harborside and therefore the flood extent is slightly smaller in the scenario, concentrated around where the walls are; the harbourside, when the walls are in place.

The pattern of flooding found confirms that the majority of the flooding in Lowestoft is caused by tidal ingress through Bascule Bridge (in this scenario), and that flooding along Hamilton Road will be independent from the barrier operation (assuming the flood walls are in place). No additional areas (compared with the do nothing/ minimum) were flooded as a consequence of the walls being in place.

7.3 Walls and tidal barrier

There is no increase in flood extent in any AEP event; when compared with do nothing/ minimum, as a result of the proposed scheme.

The trend between 5%-0.5% AEP in 2117 is the same as present day; much smaller in flood extent with no flooding of the Lake Lothing area in comparison to do nothing/ minimum 2117.

The walls and barrier 0.1% AEP in 2117 flood north of Hamilton Road extensively with a marg inal decrease in extent, compared to do nothing/ minimum, north of Lowestoft Denes. There starts to be flooding west of the barrier (east Lake Lothing and north Lake Lothing) in this AEP event. The above makes empirical sense in the fact that the walls are providing protection to the harbourside. The barrier is reducing flooding from Lake Lothing onto the floodplain by preventing the tide from entering Lake Lothing.

8.0 LiDAR analysis results and discussion

8.1 Wave overtopping only

Analysis of LiDAR for wave overtopping at the Yacht Basin resulted in maximum depths of 0.6 m directly adjacent to the wall in 2070 and 0.5 m in 2117. See Figure 23 and Figure 24.

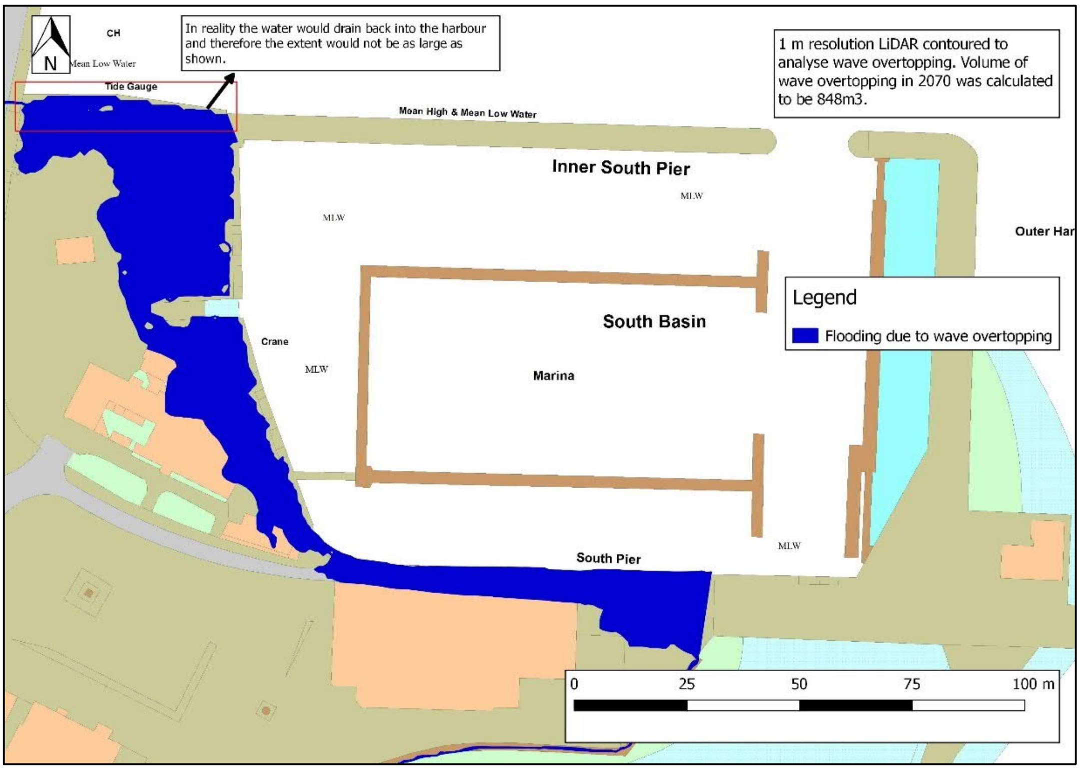

Figure 23. Wave overtopping volume (2070 rates) applied to 1 m resolution LiDAR at the Yacht Basin.

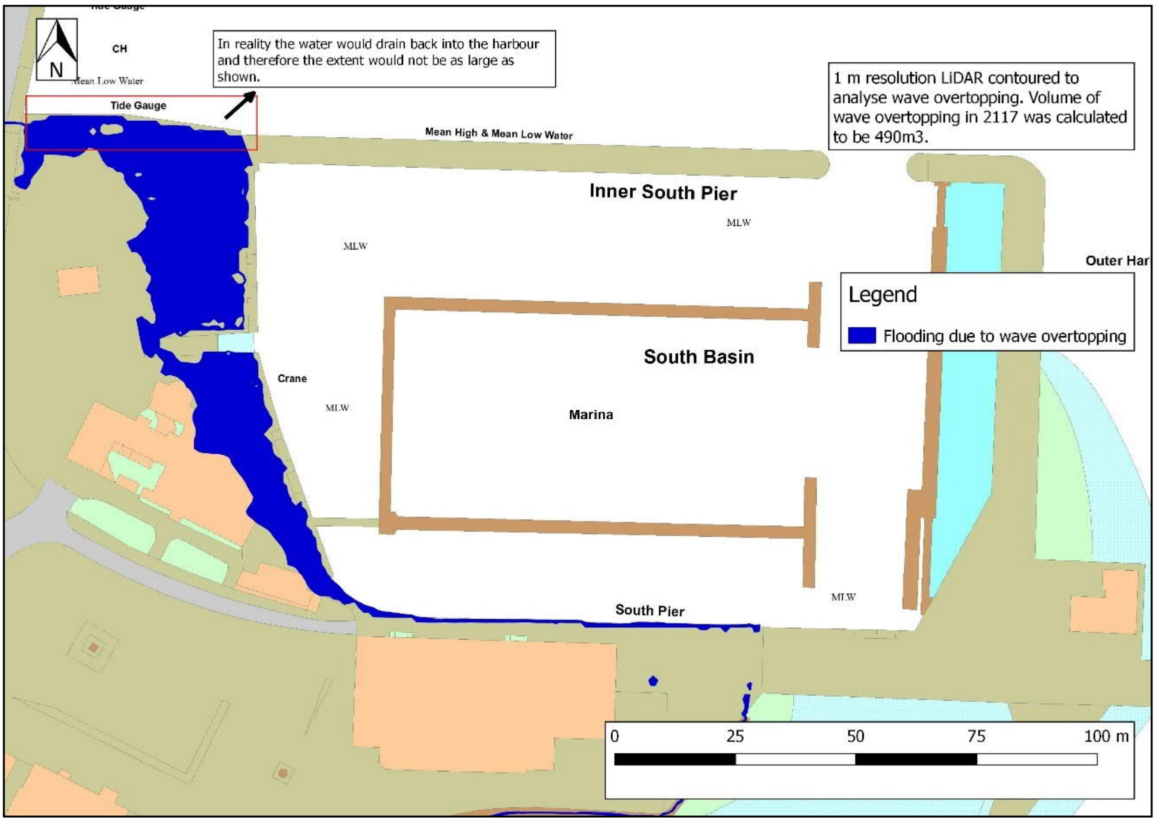

Figure 24. Wave overtopping volume (2117 rates) applied to 1 m resolution LiDAR at the Yacht Basin.

8.2 Wave overtopping and seepage

Wave overtopping, and seepage resulted in a localised maximum depth of 0.4 m at the Trawl Dock/ Basin; see Figure 25. The area corroborates well with the flooding, in terms of shape, location and depth, with the area that the model produced for wave overtopping only. Extent of flooding at this location is largely similar to the extent of flooding shown to be at high risk of surface water flooding (3.3% AEP) reported on the Environment Agency website, meaning that overall flooding experienced at this location is not worse than the current situation. Therefore, no mitigation measures are planned at this location.

Overtopping at Yacht Basin in 2070 resulted in maximum depths of 0.60m directly adjacent to the wall in 2070 and 0.50m in 2117. The area was previously shown to be a low risk of surface water flooding from the Environment Agency website, as water could freely discharge into the sea. Wave overtopping and seepage at the Yacht Basin does not greatly increase the extent and depth when compared to overtopping alone at this location. It increases the maximum depth by 0.05 m comparatively resulting in 0.65 m localised depth. See Figure 26. In reality, unless the walls were tied back to the A47 at the north, the water at this location is likely to drain over the quayside –especially with the tidal barrier in place. Therefore, the depths presented in this FRA are deemed a conservative estimate.

Flood extents at Hamilton Road show that flooding is limited to the road behind the wall and the maximum flood depth is 0.3m; the area is identified to be at low risk of surface water flooding by the ‘long term flood risk' maps on the Environment Agency flood maps. However, the draft version of the 2017/18 fluvial-pluvial flood maps shows the area to be flooded in the 5% AEP. The analysis from this FRA suggests that flooding from seepage is unlikely to affect any property in the area. In light of the limited amount of flooding and lack of disruption to services/ residential properties, it is not intended to build any mitigation measure for flooding at this location. Furthermore, the latest fluvial/ pluvial flood maps suggest flood risk following wall development may not be any worse than at present. See Figure 27. This does not flood property but results in flooding of Hamilton Road for

an approximately 155 m stretch. Additionally, when taking into account permeability; see section 4.2.3, the flood extent is much smaller and the maximum flood depth is 0.1m (see Figure 28).
As aforementioned, the displayed extents are likely to be worst-case scenarios. It is likely that some of the wave-overtopping/ seepage water will be accommodated by the existing drainage system. .

See main FRA for mitigation discussion.

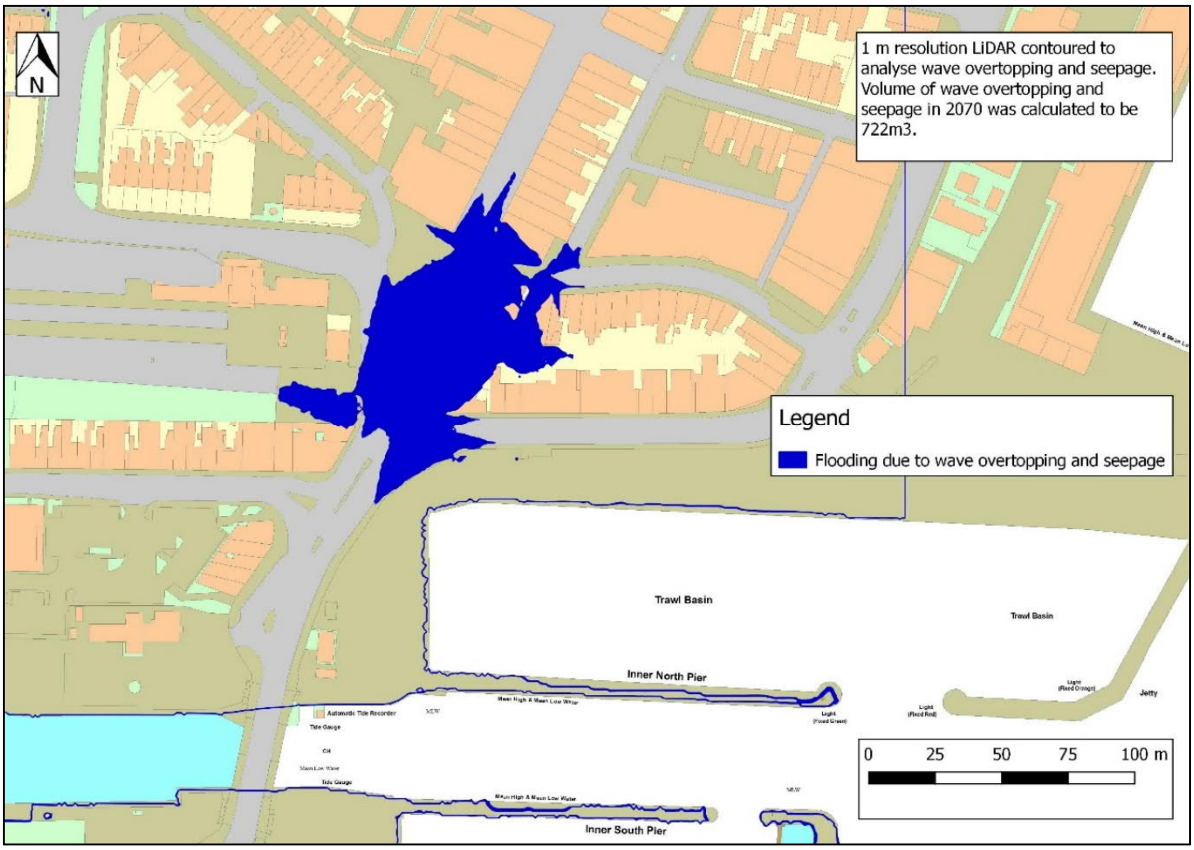

Figure 25. Wave overtopping volume and seepage for 2070 tidal events applied to 1 m resolution LiDAR at the Trawl Dock/ Basin.

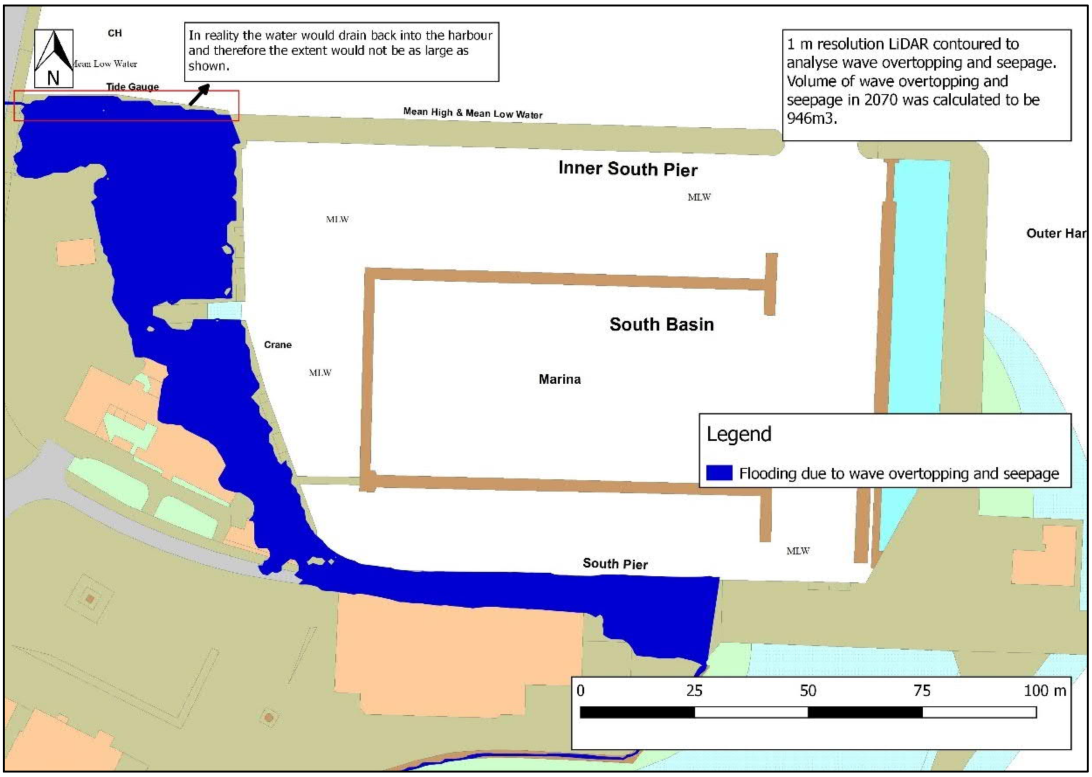

Figure 26. Wave overtopping and seepage volume (2070 rates) applied to 1 m resolution LiDAR at the Yacht Basin.

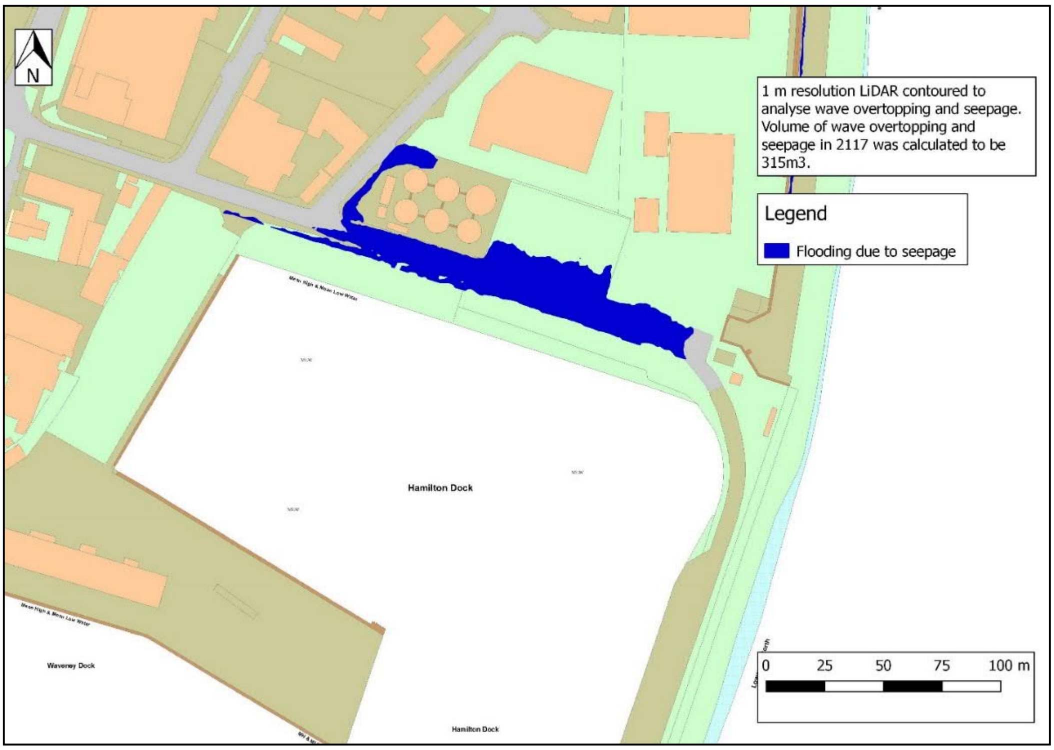

Figure 27. Seepage volumes (2117 tidal event) applied to 1 m resolution LiDAR at Hamilton Road.

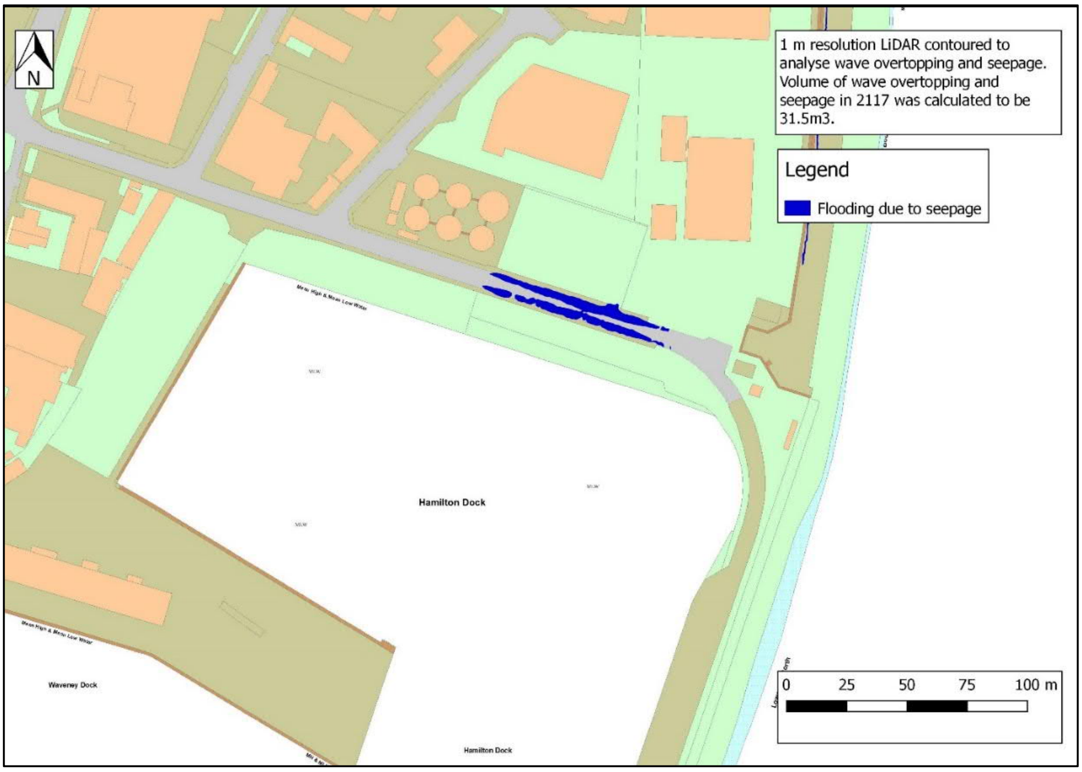

Figure 28. Flooding as a result of seepage at Hamilton Road (0.5% AEP, 2117) taking into account characteristic permeability.

9.0 Conclusion

The proposed development at Lowestoft comprises a tidal barrier at Bascule Bridge and tidal walls. The barrier and walls will provide protection to residential properties and businesses in Lowestoft up to and including the 0.5% AEP tidal event in 2070 and 2117. An adaptive approach will be taken against climate change with the barriers being built to 2070 levels in 2018 and to 2117 levels in 2070. The proposed development will be built in two phases with the walls being built first and the tidal barrier in a second phase (assumed to be the year after walls completion).

The model stability and results suggest that the model is providing reasonable output. For 0.1% 2117 events the time step and model parameters were modified to allow the model to run stably.

The changes in flood extents relatively between scenarios appear to make empirical sense.

This output appears to match 2013 indicative flood data and therefore the modelling is deemed suitable for use in analyzing risk and effects of the proposed scheme in the FRA.

` MEMORANDUM

Lowestoft FRA requirements

PREPARED BY:	Silvia Garattini
CHECKED BY:	Jayne Lamont
DATE:	March 2, 2018
PROJECT NUMBER:	676284
REVISION NO.:	1.0
APPROVED BY:	Jehangir Nawaz

1. Introduction

The Lowestoft Flood Risk Management Project (LFRMP) aims to provide a sustainable flood risk management scheme for the town of Lowestoft. The scheme is envisaged to include provision of a tidal barrier and associated flood walls to provide a standard of protection of 1 in 200 years (including climate change). The approval and consenting of tidal barrier will follow the Transport and Works Act Order (TWAO) route while the tidal flood walls will be subject of local planning permission from the Waveney District Council.

A site-specific Flood Risk Assessment (FRA) will be prepared as part of the planning application for the tidal flood walls element of the Lowestoft FRMP.

The project delivery plan includes construction of the flood walls ahead of the proposed tidal barrier. The wall alignment is shown in Figure 1. The FRA will consider both the temporary and permanent works. It is currently understood that the temporary works will involve limited amount of ground excavation and no material will be left on the floodplain, therefore permanent works will be the focus of the document.

The proposed permanent development is classified as a 'water compatible structure' and is located in Flood Zone 3 (Figure 2). Tidal flooding is considered the primary source of flood risk in the area. Tidal flooding could materialize either from direct ingress of water from the North Sea to Lake Lothing or from Great Yarmouth through the Broadlands system.

The site could also be subject to fluvial flooding from Kirkley Stream or the River Waveney (part of the Broadlands system), and to surface water flooding from the local Anglian Water sewage network. Groundwater flooding is assumed a secondary risk in the catchment (Broadlands Rivers Catchment Flood Management Plan, 2009).

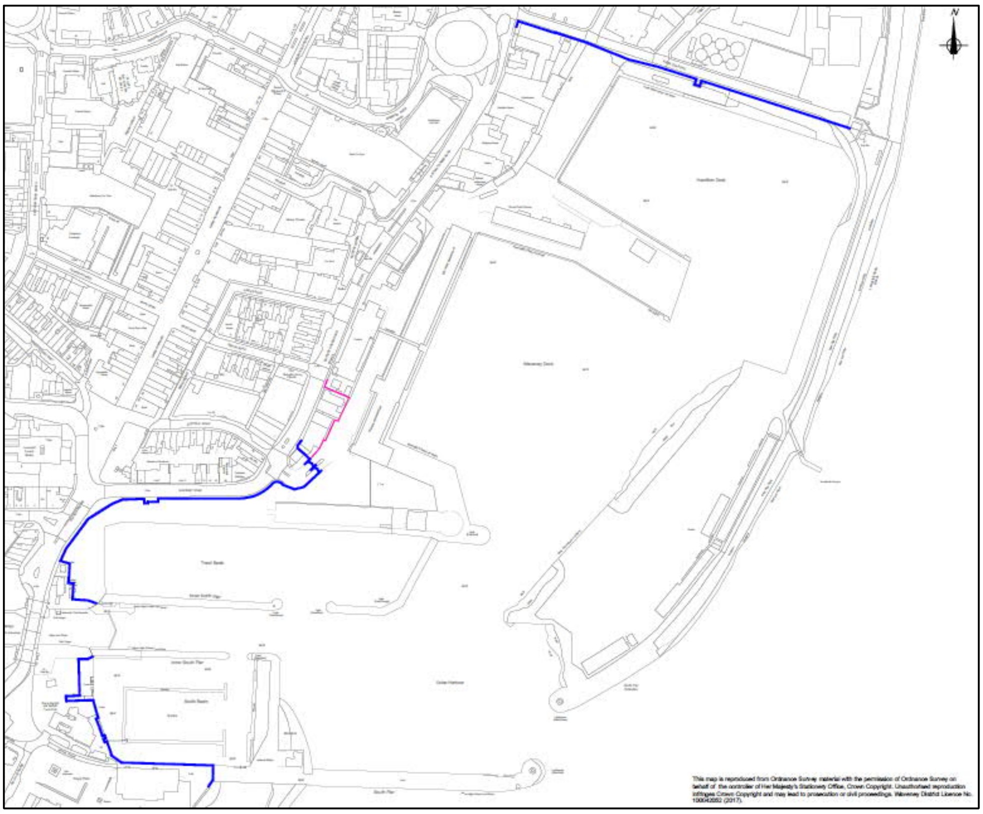

Figure 1: Location of the proposed flood walls and structures of options 3, 4, 5 and 6. Lengths are the approximate total lengths of the defence line taking into account lengths of walls, flood gates and demountable barriers.

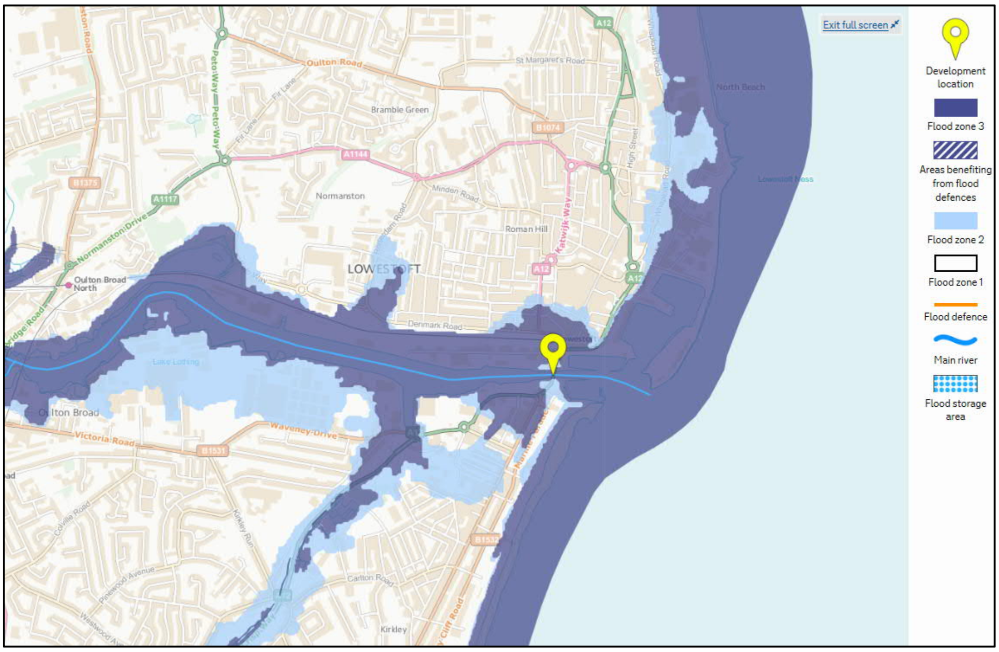

Figure 2: Flood zones in the study area (from https://flood-map-for-planning.service.gov.uk/, accessed 2nd of March 2018)

2. Objectives

This FRA considers the development proposal with regard to National Planning Policy Framework (NPPF) and addresses any flood risk concerns raised by the project team. The objectives of this FRA are to:

1. Assess existing flood risk in Lowestoft (i.e. baseline), from all sources, including: tidal flood risk, surface water flood risk, groundwater flood risk and fluvial flood risk.
2. Assess the risk of flooding in Lowestoft after the construction of the flood walls while the barrier will not be in place.

3. Available Data

To date (01/02/2018), the following data is available to support the development of this FRA:

- 2017 CH2M Lowestoft Flood and Coastal Erosion Risk Management Outline Business Case hydraulic model and outline design.
- 2017 AECOM Lowestoft Strategic Flood Risk Assessment (DRAFT)
- 2017 JBA Lowestoft Flood Risk Management Strategy (including surface water hydraulic model results)
- 2017 CH2M Lowestoft Flood Risk Management Strategic Outline Case
- 2014 Broadlands Environmental System Ltd (BESL) model (including hydraulic model, related results and report)

4. Methodology

The proposed methodology to meet the FRA objectives (as listed in the previous section) is as follows:

1. The proposed approach to assess the 'baseline' flood risk in Lowestoft is outlined in Table 1. Flood risk will be analysed both for present day conditions and in a future epoch (i.e. including an allowance for climate change). The proposed approach will make use of best available data for each source of flooding. The approach for each source of flooding will be proportional to the existing flood risk as described in Section 1.

Table 1: Proposed methodology to analyse baseline flood risk at Lowestoft

Source of flooding	Proposed Methodology
Tidal flood risk	Analysis of present day and climate change results from Lowestoft appraisal modelling. Four return periods will be considered (proposed return periods include 1 in 20 year, 1 in 30 year, 1 in 100 year and 1 in 200 year). Events to be considered will be confirmed with the relevant planning authority. The required climate change epoch will be established at a scoping meeting with the Environment Agency. Sea level rise allowances to be used will follow latest climate change guidance for planning by the Environment Agency (i.e. Upper End estimate, Table 5, "Adapting to Climate Change: Advice for Flood and Coastal Erosion Management Authorities", Environment Agency, August 2016).

Source of flooding	Proposed Methodology
Surface water flood risk	Analysis of available 2017 JBA modelling outputs. Section 106 reports will be consulted if available.
Fluvial flood risk	Analysis of available 2017 JBA modelling outputs for Kirkley Stream. Analysis of available BESL modelling outputs for the Broadlands system.
Groundwater flood risk	Analysis of readily available information from Local Authorities and internet sources.

2. We will evaluate the potential impact on tidal flood risk of the walls only scenario by building and running a hydraulic model representing the 'leading option'. Wall heights will include any freeboard allowance included in the engineering calculations. The model will be run for both overtopping and breach scenarios. Two breach locations will be selected following consultation with Waveney County Council. It is currently understood that the tidal barrier will be built shortly after the walls (12 months). We therefore propose to include a set of climate change runs for this scenario as well. The climate change epoch will be established following the EA scoping meeting.
The impact on fluvial/ surface water flood risk of the walls only scenario will be qualitatively inferred by existing modelling results.
Impact of temporary enabling works will be qualitatively assessed using available model results and information.

5. Assumptions

1. The scenarios tested will not include the proposed tidal barrier. The effect of tidal barrier will be evaluated during the TWAO application.
2. We propose the FRA to consider one climate change epoch in addition to the present day runs.
3. Kirkley Stream modelling and surface water modelling readily available and suitable for flood risk assessment.
4. BESL model outputs are suitable to evaluate fluvial flood risk from the Broadlands system.
5. Risk of combined tidal/ fluvial events is considered negligible along the East Coast.
6. Risk of wave overtopping of the walls considered negligible. Further consideration to this element will be given at detailed design stage.
7. Sensitivity runs for the tidal model will include sensitivity to Manning's n roughness and downstream water levels.
8. Model runs to analyse flood risk from tidal sources are summarized in Table 2. Currently, we assume only one climate change epoch will be sufficient for the purpose of this FRA. The required climate change horizon will be established during the initial scope meeting with the Environment Agency. Similarly, return periods to be used and required sensitivity tests will be agreed at the project start-up meeting.

Table 2: Proposed runs to evaluate tidal flood risk

Scenario	Return period (RP)/ Climate change epoch	Source/ Model file used	Total number of runs
Baseline (i.e. existing conditions)	4 RPs- Present day 4 RPs- Climate change epoch (TBC)	Lowestoft tidal model used for appraisal	8
Walls only	4 RPs- Present day 4 RPs- Climate change epoch (TBC)	Lowestoft tidal model used for appraisal modified to include wall structures	8
Walls only- sensitivity	1 RPs	Lowestoft tidal model used for appraisal modified to include wall structures	2
Walls only, breach	2RPs, 2 breach locations- present day	Lowestoft tidal model used for appraisal modified to include wall structures and breach location/ dimensions	4

TECHNICAL MEMORANDUM

Lowestoft FRA- Sequential Test

PREPARED BY:	Libby Bush/ Silvia Garattini
CHECKED BY:	
DATE:	May 23, 2018
PROJECT NUMBER:	676824
REVISION NO.:	1.0
APPROVED BY:	

Introduction

The Lowestoft Flood Risk Management Project (LFRMP) aims to provide a sustainable flood risk management scheme for the town of Lowestoft. The scheme is envisaged to include provision of a tidal barrier and associated flood walls to provide a standard of protection of 1 in 200 years (including climate change). The approval and consenting of tidal barrier will follow the Transport and Works Act Order (TWAO) route while the tidal flood walls will be subject of local planning permission from the Waveney District Council.

A site-specific Flood Risk Assessment (FRA) will be prepared as part of the planning application for both the tidal flood walls and barrier forming the Lowestoft FRMP.

The project delivery plan includes construction of the flood walls ahead of the proposed tidal barrier. The wall alignment is shown in Figure 1. The FRA will consider both the temporary and permanent works. It is currently understood that the temporary works will involve limited amount of ground excavation and no material will be left on the floodplain, therefore permanent works will be the focus of the document.

The proposed permanent development is classified as a 'water compatible structure' and is located in Flood Zone 3 (Figure 2). Tidal flooding is considered the primary source of flood risk in the area. Tidal flooding could materialize either from direct ingress of water from the North Sea to Lake Lothing or from Great Yarmouth through the Broadlands system.

The site could also be subject to fluvial flooding from Kirkley Stream or the River Waveney (part of the Broadlands system), and to surface water flooding from the local Anglian Water sewage network. Groundwater flooding is assumed a secondary risk in the catchment (Broadlands Rivers Catchment Flood Management Plan, 2009).

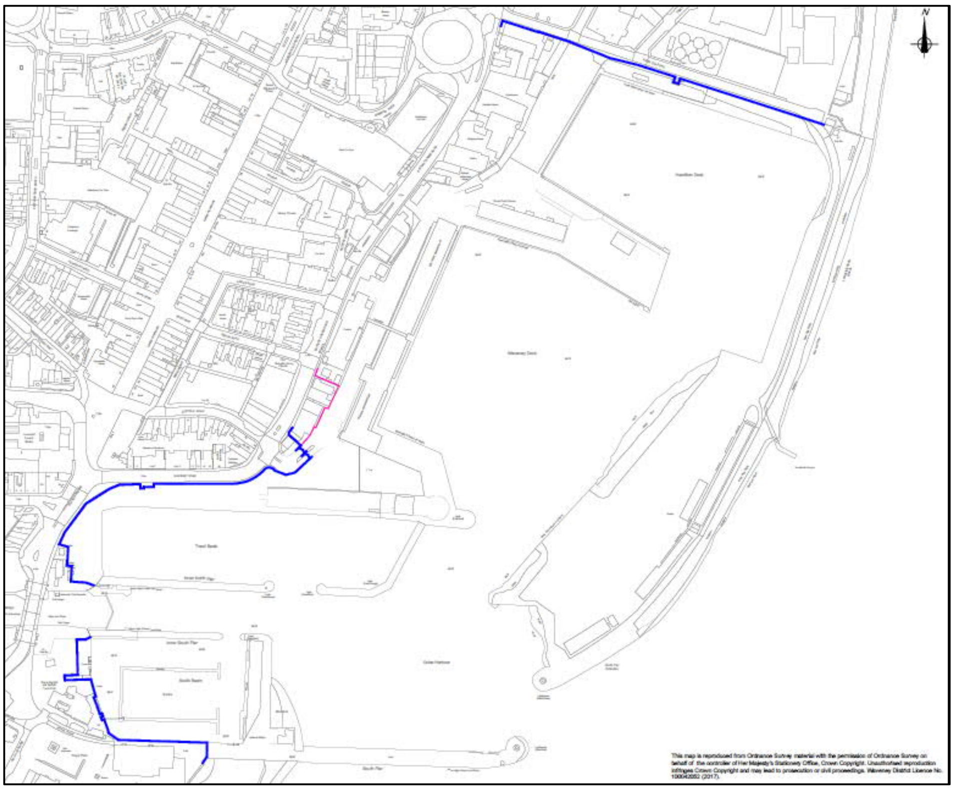

Figure 1: Location of the proposed flood walls and structures of options 3, 4, 5 and 6. Lengths are the approximate total lengths of the defence line taking into account lengths of walls, flood gates and demountable barriers.

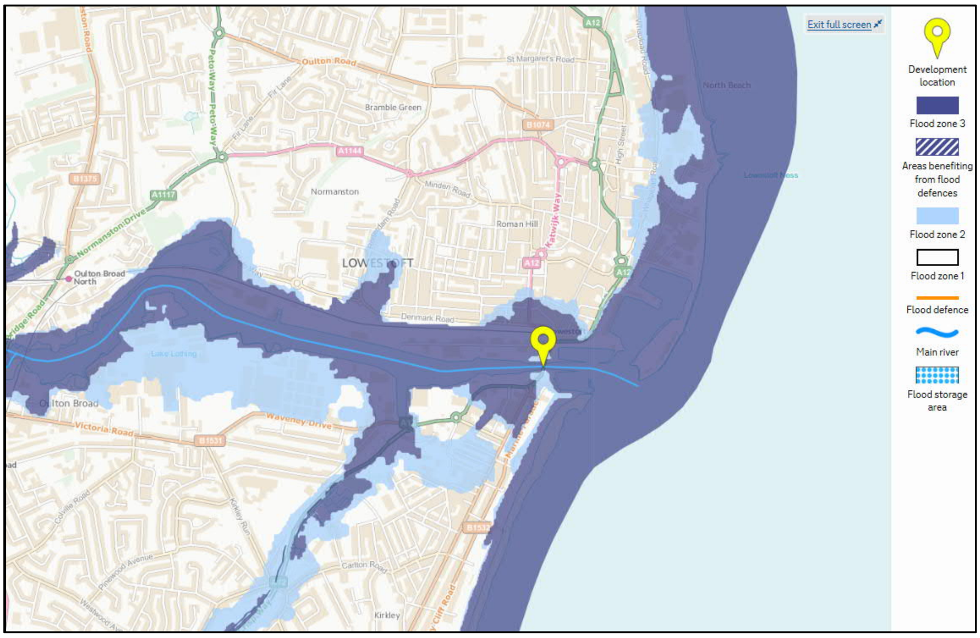

Figure 2: Flood zones in the study area (from https://flood-map-for-planning.service.gov.uk/, accessed 2nd of March 2018)

Purpose of this document

National Planning Policy Framework (NPPF) aims to ensure inappropriate development is avoided in areas at risk of flooding. The Sequential Test, required under NPPF, is a tool for determining land uses that are compatible with the level of flood risk at each development site within a Local Authority area.

This document shows the sequential approach applied to the Lowestoft Flood Risk Management Project when selecting the location of the development, in line with the Environment Agency recommendations as per 22/03/2018 email (ref. AE/2018/122619/01-L01, see Appendix E of the main FRA).

Sequential approach

The Environment Agency produces flood zones that are the starting point for the Sequential Test. Flood Zones 2 and 3 indicate the land at medium to high risk of flooding during extreme events, and Flood Zone 1 is the low-risk zone, which is all land outside Zones 2 and 3. These flood zones refer to the probability of sea and river flooding only, excluding any existing defences.

Table 1 summarises the annual probability of fluvial flooding in relation to the Flood Zones and the land uses considered appropriate for each Zone. It is based upon Table 1 of NPPF.

The proposed development of the barrier and flood defence walls in Lowestoft is within Flood Zones 3 of the Environment Agency flood maps. In accordance with Table 2 of NPPF, the proposed development will fall into the ‘water compatible’ vulnerability class, under the classification ‘flood control infrastructure’. This development is an opportunity to reduce the overall level of flood risk in the area through its layout and form.

This development would, therefore, be deemed suitable under NPPF and assessment of other sites would not be required.

Table 1: Flood Zone summary table and appropriate land uses

Flood Zone	Annual Probability of Flooding	Appropriate Land Uses
Flood Zone 1 Low probability	< 1 in 1000 (<1%) annual probability of flooding in any given year.	All land uses
Flood Zone 2 Medium probability	1 in 100 – 1 in 1000 (1% - 0.1%) annual probability of flooding in any given year.	Less vulnerable More vulnerable Water compatible Highly vulnerable uses are only appropriate in this zone if the Exception Test is passed.
Flood Zone 3 High probability	1 in 100 (1%) annual probability of flooding in any given year.	Water compatible Essential infrastructure The more vulnerable uses and essential infrastructure should only be permitted in this zone if the Exception Test is passed.

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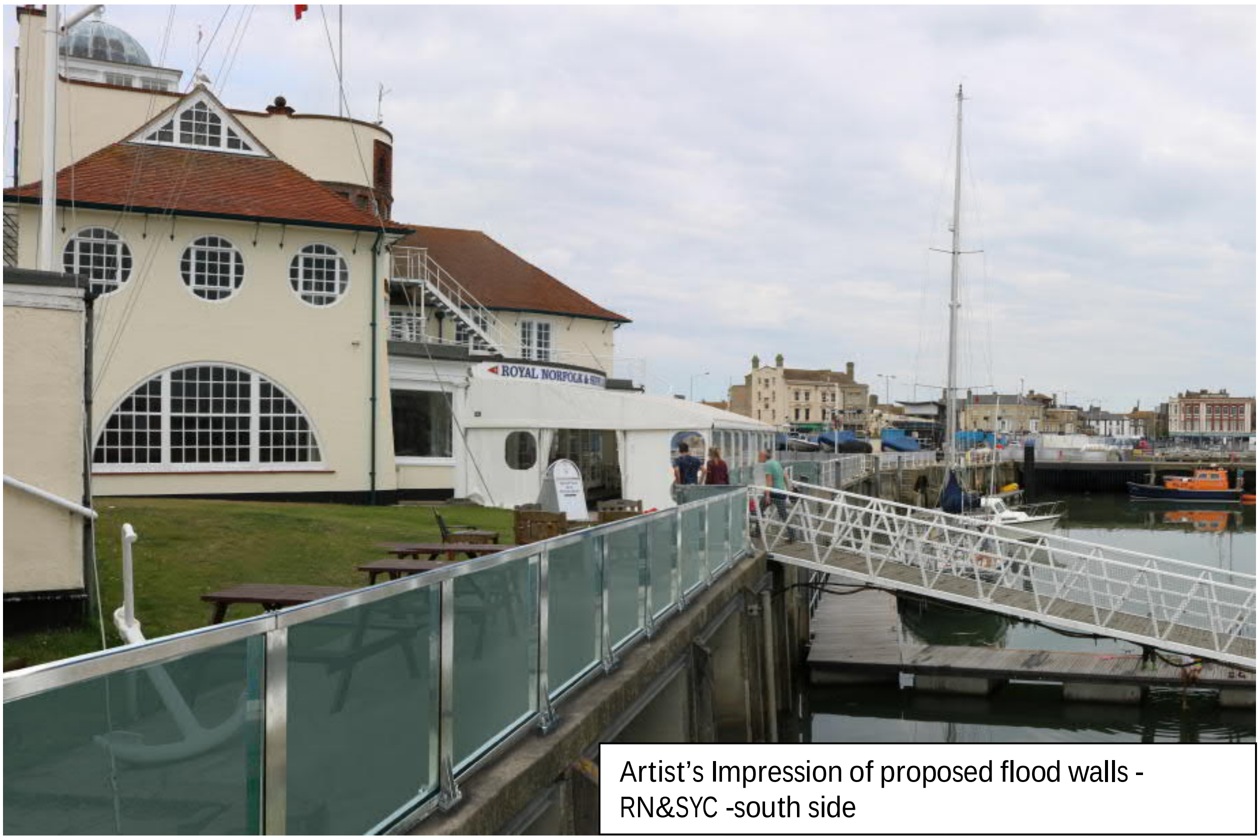
Appendix E

Provided as separate document as one of the FRA appendices.

Review of the Residual Uncertainty Assessment – Flood Walls



Artist's Impression of proposed flood walls - RN&SYC -south side

Lowestoft Flood Risk Management Project

Reference Number: CRM72114-JAC-DZ-300-MO-HY-0001

Prepared for

Waveney District Council

August 2018

ch2m

OFFICIAL

Revision History

Issue	Author	Date	Description
0	Laurent Cadieu / Tom Hunt	22/08/2018	Draft
1	Tom Hunt	18/12/2018	Update to overtopping flood volumes

Technical Check

Role	Name	Signature	Date
Checker	Tom Hunt	Tom Hunt	24/08/2018
Reviewer	Kevin Burgess	Kevin Burgess	24/08/2018

Approval

Role	Name	Signature	Date
Project Manager	Jehangir Nawaz	Jehangir Nawaz	28/08/2018

Contents

Abbreviations

RP	Return Period
AOD	Above ordnance datum
JPA	Joint Probability Assessment
RUA	Residual Uncertainty Allowance
EWL	Extreme Water Levels
AEP	Annual Exceedance Probability
JPA	Joint Probability Analysis

Summary

This assessment is to confirm the height of the proposed defences and therefore inform the Flood Risk Assessment and the detailed design of the flood walls. There are a number of approaches that could be taken to make this assessment and this note provides some detail on the approach taken

The results show that the walls heights do not need to be increased to the extents that the earlier more basic assessment previously indicated, and the proposed crest levels of 4.1mOD in 2070 and 4.65mOD in 2117 are suitable for the 0.5% AEP design event.

However, although it can be guaranteed that the proposed defences will remain stable for all the possible combinations in water levels and waves for a 0.5% AEP, there is a low residual risk that certain combination of conditions would produce wave overtopping that could create localised flooding. Due to this risk a flood model has been created and overtopping volumes input to the model to determine localized flooding.

Whilst this technical note does not include details or results from the flood model the overtopping results that are included in the flood model are presented.

Introduction

This assessment is to confirm the height of the proposed defences and therefore inform the Flood Risk Assessment and the detailed design of the flood walls. There are a number of approaches that could be taken to make this assessment and this note provides some detail on the approach taken.

The initial assessment undertaken and communicated to the client used conservative inputs. This technical note demonstrates that the initial assessment did overestimate the probability of conditions and thus the levels of overtopping that might be likely to occur.

The primary updates have included:

- Undertaking of joint probability analysis (JPA) of the wave and water levels to provide an appropriate combined wave and water level for a 0.5% AEP.
- An update of the wave transformation into the harbour using the JPA outputs.
- A detailed overtopping assessment using EurOtop 2016 empirical formula and discharge thresholds.

In addition to the crest level assessment overtopping volumes to be input to a flood model are also calculated. Whilst it may seem that the values will be the same there are subtle differences that are explored.

This technical note presents further detail on this analysis.

Crest level assessment

Flood defence crest levels obviously need to be set to provide acceptable limits to flooding and/or probabilities of occurrence. This can be simply achieved by providing a crest elevation that is above an acceptable extreme storm event. This height above an extreme water level is referred as the “freeboard”. An alternative approach is to set limits of acceptable wave overtopping and determine the structure geometry that can achieve this.

The Environment Agency have published a new freeboard guidance, “Accounting for residual uncertainty: updating the freeboard guide: Report SC120014; Environment Agency

(2017)”. However, the advice received is that projects that are not in pilot schemes should not use this guidance document until a review of the application of the guidance has been completed. In the meantime, the original Fluvial Freeboard Guidance Note (W187) with adaptation for tidal schemes or the coastal overtopping assessment approach (EurOtop: 2016) is to be used. Note that that W187 does not provide guidance for tidal and coastal schemes in its current form as noted on section 1.2.

It is worth remembering that the existing approaches do not result in any lesser design standard rather the new guidance seeks to provide a more robust analysis with greater levels of communication with the client so informed decisions can be made, along with bringing the coastal element (significant waves) into a consistent approach with fluvial assessments. To do this, particularly on coastal schemes requires a change in the application of the overtopping methods and a lot of additional work to present results which were often instinctively understood by experienced engineering practitioners.

Given the nature of this site a mixed approach has been applied which strongly leans on the Fluvial Freeboard Guidance Note (W187) with adaptation for tidal schemes. The reason for this is that the location of the new seawalls is sheltered from significant open coast wave conditions which lends itself to the more fluvial, freeboard approach.

The scheme requires flood protection until 2117 for an extreme event with a 0.5% annual exceedance probability (AEP) (also referred to as 1 in 200 year Return Period (RP)). It is recommended that this is achieved by taking an adaptive approach by providing a defence that achieves the levels of flood protection until 2070 but is sufficiently designed that adaption can be made to raise the defences to 2117 extreme storm events at a later date. The advantage of this is that excessive defences are not provided at the outset of the scheme which have high present day costs and can impact visually on the area as well allow the actual impacts of climate change to be address as we learn more.

The recommendation crest levels are as follows:

- 1 in 200 Year return period in 2070 - Wall crest level to be 4.1mOD (100mm higher than recommended earlier);
- 1 in 200 Year return period in 2117 - Wall crest level should be kept at 4.65mOD previously recommended.

These values are based upon an assessment that considered the marginal extreme water levels (0.5% AEP) plus a freeboard allowance of 0.3m. The marginal extreme water levels are as follows:

- 3.775mOD at year 2070
- 4.185mOD at year 2117

As recommended in W187 the freeboard allowance should account for physical processes that affect the defence level and adverse uncertainty in the prediction of physical process. The physical process that were discussed as relevant for this scheme were:

- Uncertainty due to Extreme water level = 0.3m. Value taken from confidence intervals from the Coastal Flood Boundary Data for 0.5% AEP. This value was confirmed by Matthew Hird, FCRM Principal Analysist, on 15/08.
- No additional uncertainly allowance has been added for wave overtopping as the assessment of the recommended crest levels showed that overtopping discharges were within the ranges of acceptable limits.

  Uncertainty has been considered through the undertaking of sensitivity analysis. This uncertainty analysis showed that despite increases in the overtopping discharges compared to the best estimate approached that recommended limits for the ultimate limit state (ULS) were not exceeded and that the service limit state (SLS) whilst exceeded would be acceptable given the robustness of normal overtopping assessments using joint probability analysis (JPA) of wave and water levels. These increased overtopping discharges in the sensitivity analysis could potentially lead to localised flooding under specific conditions of the extreme environmental conditions.

- Settlement allowances are often considered but advice has been that settlement is not an issue at this location so no allowance has been applied.

Only the overtopping assessment which is used in the above freeboard allowance is presented in this technical note.

Wave overtopping assessment

4.1 Wave conditions within the harbour

4.1.1 Joint Probability Analysis

JPA was undertaken using the Environment Agency's JPA spreadsheet (FD2308_TR2 Desk study calculator) of wave and water levels at two offshore locations near to Lowestoft harbour. The benefit of JPA is that a range of conditions are derived for each of the extreme return periods. The result of this is that the higher water levels have a smaller corresponding wave height and lower water levels have a higher corresponding wave height for a specific AEP. Previously the marginal extreme 0.5% AEP was used for both wave and water level. The reality is this would correspond to a much higher AEP.

The extreme water level for a range of AEP's (return period events) was taken from the coastal flood boundary data as supplied by the Environment Agency. Theses water levels were adjusted for a range of years to account for climate change using United Kingdom climate predictions (UKCP09) website.

	Epoch								
Event	2014	2018	2020	2021	2040	2070	2071	2090	2117
T2*	2.222	2.244	2.255	2.261	2.377	2.593	2.601	2.759	3.003
T5*	2.417	2.439	2.450	2.456	2.572	2.788	2.796	2.954	3.198
T10	2.566	2.588	2.599	2.605	2.721	2.937	2.945	3.103	3.347
T20	2.742	2.764	2.775	2.781	2.897	3.113	3.121	3.279	3.523
T30	2.850	2.872	2.883	2.889	3.005	3.221	3.229	3.387	3.631
T75	3.109	3.131	3.142	3.148	3.264	3.480	3.488	3.646	3.890
T100	3.192	3.214	3.225	3.231	3.347	3.563	3.571	3.729	3.973
T200	3.404	3.426	3.437	3.443	3.559	3.775	3.783	3.941	4.185
T500	3.690	3.712	3.723	3.729	3.845	4.061	4.069	4.227	4.471
T1000	3.912	3.934	3.945	3.951	4.067	4.283	4.291	4.449	4.693
Levels to mAOD									

Figure 1 – Coastal flood boundary data with climate change adjustment.

The extreme wave heights were derived using the 'countback method' of the State of the Nation (SON), a synthetic data set provided by the environment agency.

Figure 2 shows the JPA curves for the present day offshore conditions. Table 1 presents the 0.5% AEP results for present day, 2070 and 2117.

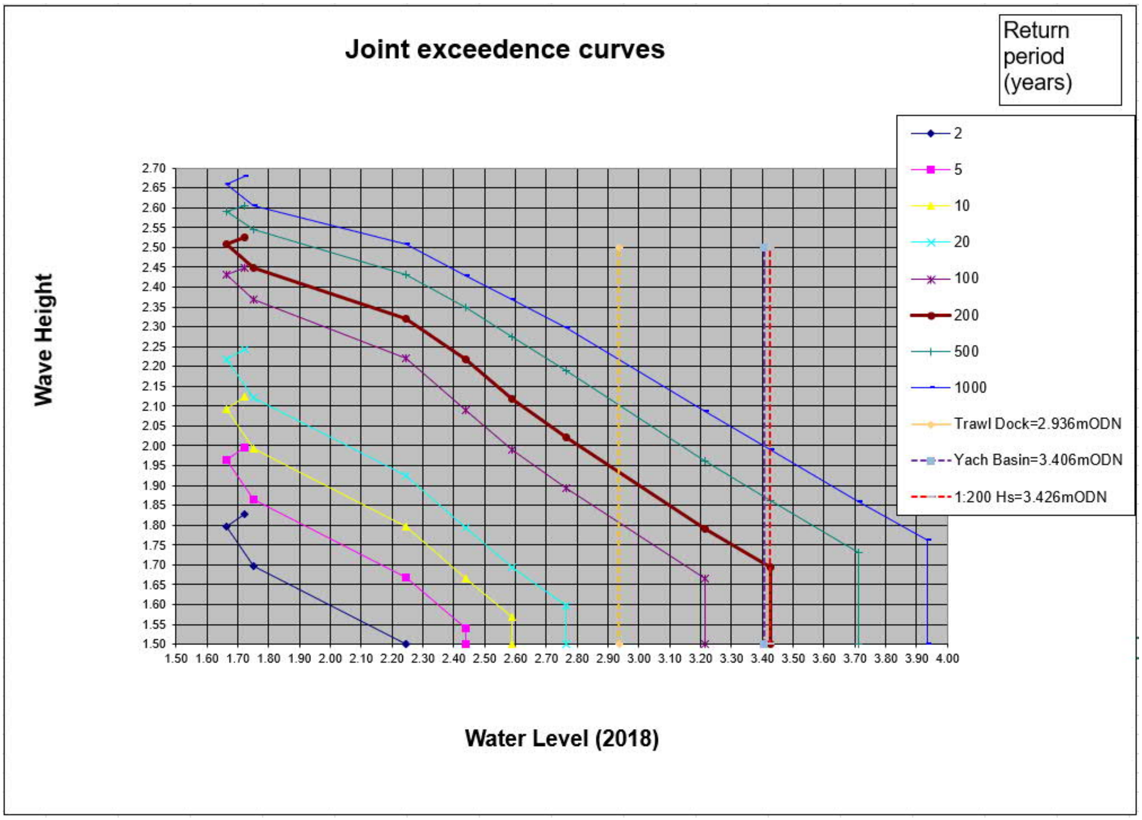


Figure 2 – Present day JPA results offshore of Lowestoft harbour

Run ID	**Extreme Water Level mODN**			**Wave height, H_s (m)**	**Peak wave period, T_p (s)**
	2018	2070	2117		
1	1.72	2.07	2.48	2.52	10.82
2	1.66	2.01	2.42	2.51	10.78
3	1.75	2.10	2.51	2.45	10.62
4	2.24	2.59	3.00	2.32	10.29
5	2.44	2.79	3.20	2.22	10.01
6	2.59	2.94	3.35	2.12	9.74
7	2.76	3.11	3.52	2.02	9.46
8	3.21	3.56	3.97	1.79	8.81
9	3.43	3.775	4.185	1.69	8.51

Table 1 – 0.5% AEP wave and water level conditions for present day, 2070 and 2117

4.1.2 Wave diffraction and transformation

Analysis was undertaken to transform the JPA waves from the offshore location to positions inside the harbour for use in overtopping analysis.

The layout and height of the harbour with inner and outer breakwaters and extreme water levels that can rise above the crest level of the inner breakwaters makes transforming the waves from the open coast to points next to the new defences complicated. In the absence of undertaking expensive and lengthy numerical modelling a couple of approaches were taken to transform the waves.

The tools and methods included Goda (2000) wave transmission formula and diffraction diagrams. In addition, the simplified method for determining wave transmission through breakwaters was considered. Each of these methods is presented in the CIRIA Rock manual: C683; 2007.

The wave heights were determined at a range of locations within the harbour for use and comparison. Figure 3 presents each of these locations. How the transformation was carried out is as follows:

- The waves at locations OH, YB and TD have all used the Goda diffraction charts to determine the wave height change from the harbour entrance. These are likely to be the most accurate waves we are transforming but do not represent the locations we require for overtopping analysis.
- The waves at locations YB1 and TD1 have taken the waves determined at YB and TD and used the simplified wave transmission calculation to transfor to within the inner basins. The simplified transmission approach has really been developed for permeable rubble mound breakwaters rather than impermeable vertical blockwork walls. However given the extreme water levels are over the height of the inner breakwaters it can give a sense of what waves within the inner basins might be.
- The waves at location A and B have used the Goda diffraction charts to determine the wave height change from the inner harbour entrance ignoring the presence of the inner breakwaters. This will result in conservative results but are useful when comparing to YB1 and TD1.

Table 2 and 3 presents the results from the transformation and diffraction analysis for the 0.5% AEP for years, 2070 and 2117.

Figure 3 – Locations of transformed waves into the harbour

Run ID	Extreme water level (mOD)	Wave heights Hs (m)						
		OH	TD	TD1	A	YB	YB1	B

1	2.07	0.73	0.45	0.05	0.38	0.66	0.07	0.38
2	2.01	0.73	0.45	0.05	0.38	0.65	0.07	0.38
3	2.10	0.71	0.44	0.04	0.37	0.64	0.06	0.37
4	2.59	0.67	0.42	0.10	0.35	0.60	0.06	0.35
5	2.79	0.64	0.40	0.15	0.33	0.58	0.08	0.33
6	2.94	0.61	0.38	0.19	0.32	0.55	0.11	0.32
7	3.11	0.59	0.36	0.23	0.30	0.53	0.15	0.30
8	3.56	0.52	0.32	0.26	0.27	0.47	0.26	0.27
9	3.775	0.49	0.30	0.24	0.25	0.44	0.31	0.25

Table 2 – 0.5% AEP Transformed waves for 2070

Run ID	**Extreme water level (mOD)**	**Wave heights Hs (m)**						
		OH	TD	TD1	A	YB	YB1	B
1	2.48	0.73	0.45	0.08	0.38	0.66	0.07	0.38
2	2.42	0.73	0.45	0.06	0.38	0.65	0.07	0.38
3	2.51	0.71	0.44	0.09	0.37	0.64	0.06	0.37
4	3.00	0.67	0.42	0.22	0.35	0.60	0.15	0.35
5	3.20	0.64	0.40	0.27	0.33	0.58	0.20	0.33
6	3.35	0.61	0.38	0.30	0.32	0.55	0.23	0.32
7	3.52	0.59	0.36	0.29	0.30	0.53	0.27	0.30
8	3.97	0.52	0.32	0.26	0.27	0.47	0.38	0.27
9	4.185	0.49	0.30	0.24	0.25	0.44	0.35	0.25

Table 3 – 0.5% AEP Transformed waves for 2117

When the results are compared between TD1 and A and compared for YB1 and B it can be seen that the larger wave heights come from A and YB1. Whilst these results maybe conservative it is considered reasonable that we use these results in the overtopping assessment to ensure a safe assessment.

4.2 Overtopping Assessment

Two overtopping assessments are required to inform the design of the flood protection.

The first assessment looks to determine the required crest level of the defences. This assessment looks to assess the ‘safe’ values in design and so includes factors to account for this safety requirement.

The second assessment is to provide overtopping quantities for inclusion in a flood inundation model to determine localised flooding due to overtopped waves. The need for this assessment is born from the fact the overtopping thresholds for ensuring the structural stability of the defences are not always insignificant. The difference in requirement is that because the flood inundation assessment is looking for the best estimate of flooding levels the mean value of overtopping is required rather than a safety in design assessment which would overstate the flooding extents.

4.2.1 Wall height overtopping assessment

a) Method

Overtopping analysis has been undertaken using the EurOtop Manual 2016. Specifically using the vertical wall, design or assessment approach found in Chapter 7. Whilst the method accurately represents the scenario at the back of the Yacht Basin it will over estimate the value at the Trawler Dock. The reason for this is that the new wall at the Yacht Basin sits along the existing quay wall alignment whereas the new wall behind the Trawler Dock is set back from the existing quay. This set back would cause some disruption of the wave and reduce overtopping.

Crest levels at coastal locations are determined to meet an acceptable overtopping discharge threshold with the amount of 'freeboard' or acceptable wave run-up included as part of that assessment. The use of JPA wave and water level inputs, the 'design or assessment approach' which includes a partial safety factor as well as other application decisions result in a robust assessment that account for the uncertainties as described in W187 guidance.

Notwithstanding the conclusion that the overtopping assessment is robust to account for uncertainty it isn't uncommon for sensitivity analysis to be undertaken to understand the potential impacts. For this scheme sensitivity analysis has been undertaken on the wave conditions and on the EWL. For the wave conditions the increase was completed by using the waves located outside of the inner basin, specifically YB and TD. This amounts to an increase in wave height of 25%. For the extreme water level (EWL) the uncertainty confidence interval determined by the Coastal Flood Boundary Data. As can be seen in Figure 2 an increase to the water level by 0.3m to the 0.5% AEP increases the storm event to a 0.2% AEP (1 in 500 year RP).

b) Discharge thresholds

Discharge thresholds are usually a range of scenarios both ultimate limit state (ULS) and service limit states (SLS). For SLS thresholds analysis is usually undertaken on lower and more frequent AEP conditions. For our assessment lower AEP conditions were not prepared given time constraints and so results for the SLS are considered conservative. The overtopping discharge thresholds for this scheme are as follows:

1) ULS – This threshold is set to maintain the integrity of the proposed structure. As located within an urban environment, the rear of the defences are heavily paved hence mitigating the risk of erosion during the overtopping event and in turn preventing the structure to be destabilised. The updated EurOtop guidance (2016) does not provide thresholds for this. Therefore, in theory overtopping would not be governing under the ULS condition beyond volumes of water impacting localised flooding. However to give a sense of what reasonable discharge rates might be the old EurOtop guidance provided a limit of **200l/s/m** for damage to paved or armoured promenade behind a seawall.

2) SLS – This discharge threshold governs practical consideration and the impacts on people and infrastructure which simply consider safety rather than flood risk.. For the SLS, a lower Return Period is usually considered, however to limit the amount of numerical work, we have only considered the 1 in 200 Year which overstate SLS assessment and therefore provide some conservatism. The EurOtop guidance provides the following discharge threshold:

    - SLS (Pedestrians) – For people at the seawall and a wave height of <0.5m There is **no limit** for overtopping. i.e. not a risk to people.

- SLS (Vehicles) – For vehicles at the seawall and a wave height of = 1.0m Limit overtopping to **75l/s/m** and/or **2000l/m** for overtopping.
- SLS (Buildings) – Building structure elements for a wave height of 1.0m limit overtopping to **1l/s/m** and/or **1000l/m**. As mentioned above, meeting this for a 1 in 200 year RP is deemed to be over-conservative. It should also be noted that the waves are lower than the EurOtop guidance as the waves are lower than 0.4m in height.

c) Results

Table 4, 5, 6 and 7 below present the results for the best assessment of the overtopping discharges for the 0.5% AEP JPA in 2070 with a wall crest height of 4.1mOD and in 2117 for wall crest heights of 4.65mOD.

Run ID	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Crest level (mOD)	Overtopping discharge (l/s/m)	V_{max} (l/m)
1	2.07	0.07	4.1	0	0
2	2.01	0.07	4.1	0	0
3	2.10	0.06	4.1	0	0
4	2.59	0.06	4.1	0	0
5	2.79	0.08	4.1	0	0
6	2.94	0.11	4.1	0	0
7	3.11	0.15	4.1	0	0
8	3.56	0.26	4.1	0.02	108
9	3.775	0.31	4.1	1.7	630

Table 4 – 0.5% AEP, 2070 overtopping results at the Yacht Basin

Run ID	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Crest level (mOD)	Overtopping discharge (l/s/m)	V_{max} (l/m)
1	2.07	0.38	4.1	0	0
2	2.01	0.38	4.1	0	0
3	2.10	0.37	4.1	0	0
4	2.59	0.35	4.1	0	0
5	2.79	0.33	4.1	0	0
6	2.94	0.32	4.1	0	0
7	3.11	0.30	4.1	0	0
8	3.56	0.27	4.1	0.14	138
9	3.775	0.25	4.1	0.50	319

Table 5 – 0.5% AEP, 2070 overtopping results at the Trawler Dock

Run ID	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Crest level (mOD)	Overtopping discharge (l/s/m)	V_{max} (l/m)
1	2.48	0.07	4.65	0	0
2	2.42	0.07	4.65	0	0
3	2.51	0.06	4.65	0	0
4	3.00	0.15	4.65	0	0
5	3.20	0.20	4.65	0	0
6	3.35	0.23	4.65	0	0

7	3.52	0.27	4.65	0	0
8	3.97	0.38	4.65	0.30	305
9	4.185	0.35	4.65	0.78	518

Table 6 – 0.5% AEP, 2117 overtopping results at the Yacht Basin

Run ID	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Crest level (mOD)	Overtopping discharge (l/s/m)	V_{max} (l/m)
1	2.48	0.38	4.65	0	0
2	2.42	0.38	4.65	0	0
3	2.51	0.37	4.65	0	0
4	3.00	0.35	4.65	0	0
5	3.20	0.33	4.65	0	0
6	3.35	0.32	4.65	0	0
7	3.52	0.30	4.65	0	0
8	3.97	0.27	4.65	0	6
9	4.185	0.25	4.65	0.06	150

Table 7 – 0.5% AEP, 2117 overtopping results at the Trawler Dock

What the tables above show is:
Most combination of wave and water level result in zero overtopping.
The maximum overtopping rates are also extremely small but are:

- At the wall behind the Yacht basin.
  - 2070 wall height 4.1mAOD – Max overtopping 1.7l/s/m or 630l/m (*).
  - 2117 wall height 4.65mAOD – Max overtopping 0.78l/s/m or 518l/m (*).

- At the wall behind the Trawl Dock.
  - 2070 wall height 4.1mAOD – Max overtopping 0.50l/s/m or 319l/m (*).
  - 2117 wall height 4.65mAOD – Max overtopping 0.06l/s/m or 150l/m (*).

(*) l/m values are the maximum volume of water predicted for a single maximum wave.

The maximum wave overtopping discharge is 1.7l/s/m and 630l/m which easily meets the ULS thresholds so we can have confidence our defence will remain stable. Under the SLS thresholds the only instance where it is exceeded is the building threshold. It is considered reasonable to accept this risk for the following reasons:

- The use of 0.5% AEP condition significantly overestimates the overtopping. Using a more appropriate and reduced extreme event such as a 10% AEP would significantly reduce the overtopping below the threshold set.
- The buildings are set back from the seawall which would further reduce the overtopping which hasn't been accounted for here.
- The maximum overtopping value is one scenario of nine. This scenario represents the highest water level but under the same extreme event lower water levels with higher wave heights are possible. These other scenarios considered show in most cases the overtopping is zero, or very low. You have a higher chance under a 0.5% AEP storm event to have zero overtopping than you are the maximum threshold.
- The methodology used has some conservatism added in as discussed through the technical note. Namely:
  - Choice of selected input wave condition.
  - Choice of empirical equations.

Results from the sensitivity analysis was undertaken, and the overtopping reported for the following scenarios:

- Increase to the wave heights. Use the wave heights in the outer Harbour and included no effects due to the inner breakwaters. This ignored any effect that would be realised by the extra distance to the defence line or the impact of the inner breakwaters. The minimum increase in wave height is approximately 26%.
- Increase to the Water level by adding the EWL uncertainty allowance (0.3m) to the JPA conditions.

Overtopping Sensitivities results.

- Wave sensitivity analysis. Minimum 26% increase in Wave height
  - At the wall behind the Yacht basin.
    - 2070 wall height 4.1mAOD. Max overtopping 8.23l/s/m or 1791l/m. 3 out of the 9 JPA combinations result in zero overtopping.
    - 2117 wall height 4.65mAOD. Max overtopping 2.84l/s/m or 1063l/m. 4 out of the 9 JPA combinations result in zero overtopping.
  - At the wall behind the Trawl Dock.
    - 2070 wall height 4.1mAOD. Max overtopping 1.46l/s/m or 575l/m. 7 out of the 9 JPA combinations result in zero overtopping.
    - 2117 wall height 4.65mAOD. Max overtopping 0.25l/s/m or 300l/m. 7 out of the 9 JPA combinations result in zero overtopping.
- Water level sensitivity analysis. Add 0.3m EWL uncertainty to the water levels.
  - At the wall behind the Yacht basin.
    - 2070 wall height 4.1mAOD. At the Yacht basin wall – Max overtopping 32.43l/s/m or 4177l/m. 7 out of the 9 JPA combinations result in zero overtopping.
    - 2117 wall height 4.65mAOD. At the Yacht basin wall – Max overtopping 13.1l/s/m or 2080l/m. 6 out of the 9 JPA combinations result in zero overtopping.
  - At the wall behind the Trawl Dock.
    - 2070 wall height 4.1mAOD. Max overtopping 17.28l/s/m or 2238l/m. 6 out of the 9 JPA combinations result in zero overtopping.
    - 2117 wall height 4.65mAOD. Max overtopping 3.89l/s/m or 789l/m. 7 out of the 9 JPA combinations result in zero overtopping.

It can be seen from these results that under SLS thresholds, the values are increases and do not meet the threshold required for buildings notwithstanding the same conservatisms identified above. For the ULS threshold the overtopping is still from exceeding the threshold so we can have confidence the structure shall remain stable under design loading.

The worst overtopping results come from the increased water level analysis for the 2070 epoch. However, any additional allowance for wave overtopping is believed to be unwarranted, given the results are for a condition:

- that occurs only against a water level that is reached 50 years in the future;

- with a wave that on average will only occur once in every 200 years and considering the conservative approach taken during this analysis;
- that condition has to be water level extreme dominant rather than wave extreme dominant (in most JPA scenarios, overtopping is not an issue);
- that is easily acceptable under the ULS condition;

4.2.2 Flood volumes

a) Method

Overtopping analysis has been undertaken using the EurOtop Manual 2016. Specifically using the vertical wall, mean value approach found in Chapter 7. This method is the same as that stipulated in 4.2.1a above but with different coefficients effectively removing the partial factors to give the representative overtopping volume for a given wave and water level. Similarly, to the previous assessment that whilst the method accurately represents the scenario at the back of the Yacht Basin it will over estimate the value at the Trawler Dock. The reason for this is that the new wall at the Yacht Basin sits along the existing quay wall alignment whereas the new wall behind the Trawler Dock is set back from the existing quay. This set back would cause some disruption of the wave and reduce overtopping.

Overtopping analysis results in a value measured in litres / second per meter length of defence. For the flood model a volume of water over a period of time where overtopping is anticipated. Overtopping is usually anticipated over the duration of the storm but is linked to the changing water levels due to the natural tidal cycle so there may be instances where during a storm overtopping does not occur. When ordinarily considering overtopping for stability design the peak overtopping value is required which occurs at the top of the tide. This is what has been determined in section 4.2.1. Because we need to understand how the overtopping quantity changes over the cycle of the tide it is necessary for us to consider a range of water levels at different time steps (usually linked to the model time steps) to more accurately represent the overtopping volumes over this tidal cycle.

The changing overtopping volumes over the tidal cycle has been determined by:

1. Determine the tidal cycle including surge.
2. Determine the water level around the peak storm at an appropriate time interval. For this exercise along with the peak water level, the overtopping has been determined hourly covering a 9 hour window around the peak along with the half hour before and after the peak water level. This duration has been selected as experience shows this will include sufficiently low water levels where no overtopping will occur and sufficiently detailed at the higher overtopping volumes.
3. The assessment has only been considered on the largest peak overtopping JPA condition. In this analysis this was Run ID 9 as can be seen in 4.2.1c.
4. The peak overtopping wave height was used with the varying water level. Whilst it is possible that the wave condition could change over the tidal cycle for a safe assessment this unlikely reduction was not considered.

b) Results

Table 8, 9, 10 and 11 below present the results for the overtopping volumes to be included in the flood models. For the 0.5% AEP JPA in 2070 with a wall crest height of 4.1mOD and in 2117 for wall crest heights of 4.65mOD.

Time stamp	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Defence Length	Overtopping discharge (l/s/m)	Time step (mins)	Overtopping Volume per time step (m^3)

(hour around peak)						
-2	3.35	0.31	165	0.00	60	0.00
-1	3.59	0.31	165	0.08	45	35.64
-0.5	3.72	0.31	165	0.46	30	136.62
Peak	3.775	0.31	165	0.99	30	294.03
+0.5	3.72	0.31	165	0.47	30	139.59
+1	3.55	0.31	165	0.04	45	17.82
+2	3.04	0.31	165	0.00	60	0.00
				Total		**623.7**

Table 8 – 0.5% AEP, 2070 overtopping results at the Yacht Basin

Time stamp (hour number)	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Defence Length	Overtopping discharge (l/s/m)	Time step (mins)	Overtopping Volume per time step (m^3)
-2	3.35	0.25	320	0.00	60	0.00
-1	3.59	0.25	320	0.01	45	8.64
-0.5	3.72	0.25	320	0.08	30	46.08
Peak	3.775	0.25	320	0.26	30	149.76
+0.5	3.72	0.25	320	0.10	30	57.6
+1	3.55	0.25	320	0.00	45	0.00
+2	3.04	0.25	320	0.00	60	0.00
				Total		**262.08**

Table 9 – 0.5% AEP, 2070 overtopping results at the Trawler Dock

Time stamp (hour number)	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Defence Length	Overtopping discharge (l/s/m)	Time step (mins)	Overtopping Volume per time step (m^3)
-2	3.76	0.35	165	0.00	60	0.00
-1	4.00	0.35	165	0.04	45	17.82
-0.5	4.13	0.35	165	0.19	30	56.43
Peak	4.185	0.35	165	0.39	30	115.83
+0.5	4.13	0.35	165	0.20	30	59.4
+1	3.96	0.35	165	0.02	45	8.91
+2	3.45	0.35	165	0.00	60	0.00
				Total		**258.39**

Table 10 – 0.5% AEP, 2117 overtopping results at the Yacht Basin

Time stamp (hour number)	Extreme Water Level (mOD)	Extreme Wave Height, H_s (m)	Defence Length	Overtopping discharge (l/s/m)	Time step (mins)	Overtopping Volume per time step (m^3)
-2	3.76	0.25	320	0.00	60	0.00
-1	4.00	0.25	320	0.00	45	0.00
-0.5	4.13	0.25	320	0.01	30	5.76
Peak	4.185	0.25	320	0.02	30	11.52
+0.5	4.13	0.25	320	0.01	30	5.76
+1	3.96	0.25	320	0.00	45	0.00
+2	3.45	0.25	320	0.00	60	0.00

	Total	**23.04**

Table 11 – 0.5% AEP, 2117 overtopping results at the Trawler Dock

The results in the table above give the overtopped volume of water during a storm for the given timestep. Note that the overtopping discharge at the peak water level is the same event as the correspond overtopping discharge for run ID 9 in section 4.2.1c. i.e. the peak mean overtopping discharge in table 8, 0.99 l/s per m is the same as the 'design and assessment', value with partial safety factors as shown for run ID 9 in table 4, 1.7 l/s per m.

The tables also provided the total volume of water anticipated over a storm event.

These results are to be input to the flood model.

It is worth remembering when viewing the flood model results that the overtopping volumes are for a storm event with a 0.5% EAP in 52 and 99 years' time. Furthermore they are the worst case combination wave and water level for a given JPA return period.

4.3 Conclusions

The walls heights do not need to be increased to the extents that earlier more basic assessment previously indicated, and the proposed crest levels of 4.1mOD in 2070 and 4.65mOD in 2117 are suitable for the 0.5% AEP design event.

However, although it can be guaranteed that the proposed defences will remain stable for all the possible combinations in water levels and waves for a 0.5% AEP, there is a low residual risk that certain combination of conditions would produce wave overtopping that could create localised flooding.

Overtopping volumes have been determined for the inclusion of a flood model using an appropriate mean overtopping assessment. The results for the flood model are presented elsewhere.

Lowestoft tidal barrier and flood walls

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Introduction

This note sets out the assumptions made in the hydraulic modelling used for the Lowestoft Outline Business Case. The hydraulic modelling exercise aims to assess the impact of the proposed flood gates, barrier and walls flood scheme to inform the economic and technical analysis of options in light of revised coastal extreme water levels made available to the project by the Environment Agency. Three scenarios were considered for the purpose of this exercise:

- Do Nothing/ do-minimum: the model includes only the existing quaysides and sea walls / coastal defences (Figure 1).

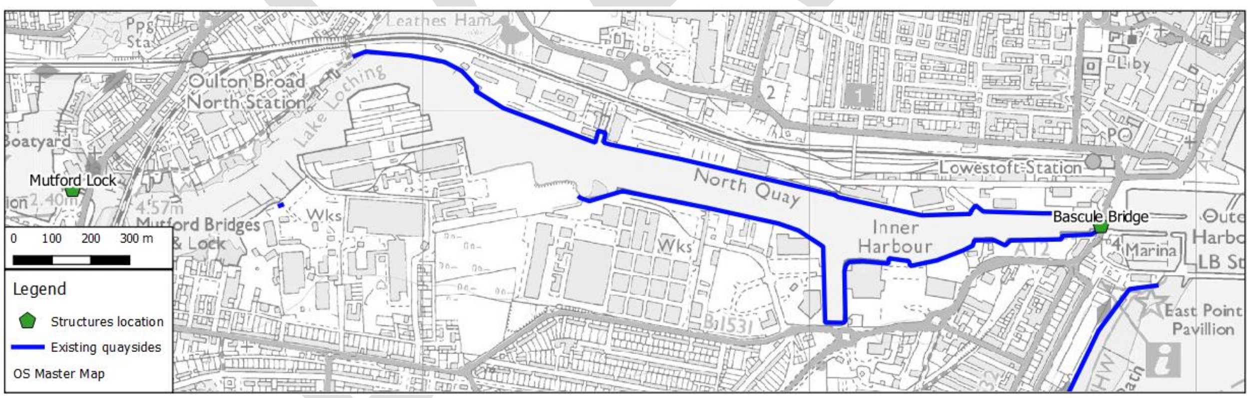

Figure 1 Location of the existing quaysides and sea walls.

- Option 3 – The option includes building new floodwalls along Lake Lothing following the alignment illustrated in Figure 2. Four sub-options were considered offering respectively a 1 in 20, 75, 200 and 500 year standard of protection. An adaptive approach was considered with two alignments modelled up to 2070 and in 2117. Design levels for the walls (excluding any freeboard allowance) is summarised in Table 1.

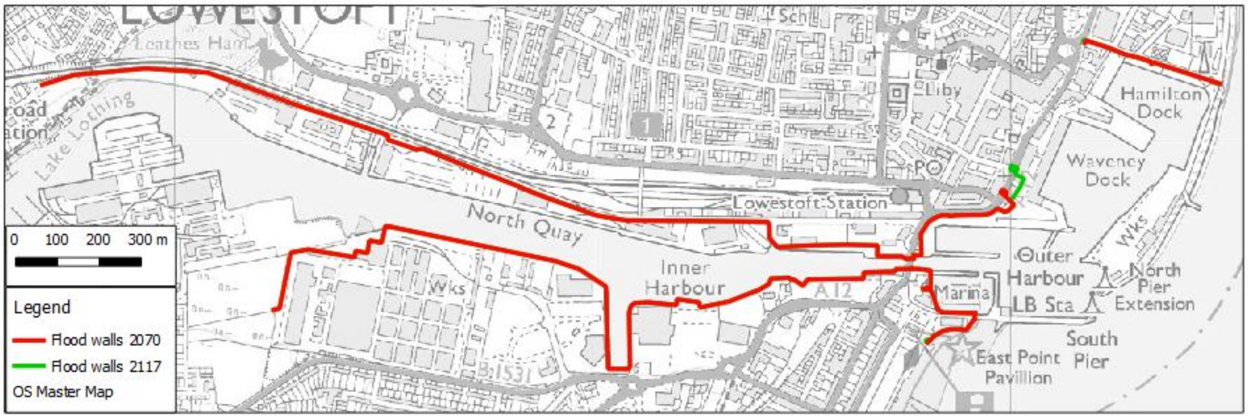

Figure 2 Location of the flood walls for alignments in 2070 and 2117 for Option 3.

- Option 5 – The option includes a tidal barrier at Bascule Bridge and walls along the outer Harbour (see Figure 3). Three sub-options were considered offering a standard of protection of 1 in 75, 200 and 500 year respectively. An adaptive approach was considered with two alignments modelled up to 2070 and in 2117.

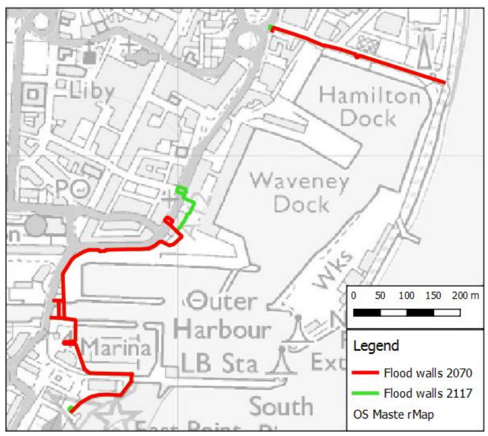

Figure 3 Location of the flood walls for alignment in 2070 and 2117 for Option 5

Table 1 Flood walls and Bascule Barrier level

		Alignment			
		2070		**2117**	
		Walls level [m AOD]		**Walls level [m AOD]**	
OPION 3	SoP 0020	3.11		3.52	
	SoP 0075	3.48		3.89	
	SoP 0200	3.78		4.19	
	SoP 0500	4.06		4.47	
		Walls level [m AOD]	**Barrier level [m AOD]**	**Walls level [m AOD]**	**Barrier level [m AOD]**
OPTION 5	SoP 0075	3.48	3.89	3.89	3.89
	SoP 0200	3.78	4.19	4.19	4.19
	SoP 0500	4.06	4.47	4.47	4.47

Data Provided

The given model of Lowestoft harbor is 1D/2D model built in FloodModeller/ TUFLOW (Figure 4). The model was built by CH2M in 2014 and was used to derive damages for the strategic outline case.

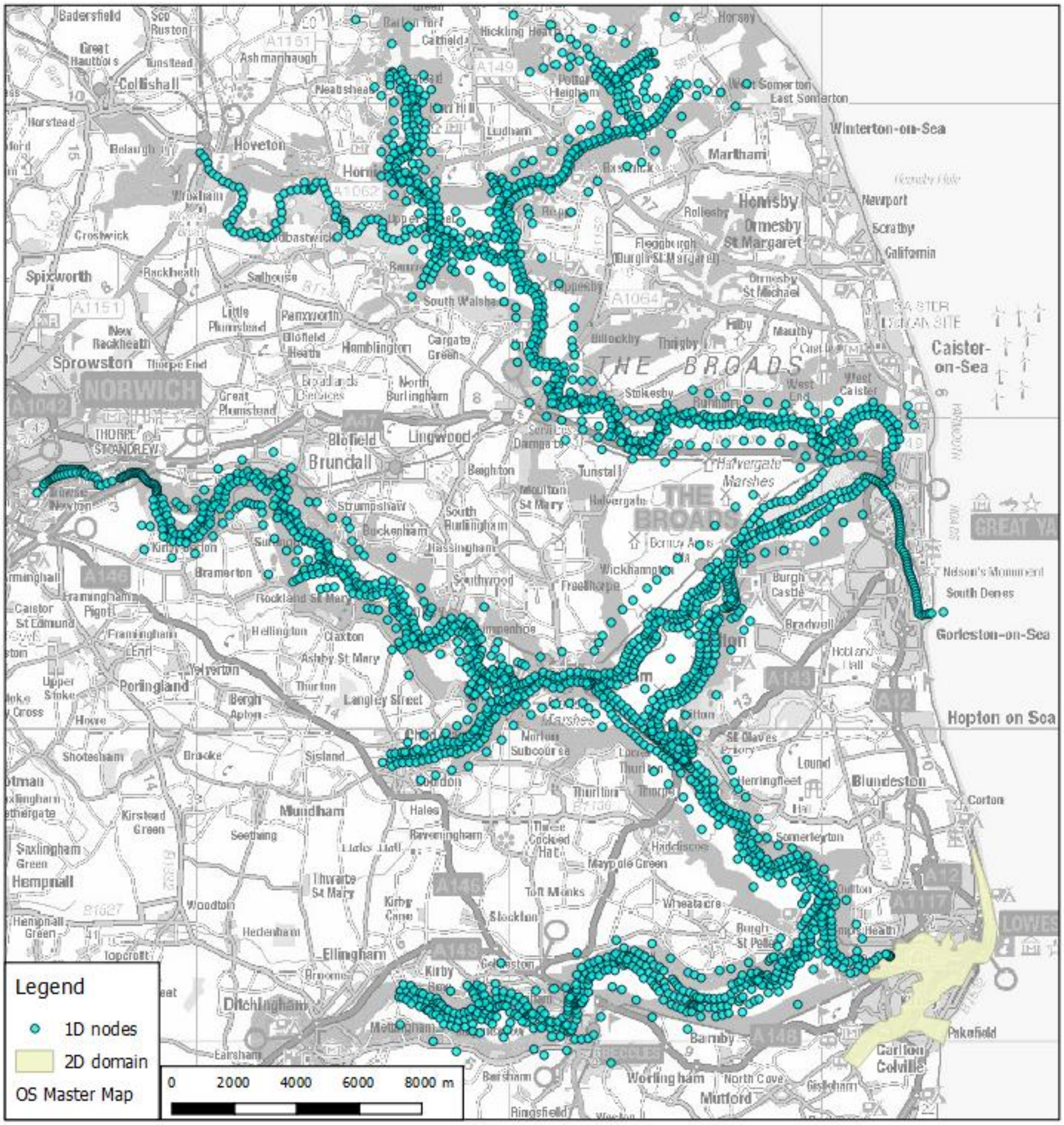

Figure 4 Extent of 1D and 2D domains

Data provided for this study include:

- 1D-2D model files and outputs for 3 scenarios: do minimum, do nothing and 'option' model
- Accompanying modelling technical note (issued on 24/03/2016)
- 2014 hydraulic modelling report

The 1D model domain covers the whole extent of the Broadlands system. The model is hydro-dynamically linked at Mutford Lock to a 2D domain at Lowestoft. Model boundaries consist of tidal head-time boundaries at Lowestoft and Great Yarmouth, and fluvial baseflows at numerous locations within the Broads.

The paragraphs below describe improvements made to the baseline model and modifications required to represent the options considered by the business case.

Methodology

Baseline Model

The baseline model provided was considered satisfactory to develop the required outputs for the outline business case. However, the following improvements were made to make sure the model was robust/ compliant with latest guidance:

- The present day tidal boundaries were extracted from the draft version of the draft Environment Agency JBA Coastal Hydraulic Model (JBA - on going – Products 6&7). Phasing in time between tidal events at Great Yarmouth and Lowestoft was assumed to be 1 hour. Sea level rise uplifts for the tidal boundaries at Great Yarmouth and Lowestoft were updated based on UKCP09 medium emission scenario (95 percentile) consistently with appraisal guidance recommendations. Please see accompanying technical note for further details.
- The sea bed level was lowered from 0.0 m AOD to -1.5 m AOD at the entrance to the outer harbour to match Lower Astronomical Tide at Lowestoft.
- A 2D grid resolution of 10 m was used for the urban area of Lowestoft; this allows a reasonable level of detail whilst keeping run times practical.
- On the west end of the 2D domain, near Oulton Broad, a HQ boundary was applied to ensure no “glasswalling” within the area of interest.
- In all scenarios, Mutford Lock was modeled as a flapped orifice unit and was assumed to be closed during tidal conditions in Lowestoft. The lock was assumed to open only when gravity discharge is possible between Oulton Broad and Lake Lothing (Figure 5).

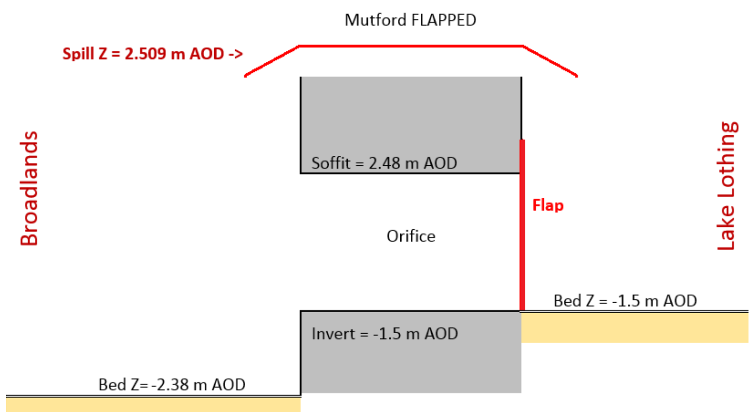

Figure 5 Schematization of the Mutford Lock in the model

- Wall on Saltwater Way A1117 – from inspection of Google Street View near Mutford Lock, a brick wall was located located on the north side of the A1117 road (Figure 6 and 7). This structure was not included in the model, because there are permeable structures on both ends of the wall which would allow for leaking during a tidal event (Figure 8 and 9).

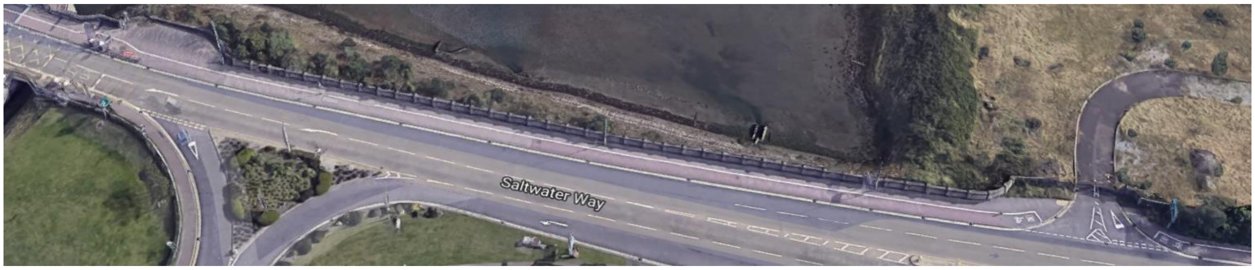

Figure 6 Wall on Saltwater Way © Google 2017

Figure 7 Brick wall on Saltwater Way © Google 2017

Figure 8 Wooden gate on the end of the brick wall © Google 2017

Figure 9 Barrier on the other end of the brick wall © Google 2017

Please note that for the purpose of deriving flood damages, the baseline model outputs were used for both the do-nothing and do-minimum scenario as there are no formal or adopted informal tidal flood defences reducing tidal flood risk to Lowestoft.

Option 3

To test the impact of the proposed flood wall alignments on the current flood risk, the following amendments were made to the 2D domain of the baseline model:

- Flood defences location and height were applied as '2d z-lines' using the levels summarized in Table 1 and the alignments reported in Figure 2.

No other modifications were made to the baseline model.

Option 5

A separate model was created for option 5 with Bascule Barrier and Lake Lothing modeled in 1D using FloodModeller (Figure 10). The approach used ensured that the operating rules could be explicitly included in the model.

Lake Lothing was modelled as a reservoir unit. The level-volume curve for the reservoir was generated based on the shape of Lake Lothing and 0.5 m resolution LiDAR data. The lowest point in the curve was set manually to start from -1.5 m AOD to match with the adjusted Lake Lothing bed level in 2D used for the other scenarios.

Bascule Barrier was modeled as a vertical sluice with logical operating rules and an orifice which works as an opening below the barrier. The designed sluice is 5 m high and 28 m width. Logical rules were applied to close the barrier when water level in Lake Lothing is higher than water level in the harbour. To ensure that water does not go over the barrier in 1D (causing numerical instabilities), the barrier height was set to 10 m in the sluice unit. However, in 2D the height of sluice was set to be equal to the peak of tide for different SoP for 2117 epoch (see Table 1). This allows the water to overtop the sluice in 2D if the tide water level will be higher than the height of the sluice.

The maximum size of the opening below the barrier was optimized to keep the max water level in Lake Lothing below 2.8 mAOD (onset of flooding for residential properties around the perimeter of Lake Lothing) in the 1 in 200 year event, in 2117. Three openings were considered: 0.20m, 0.15m, and 0.10m. The 0.10m opening was the only one meeting the set criteria (see Figure 11).

In this option, flood defences were applied as '2d z-lines' using the levels summarized in Table 1 and the alignments reported in Figure 3 to represent three different standards of protection.

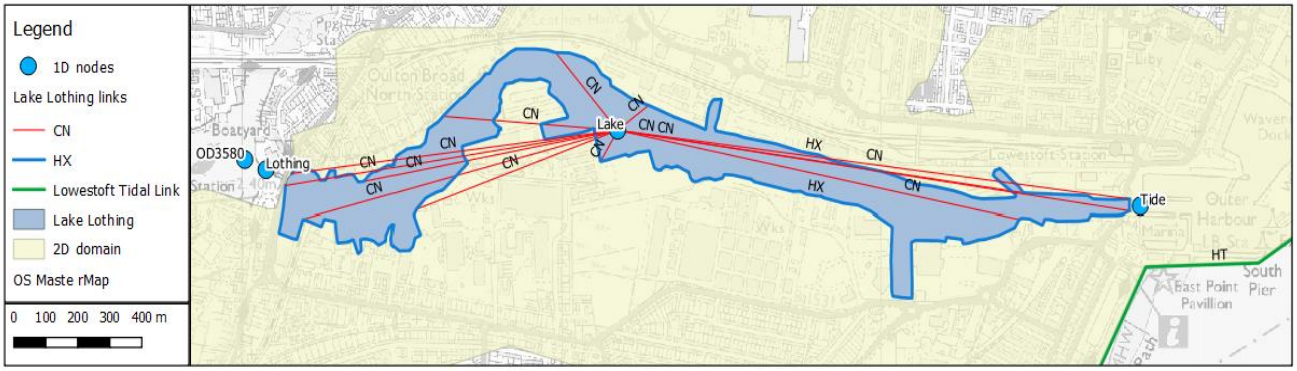

Figure 10 Mutford Lock, Lake Lothing and Bascule Barrier schematization in Option 5.

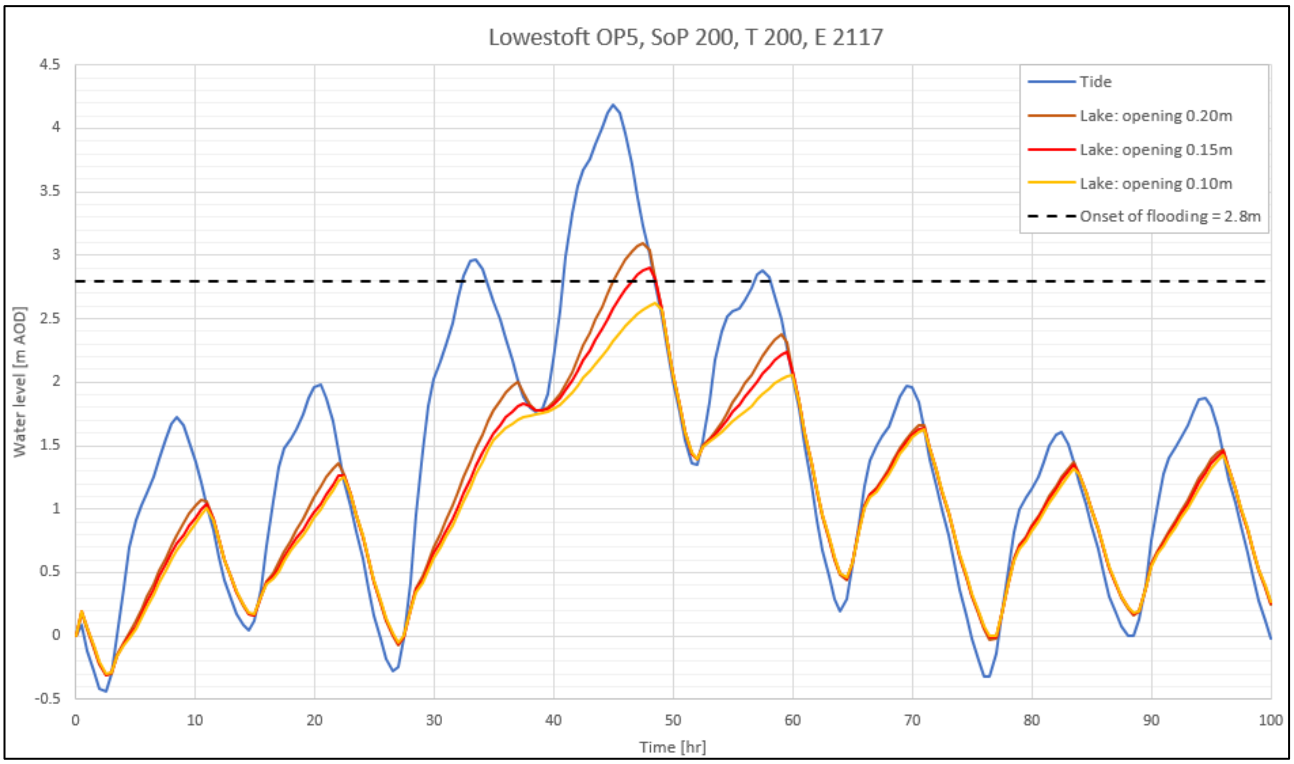

Figure 11 Water level hydrograph at Lake Lothing for three openings, 1 in 200 year event, 2117.

Model runs

For the model scenarios as detailed above the following mode simulations have been undertaken:

- Six climate change epochs (Present day-2018 (only do-minimum/ do-nothing scenario), 2020, 2040, 2070, 2070/2117 (do minimum/ do nothing and Option scenarios) and 2117, note that only the tidal boundaries are changed at the downstream ends within a scenario);
- 2-year, 10-year, 20-year, 75-year, 100-year, 200-year, 500-year and 1000-year events were run for each of the scenarios.

A total of 320 simulations have been run as part of this study.

Results

Analysis of model results show that, For Do Nothing and Option 3 scenarios, the area near Saltwater Way A1117 starts flooding for 1 in 2 year event when the water level exceeds 1.96 mAOD. For Option 5 water flows across the road from 1 in 200 year event.

In the Do Nothing scenario, flooding around Lake Lothing commences from the 1 in 10 year event, when water level exceeds 2.40 mAOD. Flooding occurs at localised low spots in the existing quaysides and sea walls, generally corresponding to slipways. Onset of flooding for most of residential properties in the vicinity of the quayside is between 2.8mAOD and 2.96mAOD.

When water level is higher than 2.60 mAOD, minor flooding occurs near the outer harbour, at road A12 (from the 1 in 10 year). The flooded area considerably increases from the 1 in 75 year event.

For option 3 (standard of protection of 1 in 20 year) minor flooding near Mutford Lock starts from the 1 in 20 year event (affecting only (boat slips and car parks). Flooding considerably increases for the 1 in 75 year event. The outer harbour starts flooding from the 1 in 100 year event. In 2117, onset of flooding for the outer harbour changes to 1 in 75 year.

For Option 3 (standard of protection of 1 in 75 year), the 1 in 200 year event causes flooding of properties near Mutford Lock, whilst in the in outer harbour water overtops the walls in the 1 in 500 year event. Flood outlines/ mechanism is similar for Option 3, standard of protection of 1 in 200 year.

Maximum water level in Lake Lothing for Option 5 is below 2.5mAOD (bank level) up to 1 in 500 year event, 2070 epoch and up to the 1 in 100 year event for 2117 epoch. Maximum water level in Lake Lothing is 2.87m AOD for 1 in 1000 year event for 2117 epoch.

Standard of protection 75 year secures properties near Outer harbour up to 1 in 500 year event in 2020, and up to 1 in 100 year for 2117 epoch. For standard of protection 200 years epoch 2020 and 2070/2177, for options 5, flooding in the outer harbour occurs for events with a severity between 1 in 500 and 1 in 1000 year. The walls and barrier with the highest standard of protection (1 in 500 year) will overtop in the 1 in 1000 year event level predicted in 2070 and in the 1 in 500 year event for 2117.

Maximum water levels in the outer harbour for the baseline scenario are lower than correspondent water levels for all the other option scenarios. Differences are limited (below 0.06 m for the 1 in 100 year event) as shown in Table 2, 3 and 4. Maximum water levels in Lake Lothing are considerably lower in Option 5 (1.3 m than for Option 3 and baseline for the 1 in 100 year event). This is due to the presence of the barrier at Bascule Bridge. Water levels in Lake Lothing are very similar for option 5 and the baseline, as expected.

For Option 5, Lake Lothing does not cause flooding in surrounding area as expected due to the presence of the barrier (Figure 13, 14 and 15). However, for 1 in 1000 year event, tide water level exceeds flood walls in the Outer Harbour and floods the surrounding area (Figure 16, 17 and 18).

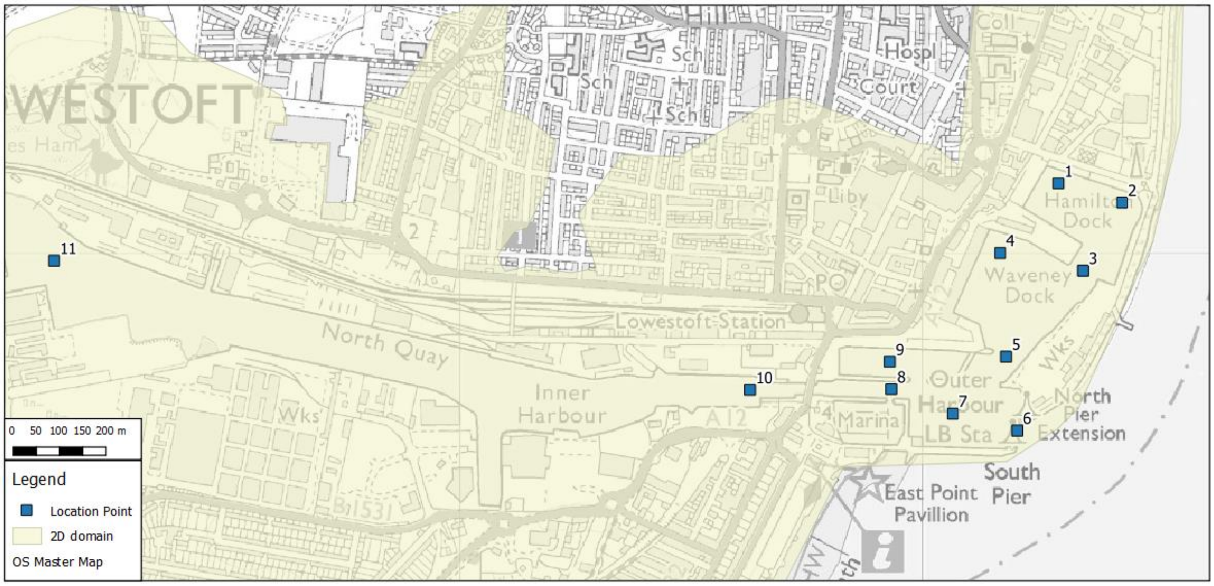

Figure 12 Location of the check points

Table 2 Maximum modelled water levels in the outer harbour and Lake Lothing – 1 in 100 year event – 2020

100yr - 2020		Max water level (mAOD)										
		Outer Harbour									Lake Lothing	
Location Point	Tide	1	2	3	4	5	6	7	8	9	10	11
Do Nothing	3.23	3.20	3.200	3.20	3.200	3.20	3.20	3.20	3.20	3.20	3.12	3.12
Option 3	3.23	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.18	3.18
Option 5	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	1.86	

Table 3 Maximum modelled water levels in the outer harbour and Lake Lothing – 1 in 200 year event – 2020

200yr - 2020		Max water level (mAOD)										
		Outer Harbour									Lake Lothing	
Location Point	Tide	1	2	3	4	5	6	7	8	9	10	11
Do Nothing	3.44	3.38	3.38	3.38	3.38	3.39	3.40	3.39	3.38	3.39	3.31	3.32
Option 3	3.44	3.40	3.40	3.40	3.40	3.40	3.41	3.40	3.40	3.40	3.34	3.35
Option 5	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	1.98	

Table 4 Maximum modelled water levels in the outer harbour and Lake Lothing – 1 in 1000 year event – 2020

1000yr - 2020		Max water level (mAOD)										
		Outer Harbour									Lake Lothing	
Location Point	Tide	1	2	3	4	5	6	7	8	9	10	11
Do Nothing	3.95	3.91	3.91	3.91	3.91	3.91	3.92	3.91	3.91	3.91	3.63	3.63
Option 3	3.95	3.93	3.93	3.93	3.93	3.93	3.94	3.93	3.93	3.93	3.58	3.60
Option 5	3.95	3.94	3.94	3.94	3.94	3.94	3.95	3.94	3.94	3.94	2.33	

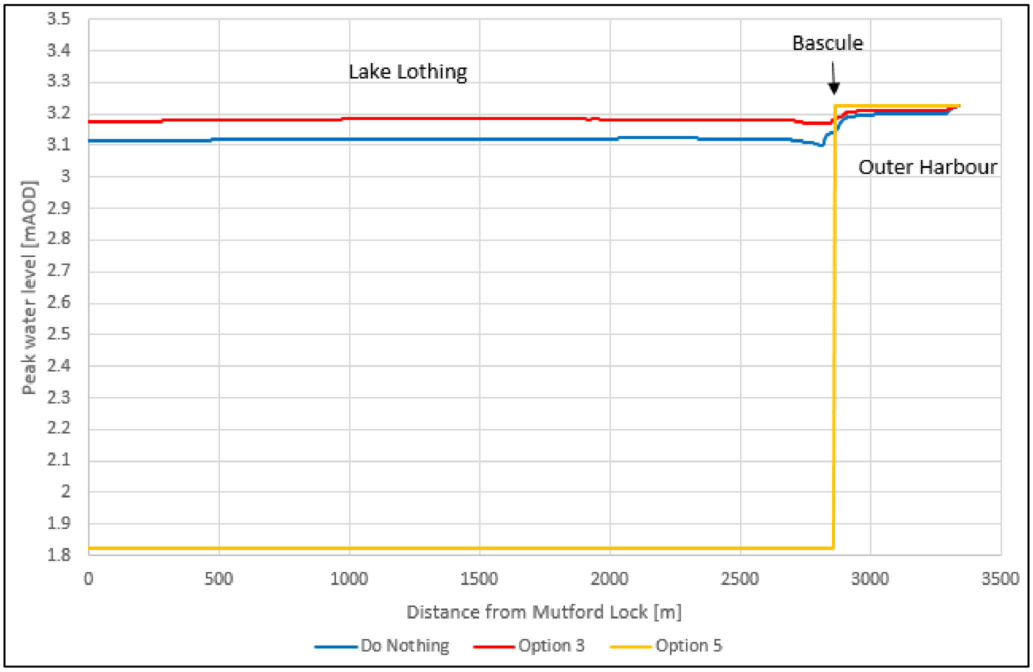

Figure 13 Long profile for 1 in 100 year event in 2020 epoch (for Option 3 and 5 results are for Standard of Protection 200 year)

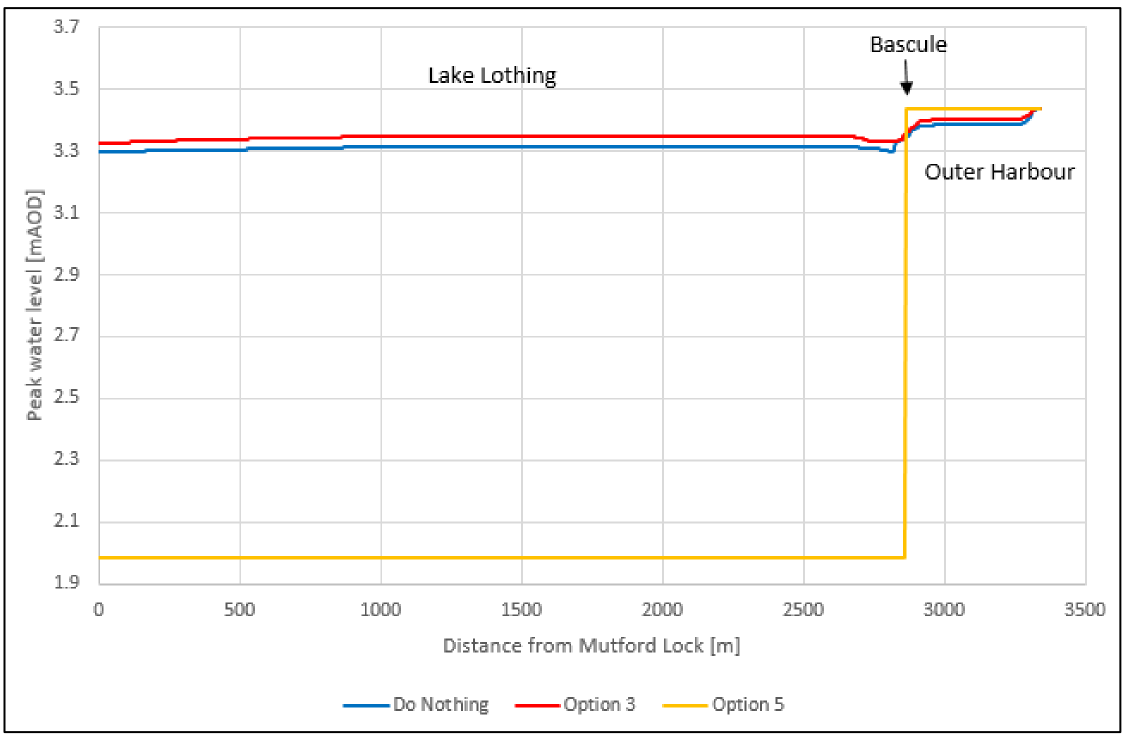

Figure 14 Long profile for 1 in 200 year event in 2020 epoch (for Option 3 and 5 results are for Standard of Protection 200 year)

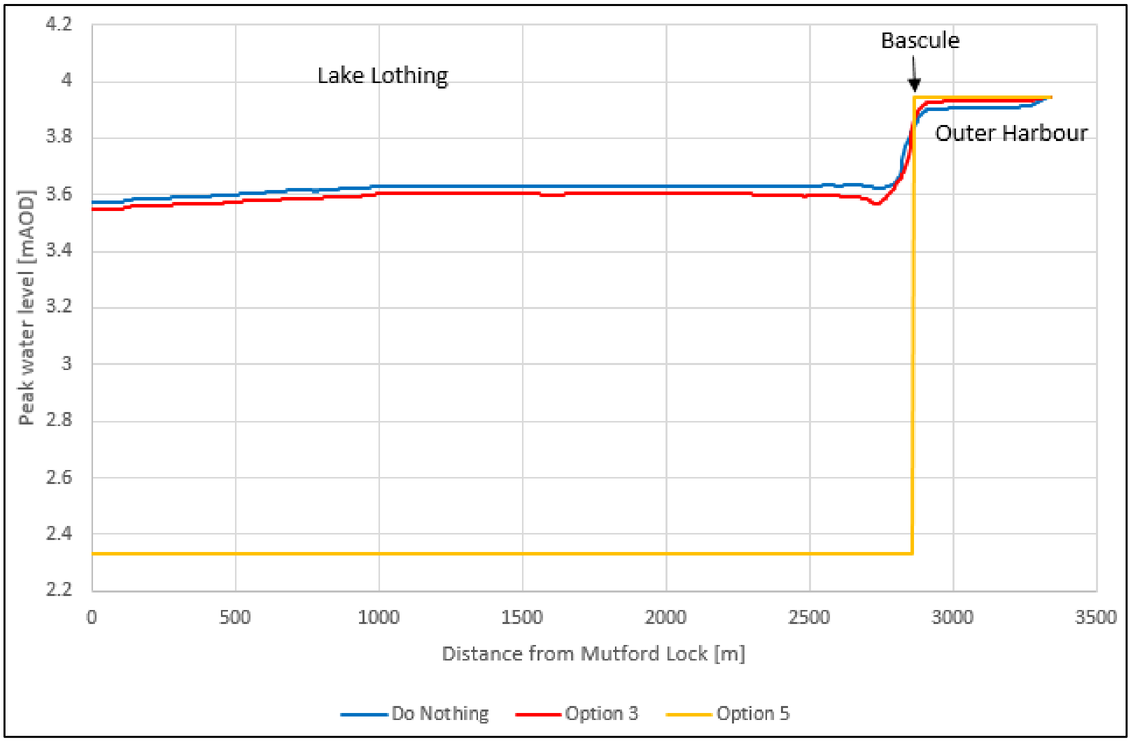

Figure 15 Long profile for 1 in 1000 year event in 2020 epoch (for Option 3 and 5 results are for Standard of Protection 200 year)

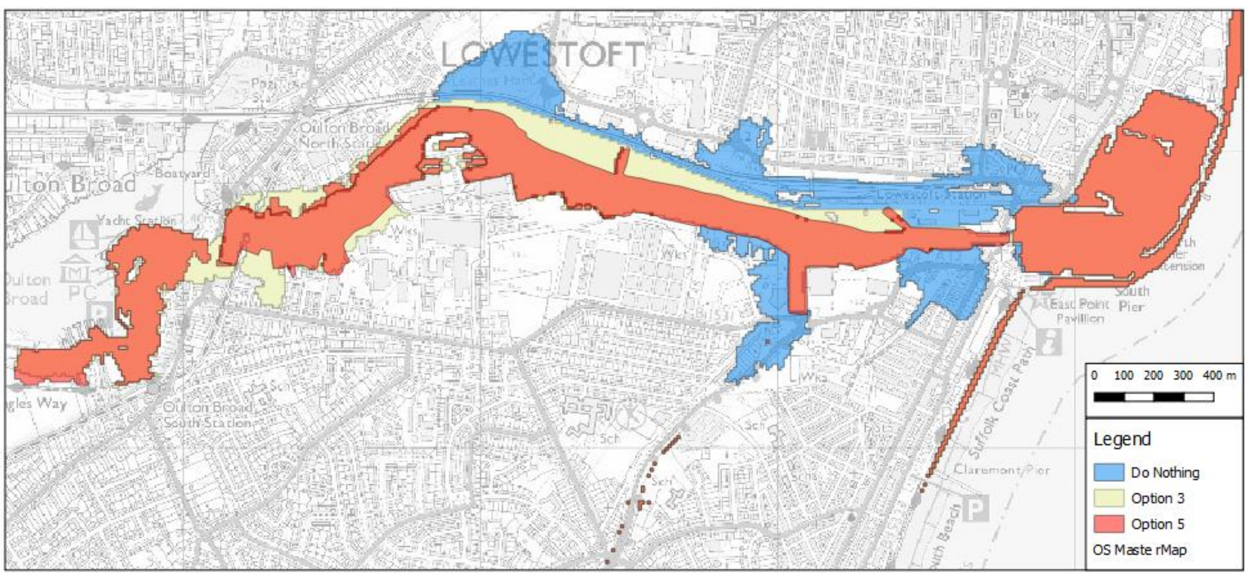

Figure 16 Maximum flood extents – 1 in 100 year event- epoch 2020

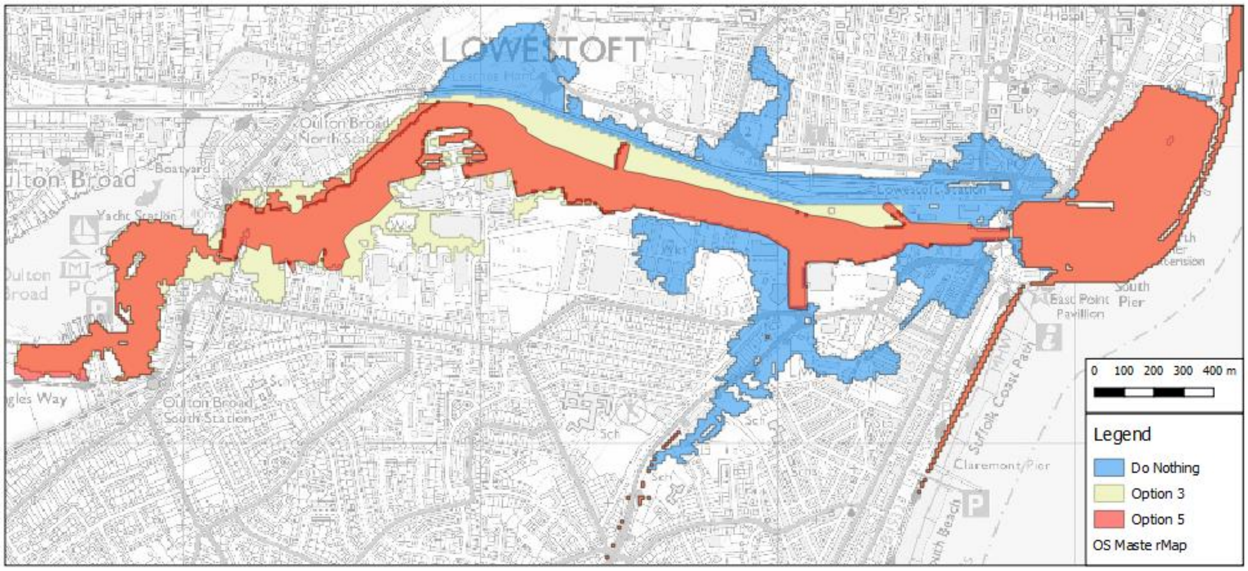

Figure 17 Maximum flood extents – 1 in 200 year event- epoch 2020

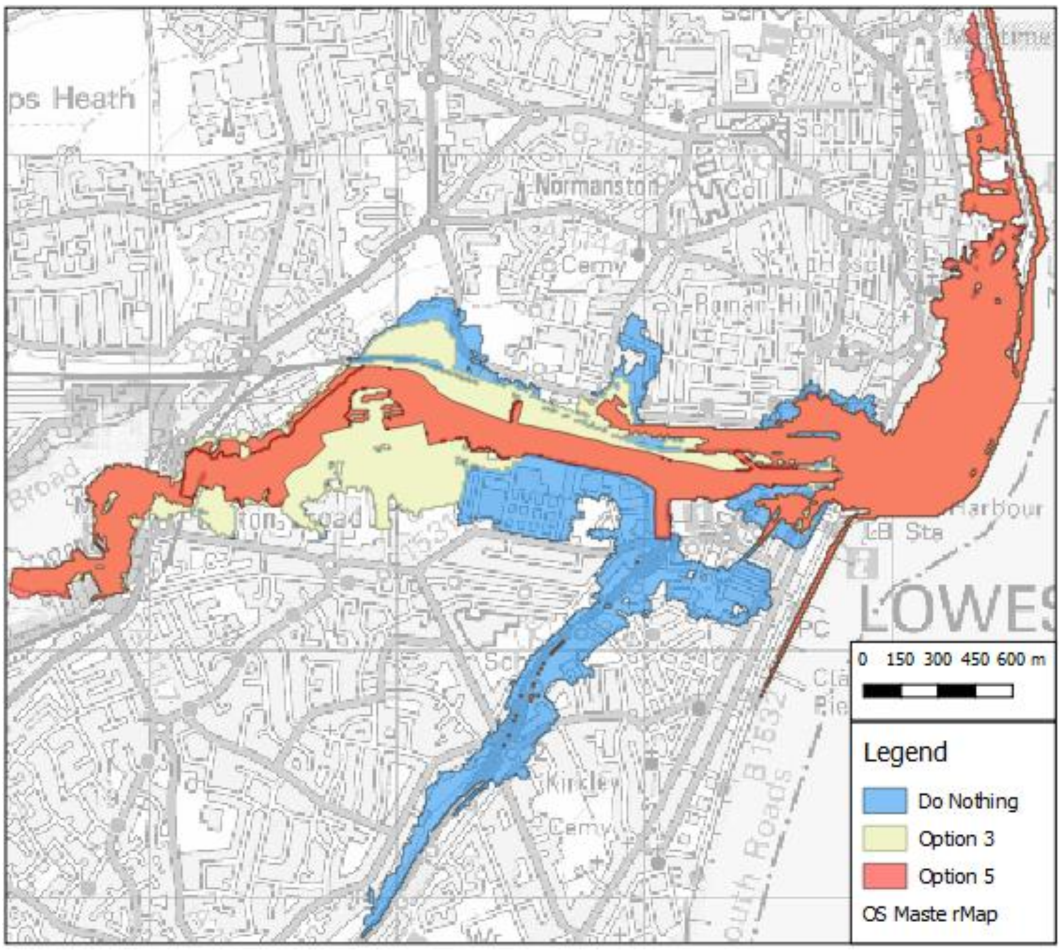

Figure 18 Maximum flood extents – 1 in 1000 year event- epoch 2020

Water levels in the harbour for 1 in 1000 year event are very similar for all the scenarios considered- 3.91 m AOD (baseline), 3.93 m AOD (Option 3) and 3.95 m AOD (Option 5) (Figure 18 and 19). At Hamilton Road, the flood extent for option 5 is bigger than the flood extent for the baseline (do-nothing), which would appear incorrect. Further analysis of the results shows that differences in maximum water level between Do Nothing and Option 5 is 0.04 m (i.e. well within model tolerance).

Also, given the model computational grid size (10m), representation of flooding mechanism in urban areas may not be fully accurate. Increase in grid resolution (5m), may assist in this respect.

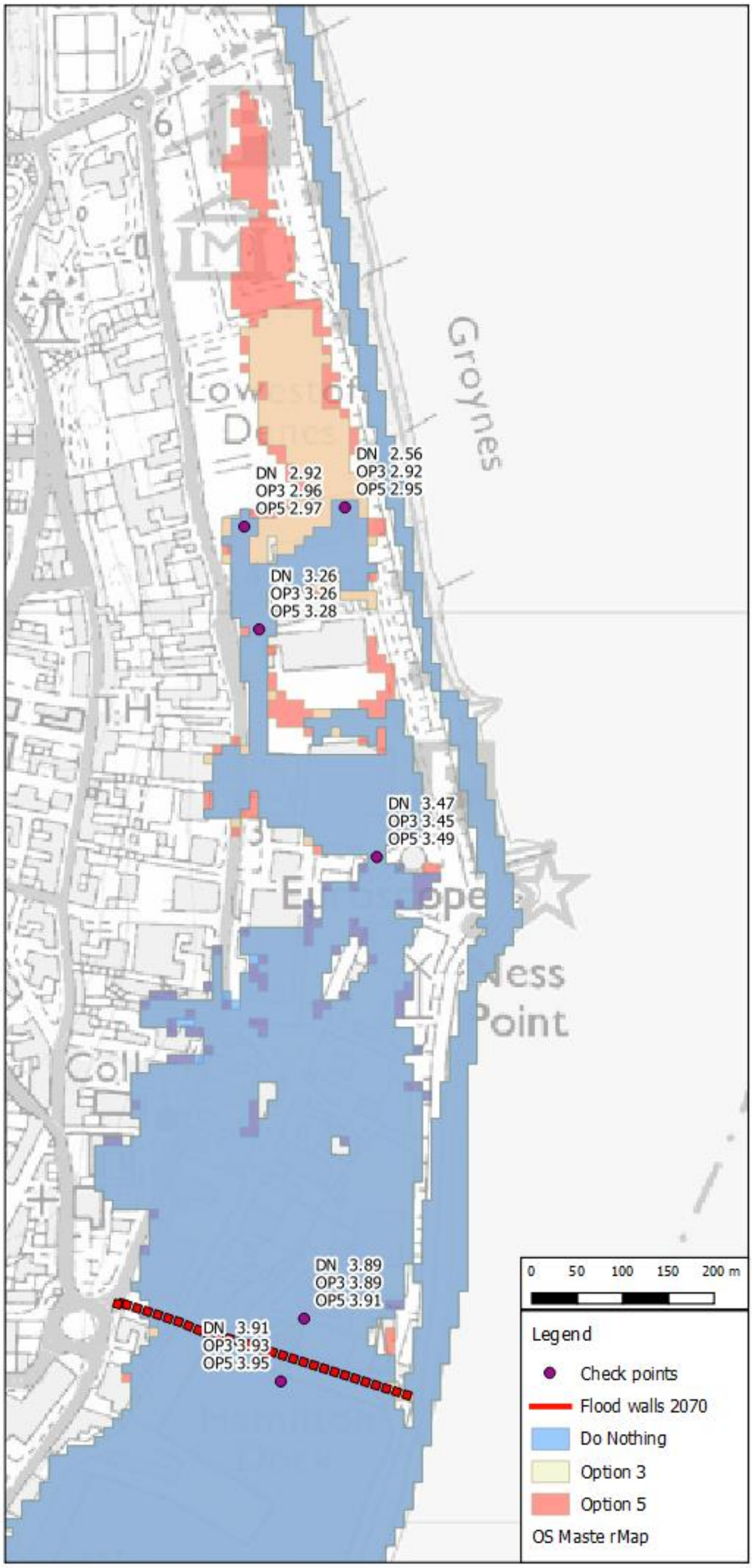

Figure 19 Maximum flood extent – 1 in 1000 year event – epoch 2020 – Hamilton Road

Conclusions

This study was performed to assess the impact of the proposed flood gates, barrier and walls flood scheme to inform the economic and technical analysis of options in light of revised coastal extreme water levels made available to the project by the Environment Agency. Three scenarios were considered for the purpose of this exercise: Do Nothing (do- minimum), Option 3 (new location and height of flood walls in the outer and inner harbour) and Option 5 (new location and height of flood walls in the outer harbour and tide barrier in front of the Bascule Bridge).

The flood walls proposed in Option 3 protect the area near Bascule Bridge (Tom Crisp Way and Waveney Drive), but area closer to Mutford Lock still suffers from flooding. Tidal barrier (and new flood walls) modelled in the Option 5 considerably decreased maximum water level in Lake Lothing.

Overall, the model is performing well and proves that proposed schemes are reducing flood risk in area surrounding Lake Lothing. The model is considered suitable to conduct the economic analysis and assess technical aspects of the options (which have not been explored as part of this note).

Appendix A

Naming convention

Logical file naming conventions were used for data management, clarity and consistency. The ISIS-TUFLOW models are labelled using following system: Study area_Model Scenario_Standard of Protection (if applicable) _Return Period_Epoch_Version number.
Example: LS_OP5_BB_0200_T0005_2020_15

The naming convention above consists of the letters, as follows:

- LS – Lowestoft;
- OP5 _BB – Option 5 Bascule Barrier;
- 0200 – Standard of Protection 200 years;
- T0005 – 1 in 5 year event;
- 2020 – Epoch 2020;
- 15 – Version number.

Quality check

To check quality and performance of the model the following actions were conducted:

- Maximum water depth rasters were subtracted between probabilities and epochs to check if the water depth increases with probability and epoch.
- Maximum water level in check points were plotted on the graphs to ensure that the water level increases with increase of probability and epoch.

Model passed the quality check.

Technical Report

Lowestoft Tidal Defences

Additional Modelling Studies

Prepared for

Waveney District Council

October 2014

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Disclaimer

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Contents

Tables

Figures

1. Summary

In early 2014, Waveney District Council commissioned CH2M HILL to assess a number of pre-defined flood defence options to reduce flood risk to the town of Lowestoft in the county of Suffolk as a result of a tidal surge event coming in from the North Sea. Lowestoft lies on the North Sea coast and is the most easterly part of the UK. The Lowestoft Tidal Defences – Additional Modelling Studies (CH2M HILL, 2014) incorporated results from a previous two studies undertaken by CH2M HILL – the Lowestoft Estuary Inception Study and the Lowestoft Tidal Flood Study (both 2013) whereby flood risk from a tidal surge was assessed for Lowestoft using a completely 2D hydrodynamic model.

This follow on study, used results from the Lowestoft Tidal Flood Study, in which flood defence options were evaluated, to carry forward the most beneficial option for further more detailed analysis. For this study there were three scenarios therefore assessed –

- Scenario 1 – Baseline ‘Do Minimum
- Scenario 2 – Tidal Barrier and Mutford Lock at the Oulton Broads remaining closed
- Scenario 3 – Tidal Barrier and Mutford Lock operating dynamically

Each option was assessed by undertaking a number of hydraulic modelling simulations which incorporated each of the three options in conjunction with 8 extreme event scenarios – 4 of the present day and 4 of future epochs in order to ascertain how each of the two options would perform under the increased flood risk predicted due to climate change.

The hydraulic model from the previous study, the Lowestoft Tidal Flood Study, has been improved in detail via the representation of Bascule Bridge (the critical structure at the mouth of the estuary) and also of Mutford Lock, which controls the passage of flow between the tidally influenced Lake Lothing and the fluvially dominated Outlon Broads system. In implementing these model improvements, the Lowestoft hydraulic model has changed from being solely 2D to a both 1D/2D one which models a coincidental tidal surge hitting the coast at Lowestoft and also Great Yarmouth. The model’s application of this tidal surge at both locations has been verified by records from the December 5th extreme event with hit the eastern coast of England in late 2013.

After a total of 24 model simulations were carried out, the performance of each of the two flood risk prevention options were assessed against the baseline ‘Do Minimum’ one. It was found that by far the greatest flood alleviation was provided by Scenario 2. Both the tidal barrier and Mutford Lock remaining closed throughout the duration of an entire extreme surge event vastly reduced flood risk to very minimal for Lowestoft from what would be catastrophic for some of the more extreme events, with there only being significant flooding for the largest event – the 1 in 1000yr plus climate change. Scenario 3 was also found to greatly reduce flood risk, although not to quite the same extent as its counterpart.

A further analysis was also conducted on the available storage capacity provided by Lake Lothing during these extreme tidal events. This was important to assess what sort of capacity the coastal lake had to take on flood volume from both pluvial and fluvial sources of flooding, given that it was highly likely that either of these flood types could be contributors to the overall flood risk during an extreme tidal event. It was found that there was significant storage volume available within the lake for Scenario 2 for every return period assessed up until the 1 in 1000yr plus climate change, whereas Scenario 3 was found to provide storage within the lake for the three smallest events modelled. These results show the effectiveness of both flood risk prevention options in reducing flood risk to Lowestoft, as the storage capacity of the lake is exceeded for even the lowest return period for the current ‘as-is’Scenario 1.

2. Background

2.1.1 Introduction

In 2012 the Environment Agency commissioned a flood study with the objectives to ascertain and gain a detailed understanding of the potential flood risk to the town of Lowestoft from a tidal surge hitting the south east coast of England from the North Sea. This study culminated with the final report entitled 'Lowestoft Estuary Inception Study, Final Project Report' (Halcrow, February 2013), which concluded that the there was a very real flood risk to the urban hinterland of Lowestoft attributed to potential storm surges occurring in the North Sea. This study was the first of its kind to be undertaken for the town of Lowestoft whereby a complete hydrodynamic 2-dimensional hydraulic model was created and the resultant project deliverables were holistic two dimensional hydrodynamic results. This approach provides a much greater understanding of the potential flood risk to Lowestoft and how the flood cell from the sea interacts with that of the fluvial orientated Oulton Broads which lies to the west of Lake Lothing.

Subsequently, following on from the Lowestoft Inception Study, a further study entitled 'Lowestoft Tidal Flood Study' (Halcrow, June 2013) was commissioned by the Waveney District Council. This study took the basis of what was uncovered in the Lowestoft Inception Study and carried it further via the assessment of a number of tidal flood risk mitigation options (5 in total). The conclusion of this additional study was that a preferred option of a tidal wall put in place at Bascule Bridge, in conjunction with new tidal flood walls erected along the outer harbour perimeter, was to be carried forward for further analysis. A BCR (Benefit Cost Analysis) was conducted where although the present day scenarios did not yield a significant benefit to cost gain, the future scenario epochs did produce a much more favourable one, given the far greater number of properties at risk of flooding due to the higher sea levels predicted for the future.

The next phase of the Lowestoft study has been to upgrade the 2-dimensional hydrodynamic ISIS 2D model to incorporate the preferred flood risk mitigation option of the tidal barrier with proposed outer harbour flood walls. This Technical Report contains the following:

- Assessment of the December 2013 tidal surge flood event
- Description of the additional modelling which has been undertaken
- Details the various scenarios analysed
- A relevant case study example
- Discusses all of the results and conclusions
- Highlights the modelling limitations

It is to be used as an addendum to the 'Lowestoft Inception Study – Final Project Report', and has been prepared for the Waveney District Council.

The next section will briefly explain the analysis undertaken in the previous 'Lowestoft Tidal Flood Study' and how it came to its concluded preferred option.

The Lowestoft study area is shown in Figure 1.

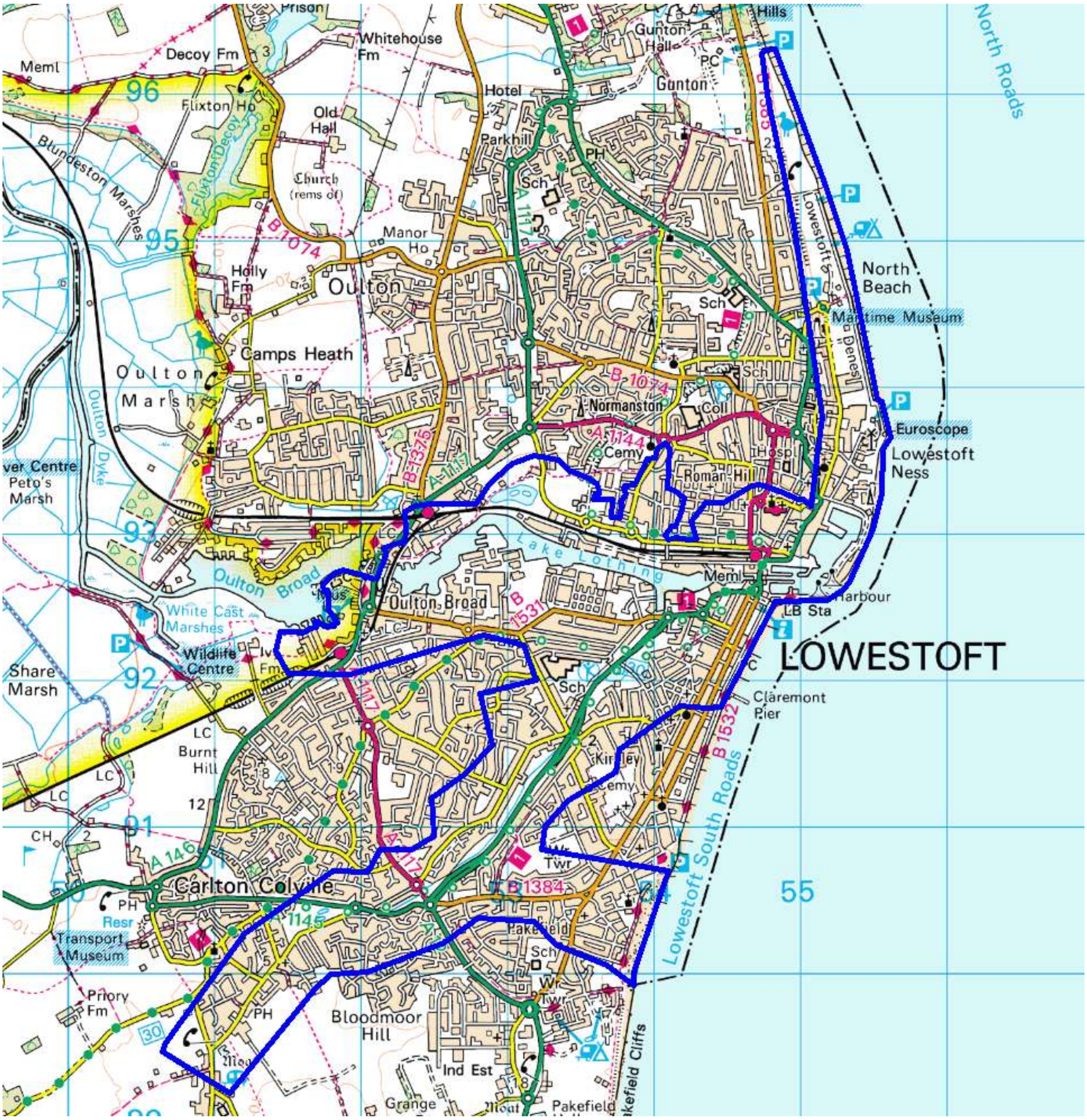

Figure 1 Lowestoft Study Area (within the blue line)

2.1.2 December 2013 Tidal Surge Event

One of the main drivers for further advancing the analysis of flood risk to Lowestoft and optimizing potential flood risk mitigation options was the tidal surge event which occurred on 6th December 2013. This event, which was the worst experienced in the UK in 60 years (since the storm surge event on 31st January 1953) caused wide scale damage, both economic and structural, across the entire south-east coast of England, including Lowestoft.

The event encompassed a tidal surge which formed out in the North Sea under a low pressure front, which in combination with high winds, a long fetch, and high tide culminated in record tidal levels along parts of the south-east coast of England.

The large scale damage caused by the flooding was one of the main drivers for this study to allow for the provision of more robust flood risk prevention measures for the urban hinterland of Lowestoft.

Figure 2 and Figure 3 below show the indicative flood extents for the December 2013 event. Figures depicting both flood damage caused by this extreme event can be seen in Appendix A.

Figure 4 below shows the tidal surge levels recorded at Lowestoft in comparison to the predicted astronomical tide. Note that in the graph shown the peak water level reached 4.72m above chart datum, which equates to 3.29mAOD, which places the event in the order of a 1 in 200yr magnitude – an extreme event which has a probability of exceedance of only 0.5% per annum.

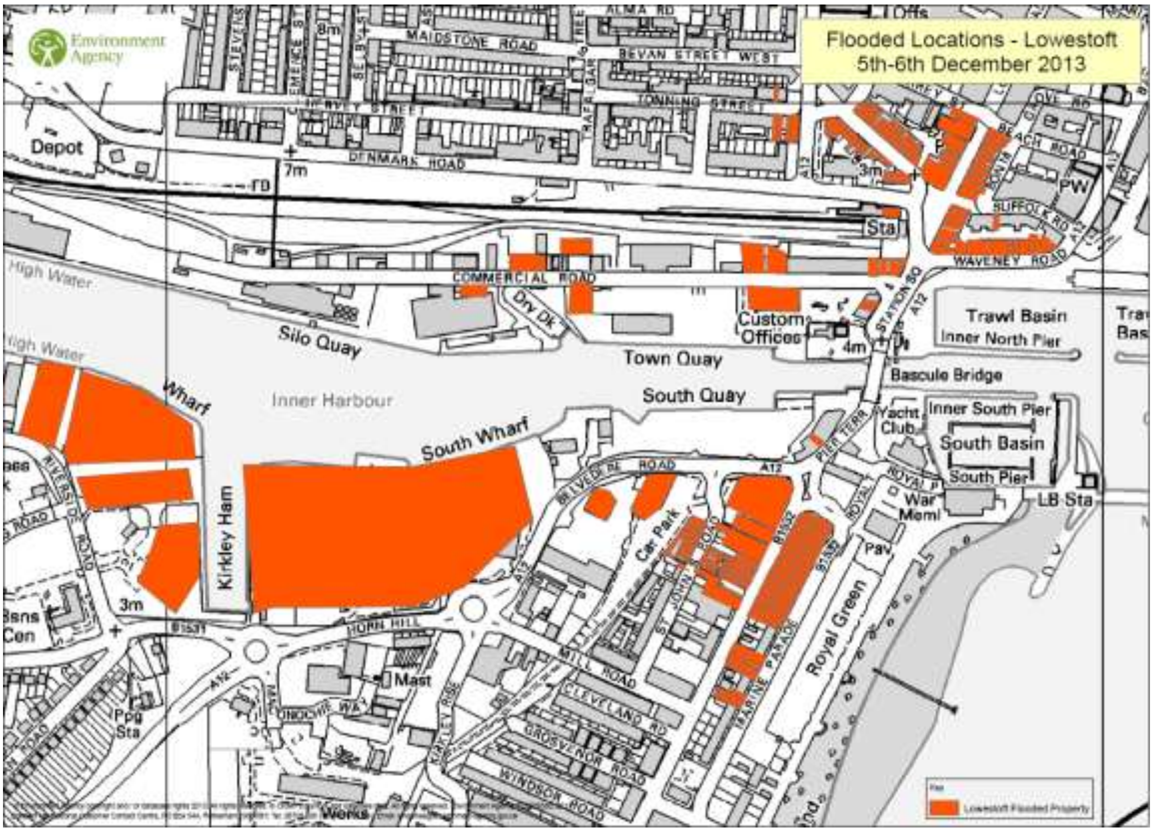

Figure 2 indicative flood locations in east Lowestoft

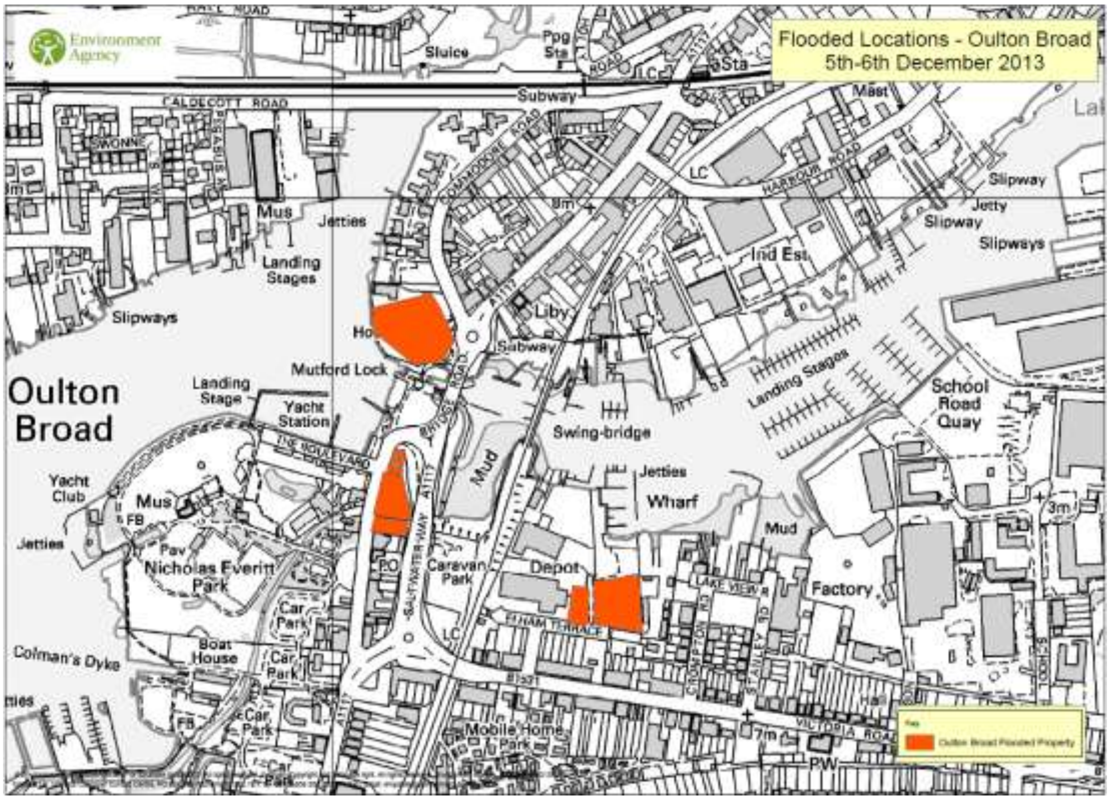

Figure 3 Indicative flood locations in west Lowestoft

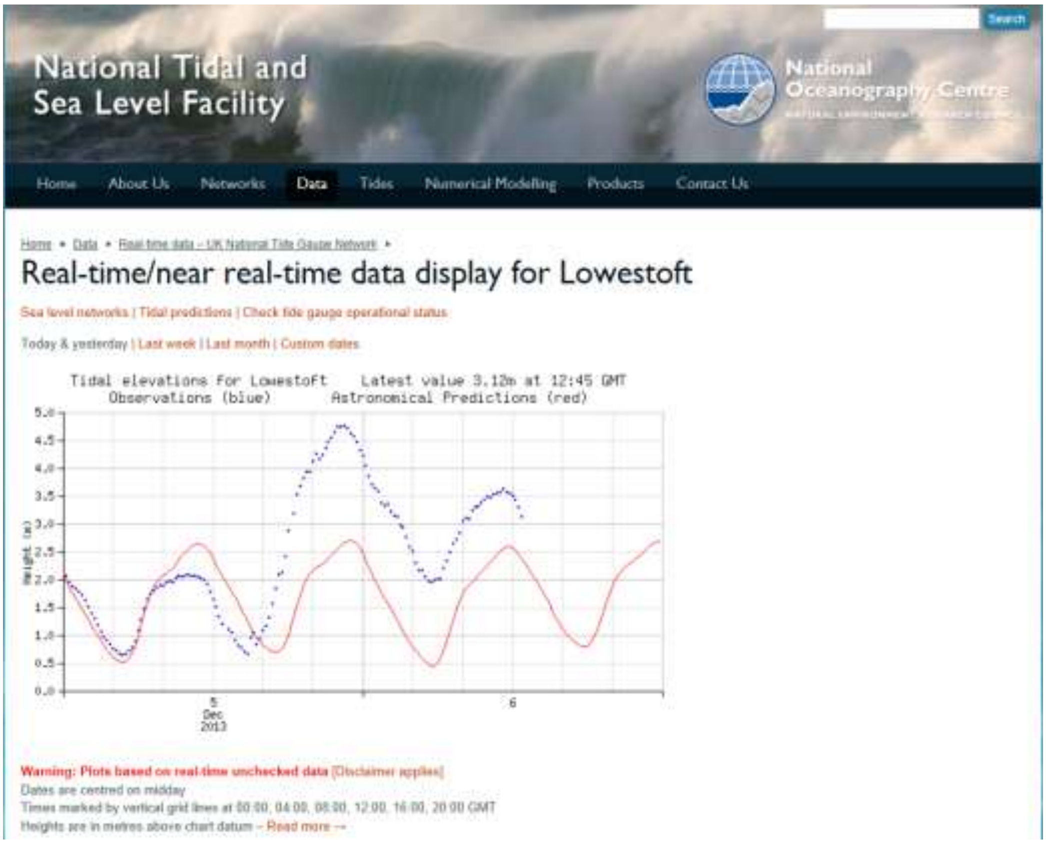

Figure 4 December 6th surge data recorded at Lowestoft tidal gauge

2.1.3 Work Done to March 2014

This study followed on from the 'Lowestoft Estuary Inception Study' and involved the assessment of five additional flood risk mitigation options, as well as the conduction of 'Do Nothing' and 'Do Minimum' scenarios. The 'Do Minimum' scenario was the same as in the 'Lowestoft Estuary Inception Study', however a new 'Do Nothing' scenario was conducted in order to ascertain what would happen should the current coastal and Lake Lothing defences fail. Maximum water levels were found to not differ considerably, with there being a couple of centimetres difference upstream and downstream of Bascule Bridge. The 'Do Nothing' scenario produced slightly higher stage upstream of the bridge and a slightly lower one downstream.

There were also two sensitivity runs conducted for Option 4 which tested whether there would be any significant differences in peak water levels should the initial water level within Lake Lothing and the harbour be increased from 0mAOD to 1mAOD and 2mAOD respectively. These sensitivity runs showed that for the larger climate change events where the defences and tidal gate are overtopped, the increase in maximum water level within Lake Lothing ranges between circa 0.2m (initial water level equal to 1mAOD) and 0.27m (initial conditions equal to 2mAOD).

Table 1 below gives a summation of the options assessed for this study.

TABLE 1 LOWESTOFT TIDAL FLOOD STUDY – OPTION SCENARIOS

Option	Description
Option 1	Do Nothing with all current coastal and estuarine defences removed
Option 2	Do Minimum (same as do minimum for the previous Lowestoft Estuary Inception Study, i.e. maintaining current coastal and estuary defences)
Option 3	Tidal defence wall all around the harbour to a design height of 3.8mAOD (1 in 1000yr present day / 200yr present day +500mm)
Option 4	Same as Design Option 3 except with a tidal lock modelled to prevent tidal flow through Bascule bridge. Tidal Lock level consistent with tidal flood walls (3.8mAOD)
Option 5	Same as Design Option 2 (previous study Do Minimum), except a tidal lock modelled to prevent tidal flow through Bascule bridge. Tidal Lock level consistent with tidal flood walls (this option assumes current tidal defences - check previous model)
Option 6	Same as Option 4 except with design levels increased to provide a standard of protection of 4.35mAOD (200yrCC-DEFRA)
Option 7	Same as Design Option 3, except with raised tidal defence walls along the perimeter of the Inner Harbour set to 3.6mAOD
Sensitivity runs	Design Option 4 set to initial conditions of 1mAOD and 2mAOD (to assess the impact that tidal lock operation rules have on flooding)

After the analysis of each of the five 'hard' defence scenarios (Options 3 - 7), the option which performed the best with regards reduction to flood risk in Lowestoft was 'Option 6'. It was therefore decided to carry this option forward for further development and analysis.

2.1.4 Purpose of Work since March 2014

This is the most recent study conducted regarding flood risk to Lowestoft and is a follow on study from the 'Lowestoft Tidal Flood Study' discussed in the previous section. The preferred option carried forward from the former has been further developed and assessed for this study resulting in a further assessment which involves detailed modelling of a further three scenarios - a 'Do Minimum' and two new option variants. The hydraulic modelling along with the resultant outcomes are discussed in detail in Section 3 of this report.

2.1.5 Grimsby Docks Example

A case study which was reviewed for this study in order to assist in deciding the best operational procedures to adopt for Scenario 3 (operational tidal gate and Mutford Lock), was that of Grimsby, a town to the south east of Hull along the right bank of the River Humber estuary. Grimsby has a tidal gate system in place which was utilised for the December 5th 2013 extreme event. Below is a concise description of the system in place in Grimsby and how the Associated British Ports operated the tidal locks in order to reduce flood risk to the town.

Grimsby is split in to two separate locked dock systems – the fish and commercial docks (see Figure 5). The commercial docks are served by a lock which has standard lock gates to prevent water flowing out of the port. It also has outer flood gates which are higher than the operational gates and are closed to prevent water entering the port on very high tides.

The River Freshney (a relatively small river with generally low flow) flows in to the commercial docks and this water flow is used to replace any water lost while locking vessels into or out of the port. The water in the port is further controlled by a sluice at the lock gates. Many ships transit the lock "on the level" (all the lock gates are open - which allows vessels longer than the lock to use the port). To achieve this the water in the dock needs to be at the same level as outside, which is achieved through synchronising the lock gates to achieve an overall balance of water levels.

At the time of the December 5th 2013 flood the River Freshney had a reasonable flow. Once the water outside of the lock gates becomes higher than inside it is no longer possible to sluice water out. With knowledge of the predicted tidal surge the water in the dock was allowed to flow out as the tide went out (necessary to retain water at sufficient depth to keep vessels afloat). When the tide turned the flood gates were closed therefore keeping a low water level in the dock. This effectively created a basin in to which the River Freshney could continue to flow without backing up in to the town.

The above operational procedure is an example of how a series of tidal lock gates were used to minimise flood risk to a coastal urban area. This was achieved by increasing the storage ability of an estuarine area for fluvial flows which would be unable to drain out into the sea once the outer tidal gates were closed and subsequently shutting the gates to prevent the tidal surge from entering the dock. This case study assisted in the decision making process for how to optimise the functionality of both the tidal gate at Bascule Bridge and the lock gates at Mutford Lock in order to reduce flood risk in Lowestoft and the Oulton Broads due to a tidal surge from the North Sea.

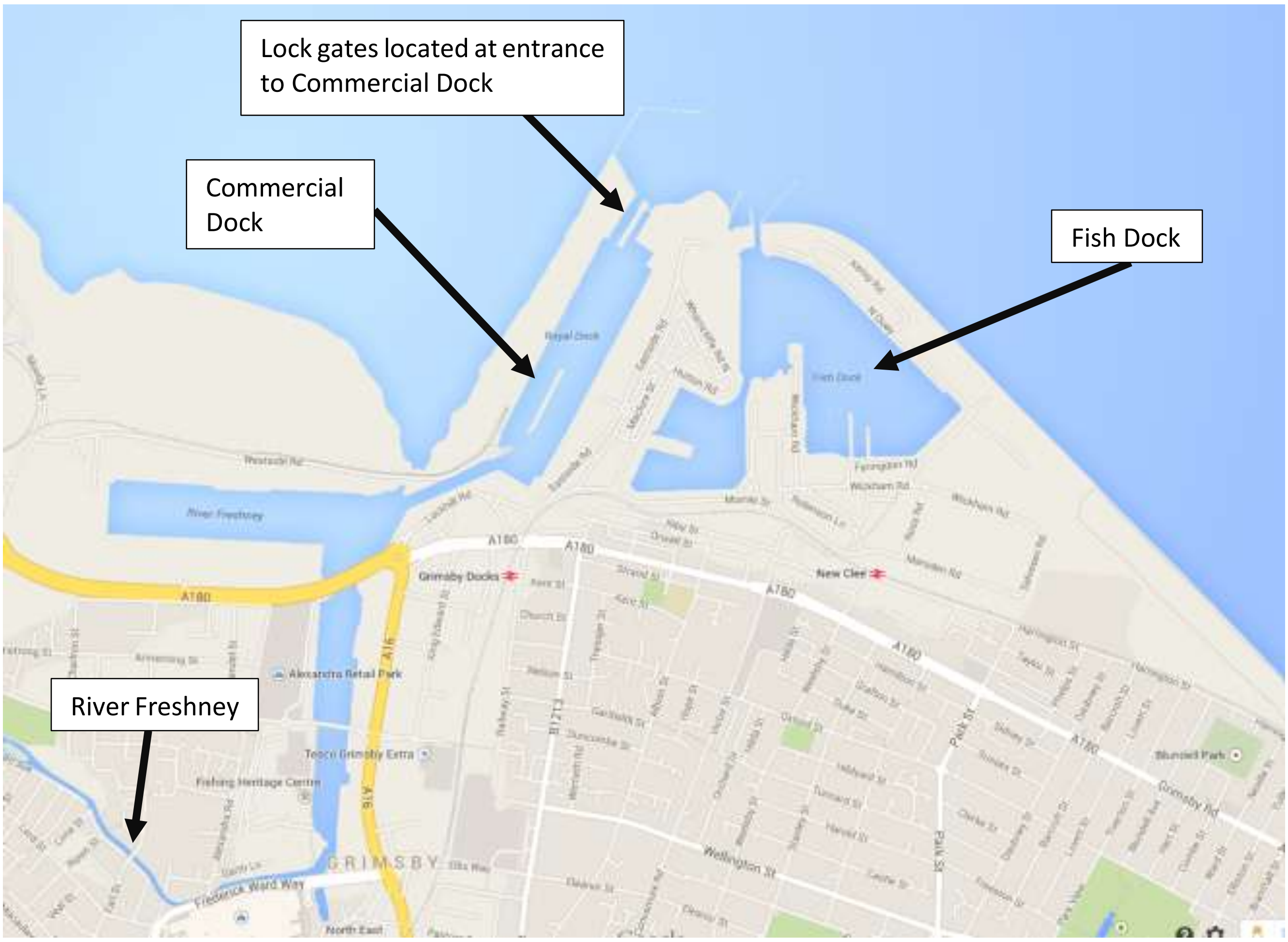

Figure 5 Grimsby docks plan

3. Further Modelling Undertaken Since March 2014

See Appendix B for figures and text describing modelling methodology in detail.

3.1 Existing Models

3.1.1 Lowestoft 2D Coastal Model

The original Lowestoft model was a solely ISIS 2D coastal hydraulic model under which the initial two Lowestoft Studies were undertaken. The tidal surge hydrograph was entered into the model along the entire coastal boundary.

3.1.2 1D BESL Model

The 1D BESL model which represents the entire Oulton Broads fluvial system including the River Waveney and Yare and their associated tributaries, is a very large ISIS 1D model which contains a considerable number of inflow units in the form of QT and ReFH ISIS inflow boundaries. This model has been developed over a considerable number of years with numerous updates and further developments being undertaken throughout its life cycle, given the complexities of the vast area which it represents.

The model was originally incorporated into the Lowestoft Estuary Inception Study to create a Head-Time (HT) boundary for the Oulton Broads end of the Lowestoft ISIS 2D model.

For this study, the 1D BESL model was linked up once again to Lowestoft estuary 2D model and the extreme tidal event was entered as:

1) A 1D Head-Time boundary at Great Yarmouth in the 1D BESL model
2) A 2D Head-Time boundary at Lowestoft in the 2D model component

3.2 Modification and Extension of the Model(s)

3.2.1 Lowestoft 1D/2D linked model

For this study one of the key objectives was to successfully link the Lowestoft 2D model with the BESL 1D model. This was required in order to create a holistic model which encompasses each of the following flood cells:

- Lowestoft tidal surge
- Great Yarmouth tidal surge
- Fluvial system of the Oulton Broads

Both models were linked and after initial stability corrections and resultant schematization changes at the link area at Mutford Lock, the model was stable for the test event of the 1 in 1000yr tidal.

Figure 6 below shows the schematization of the final linked model version used for this study.

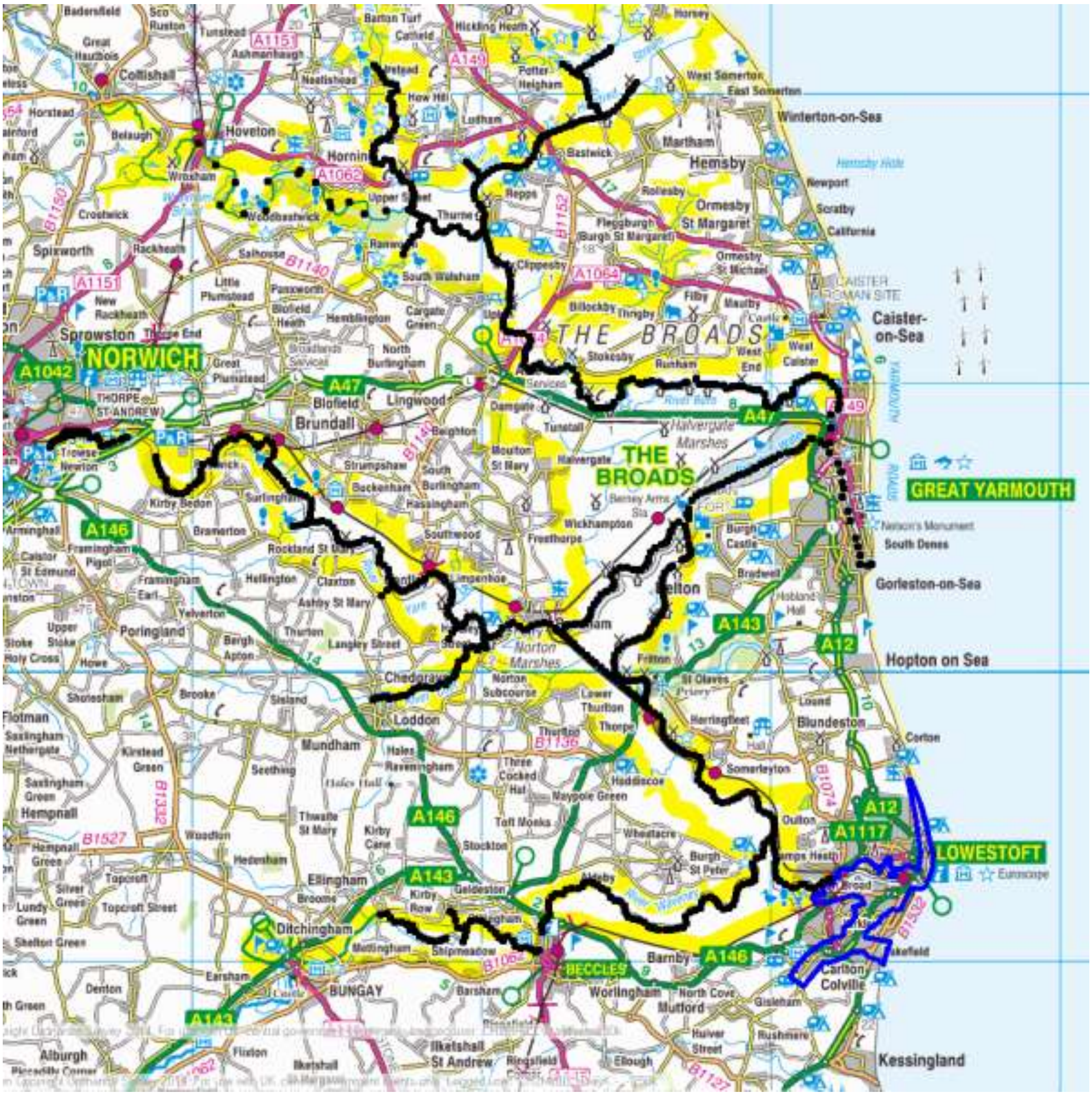

Figure 6 BESL (black dots) and Lowestoft (blue line domain) models

3.3 Verification of Modelling

Analysis of real-time tidal surge data from data supplied by the Environment Agency has yielded the following observations with regards the lag time between the tidal surge peak hitting Great Yarmouth and Lowestoft. The resultant peak Surge level and times are detailed in Table 2.

TABLE 2 LAG TIME FOR DEC 5TH EVENT

Location	Time of Peak	Peak Surge Level (mAOD)	Lag Time (hrs)
Great Yarmouth	05/12/2013 22:30	3.32	-
Lowestoft	05/12/2013 22:45	3.20	0.25

For the December 5th tidal surge event, according to recorded gauging station readings at both Great Yarmouth and Lowestoft, the tidal surge which had propagated up from the North Sea actually hit both locations at almost identical times, with a minimal lag time of 0.25hrs separating the peak surge level occurrence between both sites.

This validates somewhat how each tidal surge design hydrograph has been applied within the Lowestoft 1D/2D hydraulic model. Within the model, both tidal hydrographs have been applied over a 100hr duration, with the tidal surge peak occurring at 45hrs into the extreme event. Given that the difference in time between the peak of the tidal surge for the December 5th event at either key location has been recorded as 15 minutes, it can be assumed that the modelling approach of the surge peak occurring at the same time for each location is perfectly reasonable.

3.4 Bascule Bridge

One of the key requirements of this study has been to incorporate the structure of Bascule Bridge into the 2D model component. The main driver for switching to the Tuflow software suite was to enable the modelling of Bascule Bridge as a structure. In the legacy Lowestoft models, Bascule Bridge was not modelled as a hydraulic structure. The original models modelled the constriction in the width of the channel at the bridge between the outer and inner harbours, but did not model the structure itself, which meant that no bridge unit or soffit level was considered. This meant that should the bridge become surcharged, which would be the case for the more severe extreme events, the hydraulic loss through the bridge was not fully considered. This former schematisation was agreed upon for the previous studies and yielded acceptable results, some of which were validated by the December 2013 event.

However, for the more detailed analyses sought in this study, it was a requirement to model this critical structure completely and not merely the constriction in the channel. The purpose was twofold – firstly, to enable for a direct comparison with the previous studies' model, and possibly validate it; and secondly, to properly model the structure and its associated hydraulic effects, i.e. bridge afflux and losses.

Therefore in this study, Bascule Bridge has been modelled fully as a structure which allows for the modelling of a bridge structure and its associated losses accurately and robustly.

3.5 Proposed Tidal Barrier

Another principal requirement for this study was to model a tidal gate, both closed and dynamic, immediately in front of Bascule Bridge. The purpose of the tidal gate is to prevent the main deluge of the tidal surge from entering into the inner harbour and Lake Lothing, therefore protecting the majority of properties and services which lay to the west of Bascule Bridge. The tidal gate option has been carried forward from the 'Lowestoft Tidal Flood Study' previously and was the preferred option in conjunction with the raised outer harbour flood protection walls. There are two different scenarios involving the use of the tidal gate -

1) The fixed tidal gate which is to remain closed throughout the duration of the model simulation (Scenario 2) set to the 1 in 200yr plus climate change peak water level (4.35mAOD). This ties in with the proposed outer harbour defence wall heights.
2) The dynamic situation (Scenario 3) in which the tidal gate will begin closed and remain as such until the tidal surge from the North Sea has passed at Lowestoft. Once the surge has receded the gate will open allowing any excess water within Lake Lothing to drain out, providing the conditions for the return to the normal tidal cycle. Once opened the gate will remain open for the remainder of the simulation.

3.6 Outer Harbour Flood Walls

In the Lowestoft Tidal Flood Study the options 3, 4, 6 and 7 all proposed renewed outer harbour defence walls raised to specific heights which related to extreme event peak water levels. Option 6 which was carried forward from this former study, had these walls set equal to the peak water level for the 1 in 200yr extreme event plus climate change, which equated to a defence crest height of 4.35mAOD. For this study, these defences were carried forward and utilised again. Figure 7 shows a mixture of the proposed and existing defence types, whereas Figure 8 shows the proposed defence alignment of the new defence scheme.

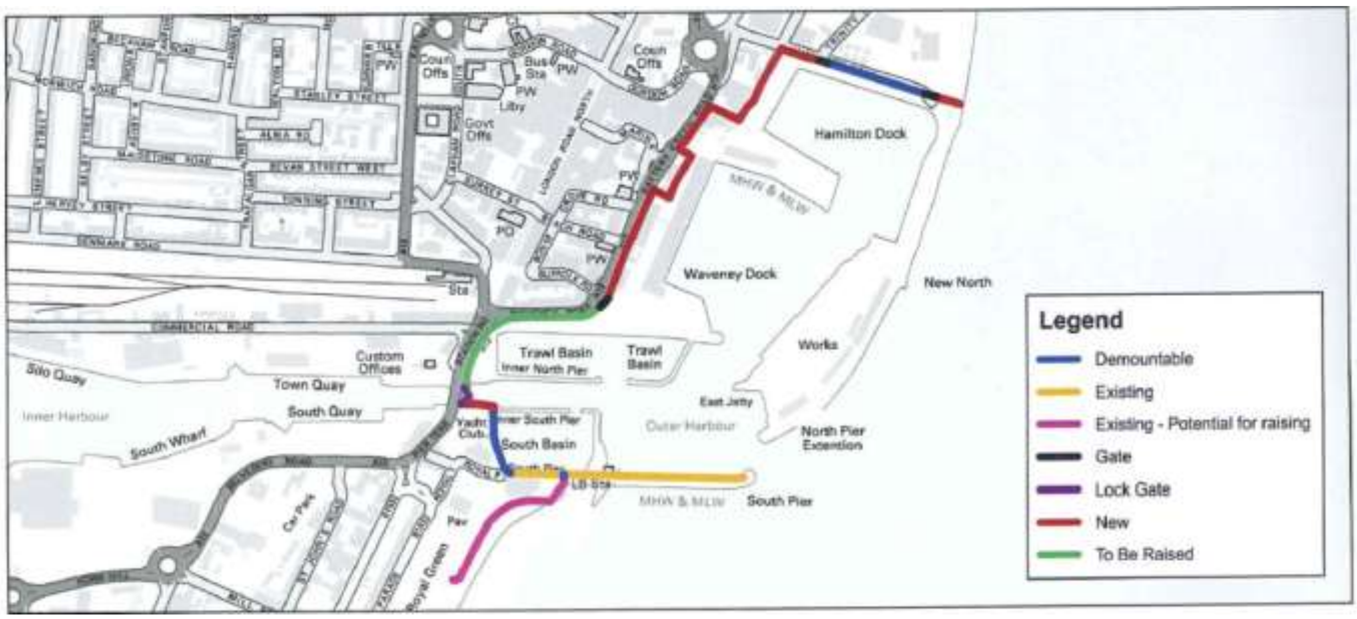

Figure 7 Both existing and prosed defences for outer harbour

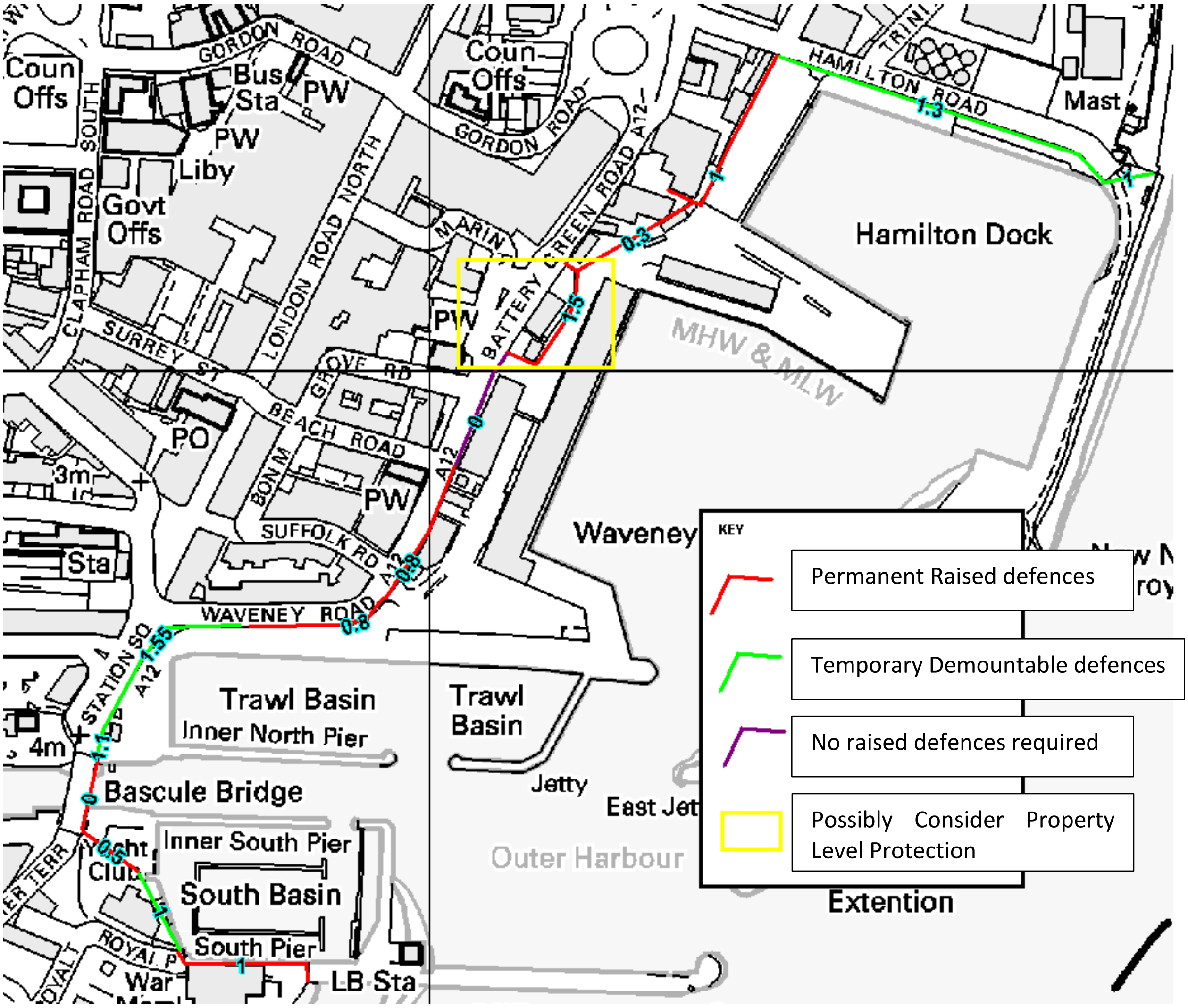

Figure 8 Proposed outer harbour defences with potential defence heights

3.7 Mutford Lock

The final key structure to be modelled in this study is that of Mutford Lock. Mutford Lock comprises of two lock gates which regulate the discharge of flow between the fluvially dominated Oulton Broads and the tidally dominated Lake Lothing. For this study, as with the tidal gate, there are two scenarios in which Mutford Lock operates.

1) Where the lock gates remain shut for the duration of the event (Scenarios 1 and 2)
2) Where the lock gates operation is optimized to reduce water levels within the Outlon Broads via having them open intermittently to allow for any excess water in the Broads to discharge into Lake Lothing (Scenario 3)

The lock is modelled within the 1D model component and is set to the levels as stated by the topo survey from 2007 which was provided for the previous Lowestoft Estuary Inception Study.

3.8 Extreme Events Modelled

The return periods assessed for this latest Lowestoft Study remain the same as before, as do the events incorporating extreme sea level rise due to climate change. Each event assessed in this study is listed in Table 3. In total there are 8 hydrological events in this study for which simulations of each scenario have been undertaken, giving a total of 24 simulations.

Note that for each extreme event modelled the duration is 100hrs with the peak of the tidal surge wave occurring at 45hrs.

TABLE 3 EXTREME EVENTS ASSESSED

Event	Present Day (2011)	Climate Change (2111)
20	Yes	Yes
100	Yes	Yes
200	Yes	Yes
1000	Yes	Yes

3.9 Scenarios Assessed

There were three scenarios assessed for this study. Each scenario was agreed upon at the project inception stage, under the objective of advancing and optimising the preferred option from the 'Lowestoft Tidal Flood Study'.

- <u>Scenario 1 - Do Minimum</u>
  this scenario is the same as it was for the 'Lowestoft Tidal Flood Study'. The scenario has been rerun under the revised model build using Tuflow, with Bascule Bridge now incorporated into the model as a structure and the results used as baseline for this study.
- <u>Scenario 2 - Preferred Tidal Gate and Wall Scheme (Static)</u>

  This scenario assumes the following:

  - That the proposed tidal barrier at Bascule Bridge is in place and remains shut for the duration of the extreme storm event
  - Mutford Lock as closed for the duration of the event

- <u>Scenario 3 – Preferred Tidal Gate and Wall Scheme (Dynamic)</u>

  This scenario assumes the interdependent dynamic operation of both the tidal gate at Bascule Bridge and Mutford Lock. It is the most complex option with the objective being to optimise the flood risk protection provided to both risk receptors in the Oullton Broads and within Lowestoft. The modelling approach adopted for this option is as follows:

  - Model the tidal gate at Bascule Bridge as fully shut until such time that the tidal surge has passed by and the tidal levels have receded substantially so as to not provide any flood risk to Lowestoft

- Model Mutford Lock as a flapped orifice to mimic the effect of the lock gates as operational and only opening to allow water to drain from the Broads at times when the stage is lower in Lake Lothing, therefore not detrimentally effecting flood risk to risk receptors within the Broads as a result of the tidal surge at Lowestoft

4. Results from the Modelling

See Appendix C for flood maps and further images highlighting modelling results.

4.1 General

Table 4 shows the sources for the figures for the results maxima tables in this section.

TABLE 4 RESULTS MAXIMA SOURCES

Location	Data source
Bascule Bridge u/s	2D PO line
Bascule Bridge d/s	2D PO line
Mutford Lock - Lake Lothing	2D PO line
Mutford Lock – Oulton Broads	1D BESL model section OD3580

4.2 Scenario 1 – Do Minimum

Scenario 1 has been modelled as the 'Do Minimum' scenario taken from the 'Lowestoft Tidal Flood Study' with the additional changes/improvements being as follows:

- The Lowestoft 2D model has been linked with the 1D BESL model which models the complex interactive fluvial and tidal system of the Oulton Broads providing a more holistic approach to modelling the numerous flood systems which influence flooding within Lowestoft
- Bascule Bridge has now been incorporated into the baseline model and is modelled within the 2D model component to allow for the true effect of this key structure to be modelled, including the hydraulic loss attributed to the bridge afflux (see Section 3.4.3)
- The spill over Mutford Lock has been re-schematised using up-to-date LiDAR to give an improved representation of the land profile over Bridge Road and to its immediate north and south (see Section 3.4.6), which is where excess flow from the tidal surge will overtop when the lock gates remain closed
- Note that for this scenario Mutford Lock remains closed for the duration of the event

Table 5 gives the maximum stage at key locations in the Lowestoft.

The figures in this section show the maximum flood extents for each of the 8 scenarios assessed.

TABLE 5 RESULTS MAXIMA AT KEY LOCATIONS

	Bascule Bridge u/s		Bascule Bridge d/s		Mutford Lock - Lake Lothing		Mutford Lock – Oulton Broads	
Location	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**
20	2.648	45.11	2.638	45.28	2.640	45.23	1.666	47
20cc	3.679	45.03	3.408	45.33	3.318	45.49	1.876	45.5
100	3.004	45.19	2.941	45.27	2.935	45.29	1.758	46
100cc	4.101	45.02	3.752	45.51	3.620	45.60	2.008	46
200	3.165	45.18	3.079	45.51	3.067	45.43	1.797	46
200cc	4.297	45.02	3.925	45.41	3.755	45.53	2.059	46
1000	3.749	45.02	3.462	45.34	3.363	45.48	1.891	46
1000cc	4.798	45.02	4.417	45.77	4.125	45.96	2.253	46

For the 1 in 20yr the main areas at risk of flooding are as follows:

- Properties along Belvedere Road and St John’s Road to the immediate south of the Inner Harbour
- The railway track and depot to the south of Leathes’ Ham
- A depot to the south of the swing bridge to the east of Bridge Road
- The entire lowland broads area to the south west of Mutford Lock

For the 1 in 100yr the additional areas at risk of flooding are as follows:

- Additional properties to the south of the Inner Harbour along Belvedere Road, St John’s Road and the B1532
- Properties to the north of Bascule Bridge along Waveney Road, Suffold Road, Denmark Road and Tonning Street at the junction with the A12 (Katwijk Way)
- Additional flooding further east along the railway north of Commercial Road and a depot
- Properties along Durban Road and the A12 and A146 are inundated at their junction
- Properties to the east of Riverside Road in the business park along the south quay of the Inner Harbour
- An additional depot and larger area inundated to the south of the railway track and Leathes’ Ham
- Properties along Elham Terrace to the east of the swing bridge

For the 1 in 200yr the additional areas at risk of flooding are as follows:

- Custom offices and more depots along the quays to the south of Commercial Road
- Properties along Maconochie Way, Kirkley Rise and Windsor Road
- Properties to the east of Riverside Road in the business park
- Industrial Estate to the west of Stevens Street and north of Denmark Road
- More depots along the North Quay and south of the railway track

For the 1 in 1000yr the additional areas at risk of flooding are as follows:

- Large area to the immediate north of Hamilton Dock as far as the industrial Estate including the Gas Works, Newcombe Road, Wilde Street, Hamilton Road and sections of Whapload Road
- Additional properties along Surrey Street, Suffolk Road, Tonning Street, Bevan Street West and Denmark Road
- To the south additional properties along Grosvenor Road, Windsor Road and Salisbury Road including a fire station
- A significant number of properties to the west of Tom Crisp Way all the way up until the A1117 Bridge
- Properties in the vicinity of the junction of Rotterdam Road and Norwich Road
- The entire Brook Business and Industrial Park and the works to the immediate east
- School Road Quay

For the 1 in 20yr plus climate change the additional areas at risk are identical to those of the 1 in 1000yr present day event, apart from the following:

- Properties along Veldac and Aldwyck Way to the north east of the A1117 bridge are not at risk
- A lesser number of the smallholdings along Blackheath Road are at risk
- The industrial estate to the north of the Gas Works along the North Beach is no longer at risk

For the 1 in 100yr plus climate change the additional areas at risk are:

- Larger area inundated north of the Industrial Estate along North Beach as far as Denes recreational ground
- To the south a significant number of properties beyond the right and left banks of the Kirkley Stream channel as far as Lowestoft Road including properties along Laxfield Way, Thornam Close, Love Lane and Silverwood Close. Also properties along Long Road along the left bank of Kirkley Stream

For the 1 in 200yr plus climate change the additional areas at risk are:

- Flood water extends approximately 500m further south along Lowestoft Road
- Generally the flood extent is very similar to that of the 1 in 100yr plus climate change event, with the 1 in 200yr one extending up to 30m further inland in some cases

For the 1 in 1000yr plus climate change the additional areas at risk are:

- To the south, properties long Beaconsfield Road, Lawson Road, Ontario Road, Claremont Road, Wellington Esplanade, Waterloo Road
- Properties along Stradbroke Road
- Towards the upstream end of Kirkley Stream properties along Low Farm, Shaw Avenue, Beech Road, Poplar Road, Ashtree Gardens and Lowestoft Road
- Properties along Deepdale, Ribblesdale, Portsch Road and Seavert on the right bank of the Kirkley Stream
- Circa 40 additional properties along Waveney Drive and Crescent

4.3 Scenario 2 – Tidal Barrier and Flood Walls (Static)

Scenario 2 is the preferred option carried forward from the 'Lowestoft Tidal Flood Study' (2013). The criteria for this option are:

- The addition of a tidal gate at Bascule Bridge with a closed gate crest height set equal to the 1 in 200yr plus climate change peak water level of 4.35mAOD. The gate remains fully shut for the duration of the event
- Proposed Outer Harbour defence walls (permanent and demountable) tied into Bascule Bridge set equal to the 1 in 200yr plus climate change peak water level of 4.35mAOD
- Mutford Lock remains shut for the duration of the event

The conditions listed above are present in order to:

a) Prevent a tidal surge of up to the magnitude of the 1 in 200yr plus climate change (second largest event in this study) from entering the Inner Harbour and Lake Lothing

b) Preventing water volume from Lake Lothing from entering into the Oulton Broads through Mutford Lock

c) Preventing excess flow in the Oulton Broads as a result of the propagation of the tidal surge at Great Yarmouth from entering into Lake Lothing

Table 6 gives the maximum stage at key locations in the Lowestoft.

The figures in this section show the maximum flood extents for each of the 8 scenarios assessed.

TABLE 6 RESULTS MAXIMA AT KEY LOCATIONS

	Bascule Bridge u/s		**Bascule Bridge d/s**		**Mutford Lock - Lake Lothing**		**Mutford Lock – Oulton Broads**	
Location	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**
20	2.673	45.03	0	0	0	0	1.652	48.5
20cc	3.731	45.02	0	0	0	0	1.717	61.5
100	3.092	45.02	0	0	0	0	1.668	48
100cc	4.151	45.01	0	0	0	0	1.740	60.5
200	3.291	45.02	0	0	0	0	1.673	48.5
200cc	4.351	45.02	0	0	0	0	1.743	60
1000	3.802	45.02	0	0	0	0	1.690	49.5
1000cc	4.857	45.01	2.996	46.12	2.854	46.17	1.779	46.5

For all of the events up until the 1 in 100yr plus climate change there the tidal surge is contained within the Outer Harbour and the only flooding is:

- The inundation of the lowland area to the south west of Mutford Lock by floodwater from the Broads. This area is generally caravan parks, car parks and a boathouse including the Nicholas Everitt Park

For the 1 in 100yr and the 1 in 200yr plus climate change the additional areas at risk of flooding due to the tidal surge at Lowestoft are –

- Belvedere Road, St John's Road and the B1532 are at risk of flooding due to a gap between the proposed and existing defence lines beyond South Pier. Flood water spills through this low point and propagates a few hundred metres westwards
- Apart from this the lowland area to the south west of Mutford Lock remains at risk from flooding from the Broads

Wide scale flooding occurs for the most extreme event modelled – the 1 in 1000yr plus climate change. This is attributed to the fact that the proposed tidal gate and Outer Harbour defences are only set to a crest height of that equaling the maximum stage achieved by the 1 in 200yr plus climate change extreme event. Therefore the 1 in 1000yr plus climate change peak stage exceeds the proposed defence crest height and overtops them, inflicting severe flood damage.

For the 1 in 1000yr plus climate change, the flood risk within the estuary and Lake Lothing (entire area to the west of Bascule Bridge) is comparable to that of the 1 in 200yr present day event for the baseline Scenario 1. This highlights how much the flood risk is reduced for the most extreme event considered in this study even when the defences are overtopped.

For the 1 in 1000yr plus climate change the following areas are at flood risk:

- Extensive flooding to the north of Lake Lothing all along the North Quay. The railway track is completely inundated. Flood water extents into an industrial estate and over Denmark Road to Norwich Road
- In the vicinity of Bascule Bridge to the north - Station Square and beyond including Waveney Road, Suffolk Road, Surrey street, Beach Road, Clapham Road South, Denmark Road, Grove Road and London Road North
- In the vicinity of Bascule Bridge to the south Belvedere Road, St John's Road and the B1532
- To the north of Hamilton Dock flood risk is similar to that of the same event for Scenario 1
- To the south of Lake Lothing flood water is generally contained by the quay walls which act as de-facto defences, apart from – some overtopping at the Kirkley Stream outfall along the A146 and some properties at risk along Durban Road and some depots at risk to the west of the Kirkley Stream outlet
- Further west, a caravan park and a depot to the east of the swing bridge and a few properties along Elham Terrace are at risk
- Apart from this the lowland area to the south west of Mutford Lock remains at risk from flooding from the Broads

Note that for the removal of flood risk to the immediate south west of Bascule Bridge for the 1 in 100yr and 1 in 200yr plus climate change extreme events, the proposed defences need only be extended slightly south beyond the South Pier by circa 30m to tie them in with the existing ones.

4.4 Scenario 3 – Tidal Barrier and Flood Walls (Dynamic)

Scenario 3 is a more complex derivative of Scenario 2 and it incorporates the dynamic operation of both:

a) Tidal gate at Bascule Bridge

b) Mutford Lock

This option looks at the optimisation of the operation of both of the above structures in order to minimize flood risk to Lowestoft. It is the most complex of the three scenarios assessed in this study and also out of any antecedent Lowestoft option considered in each of the previous studies. It is the only option to be considered thus far which uses dynamic structural conditions, i.e. changing during the event.

After much consideration, the following dynamics were deemed to have the most positive impact on the reduction in flood risk within Lowestoft –

- The tidal gate remains shut until the tidal surge has passed, with it initiating its opening sequence at 51hrs over a period of 1hr. From 52hrs onwards the gate remains fully open
- Mutford Lock gates open whenever the water level in Lake Lothing is lower than the water level in the Broads. This has been achieved through modelling the lock gates as flapped orifices

These operational parameters were maintained for each event in this scenario. Once the tidal gate opens the main surge wave has receded and tidal levels are in the process of decreasing back to normal, therefore the main flood risk has been removed for events up to the 1 in 200yr plus climate change. With regards the operation of Mutford Lock, flow results through the flapped orifice show exactly when water levels in Lake Lothing are lower than those of the Broads. Consequently this highlights the times when it is suitable to open the lock gates to allow flow to discharge into Lake Lothing and to reduce the volume of water in the Broads system.

An example of when the Mutford Lock gates could be opened for the 1 in 1000yr present day event is as follows - flow has passed through the flapped orifice from the Broads and into Lake Lothing each time tidal levels within Lake Lothing are inferior to water levels within the Broads at Mutford Lock. For the 1 in 1000yr event, a peak discharge of 45 cumecs is achieved at 61.5hrs. This coincidentally, is when the tidal is in remission and water levels within the Broads are close to their maximum, therefore producing the greatest head difference to drive the flow from the Broads into Lake Lothing.

It was found that even with the allowance for the drainage of flood volume from the Broads, the overall effect on maximum water levels is not very significant, with the overall reduction for the 1 in 1000yr present day event being 0.2m. Table 7 compares the maximum water levels occurring in the Broads at Mutford Lock for the 1 in 1000yr event.

TABLE 7 1000YR MAXIMUM WATER LEVELS IN OUTLON BROADS AT MUTFORD LOCK

Scenario	Stage (mAOD)	Time (hrs)
1	1.891	46
2	1.690	49.5
3	1.689	49.5

Table 8 gives the maximum stage at key locations in the Lowestoft. It shows that the maximum stage downstream of Bascule Bridge in Lake Lothing occurs much later than the peak in the tidal surge which occurs at 45hrs into the event. Downstream of Bascule Bridge the peak water level occurs after 57hrs for each event bar the 1 in 1000yr plus climate change. This is because the tidal gate only opens after 51hrs therefore the main tidal surge has passed and tidal levels receded by then, with the next tidal peak occurring at 57.50hrs. For the 1 in 1000yr plus climate change event, the tidal waters overtop the tidal gate and Outer Harbour defences therefore the influence of the surge peak at 45hrs is felt immediately downstream of Bascule Bridge. However this effect is localised and not enough volume of water propagates as far downstream as Mutford Lock to raise the tidal level higher than the ensuing lesser peak at 57.50hrs, after the tidal gate has opened.

The figures in this section show the maximum flood extents for each of the 8 scenarios assessed.

TABLE 8 RESULTS MAXIMA AT KEY LOCATIONS

	Bascule Bridge u/s		Bascule Bridge d/s		Mutford Lock - Lake Lothing		Mutford Lock – Oulton Broads	
Location	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**	**Peak Stage (mAOD)**	**Time of Peak (hrs)**
20	2.673	45.03	1.682	57.66	1.697	57.75	1.632	48.5
20cc	3.731	45.02	2.691	57.78	2.690	57.74	1.737	58
100	3.092	45.02	1.922	57.60	1.931	57.69	1.665	48.5
100cc	4.151	45.01	2.862	57.78	2.856	57.81	1.805	58.5
200	3.291	45.02	2.036	57.56	2.042	57.69	1.671	48.5
200cc	4.351	45.02	2.935	57.77	2.931	58.09	1.824	58.5
1000	3.802	45.02	2.317	57.57	2.32	57.68	1.689	49.5
1000cc	4.858	45.02	3.240	45.35	3.136	57.89	1.884	58

For this event, flood risk is kept to a minimum by the optimisation of the operation of both the tidal gate and Mutford Lock for all of the present day scenarios assessed, with risk only become significant for the climate change scenarios.

Flood risk for the 1 in 20yr plus climate change scenario is as follows:

- To the immediate south of Bascule Bridge Belvedere Road, St Johns Road and the B1532
- A section of the railway track and a depot to the south of Leathes' Ham
- A depot to the east of the swing bridge

Additional flood risk for the 1 in 100yr plus climate change scenario is as follows:

- A section of Pier Terr to the immediate south of Bascule Bridge
- To the south of the Kirkley Stream outfall, sections of the A146 and A12 and some properties along Durban Road
- To the east of the swing bridge some properties along Elham Terrace

Additional flood risk for the 1 in 200yr plus climate change scenario is as follows:

- Small segment of Commercial Road immediately north of the Dry Dock and Town Quay
- Tidal water spills into the Kirkley Stream channel and propagates approximately 400m upstream
- Flood water enters onto the railway track south of Leathes Ham and flows eastwards along it for circa 700m where it floods a depot

Additional flood risk for the 1 in 1000yr plus climate change scenario is as follows:

- To the north of Hamilton Dock flood risk is similar to that of the same event for Scenario 1
- To the north of Bascule Bridge and Lake Lothing flood risk is similar to that of Scenario 2, with flood risk to Station Square, Waveney Road, Suffolk Road, Surrey street, Beach Road, Clapham Road South, Denmark Road, Grove Road and London Road North
- Extensive flooding to the north of Lake Lothing all along the North Quay. The railway track is completely inundated. Flood water extends into an industrial estate and over Denmark Road to Norwich Road
- To the south additional flooding to the industrial estate to the west of Riverside Road
- To the south east of the Kirkley Stream outfall water propagates circa 350m as far as Windsor and Grosvenor Road
- Water propagates further up the Kirkley Stream channel putting some properties along Brid's Lane, Long Road, Carlton Road and Blackheath Road at risk. A riding School off Carlton Road is also at risk
- A depot and a factory on School Road Quay

The reduction in flood risk between Scenario 1 and Scenario 3 for the largest extreme event modelled (1 in 1000yr plus climate change) is considerable, with a large reduction in flood risk to the south of Lake Lothing and the Kirkley Stream channel.

4.5 Comparison with Previous Modelling Results

Given that this study involved not only significant further developments to the original Lowestoft model but also its complete rebuild with a different software (yielding the switch from ISIS 2D to Tuflow), a brief analysis was undertaken between results from both elements.

The 1 in 1000yr 'Do Minimum' event was selected to be used for the comparison, given that this is in the mid-range of all of the scenarios assessed and the most severe present day extreme event modelled. The 'Do Minimum' scenario was chosen because Scenario 1 in this study essentially models 'Option 2' from the preceding 'Lowestoft Tidal Flood Study' (Do Minimum - maintaining current coastal and estuary defences) with the addition of Bascule Bridge as a hydraulic structural unit and also using a different modelling software package in Tuflow.

Figure 9 shows the comparison between the 'Do Minimum' 1 in 1000yr event for both the original ISIS 2D simulation and the revised Tuflow one with the incorporation of Bascule Bridge. It can be seen that there are two key areas yielding a difference in flood extent –

1) The area to the immediate north of the Outer Harbour
2) The area to the south of Kirkley Stream to the immediate north of the A1117 bridge crossing

Figure 10 and Figure 11 are zoomed in to these two areas to give a better idea of where flood risk has been augmented.

In the area to the north of the Outer Harbour, additional flood risk now lies along Whapload Road, Wilde Street and the industrial estate including the Gas Works.

In the area to the south of the Kirkley Stream channel, additional flood risk now presents itself to the smallholdings along Tom Crisp Way, and to the properties which lie along Veldac and Aldwyck Way. Here there are approximately 20 additional properties at risk when compared against the previous 'Lowestoft Tidal Flood Study' 'Do Minimum' model results.

Figure 12 shows the head loss through Bascule Bridge for the original model and the revised version. It shows that the revised version has a greater head loss through the bridge contributing to a higher peak stage upstream of the bridge and a lower one downstream. This is expected as the revised model now models the bridge correctly as a structure and therefore produces a greater head loss, as the hydraulic loss of the bridge afflux is now simulated. The figure also shows how the revised model is more stable at this critical location, as the oscillations which were present in the original ISIS 2D model now eradicated in the revised Tuflow build for this study. Figure 13 shows the maximum stage profile for this event for both model versions from the coast (left side) all the way along Lake Lothing right up to Mutford Lock. Upstream of Bascule Bridge the water level is greater for the revised model in this study by circa 0.07m, and similarly the water level is reduced by approximately 0.07m downstream of the bridge.

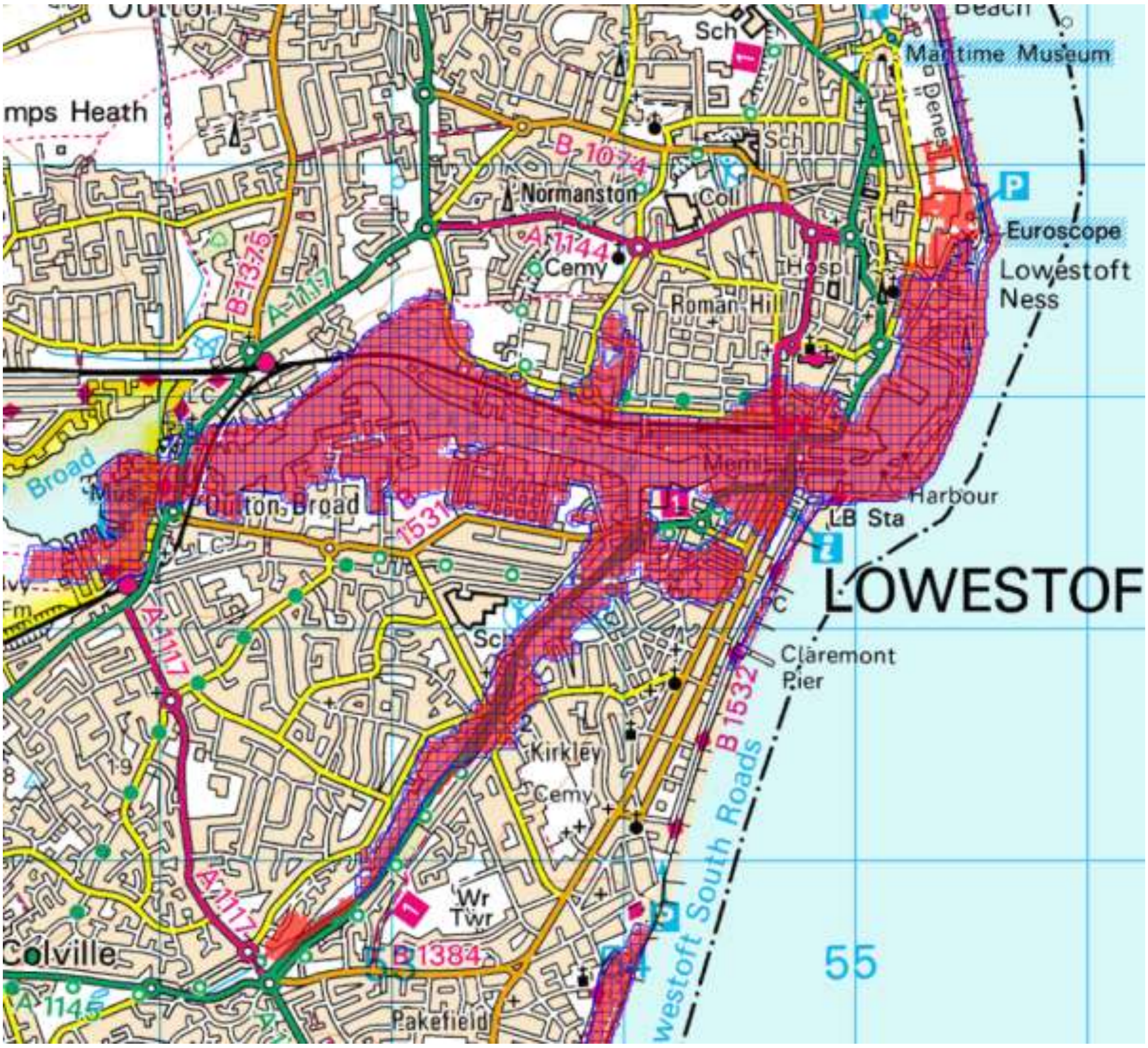

Figure 9 1000yr event comparison between the Original Lowestoft model (blue hatched) and the revised one (red)

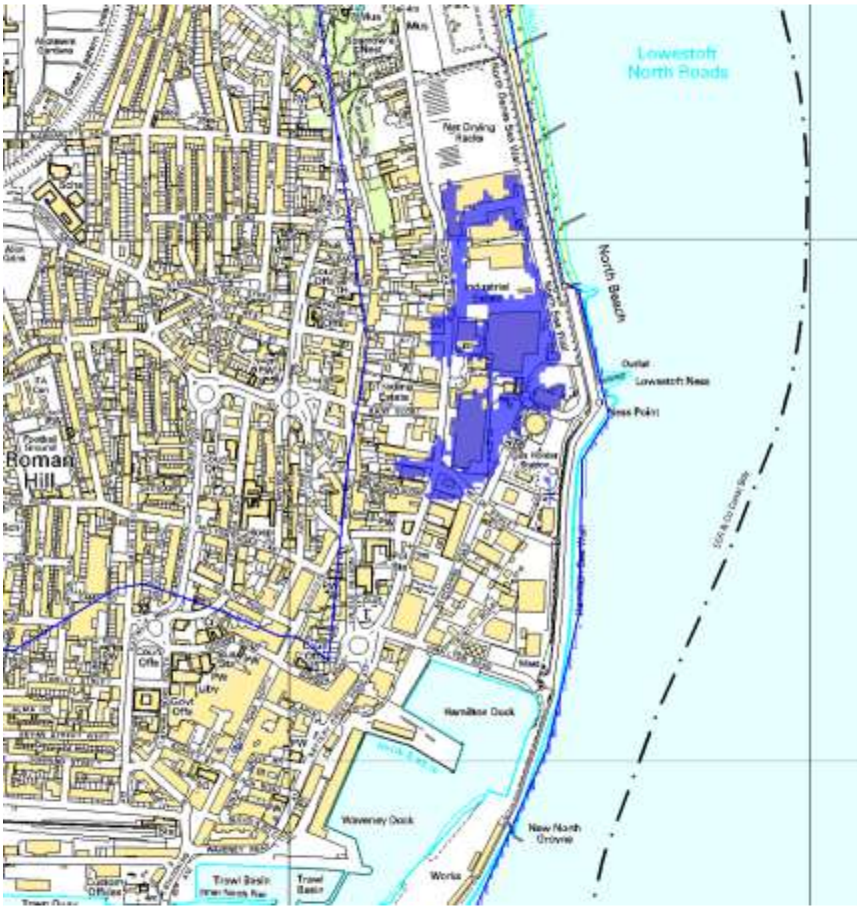

Figure 10 Additional flooding for the 1000yr event in this study north of the Outer Harbour

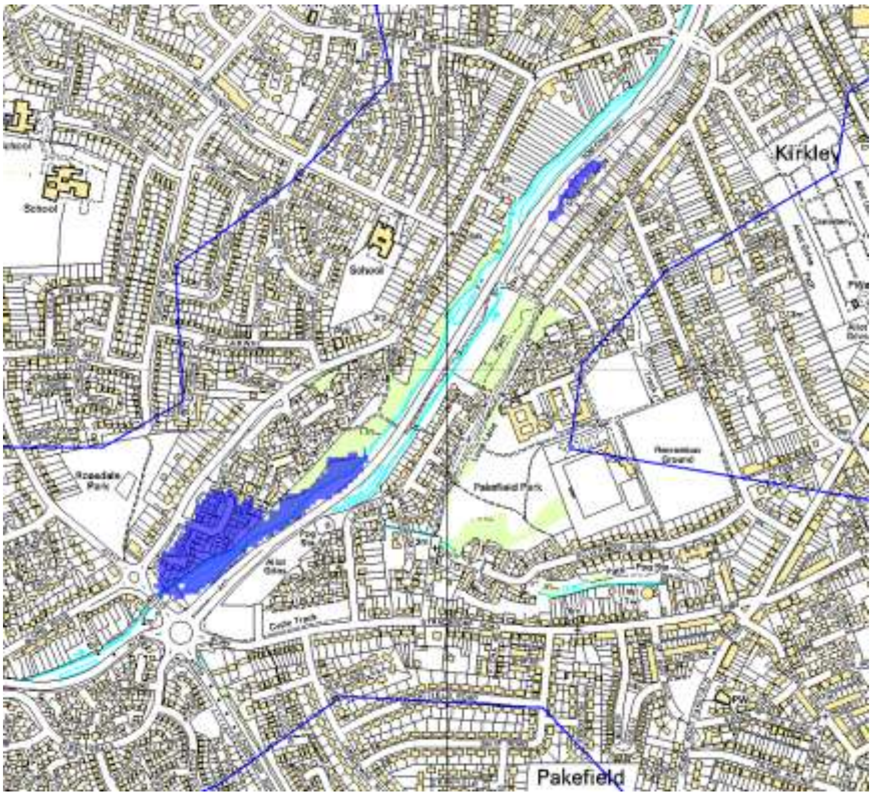

Figure 11 Additional flooding for the 1000yr event in this study along Kirkley Stream

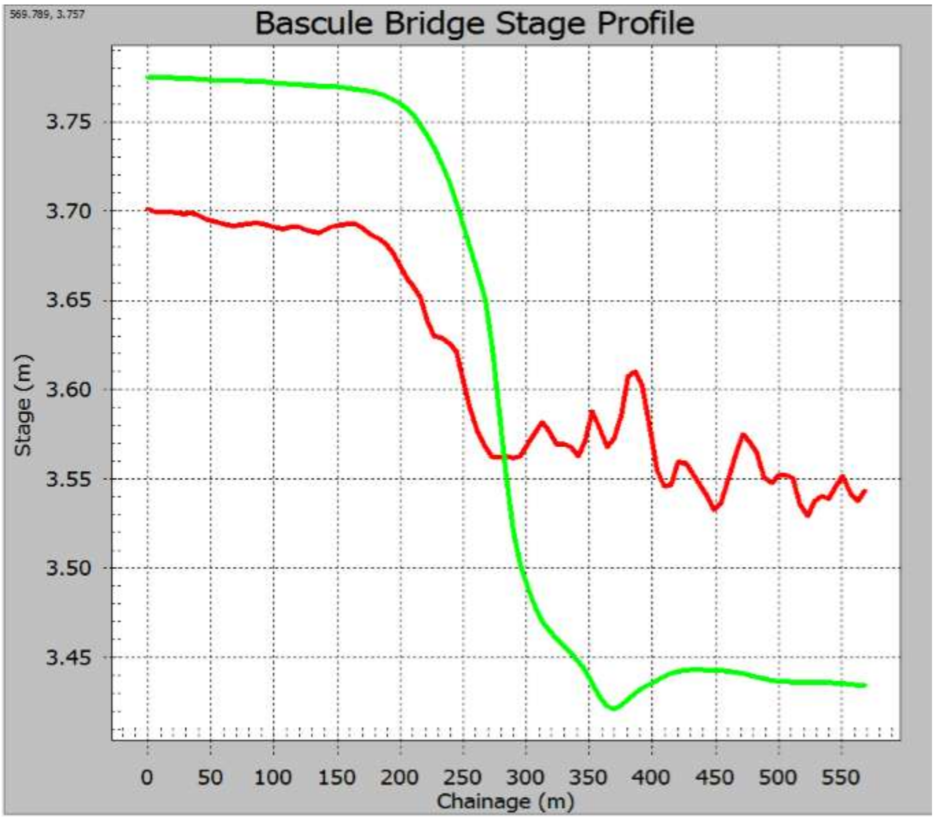

Figure 12 Head loss through Bascule Bridge for the 1 in 1000yr event (original ISIS 2D model is red, revised Tuflow version is green)

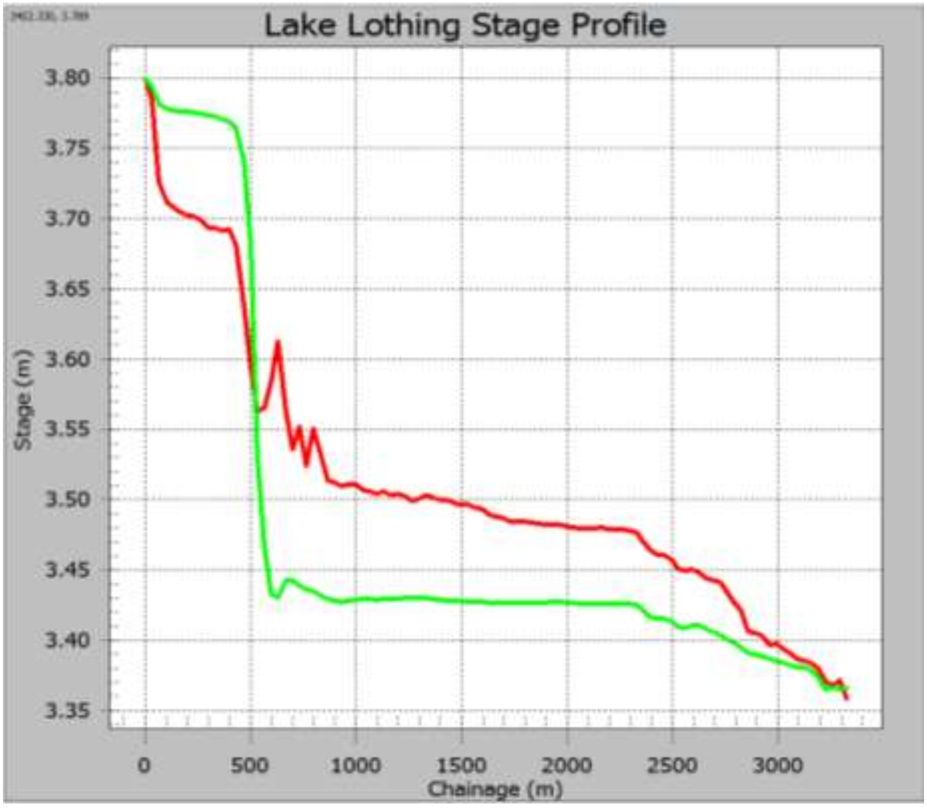

Figure 13 Head loss through Bascule Bridge for the 1 in 1000yr event from the coast to Mutford Lock (original ISIS 2D model is red, revised Tuflow version is green)

5. Available Flood Water Storage Volumes in Lake Lothing

Table 9 below shows the storage volume available within Lake Lothing for each event in which its capacity is not exceeded.

For Scenario 1, the baseline 'as-is' situation, the capacity of the lake is exceeded for every event, with flooding occurring for even the lowest event – the 1 in 20yr present day scenario.

For Scenario 2, there is a significant storage capacity available within Lake Lothing to accommodate pluvial and/or fluvial run off. Due to the effectiveness of having the tidal barrier and Mutford Lock remaining shut, this storage capacity is maintained right up until the largest event – the 1 in 1000yr plus climate change.

For Scenario 3, the Lake Lothing storage threshold is only not exceeded for the three smallest events – 1 in 20yr, 1 in 100yr and 1 in 200yr present day scenarios – with the volume storage capacity deteriorating as each event increases in magnitude. For these three events, it can be seen that the storage capacity volume is significantly reduced when compared with the capacity provided by the Scenario 2 option, with the storage volume of the 1 in 200yr present day event being slightly less than 14 times that provided by its Scenario 2 counterparts.

TABLE 9 LAKE LOTHING AVAILABLE VOLUME STORAGE

Scenario 2 (all except T1000cc)	Scenario 3 T20	Scenario 3 T100	Scenario 3 T200
704046	169174	89049	50800
*all figures in m^3			

The methodology used for measuring the storage capacity of Lake Lothing was as follows:

1) The 1 in 1000yr plus climate change results were analysed
2) The point at which Lake Lothing reaches its threshold capacity was recorded (the threshold capacity was decided as the volume stored within the lake immediately before the onset of flooding)
3) The threshold was found to be a water level of 2.14mAOD which occurs 30hrs into the 1 in 1000yr plus climate change event
4) A volume grid was created assuming that Lake Lothing is infilled up to this level of 2.14mAOD – this was taken as the 'full capacity' storage volume
5) A raster calculation within GIS software has been used to subtract the maximum water elevation results grid from this 'full capacity' one for any event where the onset of flooding has not occurred (where the onset of flooding has occurred then the storage capacity of Lake Lothing has been already exceeded and no further storage can be provided without further adding to flood risk)

Figure 14 shows Lake Lothing for the 1 in 1000yr plus climate change event at 30hrs into the extreme tidal event. Here Lake Lothing has reached capacity just before the onset of flooding.

Figure 15 shows the situation one hour later into the event (31hrs). Flooding has begun to the immediate south west of Bascule Bridge along Belvedere Road and also along the railway line at Leathes' Ham.

Figure 16 shows the storage depth provided within Lake Lothing before it becomes completely infilled and the risk of flooding occurs. It shows how the far lower water level for the Scenario 2 option provides a much greater freeboard in which the water levels can rise before causing flooding.

Figure 17 depicts a stage/volume curve for Lake Lothing. It shows the approximate rate at which the volume stored within the lake increases with water level.

Figure 14 Lake Lothing at full storage capacity (2.14mAOD)

Figure 15 Lake Lothing at onset of flooding

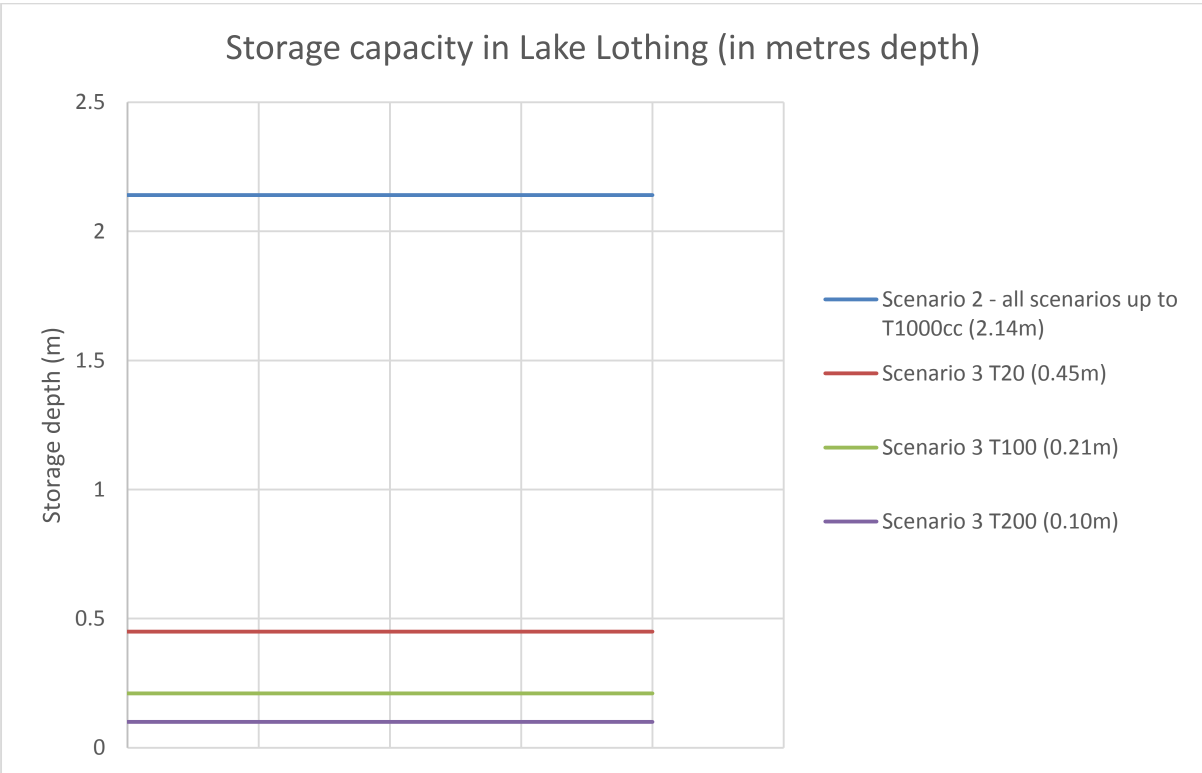

Figure 16 Lake Lothing storage capacity represented by depth

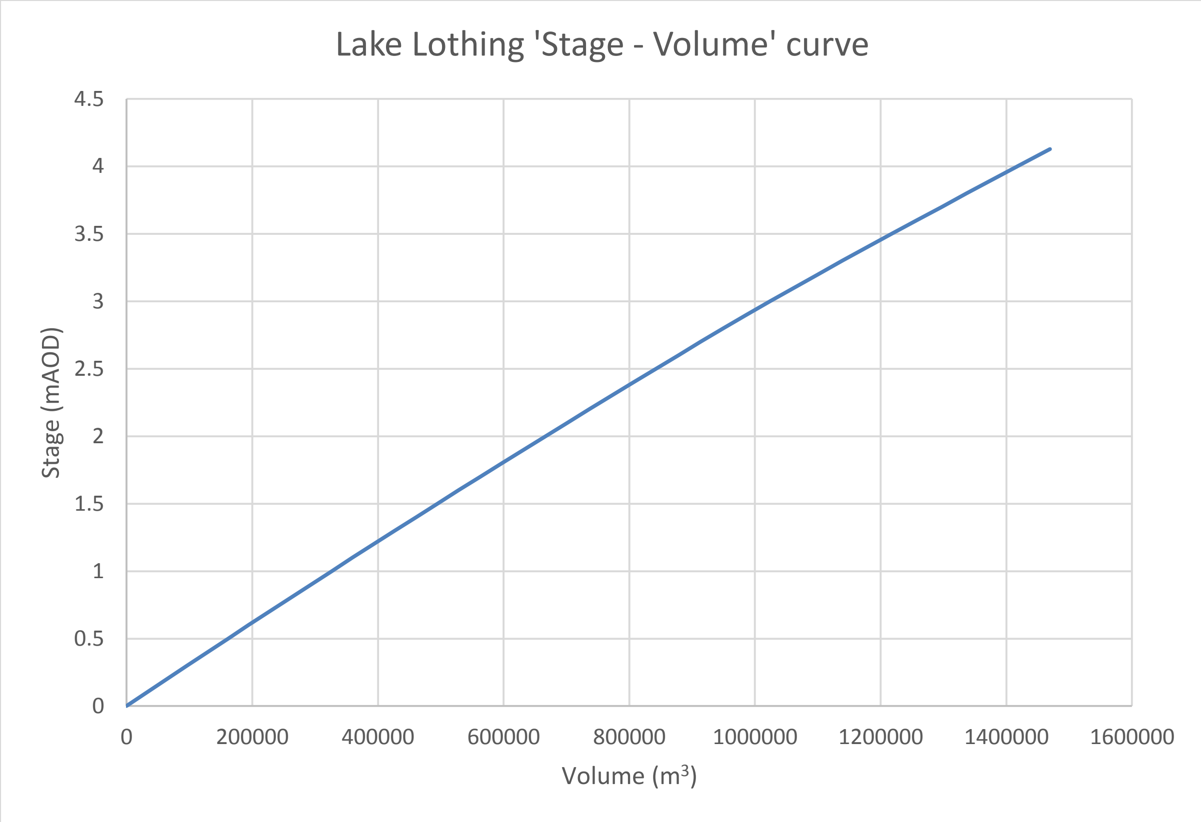

Figure 17 Lake Lothing 'Stage-Volume' curve

6. Conclusions

This study has produced the most complex and complete hydrodynamic hydraulic model to date for the Lowestoft area. The final model versions for each of the three scenarios undertaken in this study have been further developed and improved from the legacy models built in the preceding Lowestoft studies of the Lowestoft Estuary Inception Study (Halcrow, 2012) and the Lowestoft tidal Flood Study (Halcrow, 2013). The improvements made are summarized below:

- Conversion of a solely ISIS 2D model to a dynamic 1D/2D ISIS/Tuflow one
- Linked the 2D component to a robust ISIS 1D model which has been vastly developed over a large timespan (circa 10yrs) to represent the entire fluvial and tidal system within Oulton Broads
- Bascule Bridge now modelled as a structure
- Insertion of a proposed tidal gate modelled as both closed and operational
- The modelling of Mutford Lock as open and operational

Incorporating each of these aspects into the original Lowestoft model has resulted in a much improved 1D/2D hydraulic model which now gives us a more holistic representation of the complex hydraulic system which exists between the Oulton Broads, Lake Lothing and the Lowestoft Harbour. Whereas previously the downstream boundary was merely a fixed Head-Time one set equal to the peak water level reached at Mutford Lock for the 1 in 1000yr present day scenario, which was being overly conservative; now the model has a completely interactive link with the 1D BESL model which itself has the dynamic event of the tidal surge propagating through it from Great Yarmouth. This gives a significant advantage in predicting flood risk in that now how the flood system within the Oulton Broads during an extreme tidal event interacts with the flood system within Lake Lothing and Lowestoft during an extreme tidal surge can be seen. There is no longer the ambiguity of assigning a fixed Head-Time boundary at any location within the hydraulic model. Also, the recent hydrology updates undertaken for the 'Lowestoft Estuary Inception Study' which devised updated tidal boundary hydrographs for an extreme tidal surge at Lowestoft, also included revised tidal hydrographs for Great Yarmouth. These updated tidal boundary curves for Great Yarmouth were able to be incorporated into the 1D BESL model once it was linked up with the 2D Lowestoft element. These design tidal hydrographs were derived using the latest guidance at the time of the 2012 study - 'DEFRA cot 2006 Climate change guidance' and UKCIP 09 'Adapting to climate Change Guidance, August 2011', and so are still considered to be robust and the most advanced possible at the time of this study.

From this study and its defined three scenarios, the following conclusions can be made:

- **<u>Scenario 1</u>** – this has been an improvement in model built on the previous Lowestoft model versions, and now provides more reliable and robust results. It has consisted of a schematisation which best represents the current 'as is' situation and for this reason was suitable for use as a baseline scenario against which the two option scenarios can be compared in order to gauge the effects, both positive and negative, of each option
  The projected flood risk to Lowestoft for this baseline data has increased upstream of Bascule Bridge, with peak water levels increasing by circa 0.07m, and water levels within Lake Lothing have reduced by an average of approximately 0.07m.
- **<u>Scenario 2</u>** – this option incorporates a tidal gate and proposed Outer Harbour flood defences set to a crest height equal to the 1 in 200yr plus climate change maximum water level. It is the most effective option, for which flood risk up until the largest modelled event, the 1 in 1000yr plus climate change, is almost negligible. The exception is the slight inundation of the area to the immediate south and south west of Bascule

Bridge for the 1 in 100yr and the 1 in 200yr plus climate change events, as a result of a gap between the proposed existing defence line just beyond the South Pier. The reduction in flood risk even for the 1 in 1000yr plus climate change event, which overtops the proposed defences and tidal gate, is so great that it reduces the catastrophic flooding to the south of Lake Lothing to only a small number of properties. It is for this reason that this option is recommended to be brought forward as the most effective at reducing flood risk to the urban area of Lowestoft.

- **Scenario 3** – This option incorporates an operation tidal gate which remains closed until after the peak of the tidal surge has passed. In addition to this, Mutford Lock is fully operational with the gates opening anytime water levels within Lake Lothing is less than those within the Oulton Broads at Mutford Lock. The objective of this scenario is to optimise the operation of both the tidal gate and the lock gates at Mutford Lock. This aim is to see whether flood risk within the Oulton Broads can be reduced by allowing excess flood volume (contributed to the tidal surge from great Yarmouth propagating through the Broads) to drain out into Lake Lothing once the tidal surge has passed at Lowestfoft. The findings from this scenario are that even if the tidal gate at Bascule Bridge opens after the main peak of the tidal surge has passed, the flood risk within Oulton Broads beyond Mutford Lock is not significant, with peak water levels reduced by circa 0.2m for the 1 in 1000yr event. However, flood risk within Lowestoft for the 1 in 1000yr event is not increased when compared with Scenario 2. Therefore, having both Mutford Lock and the tidal gate operational is beneficial to maximum flood levels in the Oulton Broads without detrimentally effecting those within Lake Lothing. However, for the climate change scenarios, flood risk begins to increase as a result of the opening of the tidal gate once the main tidal surge wave has passed. This is due to the overall tidal peak being increased by 1.08m, which means that the tidal peak which follows the principal surge one, still achieves a significant height to enable flood waters to inundate overland areas. As a result of the increase to flood risk for the climate change events for Scenario 3 when compared with Scenario 2, the following has been concluded:
    - For the present day scenarios the allowance for the operation of both the tidal gate at Bascule Bridge and the lock gates at Mutford Lock has a beneficial effect on flood risk within the Oulton Broads without detrimentally effecting it within Lowestoft. Therefore should the benefits of the reduction in flood levels within the Broads prove to outweigh the complexities, cost and associated degradation of the structures as a result of their operation, this option should be utilised
    - For future scenarios where sea levels could see a rise of greater than 1m, the additional flood risk as a result of opening the tidal gate once the tidal surge peak has surpassed renders this option less attractive, and the conditions for Scenario 2 should be enforced

Volume Storage

Lake Lothing provides a method of transport for ships and cargo during normal tides, with the passageway provided when Bascule Bridge opens its bridge deck. However, in times of flood, whether pluvial, fluvial and/or tidal, it transforms itself into a critical flood storage reservoir. Provided that the volume storage capacity of this reservoir is not exceeded, it can contain massive quantities of water, thereby protecting the urban area of Lowestoft from large scale flooding. It does this by acting as a drain for both pluvial and fluvial floodwater which flows naturally into it from outlets and overland flow paths. It acts as a giant bath for any tidal surge which hits the coast by containing it for as long as its storage capacity is not exceeded. However, it is during times when its capacity is exceeded where the gravest flood risk presents itself to Lowestoft. Therefore it is imperative to maintain at least some storage capacity within

Lake Lothing during an extreme tidal event, to allow for the drainage of any possible pluvial and fluvial floodwater which may occur.

For the baseline 'Do Minimum' scenario, the storage capacity of the lake is exceeded even for the smallest extreme event modelled – the 1 in 20yr present day scenario. However, for the option scenarios, this study has shown that both options provide sufficient flood reduction measures to maintain some storage capacity within the lake for the present day (scenarios 2 and 3), and indeed future epoch extreme events (scenario 2). With the flood threshold of Lake Lothing not being exceeded, the flood risk to Lowestoft due to all forms of flood risk – tidal, fluvial and pluvial – is further mitigated due to the incorporation of each flood risk options assessed for this study.

7. Limitations

For a study of this complexity, with large-scale detailed 1D and 2D hydraulic models, hydrology for extreme events and numerous critical hydraulic structures, there are always a number of limitations which influence the final results. The limitations within this study are listed below:

- For Scenario 3, given the limited time and budget, there was the inability to undertake many combinations of the operation of both the tidal barrier and lock gates at Mutford Lock. Given that this is such a complex option in which the changing of any parameters could vastly effect flood risk, possibly further variants of the system outlined in this study should be undertaken in order to optimise flood risk mitigation
- For this study, tidal boundary hydrographs have only been developed for a total of four extreme tidal surge events and their associated future epoch climate change scenarios. It could possibly be beneficial to undertake further analysis for an increased range of scenarios
- The interaction of the tidal flood cell with the fluvial flood cell of Kirkley Stream has not been considered. It could be beneficial to incorporate Kirkley Stream into the hydraulic model to attain a more holistic viewpoint of the entire flood system affecting Lowestoft, which might yield a greater confidence in the model output
- The Lake Lothing storage capacity calculations have been conducted assuming, as has been the case for the option modelling, that an initial water level of 0mAOD has been maintained within Lake Lothing for the inception of an extreme event. Given that the tidal water level within the estuary decides on the available storage capacity within Lake Lothing, and this storage capacity is a critical factor in determining how much pluvial and fluvial runoff can be stored, it is recommended that further detailed calculations are undertaken under a range of possible tidal levels. This would allow for a more informative correlation between a varying tidal water level maintained within Lake Lothing and the resultant storage capacity.

8. Glossary

mAOD	metres Above Ordnance Datum
EA	Environment Agency
MHWS	Mean High Water Spring
SLR	Sea Level Rise
CC	Climate Change
AEP	Annual Exceedance Probability
RP	Return Period
DTM	Digital Terrain Model
FSA	Flood Storage Area
HTBDY	Head-Time Boundary
QTBDY	Flow-Time Boundary
Defra	Department for Environment, Food and Rural Affairs
UKCP09	UK Climate Projections

Groundwater Technical Note

Lowestoft Flood Walls

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This document has been issued and amended as follows:

Version	Date	Description	Created by	Verified by	Approved by
0	11th January 2019	Groundwater Technical Note – Lowestoft Flood Walls	Sam Wood	Toby Gill	Laurent Cadieu

Contents

Introduction

1.1. Background

As part of the proposed Lowestoft Flood Wall Scheme, impermeable barriers, generally sheet piled walls, will be provided to limit the flow of flood water beneath the proposed flood walls. The hydraulic conductivity of these barriers will be low enough that groundwater flow which is normally discharging to the sea will be impeded. Therefore, this groundwater technical note has been undertaken to establish the risk of groundwater flooding post construction and to satisfy the requirement of a site-specific Flood Risk Assessment as detailed on page 48 of the 2008 Suffolk Coastal and Waveney District Strategic Flood Risk Assessment (SFRA).

1.2. Limitations of Groundwater Technical Note

This groundwater technical note assessment assumes that the strata has been suitably characterised by CH2M to assess groundwater flood risks and that there are no sensitive structures located in the immediate proximity of the proposed Flood Wall Scheme such as sewers or basements that would require more detailed field investigation and assessment with respect to groundwater flooding. It also assumes that the study area does not rely on infiltration drainage that may be affected by high groundwater levels.

2. Proposed Design of Flood Defences

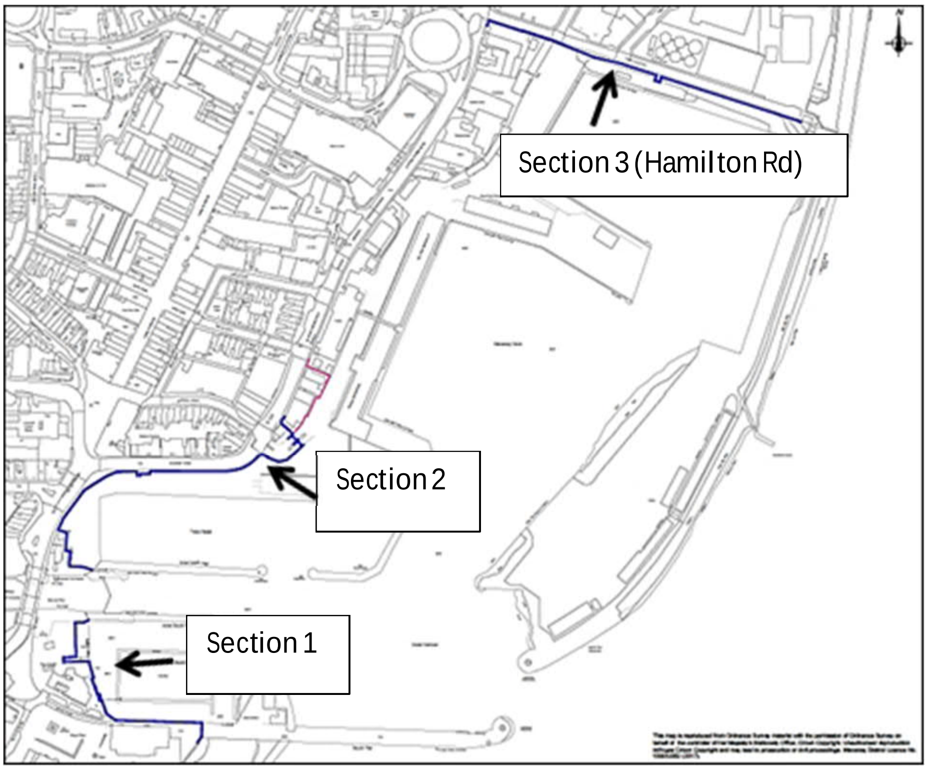
2.1. Locations and Length

The flood walls are required to link the tidal barrier structure to high grounds and existing coastal defences. The tie-in flood walls will comprise the provision of a combination of flood walls, demountable barriers and flood gates that will be up to 1.6m high subject to existing ground levels. The proposed flood walls can be split in 3 sections and are summarised in Table 2.1 and shown in in Figure 2.1.

Table 2.1: Flood Wall Descriptions and Lengths

Section	Name	Description	Proposed Length (m)
1	Southern Flood Walls	Includes Royal Norfolk and Suffolk Yacht Club to South Beach peninsula	242
2	Northern Flood walls	Located between the dock basins and the Bridge Control including flood walls (Waveney Road)	320
3	Hamilton Rd	Located to the north of Hamilton Dock along Hamilton Road	340

Figure 2.1: Flood Wall Locations



3. Existing Ground and Groundwater Conditions

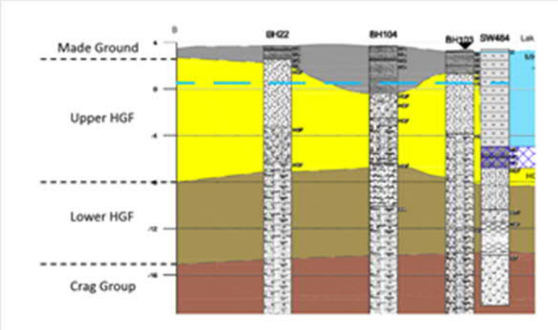
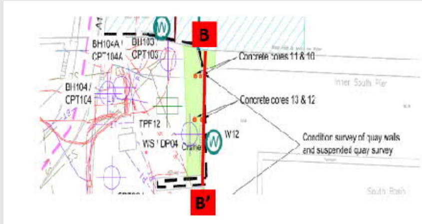
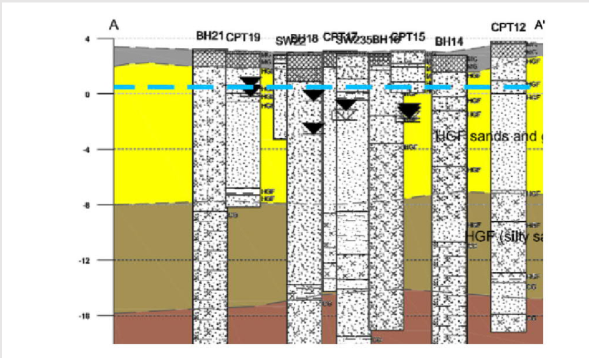
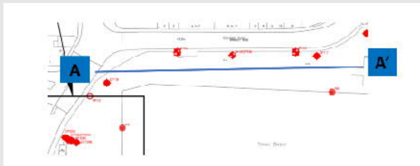
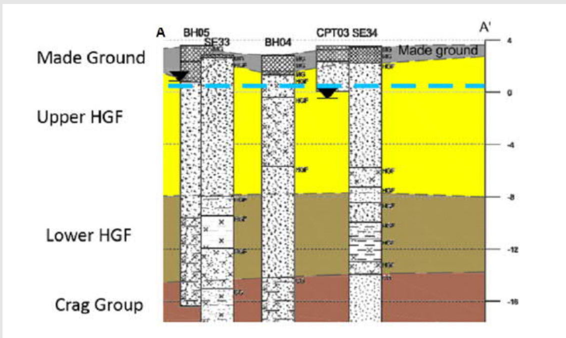
3.1. Site Geology

Made Ground across the site is of limited thickness, consisting typically of hard surfacing and subbase materials. The Made Ground is underlain by the Happisburgh Glacigenic Formation (HGF), which comprises an upper and lower layer. The upper layers consist of sands and gravels whereas the lower layer is defined by silty sands. The border between these deposits is located at approximately -8m AOD. Deposits of alluvium and Tidal River Deposits also surround the proposed flood defences. At approximately -14m AOD, the HGF deposits are underlain by the Crag Group sediments consisting of medium dense to dense sand.

Typical geological cross sections with water levels are shown in Figure 3.1.

Figure 3.1: Site Geology

Section	Name	Generalised Geological Profile	Location of Cross Section

1	Southern Flood Walls		
2	Northern Flood walls		
3	Hamilton Rd		

Note: Refer to Flow Rate Calculation Reports for further detail (see References).

3.2. Hydrogeology

The Happisburgh Glacigenic Formation is classified by the EA as a Secondary A Aquifer. These have permeable layers capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers. These are generally aquifers formerly classified as minor aquifers. The Upper HGF, having a higher proportion of sands and gravels, will comprise the more permeable unit. The Crag Group is classified as a Principal Aquifer. These are layers of rock or drift deposits that have high intergranular and/or fracture permeability - meaning they usually provide a high level of water storage. They may support water supply and/or river base flow on a strategic scale. In most cases, principal aquifers are aquifers previously designated as major aquifer. The flow system is controlled by the alternating layers of clays, silts and sands and their contrasting permeabilities. In the vicinity of the proposed Flood Wall Scheme, the existing harbours, tidal defences, surface watercourses and variable geology creates complex set of boundary conditions. The sea is considered to be the ultimate discharge point for groundwaters in the area.

3.3. Permeability

The permeabilities of the geological units have been assessed from a mixture of grain size analysis and slug tests. Assessed permeabilities that have been used by CH2M for the design of the flood defences are summarised in Table 3.1. The HGF has a wide range in permeability values and is heterogeneous.

Table 3.2: CHM2 Assessed Permeabilities

Stratum	Aquifer Designation	Permeability m/d	
		Range	Characteristic Value
Made Ground (Sandy gravels – above 1m aod)		1 to 86	9
Upper HGF (1 to -8m aod)	Secondary A Aquifer	0.01 to 86	1
Lower HGF (-8 to -14m aod)		0.1 to 9E-06	As range
Crag Group (below -14m aod)	Principal Aquifer	0.001 to 1	0.01

3.4. Groundwater Monitoring

The 2016 ground investigation and post fieldwork monitoring by White Young Green generally recorded groundwater strikes and monitoring levels between 0.5maod and 1.0maod through the winter flood season from October 2016 to April 2017, typically occurring in the upper HGF sand layer along the northern floodwall and in the Made Ground along the southern floodwall (between October 2016 to April 2017, groundwater levels were generally 2 to 3.6m bgl). The groundwater levels recorded did not vary significantly across the monitoring period, generally within 0.5m. There was no evidence of large widespread groundwater fluctuations that could cause clearwater flooding i.e. water rising above the land surface in a response to extreme rainfall.

There is only a minor lag difference of up to 1 hour between peak tide level (hydraulic conductivity with the North Sea) and peak groundwater level which indicates that the strata is relatively high permeability, and there is a quick but not instantaneous response in groundwater levels particularly during flood events (which is constituent with a water table as opposed to a confined aquifer).

Groundwater flow except where influence by shallow structures and drainage, would be expected to be broadly parallel to the coast. Therefore, Sections 1 and 2 are likely to broadly parallel, and Section 3 perpendicular to the direction of regional groundwater flow (refer to Figure 2.1).

3.5. Regional Hydraulic Gradient

The regional hydraulic gradient at the coast, the ultimate discharge point for shallow groundwaters would be expected to be very flat (typically <<0.5%).

3.6. Groundwater Flooding

Groundwater flooding is assumed a secondary risk in the catchment (Broadlands Rivers Catchment Flood Management Plan, 2009). The predominant risk to flooding in Lowestoft is tidal. We understand that there is no anecdotal evidence for groundwater flooding.

3.7. Topographic Considerations

The topographic profile of Section 2 (northern area) from high ground falling seaward will promote groundwater flows in an easterly direction. Sheet piling in this area may have the greatest potential to affect the natural flow of groundwater and land drainage. However, in Section 1 (southern area), the topography profile is reversed with the land reducing in elevation from the coast to the Kirkley river valley and there is the potential for groundwater flow/saline intrusion from the coast inland.

4. Impermeable Barrier Design

4.1. Types of Impermeable Barrier

Steel sheet piles (SSP) will be used to limit the flow of flood water beneath the above-ground floodwall structures. Alternative seepage barrier techniques might be used near sensitive structures / services. This might take the form of continuous flight auger (CFA) piling with grout curtain or intersecting secant piling. Therefore, it is possible that some flow may leak through the barrier in such locations.

4.2. Proposed Depth

The toe level of the impermeable barriers has been assessed by using Plaxis 2D and Seep/W models. This has been modelled under steady state conditions to suit stability in accordance Eurocode 7 and limit seepage rates underneath the flood walls for the design high tide conditions (I in 200 years including climate change for the design life of 100years). A toe level of -5.2mAOD or typically 8.5m below ground level has been recommended

4.3. Seepage Rates through Steel Sheet Piles

The steel sheet piles themselves are completely impermeable and therefore the only potential pathway for groundwater to pass through the SSP is via the interlocks. The interlocks are used to connect the individual sheet pile to form a continuous wall. During installation, each sheet pile is guided laterally by the interlock (clutch) of the previously driven sheet pile. A small amount of leakage through the clutches can be expected.

4.4. Steel Sheet Pile Design

The SSP are required to avoid hydraulic failure behind the walls and to minimize localised flooding from seepage during a tidal surge event. However, as a full seepage cut-off will not be provided, groundwater flows will continue across the proposed structure albeit delayed in time. Selected design elements of the floodwall relevant to groundwater flooding are summarised in Table 4.1 (as taken from the Technical Notes in the References). It is proposed that the new SSP will be located adjacent to 70% of the Upper HGF (it is not proposed to install sheet piles to the base of the less permeable Upper HGF.). The existing SSP in the Southern section are located adjacent to only 47% of the Upper HGF.

Table 1.1 Key Steel Sheet Pile Design Parameters

Design Element (dry side of the floodwall where applicable)	Elevation/Thickness (m aod)				
	Section 1 – Southern Flood Walls		Section 2 – Northern Flood Walls	Section 3 - Hamilton Road	
	CH0 to CH30	CH70 to CH130	CH0 to CH260	CH 0 to 120m	CH 120 – 300m
Elevation of Existing Ground Level at dry side of the floodwall	+3.00m aod		+2.80m aod	+3.60m aod	3.10m aod
Elevation of groundwater level on the dry	+0.5	N/A (assumed +3.00m aod)	+0.5m aod	+0.5m aod	+0.5m aod

side of the floodwall					
Unsaturated zone thickness (dry side)	2.5m	0	2.3m	3.1m	2.6m
Base of Made Ground	+1.35m aod	1.35m aod	+0.9m aod	+0.8m aod	+1.30m aod
Floodwall toe elevation (% of Upper HGF piled)	-5.20m (70%)	-3.0m aod (47% - Existing structure)	-5.20m (69%)	-5.20m (68%)	-5.20m (70%)
Base of Upper HGF	-8m aod				-7.9m aod

5. Potential Up-gradient Impact of Steel Sheet Piles on Groundwater Flow and Groundwater Flooding

5.1. Potential Upgradient Impact of Steel Sheet Piles

Underground obstacles to groundwater flow, such as SSP, modify the groundwater flow because the structure partially reduces the aquifer section. Thus, effective transmissivity is reduced, leading to a rise in the water table upgradient and a lowering downgradient. These modifications of the water table can have negative consequences and potentially, it could have two impacts on groundwater flows:

- Impede the flow of groundwater with head increases close to the structure; and/or
- Impact the groundwater budget of the flow system with head increases over long distances

The risks of impeding groundwater flow and causing rising water levels upgradient include damage to buildings by flooding of lower levels. Other impacts associated with the rise in heads include reduction of the bearing capacity of shallow foundations, expansion of heavily compacted fills under foundation structures, settlement of poorly compacted fills on wetting, corrosion of foundations, increase in the need for drainage in temporary excavations, slope stability issues, damage to services and propagation of contaminants contained in the partially saturated zone.

5.2. Qualitative Assessment of Steel Sheet Piles on Groundwater Flooding

The concern is that the hydrostatic barrier effect of the SSP will cause an increase in head upgradient of the barrier due to the loss of transmissivity induced by the underground construction and may cause groundwater flooding. Any increase in head upgradient of the SSP post construction is however considered to be small given that:

- Groundwater levels are typically greater than 2 to 3.6m bgl, therefore small changes in groundwater level because of the SSP would not immediately result in increased groundwater flooding risk.
- Extensive barriers, including the harbour wall and associated structures (refer to Figure 2.1 and References), already exists along the study area. Therefore, conceptually, it is unlikely that the complex hydrogeological regime at the coast will be significantly changed - the SSP will simply form yet another barrier with limited cumulative impact on groundwater levels (the SSP does not fully penetrate the Upper HGF).
- The SSP does not form a very long linear structure (e.g. cuttings for roads railways and tunnels for example) and sit within with low permeability strata where significant effects of barrier systems on groundwater levels have typically been proven.
- The SSP do not form watershed-scale barriers to groundwater flow. The HGF in which they are installed, outcrop in a much wider area. Groundwater flows will naturally find alternative path of least resistance through the ground at tie-in points, interlocks connecting the sheet piles or behind the proposed flood defences along Lake Lothing. Therefore, the SSP, are unlikely to significantly disturb the mass balance of the groundwater flow system.
- The impact/flow across the sheet piling is partially dependent upon the difference in hydraulic head across the sheet pile (in combination with the total height of the sheet piling and characteristics of the soils in which the sheet pile is driven). Given that the regional gradient at the coast will be very low combined with relatively permeable Upper HGF, any impact on upgradient heads is also likely to be low (and groundwater flows will naturally find alternative path of least resistance).
- The HGF are relatively permeable and from the monitoring undertaken, there is a lack of significant groundwater level fluctuations in response to rainfall. This implies that there is reasonable available storage and that any local impact of the structure is likely to result in nominal head changes under steady state conditions.

Furthermore:

- Section 3 is likely to be perpendicular to the coast/regional groundwater flow direction and have a limited impact on the existing groundwater regime.
- The sheet piles will increase the tidal lag, i.e. delay the rise in groundwater levels inland caused by the tide and hence help further reduce the potential for increased groundwater levels particularly during tidal flood events.
- In Section 1 (Southern Area) the topography profile is reversed with the land reducing in elevation from the coast to the Kirkley river valley and there is the potential for groundwater flow from the coast inland. Therefore, increases in groundwater levels in this setting would seem unlikely.

5.3. Requirement for Analytical and Numerical Analysis

Analytical solutions are not readily available since the barrier effect problem has not been adequately formalised. Whilst it is possible to use the existing SEEP/W models to undertake transient analysis, there is some uncertainty whether the model assumptions are applicable to the site. Flow around barriers however could be modelled with numerical models, but to achieve reasonable accuracy requires fine grid near the barrier and extremely fine spacing where flow curls around the end of a barrier. However, given the complex boundary conditions and low sensitivity of the site to groundwater flooding, numerical modelling is not deemed necessary to substantiate the level of risks associated with the proposed seepage barrier on groundwater flow. If further confidence is required/sensitive structures identified and further assessment required, it would be more practical to undertake groundwater monitoring and if appropriate undertake corrective actions to allow groundwater to pass through or bypass the SSP.

6 Conclusions

Post construction of the SSP, whilst impacts localised to the SSP in the short term may occur before steady state conditions are established, it is likely that the risk of widespread groundwater flooding will remain low and be unaffected by the proposed works.   If further confidence or assessment of sensitive structures is identified, groundwater monitoring and if appropriate, mitigation measures, should be considered as part of the SSP design.

7 References

- E-mail from Cadieu, Laurent/UKP dated 6th December 2018
- Jacobs. November 2018. Flood Risk Assessment. Lowestoft Flood Walls and Barrier
- Jacobs. November 2018. Technical Note: Flow Rate Calculations. Hamilton Road. CH0 to CH320.
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- Jacobs. November 2018. Technical Note: Flow Rate Calculations. Yacht Club CH70 to CH130
- Jacobs. November 2018. Technical Note: Flow Rate Calculations. Waveney Road CH0 to CH260
- WYG. January 2017. Ground Investigation Factual Report.