The Lake Lothing (Lowestoft) Third Crossing Order 201[*]

Document 6.3: Environmental Statement Volume 3 Appendices

Appendix 18A

Annex A: Environment Agency Consultation

Author: Suffolk County Council

Mr Michael Wilks
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IP1 2BX

Our ref: AE/2016/120907/01-L01
Your ref: *

Date: 05 October 2016

Dear Mr Wilks

THIRD RIVER CROSSING, LAKE LOTHING ENVIRONMENTAL STATEMENT - FLOOD RISK ASSESSMENT METHODOLOGY

Thank you for consulting us on your Flood Risk Assessment methodology. We have reviewed the document submitted and are pleased to see that the most recent flood modelling undertaken by CH2MHill on behalf of Waveney District Council dated 2014 will be used and will be reviewed as part of the study.

Model Runs

We have noted that the model will be run for the 0.5% Annual Exceedence Probability event with and without climate change allowances and the 0.1% AEP event. We would recommend that the 5% AEP with and without climate change is also considered as this is considered the functional floodplain in the SFRA. Climate change should also be considered on the extreme 0.1% AEP climate change event. It may be useful to refer to the Lowestoft Cumulative Land Raising Study undertaken in 2008 and available here which undertook a similar exercise:

http://www.eastsuffolk.gov.uk/assets/Planning/Waveney-Local-Plan/Cumulative-Land-Raising-Study/01-Cumulative-Land-Raising-Study-Main-Document.pdf

We agree with the approach to undertake a baseline and post development run. It is important to ensure that the proposed crossing does not increase flood risk elsewhere and where possible reduces flood risk overall in line with Paragraph 102 of the National Planning Policy Framework (NPPF). If the modelling shows there is likely to be an impact elsewhere mitigation will be required, potentially in the form of compensatory storage.

Climate Change

As the proposals will be considered as a Nationally Significant Infrastructure Project (NSIP) you should refer to the National Policy Statement for National Networks paragraphs 4.41 – 4.44. It is important that the impact of and resilience to future flooding is considered and mitigation against future flood risk elsewhere is implemented where necessary. Section 4.41 of the NPS states that if transport infrastructure has safety-critical elements and the design life of the asset is 60 years or greater, the applicant should apply the UK Climate Projections 2009 (UKCP09) high emissions scenario against the 2080's projections at the 50% probability level.
UKCP09 relative sea level rise projections are available for three emission scenarios for the 10th, 50th and 90th percentiles. They are available on the UKCP09 user interface on their website. These allowances should be used to inform the design and mitigation of the crossing.

You will also need to determine the lifetime of the crossing. If the lifetime is significantly beyond 2115 we recommend that mean sea level rise projections are extrapolated out to 2200 using a linear approach, based on the rate of rise between 2105 and 2115.

Safety critical elements of the design should be assessed against the H++ estimates (high risk, low probability scenario) for sea level rise to assess a credible maximum scenario. We would not normally expect the design or mitigation to be provided to this level but the crossing should be assessed against this scenario to understand the picture of risk. This data is also available on the UKCP09 website.
You should be aware that the next set of climate change projections (UKCP18) replacing UKCP09 is due in 2018.

We are happy to be consulted throughout the production of the FRA and model re-run to provide advice and guidance in accordance with our cost recovery programme. We would ask that the model is submitted for review once complete along with the FRA and modelling technical note.

Yours sincerely

[redacted]

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End

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Our ref: AE/2016/121040/01-L01
Your ref: *

Date: 23 November 2016

Dear Mr Wilks

LAKE LOTHING ENVIRONMENTAL STATEMENT - FLOOD RISK ASSESSMENT METHODOLOGY THIRD RIVER CROSSING, LAKE LOTHING, LOWESTOFT

I write in response to your email enquiry of 31 October requesting clarification regarding methods for extrapolating data where the design life of the project exceeds the published UK Climate Projections 2009 (UKCP09) and appropriate use of the H++ scenarios. There is considerable overlap for the questions posed and so our flood risk specialist has answered your questions as one single reply.

Use of Climate Change scenarios and extrapolating data
Before we can determine the appropriate climate change allowances it is important to note the text in the National Planning Policy Statement. It states that if transport infrastructure has safety-critical elements and the design life of the asset is 60 years or greater, the applicant should apply the UK Climate Projections 2009 (UKCP09) high emissions scenario against the 2080's projections at the 50% probability level. Therefore it is important to determine if the bridge has safety-critical elements or is considered safety critical as this will inform the climate change allowances that need to be considered and if you need to consider the high emissions climate change scenario and H++ scenario.
If the bridge is considered safety critical the high emissions scenario and H++ scenario needs to be considered as outlined in our previous rs. As the lifetime of the proposal is up to 2140 climate change should be considered over this lifetime.
Please accept my apologies for the confusion in relation to the data available on the UKCP09 website. You are correct that the data on the UKCP09 website is only available up to the year 2100. For the high emissions scenario you will need to extrapolate out to 2140 using a linear approach.
The H++ data is also not available on the UKCP09 website. For the H++ scenario data please refer to Table 5 of the following document: https://www.gov.uk/government/publications/adapting-to-climate-change-for-risk-management-authorities. The table provides allowances up to 2115. The guidance

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does not provide instruction on how to extend these allowances beyond 2115 again you will need to determine a suitable approach for our consideration.
As stated above these allowances are only applicable if the bridge has safety-critical elements so it is important this is confirmed first.

We look forward to receiving the revised model for review in due course.

Yours sincerely

[redacted]

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Our ref: AE/2017/121576/02-L01
Your ref: *

Date: 25 May 2017

Dear Julia

LAKE LOTHING ENVIRONMENTAL STATEMENT - INTERIM FLOODING ASSESSMENT REPORT THIRD RIVER CROSSING, LAKE LOTHING, LOWESTOFT

Thank you for consulting us on the Interim Flood Risk Assessment and draft model. We have reviewed the model submitted and our comments can be found in the attached documents entitled 'Lowestoft 3rd Crossing Model Review Certificate' and 'Review_Questions_Reference_List'. The issues highlighted should be addressed. We are happy to be re-consulted once this has been reviewed. We have also reviewed the accompanying report and have the following comments to make.

The report submitted clearly sets out the development, reasoning and justification for the modelling work undertaken. It is understood that this is an interim report and not a full Flood Risk Assessment (FRA). A full FRA will be undertaken once the design of the crossing has been finalised.

A review of the existing models in the area has been undertaken. A new 2D model has been constructed in order to get the level of detail required for this scheme. This model will be used to assess the impact of the proposed third crossing of Lake Lothing. We note that the model has been run for a baseline and post-development scenario for the 5% (1 in 20), 0.5% (1 in 200) and 0.1% (1 in 1000) annual probability event both with and without climate change as previously advised. Fluvial inputs for three watercourses have been assessed and input into the model as detailed in section 3.3 of the report. We note that the flood events quoted above were assessed. For future reference we would usually consider the design event for fluvial flooding to be the 1% (1 in 100) annual probability event rather than the 0.5% (1 in 200) annual probability which is the design event for tidal flooding. This should not be an issue as the 0.5% event is a larger event and as stated in section 3.3.5 the model was found to be insensitive to fluvial inflows as the harbour is tidally driven. As a result the final model will not include a fluvial representation as stated in section 4.3.6.

Two climate change scenarios have been run as detailed in section 3.2.5 and 3.2.6. Please refer to our previous email correspondence with Julia Hunt of 11/04/17 and 28/04/17 which discusses the climate change scenarios that should be considered and the guidance in the National Policy Statements on this topic. This email also discussed the Environment Agency's Extreme Sea Levels that have been used in the model. It is important to note that we are in the process of revising our flood modelling for the Essex Norfolk and Suffolk coast and that new extreme sea levels are available. We advised that these could be requested by emailing Enquiries_EastAnglia@environmentagency.gov.uk.

We are pleased to see that the final FRA will assess the offsite impacts in both the post development and during construction phases as noted in section 5.3.1. Section 6.1.9 also states that the final FRA will assess the flood risk to the scheme itself which is important to understand. This is particularly important if the crossing is considered safety critical and essential infrastructure and therefore will be designed to remain operational in times of flood.

Whilst we note the bridge deck itself is above the 0.1% (1 in 1000) H++annual probability flood level consideration should also be given to the flood risk posed to the remainder of the scheme to inform decision makers on the safety of the crossing in the event of a flood.
Figure 1-2 shows the proposed road alignment of the C13A crossing design. It would be useful to know if the road network is likely to be raised as this would need to be considered in the FRA. This could remove floodplain storage and alter flood flow paths.
Once the design of the bridge has been finalised it would be helpful to include a cross section of the crossing including elevations within the FRA.

Figure 2-1 shows the extent of the existing CH2M 1D-2D model. It is understood the new model developed for this study will have a smaller domain. Section 4.2.2 states that it was not deemed necessary to include the majority of the Kirkley Stream floodplain as it is outside of the study area for this assessment. Further justification is required to explain why this decision has been taken. The post-development maps provided in section 5.1 appear to show changes in depth across the Kirkley Stream floodplain so the crossing could have impacts in the section of floodplain not included. Has this section of Kirley Stream not been included as the impacts are considered negligible?

We note that verification against the 2013 tidal surge historic flood extent has been undertaken and a good commentary is provided in section 4.5 of the report. It should be noted that we hold photographs and accompanying location maps which may aid this verification and improve the understanding of the historic outline provided. If this information has not be obtained already and would be useful it may be requested by emailing our Customers and Engagement team on the email address above.
Section 5.3 discusses the post-development results for present day and climate change events. Tables and maps have been provided to illustrate the change in level and depth in Lake Lothing and the harbour itself as well as the surrounding floodplain. The change in level and depth appears to be small generally speaking. However, section 6.1.7 correctly identifies that mitigation will still need to be investigated in line with the proposed mitigation approach in the Environmental Impact Assessment Scoping Report dated February 2017 which was previously submitted to us for review. Section 6.1.8 goes on to say that as the design of the crossing has not been finalised it is hoped that the need for flood mitigation can be designed out, which would be the first preference. If

mitigation is required, we are pleased to note that this will be done in consultation with the Environment Agency.

We trust that this information is helpful.

Yours sincerely

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cc Suffolk County Council

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As stated in our previous email response dated 28/04/17 it is not clear which climate change allowances should be applied using the policy and guidance available. However the NPS for National Networks states the applicant should apply the UK Climate Projections 2009 (UKCP09) high emissions scenario against the 2080 projections at the 50% probability level over the lifetime of the infrastructure.

A recent investigation has found that these levels (50% high emissions) can be lower than those provided in the NPPF sea level allowances in Table 3 available on our website here: https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances#table-3.

It is understood that this is because the tidal UKCP09 projections available on the UKCP09 website are based on the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report. Since this was published the possible magnitude of sea level rise has attracted renewed attention, and a number of researchers have suggested that the IPCC numbers underestimate the potential sea level rise range during the 21st century.

For this reason the 'Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities' document recommends that RMAs do not use the central estimates (50^{th} percentile) of relative sea level rise from UKCP09 as the climate change allowances for their investment decisions. Instead, it is recommended that the upper confidence band (95^{th} percentile) medium emission projection is used as the climate change allowance. These allowances are provided in Table 5 on page 15 of the document referred to above.

Therefore the tidal sea level allowances within Table 3 of the NPPF on our website were not changed to reflect the UKCP09 model as it was seen to be an underestimated. On this basis it is possible that both the medium and high emissions scenarios tidal allowances are lower than those provided in the NPPF Table 3.

Therefore we recommend that a comparison is made between the following allowances to understand the difference between them and establish the worst case. This does not mean that the model needs to be run for all of these scenarios rather a comparison of the mm per year allowances and a calculation of the total climate change allowance over the lifetime of the crossing can be made.

We would recommend that the worst case allowances should then be used to inform the design of the crossing.

Please note the list below does not include the H++ scenario which should still be run as well. As discussed previously we would not expect mitigation to this level.

- NPPF Table 3 tidal allowances.

- UKCP09 50% high emissions (as advised in section 4.41 of the NPS for National Networks)

- UKCP09 95% high emissions

- UKCP09 95% medium emissions (as advised on page 14 of the Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities).

- Upper end allowance in Table 5 of the Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities.

You will note that we have not included the UKCP09 50% medium emissions allowance. This is in line with the guidance on page 14 of the Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities which states that the central allowances should not be used. We have included the UKCP09 50% high emissions allowance as this is specifically required in the National Networks NPS.

We would be happy to discuss this further in a telephone conversation if it would be helpful as we appreciate the varying guidance available on this topic is not clear.

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Our ref: AE/2018/122631
Your ref:

Date: 08 May 2018

Dear Julia

LAKE LOTHING THIRD CROSSING: FLOOD RISK ASSESSMENT AND MODEL FILES

Thank you for consulting us on the draft Flood Risk Assessment (FRA) and updated model. These documents have been reviewed by our flood risk specialists and our national flood modelling team whose comments and observations are detailed below. I have appended to this letter the review questions and certificate detailing what has been considered in the review of the submitted Tuflow model. You will note from the certificate that there is one area of major concern, a minor issue and one item that is not considered best practice.

Flood Modelling

We have reviewed the model submitted and our comments can be found in the attached documents entitled 'Lowestoft 3rd crossing review cert_18042018' and 'Review_Questions_Reference_List'. The issues highlighted should be addressed. The main points raised are that the results for all runs should be provided and that any investigation of model error messages should be documented in the model report.

Calibration

In addition we note that the model could not be calibrated so it was verified against the 2013 tidal surge. Section 4.6 of the draft FRA discusses this and highlights a few areas where the model does not show the flooding detailed within the historic flood map and justifies this with various explanations. This could also be justified by the fact that the 2013 flooding did not solely occur because of overtopping. It is understood that water was able to flow through a broken tidal flap on one of the outfalls into Lake Lothing.

Kirkley Stream

As mentioned in our previous response dated 25 May 2017 it is understood the new model developed for this study has a smaller domain than the previous modelling in this area. It is understood that it was not deemed necessary to include the majority of the

Kirkley Stream floodplain as the impacts are considered negligible. Please can it be clarified whether this means that there is an increase in food depth of up to 0.02m? Has it been confirmed that there will not be an increase in flood extent here which could be considered a major impact?

We are happy to be re-consulted once this has been reviewed.

Flood Risk Assessment

We have also reviewed the accompanying draft FRA and have the following comments to make.

An FRA should assess all sources of flooding and provide sufficient information on the characteristics of flooding at the site, such as frequency, depth, hazard, velocity, speed of onset, and duration. In this case the off-site risk must also be considered in the same way in order to determine if there is any significant change to flood risk elsewhere. The FRA details the likely levels and depths of flooding in the baseline and scheme scenarios but it does not illustrate the likely hazard expected as a result of the flooding. Whilst we accept that the bridge deck itself is well above even the H++ levels the approach roads are still at risk. During a flood, the journey for site users to safe, dry areas completely outside the extent of a 1% (1 in 100) / 0.5% (1 in 200) flood event (including allowances for climate change), should not involve crossing areas of potentially fast flowing water. Safe access and egress routes should be assessed in accordance with the guidance document 'FD2320 (Flood Risk Assessment Guidance for New Developments)'. This guidance should be used to add more detail to the FRA to illustrate the risk expected to the roads and bridge during an event so that the planning inspectorate fully understands the risk posed to the scheme and so they can make an informed decision on flood risk.

Where safe access cannot be achieved an emergency flood plan must be considered. The plan should deal with matters of evacuation and refuge, and should demonstrate that people will not be exposed to flood hazards. The emergency flood plan should be submitted as part of the FRA and will need to be agreed with the planning inspectorate. As this development is a bridge rather than a residential development the nature of the plan will of course be different. The plan may need to consider issues such as whether the bridge will be closed in the event of a flood. We are pleased to note that a flood response plan will be produced for the 'during construction' phase as well.

It should be noted that the Environment Agency does not normally comment on or approve the adequacy of flood emergency response procedures accompanying development proposals, as we do not carry out these roles during a flood. Our involvement with this scheme during an emergency will be limited to delivering flood warnings to occupants/users covered by our flood warning network.

The Planning Practice Guidance to the National Planning Policy Framework states that those proposing developments should take advice from the emergency services when producing an evacuation plan for the development as part of the flood risk assessment.

In all circumstances where warning and emergency response is fundamental to managing flood risk, we advise that the inspectorate formally considers the emergency planning and rescue implications of new development in making their decisions. As such, we recommend Emergency Planners and the Emergency Services are consulted to determine whether the proposals are safe in accordance with the guiding principles of the Planning Practice Guidance (PPG).

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Impact Assessment Criteria & Mitigation
Table 6-2 and 6-3 illustrate the impact assessment criteria employed to assess whether mitigation is required for any changes in flood risk as a result of the scheme. As we previously highlighted in our response to the scoping report opinion dated 28 March 2017 the impact assessment criteria presented provides a basic framework for assessing whether mitigation is required. However we would advise that any increases in flood risk to any vulnerability of development should be investigated to establish the likely consequence upon that specific site/development.
The scheme has been designed to produce a 'negligible' effect on flood risk. Section 7 of the FRA discusses flood risk mitigation and suggests that mitigation is not required as the maximum increase in flood depth in the design event 0.5% (1 in 200) annual probability event with an allowance for climate change is up to 0.02m in the floodplain which is classified as negligible in Table 6-2. Whilst 2cm is likely to have a minor impact elsewhere the FRA should still identify and quantify any changes in flood depth, extent, frequency and hazard and illustrate the consequences of these changes upon the receptors in the area in more detail. We are unlikely to object on this point as the depths are small and are likely to be insignificant but we suggest this is discussed in further detail in the FRA in order to illustrate and justify the flood risk impact to the planning inspectorate so they may make an informed decision.

The FRA could also provide further detail to illustrate the changes in flood risk between the baseline and scheme scenarios. At present the FRA does not show exactly where the areas of change in flood risk are or discuss the receptors that would be impacted in the floodplain. We note that the model report contains depth mapping in Figures 5-2 and 5-3 which shows the changes in flood depth and where they occur. It would be useful to have these for a range of events and displaying hazard rating with some discussion to explain what this impact will mean.

Section 7.1.1 states that mitigation should be provided in line with table 6-3 for highly vulnerable development and suggests this is not required due to the current high depth of flooding at that location. Therefore an additional 2cm will not have an impact. This provides some justification but this should be justified and explained for any increases in flood depth. For example will these changes in flood depth mean more properties are at risk than before? What are the receptors in the area? Is the change of 2cm likely to have an impact on the existing flood depths in the floodplain? Again we agree the depths are small but it is still important to illustrate the impact of the proposed scheme upon flood risk to the planning inspectorate so they can make an informed decision.

It should be noted that similar increases in flood depth (of approximately 2cm) were considered minor within the Lowestoft Cumulative Land raising Study which was undertaken by Scott Wilson on behalf of Waveney District Council dated June 2008. This study could be considered in the FRA.

In addition to the above please can it be confirmed how the change in depths quoted for the floodplain were derived? Are these based on the in channel points (P-1 to P-16) or are they based on the on-site depths within the floodplain? Is there an increase in 2cm across the whole floodplain area? Is this an average or the maximum change? Please can it also be confirmed that there is no change in flood extent as this is not discussed or evidenced clearly. It would be useful to have comparable maps of the baseline and scheme scenarios for a range of events within the FRA to clearly illustrate any changes in extents. It is important to note that flood extents must not be increased as a result of the scheme.

Flood Risk During Construction

It is understood that cofferdams will be required in order to install and construct the bridge crossing. Section 8 of the FRA states that construction within Lake Lothing will last approximately ten months. Section 8.1.3 states that the coffer dams will temporarily displace water within Lake Lothing and reduce flood storage.

The cofferdams will be designed to incorporate removable walls so they may be flooded should an event occur that would exceed the height of the quay wall. It is not clear how the removal of the cofferdam walls would be instigated. When would the removable walls be taken out? How would it be known when a significant enough flood event would occur to warrant this? It should also be determined how quickly it could be removed. Is it possible for it to be removed quickly enough before the effect of a flood is felt? Also is there a possibility that once the cofferdam wall is removed it could damage the works and could building materials/chemicals could enter the watercourse and harm the environment?

It would be helpful to understand why the cofferdams have not be included as a model run to illustrate their impact upon flood risk. A model run may show that there is no impact upon flood risk as the current day runs incorporating the scheme do not appear to increase flood risk elsewhere. Potentially this may mean the removal of the cofferdams may not be necessary as a flood risk mitigation measure. As the proposals are temporary (10 months) climate change allowances would not need to be considered.

Flood Risk Activity Permit

As advised in our previous responses under the Environmental Permitting (England and Wales) Regulations 2016 an environmental permit for flood risk activities may be required for work in, under, over or within 8m of a fluvial main river or flood defence structure or culvert or within 16m of a tidal main river or flood defence structure or culvert. The proposed third crossing will cross the main river known as the 'Lake Lothing Landspring and Tributary' and the facilitating works will include cofferdams within Lake Lothing itself. A bespoke permit is therefore likely to be required for both the permanent and temporary works.

The Environmental Permitting Regulations take a risk based approach that enables us to focus regulatory effort towards activities with highest flood or environmental risk. Lower risk activities can be excluded or exempt and only higher risk activities will require a permit. The bridge crossing itself will require a bespoke permit. Any other facilitating works may fall under one or more of the following:

- An Exclusion
- An Exemption
- A Standard Rules Permit
- A Bespoke permit

Application forms and further information can be found at: https://www.gov.uk/guidance/flood-risk-activities-environmental-permits. If you require further advice please email FDCENS@environment-agency.gov.uk.

It is possible to dis-apply the requirement for these permits and consider these under the Development Consent Order itself. If this is preferred we will require greater detail as part of the DCO application so we may undertake the assessment required in order to satisfy a permit. Detailed design drawings and method statements for how the works will be undertaken will be required and will need to be agreed with the Environment Agency. We may also need to append certain conditions that we would usually append to a permit.

If you have not already done so we recommend you contact the Marine Management Organisation (MMO) as some of your work may need to be considered under an MMO licence.

Strategic Flood Risk Assessment (SFRA)
The FRA refers to the 2008 SFRA for the area. This is currently being updated by Waveney District Council and Suffolk Coastal District Council (known as East Suffolk Council). The data referred to in the SFRA has now been superseded. It may be possible to contact East Suffolk Council to obtain this document once it is completed to ensure the most up to date version is being referred to in the FRA. This may depend on the timescales of the scheme and SFRA as to whether it can be included.

Other advice: Other Sources of Flooding
In addition to the above flood risk, the site may be within an area at risk of flooding from surface water, reservoirs, sewer and/or groundwater. We have not considered these risks in any detail as we are not a statutory consultee on these sources, but you should ensure these risks are all considered fully.

I hope that you have found this information useful.

Yours sincerely

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End

The Lake Lothing (Lowestoft) Third Crossing Order 201[*]

Document 6.3: Environmental Statement Volume 3 Appendices

Appendix 18A

Annex B: Hydraulic Modelling Report

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Foreword

This Flood Risk Assessment relates to an application ('the Application') submitted by Suffolk County Council ('the Council' / 'the Applicant') to the Secretary of State (through the Planning Inspectorate) for a Development Consent Order ('DCO') under the Planning Act 2008.

If made by the Secretary of State, the DCO would grant development consent for the Applicant to construct, operate and maintain a new bascule bridge highway crossing, which would link the areas north and south of Lake Lothing in Lowestoft, and which is referred to in the Application as the Lake Lothing Third Crossing (or 'the Scheme').

This Flood Risk Assessment has been prepared in accordance with the requirements of section 37(3)(d) of the Planning Act 2008 and regulation 5(2)(e) of the Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009 ('the APFP Regulations'), and in compliance with relevant guidance.

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Abbreviations

ABP	Associated British Ports
AEP	Annual Exceedance Probability
AOD	Above Ordnance Datum
CD	Chart Datum
DCO	Development Consent Order
EA	Environment Agency
ESL	Extreme Sea Levels
FEH	Flood Estimation Handbook
FRA	Flood Risk Assessment
NPPF	National Planning Policy Framework
NTSLF	National Tidal and Sea level Facility
ReFH	Revitalised Flood hydrograph
SCC	Suffolk County Council
UKCP09	UK Climate Projections
WDC	Waveney District Council

Figures

Tables

1 Introduction

1.1 Overview

1.1.1 As part of the Scheme, a hydraulic model has been built to assess flood risk to the Scheme and the impact of the Scheme on flood risk elsewhere. This report describes the development of the hydraulic model built to inform the Flood Risk Assessment (FRA) for the Scheme.

1.1.2 This report specifically demonstrates that the hydraulic model used in this assessment is suitable for use and produces robust results. The FRA document itself should be referred to for wider discussion of the model results and the Scheme. A drainage strategy has also been developed for the Scheme, which forms part of the Development Consent Order (DCO) application and should be read in conjunction with this report and the FRA.

1.2 Study area

1.2.1 Lake Lothing is used as a commercial transport hub with a number of large ship berths on either side. The lock at Mutford Bridge at the upstream end of the lake controls the water flow between Oulton Broad and Lake Lothing and allows the passage of small leisure vessels. Lowestoft currently has two road bridge crossings; the A47 Bascule Bridge and Mutford Bridge as shown in Figure 1-1. These are the only two methods for traffic to cross Lake Lothing. In addition to the road crossings there is a railway crossing near Mutford Bridge as shown in Figure 1-1.

1.2.2 Three small fluvial catchments discharge into Lake Lothing; the watercourses associated with these catchments are Kirkley Stream and two small unnamed drainage channels. Kirkley stream is approximately 4.4km long and flows in a northerly direction into the southern side of Lake Lothing. One of the unnamed drainage channels is also on the south side of Lake Lothing and the other is on the northern side.

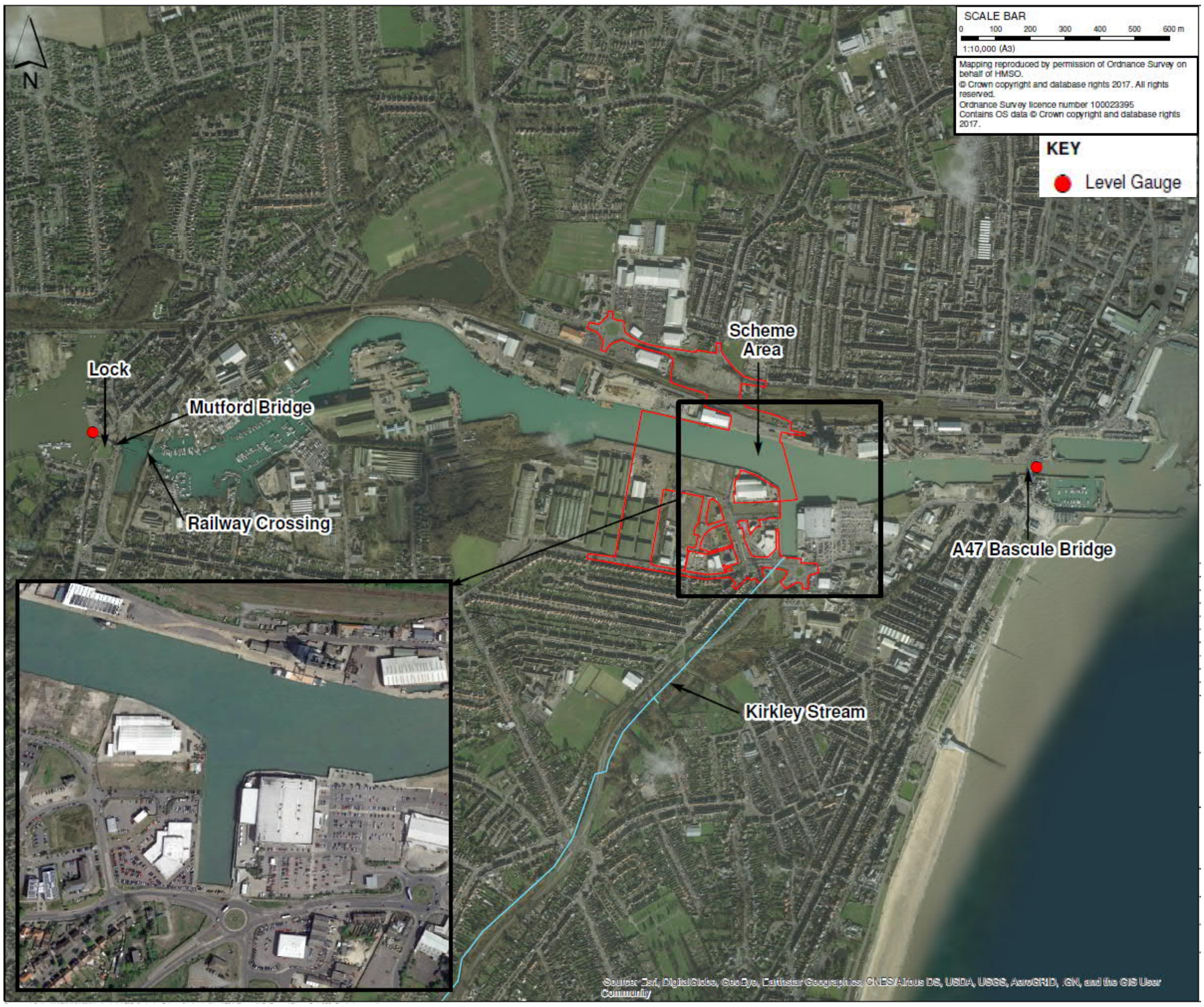


Figure 1-1 - Scheme Location

1.3 The Scheme

1.3.1 The bridge and the new road layouts are shown on Figure 1-2 and Figure 1-3. The Scheme consists of a central bascule bridge supported by concrete piers approximately 0.8km upstream of the existing A47 Bascule Bridge.

1.3.2 Two large central piers support the centre bascule span within Lake Lothing. The central deck height is approximately 16mAOD. The access road layout includes a total of two new roundabouts, two embankments and a small network of paved roads. Consequential amendments are also made to the existing road network on the north and south side of the scheme, including a new access road on the south side linking Riverside Road and Waveney Drive.

1.4 Previous studies

1.4.1 An existing 1D-2D hydraulic model of Lake Lothing was made available for this study. The model was built by CH2M-Hill for use in the Lowestoft Flood Risk Management Strategy (2016). The model has been used to investigate the impact of various coastal flood defence options on Lowestoft and the surrounding area. A comprehensive review of this model has been carried out as part of this assessment to inform the modelling approach for this study (Section 2.2).

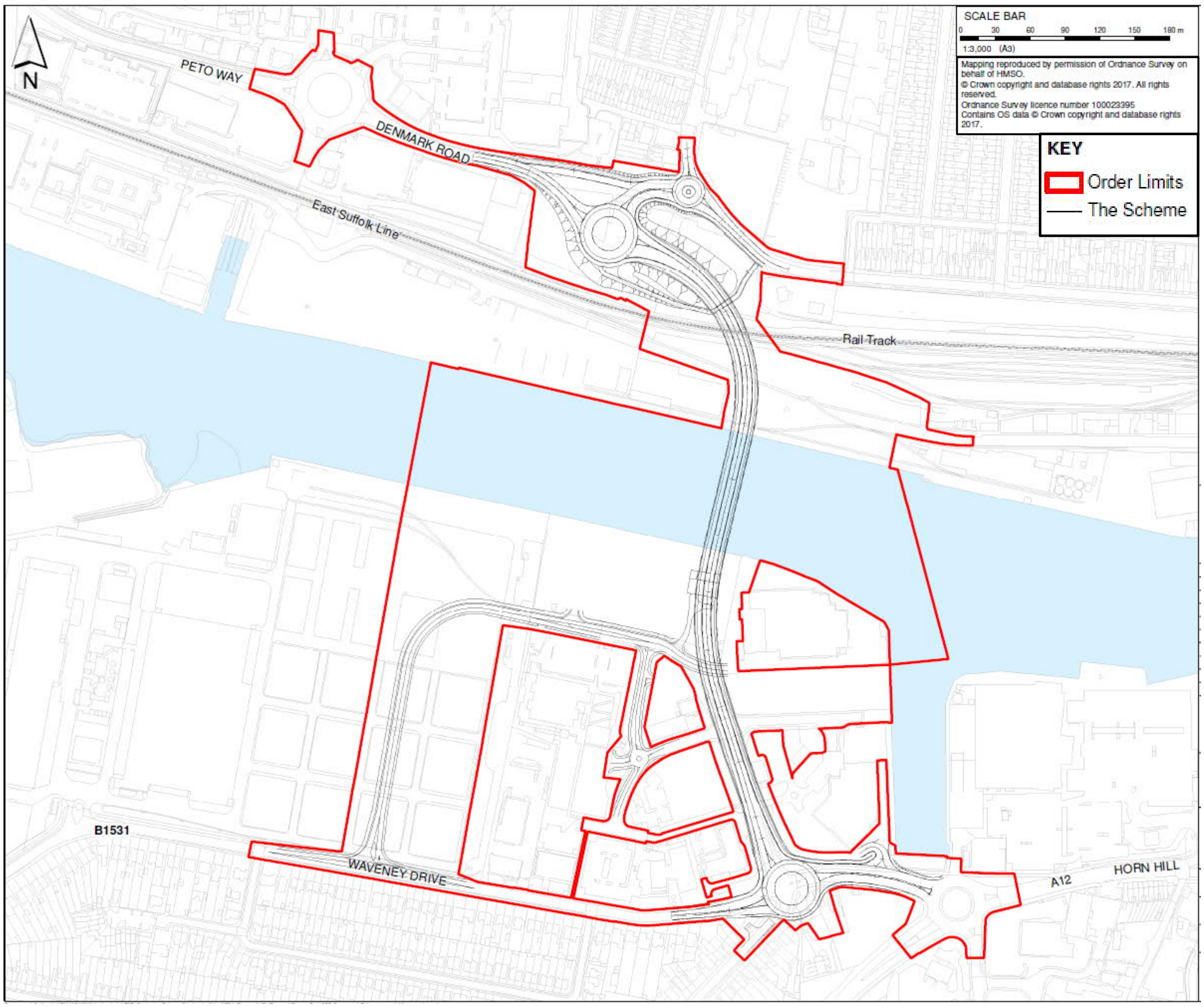


Figure 1-2 - Road alignment of the Scheme

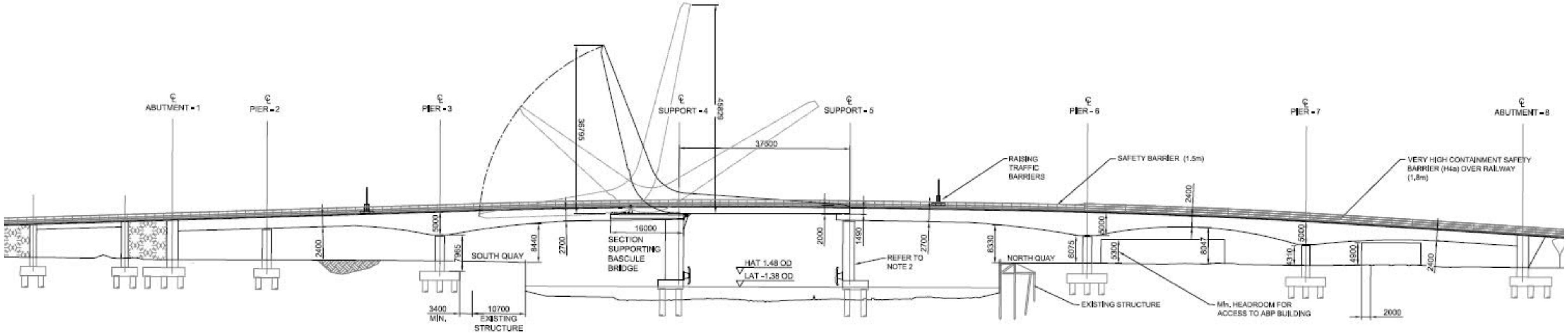


Figure 1-3 - Scheme long section with elevations

2 Data Collection and Review

2.1 Overview

2.1.1 The data listed in Table 2-1 was collected as part of this study. All of the data collected for the study has been reviewed and its suitability for use in this assessment determined. A large part of the data review process was a review of the existing hydraulic model of Lake Lothing and the outer harbour provided by CH2M Hill on behalf of Waveney District Council (WDC) for use in this assessment.

Table 2-1 - Summary of data collected

Data	Source
1D-2D ISIS TUFLOW Lake Lothing model	WDC/ CH2M Hill
Version C19 design for the Scheme	WSP
OS Mastermap As built construction drawings for existing crossings. (A47 Bascule Bridge, Lock at Mutford Bridge and Mutford Bridge) Previous study reports[1]	Suffolk County Council (SCC)
Bathymetric survey	Associated British Ports (ABP)
2015, 0.5m LiDAR Extreme sea levels Daily average gauge data for Lake Lothing and Oulton Broad	Environment Agency (EA)
Tidal levels in Lake Lothing charts	National Tidal and Sea Level facility (NTSLF)
Topographic data on the North and South Quay	WSP

2.2 CH2M Hill Model Review Summary

2.2.1 CH2M Hill developed a 1D-2D ISIS TUFLOW model as part of the Lowestoft Flood Risk Management Strategy. The model was reviewed to determine whether it could be used in this assessment. In this section, an overview of the major findings of the model review is provided, the full model review is provided in Section 7.1 – Supporting Documents.

2.2.2 The CH2M Hill existing model has a 2D domain covering Lake Lothing, the outer harbour, the floodplain and strips of land close to the coast where tidal overtopping may occur as shown in Figure 2-1. The model received for use in this assessment has a small 1D domain representing the eastern part of Oulton Broad and the lock at Mutford Bridge (also shown on Figure 2-1).

[1] *Lowestoft tidal barrier - outer harbour water level modelling investigation – 2016*
Lowestoft Tidal Defences Additional Modelling Studies – 2014
Lowestoft Flood Risk Management Strategy - 2016

The model received is actually an extract from a larger model that represents the Broadlands river system in 1D. As this assessment is focussed on Lake Lothing, it was not necessary to model the Broadlands river network as part of this study.

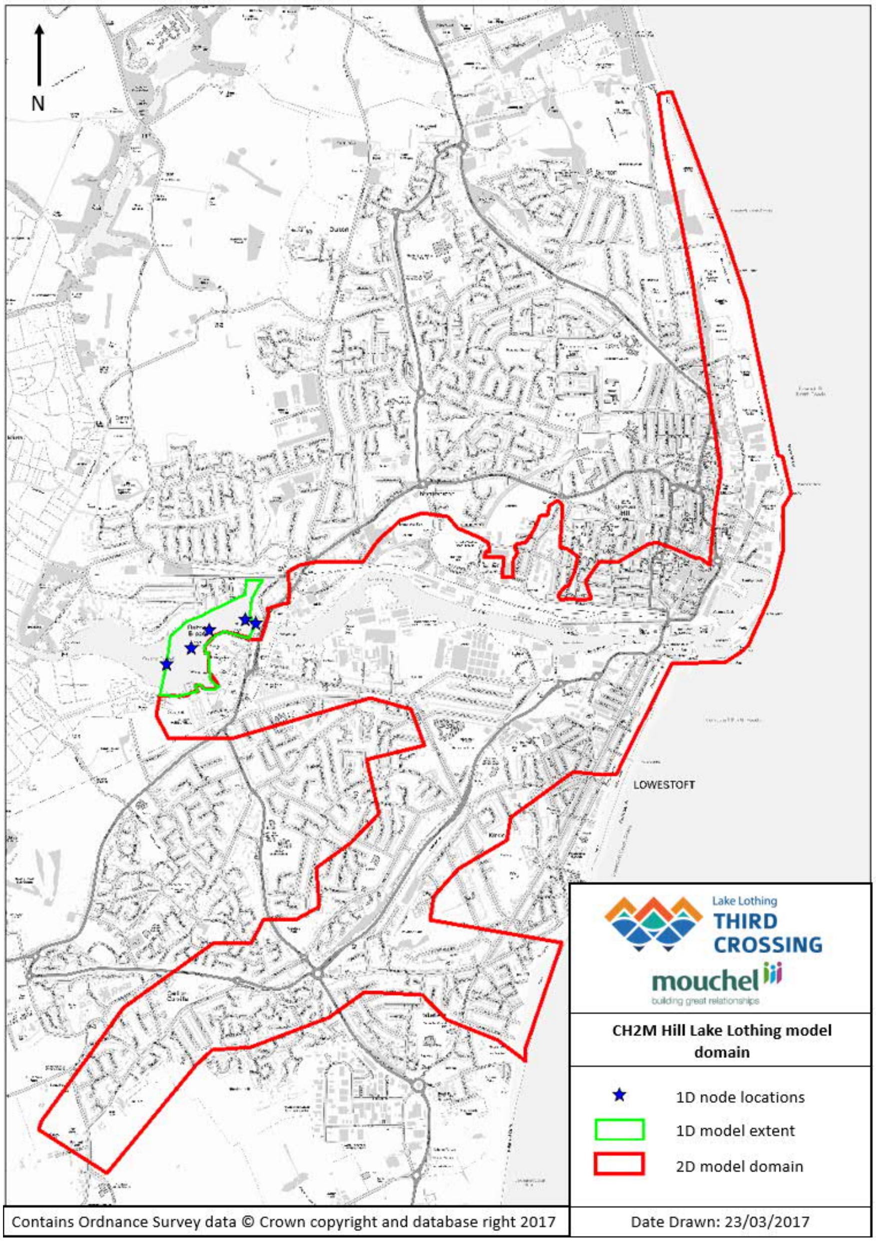


Figure 2-1 - CH2M Hill existing 1D-2D model extent

2.2.3 The existing model represents the A47 Bascule Bridge as a flow constriction unit in the 2D domain. The dimensions of the bridge were specified by estimation from photographs because the as-built drawings were not available. The Mutford Bridge opening across Lake Lothing is not represented within the existing model but the deck level of the bridge is represented in 2D and forms a boundary between the 1D and 2D model domains. The Lock at Mutford Bridge is represented in the 1D domain to enable the lock gates to be simulated in the open and closed positions. The railway crossing is not represented in the model.

2.2.4 The model represents Lake Lothing and the outer harbour bed level with a standard value of -1.5mAOD. The topography elevations for the floodplain are based on the 2m resolution, 2014 LiDAR flight.

2.2.5 The model represents the existing defences on the coast by increasing elevations along the coastal boundary of the model to the height of the defences where they occur. There are defences located south of the outer harbour protecting the promenade from coastal flooding and erosion. The harbour walls in Lake Lothing are not formal defences but do provide additional storage within Lake Lothing and their levels are stamped onto the model grid.

2.2.6 Roughness has been applied across the 2D domain of the existing model using Manning's n values to represent different land uses based on OS mastermap. A number of roughness patches are used in the existing model where a high roughness value is applied across a wide area in order to stabilise the model. A roughness patch has been applied along the coastal boundary of the existing model to ease the transition of water from the tidal boundary onto the floodplain. The reason this roughness patch is required in the model is because there is a discrepancy between the initial water level of the tidal boundary (-0.5mAOD) and the initial water level set across the 2D domain (0.0mAOD), the roughness patch allows the model to run despite the sudden change in water level at the coastal boundary at the start of a simulation.

2.2.7 The existing model uses a 1D domain to simulate the lock at Mutford Bridge open and close scenarios. An arbitrary inflow is specified to ensure the 1D domain does not run dry. The full 1D extent of the larger Broadlands river network was not provided for use in this assessment. Five 1D cross sections are included in the model provided for this study (as shown on Figure 2-1), which represent approximately a 680m reach of Oulton Broad to the lock at Mutford Bridge.

2.2.8 The tidal boundary in the existing model had a peak level of 3.11mAOD for the 1% Annual Exceedance Probability (AEP) event. The tidal and fluvial hydrology of Lowestoft has been assessed and updated as part of this study, this is discussed further in Section 3.

2.2.9 The review of the existing model concluded that a number of updates were required to ensure the model was suitable for use in this assessment including obtaining accurate structure details, using bathymetry to represent the bed of Lake Lothing, using the most up to date LiDAR data to represent the floodplain, stabilising the model to remove the need for roughness patches and removing the 1D domain and representation of Oulton Broad from the model. Given the updates required to ensure the existing model was suitable for use in this assessment and the different application of the model in this assessment compared to the Lowestoft Flood Risk Management Strategy, it was decided that a new model would be developed for this assessment. Further details of the model developed for this study are provided in Section 4. The focus of this assessment is the local hydraulic effects of the Scheme, therefore there is a need to use the most recent and accurate data, particularly close to the Scheme site. The CH2M Hill model was developed for a different purpose and is still valid but it is necessary to refine and incorporate more detail into the model developed for this assessment to determine the impacts of the Scheme on the hydraulics within Lake Lothing.

2.3 Additional Data

2.3.1 Drawing 2.9 Engineering Section Drawing Mainline (Sheet 2 of 2) has been used to obtain the level data for the Scheme in the post-development model built for this study. Details of the new access roads for the Scheme were also provided. The WSP Highways team have collected topographic data on the north and south quay of Lake Lothing that has been used to inform this assessment.

2.3.2 SCC as lead local flood authority provided a number of datasets and documents for use in this assessment. OS mastermap data covering Lowestoft was provided, which includes land use classification. SCC also provided as-built drawings for the existing road crossings over Lake Lothing.

2.3.3 ABP has provided a detailed bathymetric survey of Lake Lothing and the outer harbour. The dataset contains points measured from Chart Datum (CD) within the harbour taken on a boat that traversed the inner and outer harbour. The levels on the bathymetric survey have been sensibility checked against topographic survey levels on the north and south quays of Lake Lothing and the bed levels appear reasonable. In order to use the data collected during the bathymetric survey, it was necessary to convert the levels provided from CD to mAOD as all other level data used in this assessment is in mAOD. Lowestoft CD is -1.5mAOD and is defined as the approximate level of the lowest astronomical tide at Lowestoft. The bathymetric survey data points are converted to mAOD by adding -1.5m from each level recorded in the survey.

2.3.4 The EA has provided several datasets; the 2015, 0.5m resolution LiDAR dataset, Extreme Sea Levels (ESL)[2] and daily water level data recorded in Lake Lothing (at the A47 Bascule Bridge) and in Oulton Broad (at Mutford Bridge) as shown on Figure 1.1. LiDAR levels were checked against topographic survey where possible and a good correlation was found, therefore the LiDAR was deemed suitable for use in this assessment. There have been no significant changes in the Lowestoft area since 2015 that would impact on the flood dynamics, therefore the LiDAR flown in 2015 is deemed to be valid to represent the present day (2017) floodplain levels. It can also be assumed that while the surface may change in the future, any future developments will be required to have a neutral impact on flood risk and therefore the existing LIDAR data is valid to use for future climate change scenarios. The daily level data provided by the EA was analysed to determine the relationship between levels in Lake Lothing and Oulton Broad. Levels in Lake Lothing are higher than those on Oulton Broad as shown in Figure 2-2. This shows that the water level on Oulton Broad is predominately controlled by the water level of the River Waveney, which flows into Oulton Broad and not directly influenced by the water level in Lake Lothing. However, during high tidal events the lock at Mutford Bridge can be overtopped allowing water from Lake Lothing into Oulton Broad.

[2] Open Coast (CFBD) Flood Risk Study, JBA, 2014

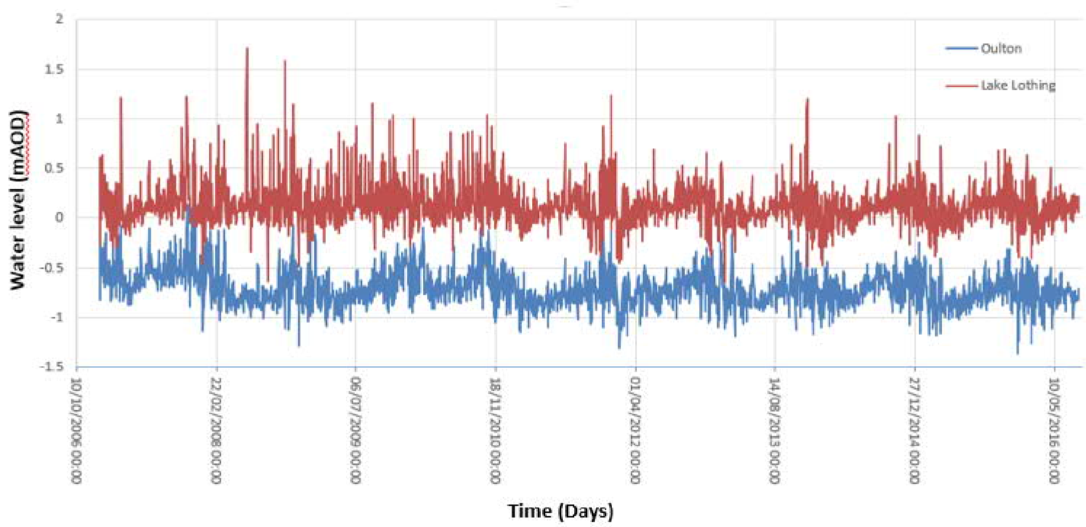


Figure 2-2 - EA level gauge comparison

3 Hydrology

3.1 Overview

3.1.1 The hydrology of Lake Lothing has been analysed and the EA have specified the design events and climate change scenarios to be considered in this study (correspondence with the EA is provided in Annex A of the FRA). Tidal levels have been derived to define the eastern boundary of the hydraulic model that represents sea levels along the Lowestoft coast. EA guidance on estimating design sea levels[3] has been used to derive the tidal boundary used in the model. Fluvial flows have been calculated on the three watercourses that discharge into Lake Lothing to allow the fluvial inputs to be included in the hydraulic model. Fluvial inflows to the model have been estimated following the EA Flood Estimation Guidelines[4]. Climate change allowances have been calculated by considering the worst case scenario from a number of methods in line with the requirements from the EA.

3.1.2 The EA has requested that three return period events are investigated in this assessment; 5% AEP, 0.5% AEP and 0.1% AEP. The three design events will be assessed for the present day (2017) and two climate change scenarios as required by the EA (Annex A of the FRA document).

3.1.3 A summary of the calculations undertaken to define the hydrological boundaries of the model is provided below with more detail provided in Section 7.2 – Supporting documents.

3.2 Tidal Curve Derivation

3.2.1 The EA guidance[3] sets out a 10 step procedure to generate a tidal curve:

1. Check study location is outside of estuary boundaries;
2. Select an appropriate chainage point for extreme sea levels;
3. Select an annual exceedance probability peak sea level;
4. Consider allowance for uncertainty;
5. Identify base astronomical tide;
6. Convert levels to Ordnance Datum;
7. Identify surge shape to apply;
8. Produce the resultant design tide curve;
9. Sensitivity testing; and
10. Apply allowance for climate change.

[3] SC060064/TR4: Practical Guidance Design Sea Levels and Open Coast (CFBD) Flood Risk Study (2014) JBA for the Environment Agency.

[4] Flood Estimation Guidelines Technical Report 197_08, Environment Agency, 2015

3.2.2 The procedure above makes use of several datasets which are provided as part of the guidance:

- Estuary Boundaries;
- ESLs from Open Coast (CFBD) Flood Risk Study, JBA 2014;
- Gauge Sites;
- Confidence Intervals; and
- Surge Shapes.

3.2.3 The tidal curve has been derived using the process set out in Section 3.2.1. As discussed in detail in Section 7.2 - Supporting Documents, the first four steps in the process make use of the datasets provided to obtain the required data for the site. The remaining steps require the manipulation of the data to obtain the tidal curve.

3.2.4 The procedure uses the available data to create an astronomical tidal profile, in the assessment it was deemed appropriate to use the tidal curve from the CH2M Hill existing model and scale to the required peaks in Table 3-1 (ESLs). The existing model tidal curve was scaled to the ESLs using the surge shape for Lowestoft provided with the guidance. This procedure is explained in detail in Section 7.2 - Supporting Documents.

3.2.5 In order to consider the impact of and resilience to future flooding, the model has also been used to simulate future flood events with an allowance for climate change included. Climate change has been represented by increasing tidal levels only to represent sea level rise in the future. The design life of the Scheme is 120 years.

3.2.6 In line with the recommendation from the EA, the climate change sea level rise has been defined as the worst case scenario following an assessment of five different guidance documents. The guidance documents recommended by the EA were:

- National Planning Policy Framework (NPPF)-Table 3;
- UK Climate Predictions 2009 (UKCP09) 50% High Emissions (HE);
- UKCP09 95% HE;
- UKCP09 95% Medium Emissions (ME); and
- Upper End, Adapting to Climate Change, 2016.

3.2.7 An assumption has been made that the Scheme is unlikely to be constructed before 2020; therefore for the climate change calculations it was deemed appropriate to calculate sea level rise between 2020 and 2140. None of the documentation stretches that far into the future, therefore the predictions were extrapolated using a linear method as agreed with the EA. The climate change sea level increase worst case scenario was 1.54m from the NPPF-table 3. This has been applied to the tidal curves representing the present day scenario in order to create tidal curves representing the climate change scenario for each design event.

3.2.8 Due to the safety critical nature of the Scheme, the EA have also requested that the design is assessed against the UKCP09 H++ estimates (high risk, low probability scenario) for sea level rise to assess a credible maximum scenario. However, the EA have stated that mitigation will not need to be provided up to the H++ scenario. The H++ allowances for change to relative mean sea level up to the year 2115 are provided within the EA's Adapting to Climate Change guidance. The data has been extrapolated using a linear approach to calculate the rate of sea level rise from 2116 to 2140 to cover the design life of the Scheme. For details on the climate change calculations, see Section 7.2 - Supporting Documents.

3.2.9 The final ESLs are shown in Table 3-1. The ESLs are provided by the EA and the climate change levels and H++ climate change levels have been calculated from these using the methods described above.

Table 3-1 – Peak sea level for each event

Event	5% AEP (mAOD)	0.5% AEP (mAOD)	0.1% AEP (mAOD)
ESL	2.74	3.4	3.92
Climate change	4.28	4.94	5.46
H++ event climate change	5.84	6.5	7.02

3.2.10 Figure 3-1 shows the tidal curves that have been derived for use in this assessment.

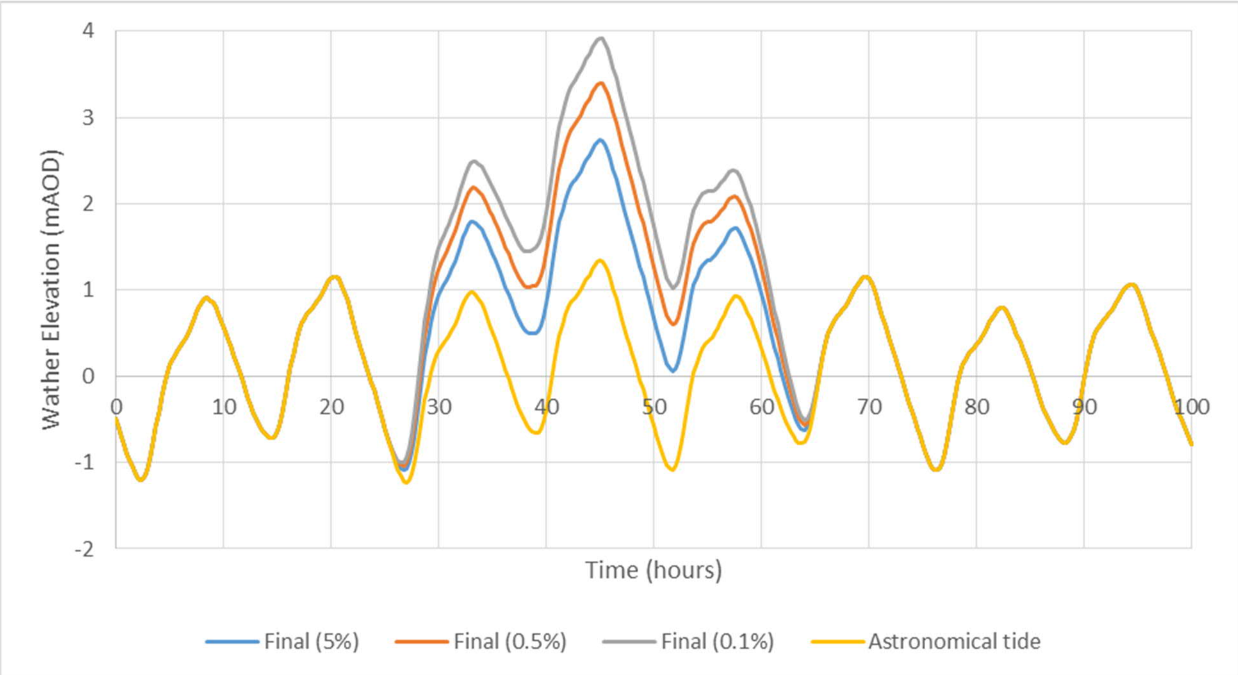


Figure 3-1 - Tidal curve for 5%, 0.5% and 0.1% AEP present day events

3.3 Fluvial Hydrology

3.3.1 There are three tributaries that discharge directly into Lake Lothing. A hydrological assessment using the Flood Estimation Handbook (FEH) methods[5] has been carried out for each catchment to derive peak flows and hydrographs. Updated methods (FEH13 & ReFH2)

[5] *Flood Estimation Handbook (Institute of Hydrology, 1999)*

and updated software (WINFAP4) have all been published recently, however current industry guidance does not require the use of these methods and software.

3.3.2 Flows have been derived for the 5%, 0.5% and 0.1% AEP events in line with the tidal events derived. Figure 3-2 shows the catchment areas for each of the watercourses.

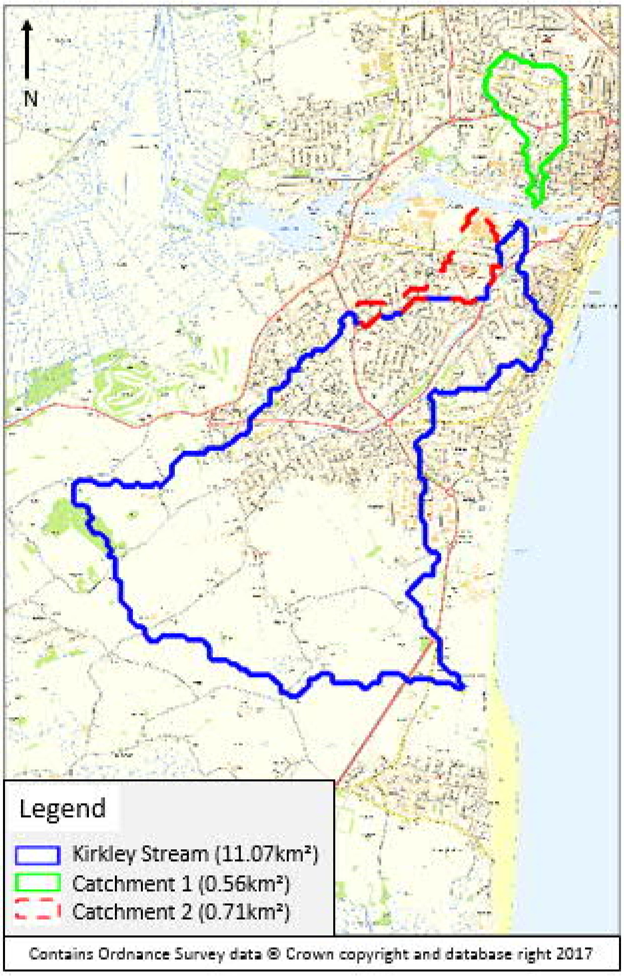


Figure 3-2 - Fluvial catchment locations

3.3.3 Kirkley stream and catchment 1 flow into Lake Lothing from the south and catchment 2 flows into Lake Lothing from the north. The catchments are all classed as either heavily urbanised or very heavily urbanised.

3.3.4 The FEH Statistical method, Revitalised Flood Hydrograph (ReFH) method and the ReFH Urban method have been used to calculate peak flows. The ReFH and ReFH Urban methods have both been used to produce hydrographs. When comparing the results, it was found that the ReFH and ReFH Urban method produced anomalous results in catchments 1 and 2 which has led to unrealistic peak inflows for such small catchments. The FEH methods are only recommended for catchments $0.5km^2$ in size and greater, therefore catchments 1 and 2 are at the lower limit of suitability for the FEH methods (see Section 7.3 – Supporting Documents for further discussion). As all catchments are small urbanised catchments, it was decided that the FEH Statistical method would be used to define peak flows and the ReFH hydrographs have then been scaled to the peak flows to create model inflows for each of the fluvial catchments. A detailed account of the hydrological assessment is provided in Section 7.3 – Supporting Documents. Table 3-2 shows the peak fluvial flows used in this assessment.

Table 3-2 - Final fluvial design flows

Name	Flood peak (m^3/s) for the following return periods in years								
	20	20cc (25%)6	20cc (65%)7	200	200cc (25%)[5]	200cc (65%)[6]	1000	1000cc (25%)[5]	1000cc (65%)[6]
Kirkley	1.79	2.24	2.95	2.7	3.38	4.46	5.08	6.35	8.38
C1	0.15	0.19	0.25	0.27	0.34	0.45	0.54	0.68	0.89
C2	0.17	0.21	0.28	0.3	0.38	0.5	0.65	0.81	1.07

3.3.5 Although the fluvial inflows to Lake Lothing have been considered and flow estimates calculated as part of this assessment, it was found during sensitivity testing of the hydraulic model developed for this assessment that the model results were insensitive to the fluvial inflows. The sensitivity analysis undertaken as part of this assessment is discussed in Section 4.3.

[6] Based on Anglian river basin district for a design life of 100 years – central value. (Adapting to climate change – Guidance 2016)
[7] Based on Anglian river basin district for a design life of 100 years – upper value. (Adapting to climate change – Guidance 2016)

4 Modelling Methodology

4.1 Overview

4.1.1 A 2D TUFLOW model of Lake Lothing and the outer harbour has been developed for this assessment. Baseline and Scheme versions of the model have been created and other scenarios have been used to test the sensitivity of the model to a range of parameters as discussed in Section 4.3. Following the model review of the CH2M-Hill model, it was concluded that a new 2D model would be required. The model build for this study is detailed in Section 4.2. Section 4.3 describes the sensitivity testing undertaken on the model developed for this study and the outcomes of this. Section 4.4 describes the model verification process that has been undertaken.

4.2 Model Domain

2D Model Domain

4.2.1 The model domain extends from the lock at Mutford Bridge in the west to the coastal boundary in the east covering Lake Lothing and the outer harbour plus surrounding floodplain. A small section of Kirkley stream has been included in the 2D domain, it was considered unnecessary to include the upper reaches of the stream within the 2D domain as the impact of the Scheme on the area of Kirkley Stream is insignificant. An outflow boundary has been included across Kirkley Stream to allow passage of water in high water events preventing a glass walling effect at the edge of the domain. The impacts of this are discussed in the Section 4.3.

Figure 4-1 - 2D Model domain

4.2.2 A 5m cell size has been used within the 2D domain in order to enable the modelling of urban flow paths through Lowestoft whilst still maintaining reasonable model run times. Initially a 10m cell size was chosen for the 2D domain but the cell size was reduced following EA review of the model (the EA review is discussed further in Section 4.4).

4.2.3 The lock at Mutford Bridge has been simulated as closed for all scenarios modelled. It has been assumed that during high water events, the lock gates will remain closed.

Floodplain Roughness

4.2.4 Manning's n roughness values have been used to represent different land uses across the 2D domain as shown in Table 4-1. Roughness values have been applied based on the land use classification within the OS mastermap data supplied by SCC. Buildings have been represented in the 2D domain using high roughness values to slow the flow of water through them and to account for the fact that they will provide some storage during flood events. Additionally the stubby buildings method has also been used, increasing levels within building footprints by 0.2m to represent a threshold. This means that the model simulates flood flow paths around buildings and was a requirement of the EA flowing their review of the model developed for this assessment (see Section 4.4 for more details on the EA review). There are no roughness patches included in the model.

Table 4-1 - 2D domain roughness values

Item	Roughness (Manning's *n*)
Buildings and Structures	1
Roads and Paths	0.02
Water	0.03
Natural Surfaces	0.05
Manmade Surfaces	0.04
Rails	0.02

Model Topography

4.2.5 The bathymetric data provided by ABP, once converted from CD to mAOD (see Section 2.3) has been used to define the bed levels of Lake Lothing and the outer harbour within the model. The dataset recorded in spring 2016 consists of some 180,000 data points taken from a boat traversing the harbour. Towards Mutford Bridge, only the centre of Lake Lothing was included in the bathymetric survey as shown on Figure 4.2. Where this occurs, the model has been set to interpolate between the bathymetric survey points and LiDAR levels on land. This method is suitable as there are no formal docking/boat moorings in these areas, which would generate large changes in elevation as is expected when harbour walls are present.

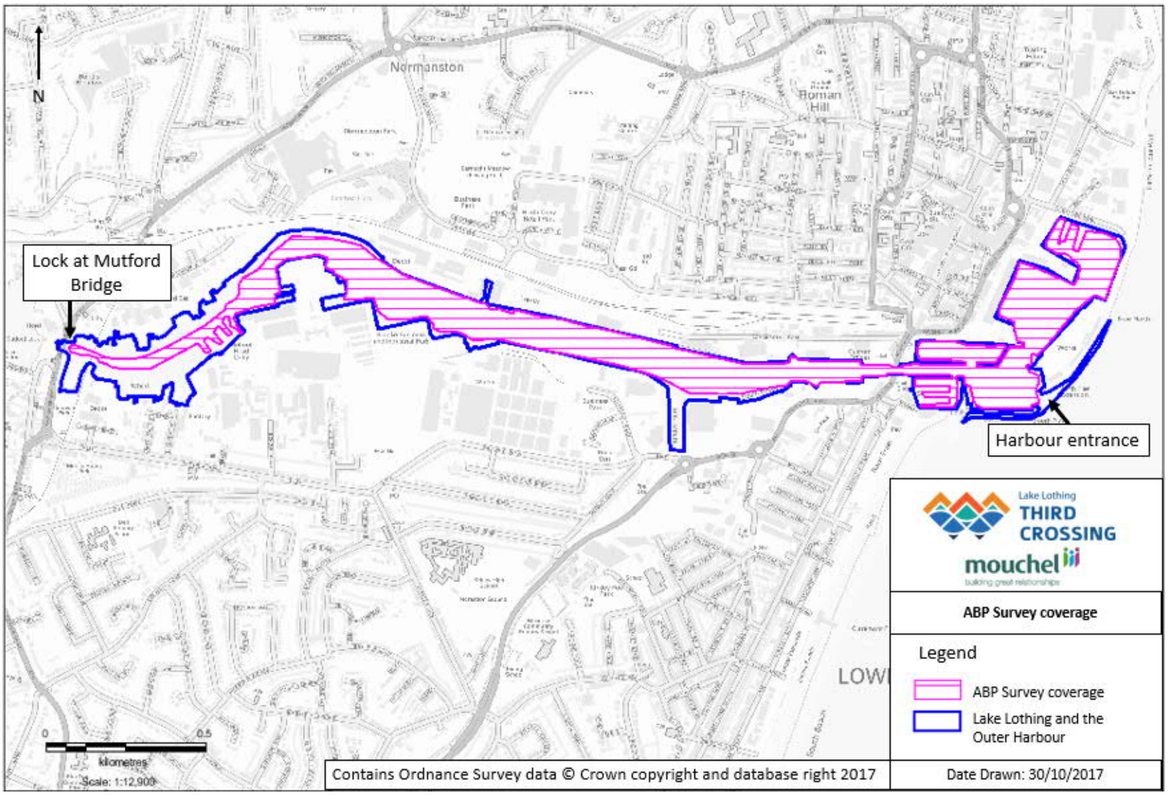


Figure 4-2 - ABP bathymetric survey coverage in Lake Lothing

4.2.6 Bathymetry data for the North Sea was not available, the lowest depth recorded towards the sea in the ABP survey is at the entrance to the outer harbour. The level recorded at the entrance to the outer harbour has been extended to the edge of the 2D domain to represent the bed level of the North Sea for the small area of the model where part of the sea is included in the model domain. As the area included in the model outside of the harbour is small (approximately a 40m strip from the harbour entrance, Figure 4-2), this method provides suitable accuracy.

4.2.7 LiDAR from the 2015 flight at 0.5m resolution has been used for the floodplain elevations. There is complete coverage of the 2D domain (Figure 4-1) using this dataset and the data has been compared to a number of surveyed points. There is a good correlation between the LiDAR and topographical data, therefore the LiDAR is considered suitable for use.

Boundary Conditions

4.2.8 The North Sea tidal boundary is located to the east of Lowestoft as shown on Figure 4-3. The tidal curves derived for this assessment as summarised in Section 3.2 have been applied to this boundary in the model. The tidal boundary has been applied close to the outer harbour entrance representing the worst case scenario, enabling the highest sea level for a given scenario to be simulated at the harbour entrance.

4.2.9 Two HQ boundaries were required in the model to allow water to flow out of the 2D domain where in reality water would continue to spread across the floodplain, the location of these boundaries are shown on Figure 4-3. At these boundaries, the model uses a rating curve based on the topography and roughness of the floodplain to control the release of water from the model.

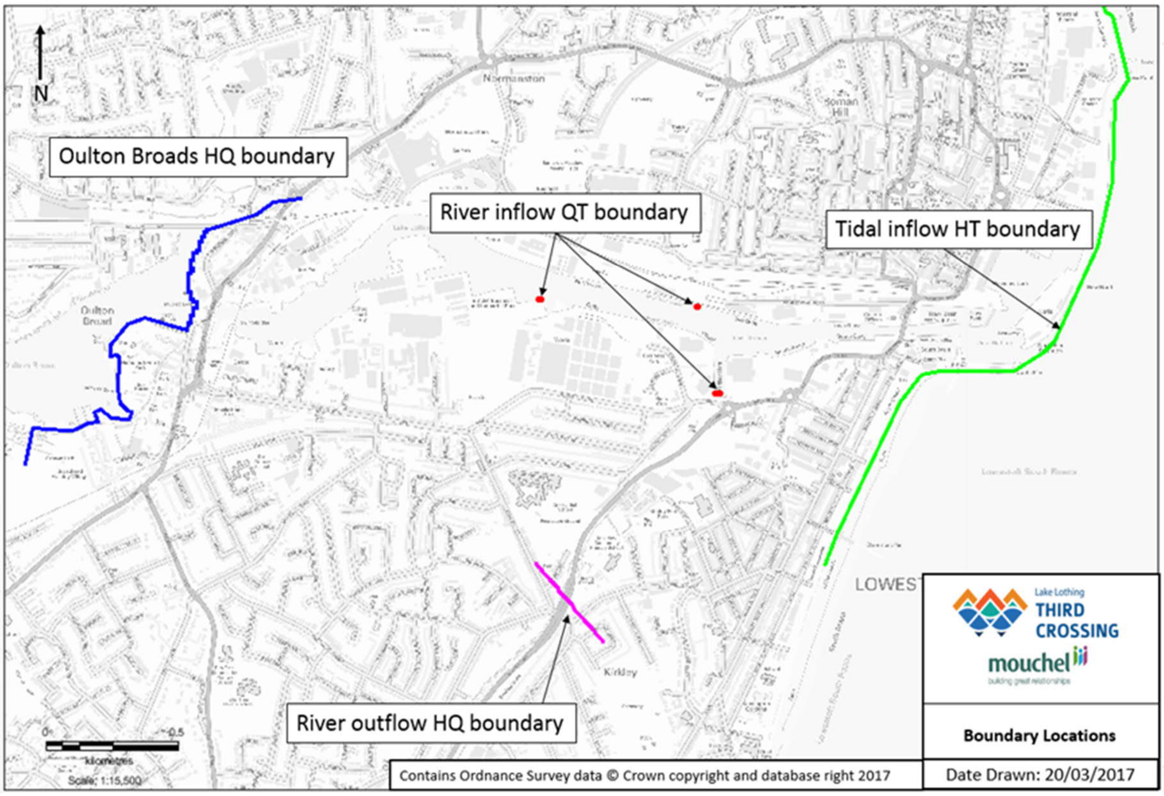


Figure 4-3 - Model boundary conditions

Initial Water Level

4.2.10 The initial water level in the model is set to -0.5mAOD across the entire 2D domain as this is the initial water level in the design tidal curves calculated as described Section 7.2 – Supporting Documents. Setting the initial water level to the same elevation as the start of the tidal boundary reduces the potential for model instabilities likely with sudden movements of large volumes of water in the model domain. This also reduces the need for an extended period of time to ‘warm up’ the model, reducing the overall simulation length. The model is assumed to be insensitive to the initial conditions as there are three tidal cycles prior to the peak tidal level occurring within the tidal inflow (see Figure 3-1).

Structures

4.2.11 The lock at Mutford Bridge, Mutford Bridge itself and the A47 Bascule Bridge have been represented in the model developed for this assessment. The lock at Mutford Bridge has been represented as closed for all the model scenarios considered in this assessment as it is assumed that the lock gates would be closed during flood events. This is consistent with current operational procedure. Assuming the lock gates are closed at the start of the model run is a conservative approach as it means there is no transfer of water via the lock between Lake Lothing and Oulton Broad during the initial tide cycles in the model run. In reality, there may be times when the lock gates are open leading up to a flood event and therefore the model may overestimate levels during the early stages of a flood event but the peak tidal level would be insensitive to the assumption that the lock gates are closed. The lock at Mutford

Bridge has been represented in the model by stamping the top level of the lock gates onto the 2D model domain meaning water can only overtop the gates and not flow through them.

4.2.12 The A47 Bascule Bridge and Mutford Bridge are both represented using 2D flow constriction units, the elevations from the as-built drawings were used to define the bridge openings, deck levels and any railings. The flow constriction units represent the blockage caused by each structure across the channel whether it is partial (i.e. piers in the channel) or total (i.e. a solid bridge deck) and the energy loss across each bridge to enable bridge hydraulics to be modelled accurately.

Baseline Model

4.2.13 Once the baseline model had been developed as described above, sensitivity tests were undertaken to determine the sensitivity of the model to various parameters as described in Section 4.3 below. Following the sensitivity testing, a Scheme version of the model was constructed as described below.

Scheme Model

4.2.14 To represent the Scheme in the model, the approach ramps to the bridge are represented by increasing the local topography as appropriate using z shapes to create the elevated structures within the model domain. The bridge crossing is represented using a flow constriction unit to accurately model the head loss through the bridge. This takes into account the total cross-sectional blockage of the support piers and piled foundations underneath the bridge deck both within Lake Lothing and on land. This method was chosen as it represents the additional flow under the pile cap in the water channel. The impact of the bridge would have been overestimated if the central piers were simply modelled by increasing the grid elevations at the pier locations. The two piers in Lake Lothing have a combined cross-sectional area of $140m^2$ underneath the bridge deck. The piers supporting the access ramps on land have a combined cross-sectional area of $62m^2$ and the individual pier sizes range from 8-$14m^2$. In order to be conservative within the model, the total pier cross-sectional area has been represented as 10% of the total cross-sectional area underneath the bridge deck equating to approximately $280m^2$.

4.2.15 The northern approach ramp is represented in the model using a gradual slope starting at ground level and increasing to approximately 9mAOD (deck level at the northern extent of the bridge). The southern approach has been modelled by a gradually elevated embankment and a small bridge over the new access road to the industrial estate. Similar to the main span, this small bridge is not expected to be flooded in the 1000 (0.1%) H++ therefore direct simulation is not required.

4.2.16 The deck crossing is not expected to be inundated during an extreme event. The bridge deck is at a minimum of 9mAOD which is above the 0.1% AEP H++ sea level. For this reason is it sufficient to set the deck level to an average elevation above the maximum water level in the flow constriction. By applying a percentage blockage to the area under the bridge deck, the head loss expected due to the constriction and blockage of the piers is simulated.

4.2.17 In addition to the raised embankments and central piers, the new roads associated with the third crossing have been represented in the model by changing the manning's n values on the floodplain to 0.02 along the route of the new roads.

4.2.18 In addition to the large central piers, there are smaller columns supporting the central span of the bridge. These columns are approximately 1.5m in diameter at various spacing in Lake Lothing and on the adjacent floodplain. Due to the size of each column, it is considered appropriate to consider the total blockage of the smaller columns and include them in the total blockage calculation in the flow constriction unit.

4.3 Model Sensitivity Testing

4.3.1 The sensitivity of the model developed for this study to various parameters has been tested, the baseline model (described in Section 4.2) was used in the sensitivity testing and tests were carried out for the 0.5% AEP event. Sensitivity of the model to the following parameters has been tested:

- Roughness;
- Fluvial inflows;
- Tidal levels; and
- Railway bridge representation.

4.3.2 Table 4-2 explains the versions of the model that have been developed for the sensitivity testing and how each of the parameters listed above has been changed to test their impact.

4.3.3 To assess the impact of the parameters listed in Table 4-2 on the model results, a number of points across the model domain have been selected as comparison points. At these points the results of the sensitivity tests will be compared to the baseline model results. Figure 4-4 shows the locations of the comparison points and Table 4-3 lists the locations and provides the easting and northing values for each point.

Table 4-2 - Sensitivity tests

Sensitivity Test	Purpose	Change
Baseline	Baseline model	N/A
Roughness	To test the effect of the roughness of the 2D domain	Change floodplain roughness by +/-20%
River inflows	To test the impact of the fluvial river inflows on flood levels and extent	Fluvial inflows are applied in the 2D domain. (Two simulations representing 50% AEP 0.5% AEP fluvial events)
Astronomical tide	To test the effect of the tidal boundary	The scaled astronomical tide with a peak water level of 1.65mAOD is applied at the North Sea boundary of the 2D Domain
Railway	To test the impact of the Railway Bridge on peak water levels	Railway bridge represented in model using flow constriction unit with estimated elevations (surveyed/as-built elevations not available)

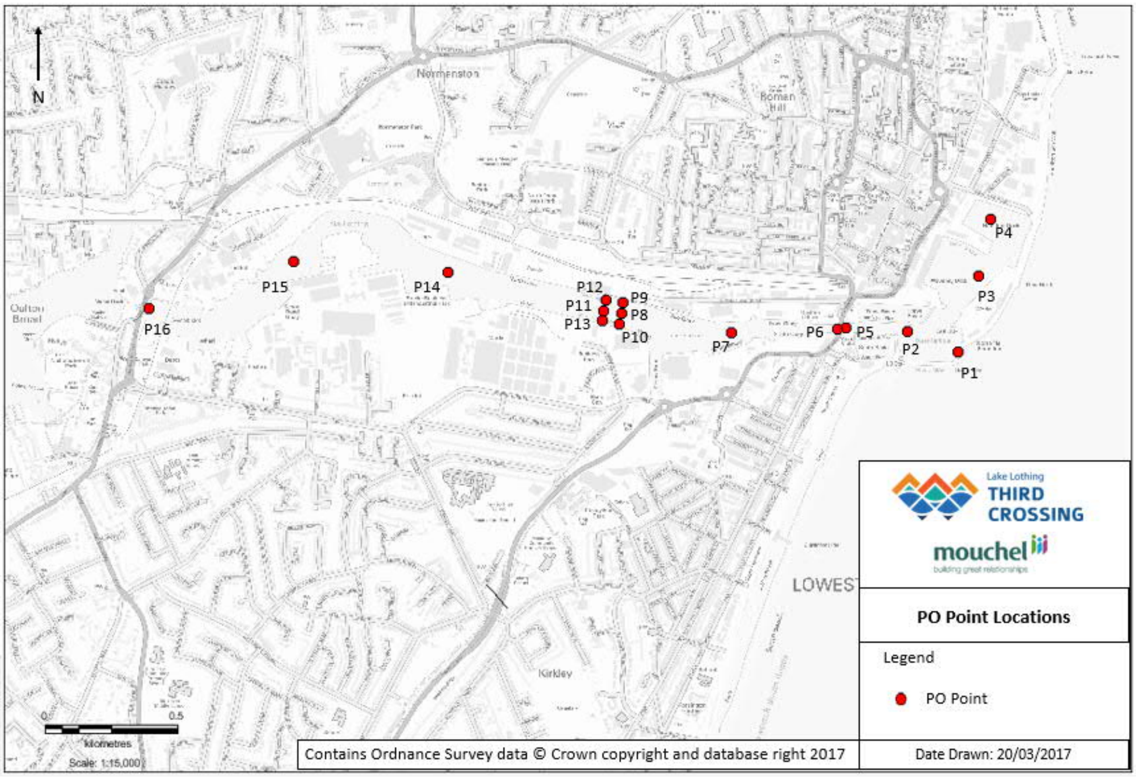


Figure 4-4 - Comparison points

Table 4-3 - Comparison point data

Point	Location	Easting	Northing
P1	Harbour entrance	655199	292617
P2	Outer harbour	655322	293120
P3	Outer harbour	655275	292908
P4	Outer harbour	655006	292695
P5	Downstream A47 Bridge	654776	292710
P6	Upstream A47 Bridge	654743	292707
P7	Lake Lothing – between A47 Bridge and third crossing location	654345	292693
P8	Eastern side of third crossing location	653929	292766
P9	Eastern side of third crossing location	653937	292805
P10	Eastern side of third crossing location	653924	292725
P11	Western side of third crossing location	653865	292776
P12	Western side of third crossing location	653870	292816
P13	Western side of third crossing location	653857	292739
P14	Lake Lothing between third crossing location and Mutford Lock	653276	292917
P15	Lake Lothing between third crossing location and Mutford Lock	652697	292960
P16	Downstream Mutford Lock	652151	292785

4.3.4 Table 4-4 shows the water level results for each sensitivity test rounded to the nearest 0.01m at each of the comparison points listed in Table 4-3 with the points either side of the Scheme highlighted in yellow. The results show that the tidal levels forced at the North Sea boundary have the largest impact on the modelled water levels. Lake Lothing is a tidally driven harbour and is very sensitive to changes in the tidal levels.

4.3.5 There are three fluvial inflows to Lake Lothing and hydrological analysis has been undertaken to define these within the model (Section 3.3). Figure 4-3 shows the locations of the river inflows, the influence of these on model results are tested in this sensitivity test. The precise location of the outfalls of catchment 1 and catchment 2 into Lake Lothing were unknown. As a result a location close to the grid reference at the downstream of each catchment as defined in FEH was chosen for the inflow location assuming the watercourses are culverted on their approach to Lake Lothing and discharge via a pipe.

4.3.6 The sensitivity testing shows that the fluvial inflows only have a small, localised impact on the water levels predicted by the model, this is as expected as the harbour is tidally driven. As the river inflows have a negligible impact on the water level, it has not been deemed necessary to include their representation in the final model developed for this assessment.

4.3.7 The impact of including representation of the railway bridge approximately 100m from the Mutford Bridge has been tested by including the structure in the model as a flow constriction unit. Elevation data was not available for the bridge, therefore levels were estimated based on photos and comparison with the Mutford Bridge. A conservative estimate of the flow constriction provided across the channel by the railway bridge was applied. The results in Table 4-4 show that including the bridge in the model has a negligible impact on the water levels predicted in Lake Lothing. Due to the negligible impact of including the railway bridge in the model, the bridge has not been represented in the model used for this assessment.

4.3.8 The sensitivity of the model to the roughness values applied across the 2D domain has been tested. Neither an increase nor a decrease of 20% in the roughness values causes a significant change to the water levels predicted in Lake Lothing by the model. As such, the roughness values presented in Table 4-1 based on different land uses are deemed appropriate.

4.3.9 The sensitivity testing has shown that the model is most sensitive to the tidal levels forced at the coastal boundary of the model. All of the other sensitivity tests produce negligible changes to the baseline model. Following the sensitivity testing, only one change was made to the baseline model as described in Section 4.2, the fluvial inflows were removed as they had a negligible impact on the model results. This improved model stability and slightly decreased the run time. As a result, the slight loss of functionality was deemed appropriate given the overall model improvement.

Table 4-4 - Sensitivity test results (Blue=decrease in water level compared to baseline, red=increase in water level compared to baseline)

Point	Model Predicted Water Level (mAOD)						
	Baseline	Increase Roughness	Decrease Roughness	Qmed	Rivers	Astronomical	Railway flow constriction
P1	3.26	3.25	3.26	3.25	3.25	1.65	3.26
P2	3.25	3.25	3.25	3.25	3.25	1.65	3.25
P3	3.26	3.26	3.26	3.26	3.26	1.65	3.26
P4	3.26	3.26	3.26	3.26	3.26	1.65	3.26
P5	3.20	3.20	3.20	3.20	3.21	1.65	3.21
P6	3.19	3.18	3.19	3.19	3.19	1.66	3.19
P7	3.20	3.20	3.20	3.20	3.21	1.66	3.21
P8	3.20	3.20	3.20	3.20	3.21	1.66	3.21
P9	3.20	3.20	3.20	3.20	3.21	1.66	3.21
P10	3.20	3.20	3.20	3.20	3.21	1.66	3.21
P11	3.20	3.20	3.20	3.20	3.21	1.66	3.21
P12	3.20	3.20	3.20	3.20	3.21	1.66	3.21
P13	3.20	3.20	3.20	3.20	3.21	1.66	3.21
P14	3.20	3.20	3.20	3.20	3.21	1.67	3.21
P15	3.19	3.19	3.19	3.19	3.20	1.67	3.20
P16	3.16	3.16	3.16	3.16	3.16	1.67	3.14

4.4 EA review

4.4.1 Once the draft model had been built, it was submitted for review to the EA in line with their recommendations. The EA recommended that two changes should be made to the model, these were using the stubby buildings method to represent buildings within the model and to reduce the cell size used from 10m to 5m.

4.4.2 The stubby buildings method includes raising the model grid at building footprints by 0.2m in order to simulate a threshold to the buildings. In the absence of survey of building thresholds within Lowestoft, it has been assumed that all buildings within the 2D domain have a threshold level 0.2m above ground level. This method allows for better representation of flow paths around buildings than using increased roughness values only to represent buildings. Buildings have also been assigned an increased roughness value to mimic the slowing of flow that would occur in a building once flood waters increase above the threshold level.

4.4.3 With the 10m resolution grid, the model runtimes are in the order of 4 hours and the model is stable. As such, the EA has recommended that the cell resolution is increased. Following an analysis, a 5m resolution has been used. This provides a balance between reasonable run times and model accuracy, especially in terms of modelling urban flow routes through Lowestoft.

4.4.4 The EA review questioned why wave overtopping was not included in the modelling undertaken for this assessment. Wave overtopping from the open coast has been considered but it was judged not to be critical in this assessment as the main flood risk to Lowestoft is tidal inundation. The Scheme itself is approximately 1km from the coastal boundary, therefore wave overtopping will not have an impact on the Scheme.

4.4.5 Wave overtopping is a residual uncertainty and it would only have an impact on flood levels on the floodplain when the coastal defences are not overtopped by the tidal levels. However it should also be noted that at lower water levels, the arrangement of the harbour entrance prevents significant transmission of waves into Lake Lothing. Once the defences are overtopped, wave action has less of an impact than when water levels are below the height of the defences. Wave overtopping is judged to be a small residual uncertainty and sensitivity testing of the tidal boundary has shown that the peak tidal level has the greatest impact on the maximum flood levels predicted for each return period event. The impact of wave overtopping is expected to be less than the impact of the parameters tested in the sensitivity assessment. Therefore a precautionary uncertainty approach has been taken by modelling the peak tidal water level for each return period event, our calculations to define the tidal boundaries used within the model do include an allowance for storm surge as recommended in the coastal flood boundary conditions for UK mainland and islands SC060064/TR4: Practical Guidance design sea levels.

4.4.6 The EA recommended the use of the Open Coast (CFBD) Flood Risk Study to define ESLs. This is the most up to date ESL dataset and has recently been adopted by the EA. The ESLs calculated by this study have been used in this assessment as discussed in Section 3.2.

4.5 Model Stability

4.5.1 For the purposes of measuring the stability of the model, the 0.5% AEP climate change event was chosen. Cumulative mass balance within the model has been checked in order to understand the stability of the model. Typically for a stable simulation a value of ±1% is expected, however in some circumstances values slightly outside of this range may be acceptable.

4.5.2 The cumulative mass balance percentage throughout the 0.5% AEP climate change event is shown in Figure 4-5. The maximum value is 0.7% which shows the model is stable especially for a tidal model with very large inflows and sudden changes in water volume within the model due to the tidal cycles.

4.5.3 The total volume of water (Figure 4-6) entering the model is similar to the total volume out, this gives confidence that the boundary outflows on Oulton Broad and Kirkley Stream are functioning correctly by removing any excess water and preventing unrealistic pooling at the model boundaries.

4.5.4 During the 0.5% AEP climate change event, there were nine warnings during simulation relating to negative depths. These have not caused any model stability issues or anomalous results and are therefore deemed acceptable.

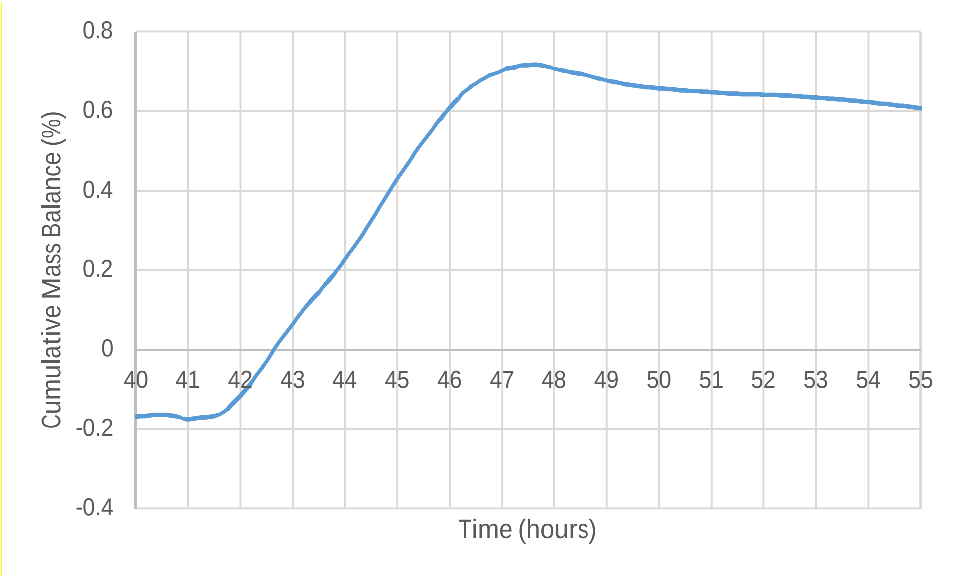


Figure 4-5 – Cumulative Mass balance for the baseline 0.5% AEP climate change event

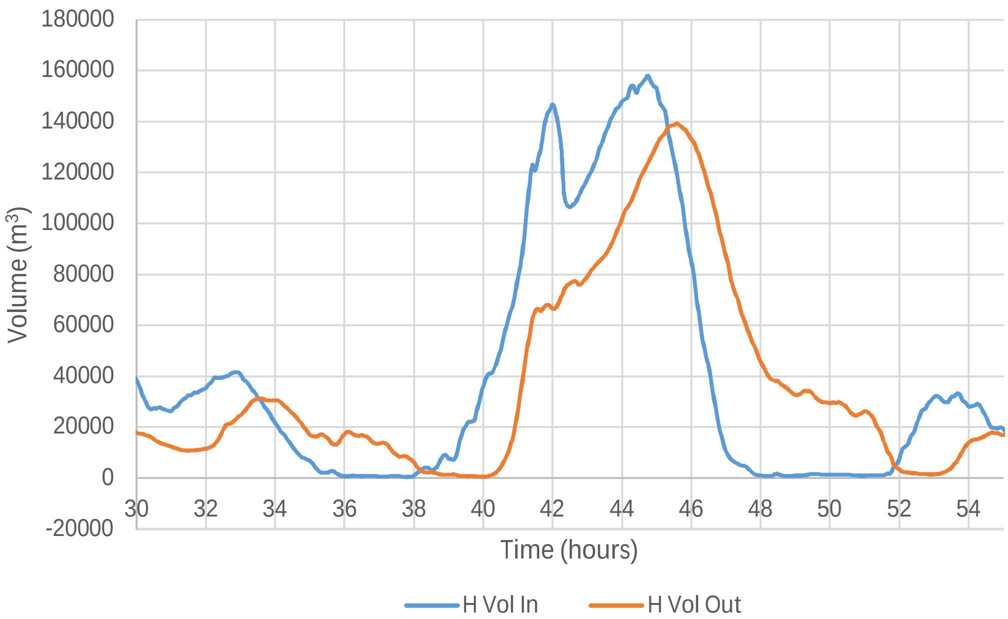


Figure 4-6 - Volume in and out for the 0.5% AEP climate change baseline simulation

4.6 Model Verification

4.6.1 Following the model build and sensitivity testing, verification of the baseline model was undertaken using observations of past flood events and EA flood maps. It was not possible to calibrate the model as there is only one level gauge within Lake Lothing and this has been used to define the tidal boundary for the verification model run. As Oulton Broad is not represented in the baseline model and levels here are driven by tidal levels at Great Yarmouth via the River Waveney as well as Lowestoft, the level gauge on Oulton Broad could not be used to calibrate the model.

4.6.2 The event chosen for model verification was the 2013 tidal surge event in Lowestoft between the 5th and 6th December. The event caused widespread flooding due to a tidal surge in the North Sea. The surge, combined with the high tide tracked down the east coast of England causing damage to properties near the coastline. Due to the size of the 2013 event and as it occurred relatively recently, there is a good amount of data and anecdotal evidence for the flood event.

4.6.3 The level data provided by the EA for this assessment at the Lowestoft gauge is daily averaged levels, therefore the NTSLF website was checked and showed that the peak high tidal level was approximately 4.75m CD (3.25mAOD) during the 2013 event. Figure 4-7 shows the NTSLF gauge data at the time of the 2013 tidal surge event. The graph shows the water depths in chart datum. The conversion to mAOD from chart datum in Lowestoft is -1.5m. On the chart the red line represents the predicted tidal curve and the blue dots represent the recorded data at the gauge site.

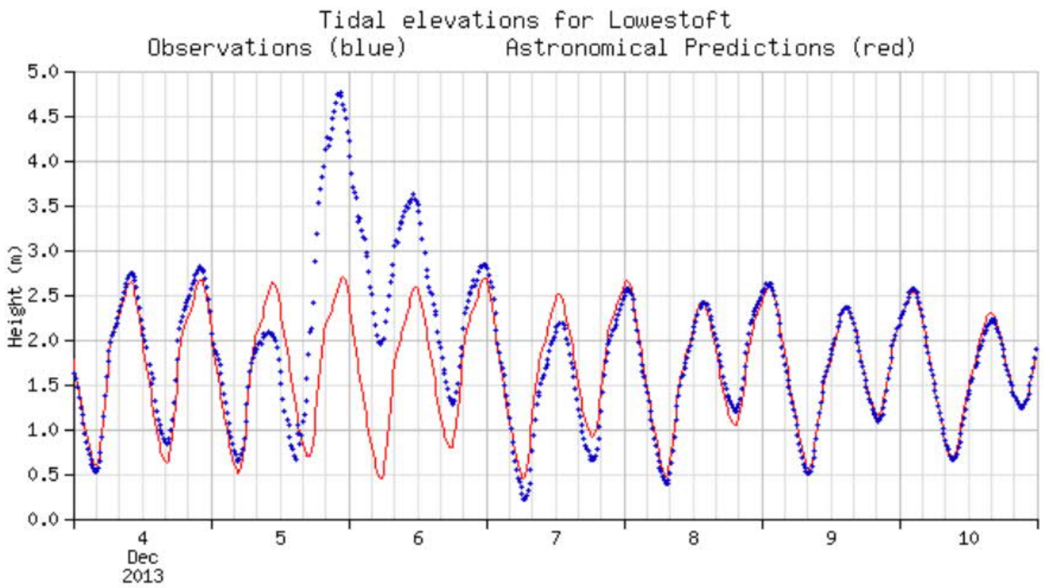


Figure 4-7 - Levels (mCD) at Lowestoft Gauge. (National Tidal and Sea Level Facility website, extracted 2016)

4.6.4 Figure 4-8 shows the tidal curve derived in CD for the 2013 event used in the model to simulate the 2013 event. The curve was initially created by scaling each peak of the astronomical tide to the corresponding peak in the NTSLF data set. Further scaling was required to simulate the 2013 event in the model to ensure the recorded water level of 3.25mAOD at the gauge site was achieved. For the tidal boundary in the model, the curve shown in Figure 4-9 was converted to mAOD as discussed in section 2.3. The tidal curve simulated at the eastern tidal boundary of the model was scaled to a peak of 3.35mAOD for the verification run as this ensured that the level of 3.25mAOD was achieved at the gauge site within the model. With the tidal inflow scaled to a peak of 3.25mAOD, the water level at the gauge site (on the eastern side of the A47 Bascule Bridge) was predicted to be too low compared to the level recorded during the 2013 event.

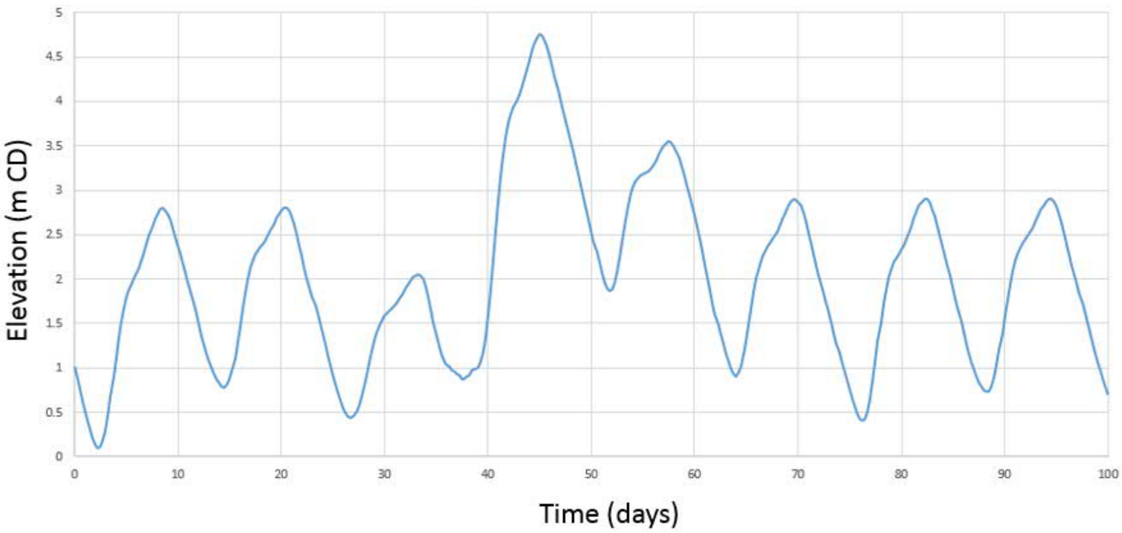


Figure 4-8 - 2013 event tidal curve

4.6.5 The EA maintains a historic flood map for the UK showing the extent of previous flood events across the country. The historic flood map represents the 'considered and accepted' flood outlines from 1946 onwards based on anecdotal evidence, it should be noted that not every flood event that has occurred since 1946 is included in the dataset. The absence of coverage by the historic flood map does not mean an area has not flooded previously, nor does it mean it will not flood in the future. No further information other than the flood outline is provided. The two largest flood events at Lowestoft since 1946 occurred in 1953 and 2013, therefore it is assumed that the historic flood map provides the flood extent from either one of these events or is a combination of both.

4.6.6 The results of the model verification run were compared to the historic flood map as shown on Figure 4-9. Overall, there is good agreement between the predicted flood extent for the 2013 event and the historic flood map. The historic flood map does not appear to show the full extent of flooding for such a large event. The flood extent predicted by the model in the outer harbour and along the north quay match well with the historic flood map.

4.6.7 At Leathes' Ham, area 1 shown on Figure 4-9 to the north of Lake Lothing, the model predicts flooding that is not shown on the historic flood map. Leathes' Ham is a natural flood basin and this potentially explains why it is not included in the historic flood map. Similarly, the flood extent along the Kirkley Stream channel (area 2 on Figure 4-9) may not be shown on the historic flood map because this is considered part of the river. The area between Kirkley Ham and the A47 Bascule Bridge (area 3 on Figure 4-9) shows flooding in the historic flood map that is not replicated in the model results. The elevations of the LiDAR and harbour walls have been checked and show that the area is predominately above the tidal level recorded at the gauge site for the 2013 event. The historic flood map may represent the 1953 event in this area, during that time a ship yard was positioned on this corner with a slipway and significantly lower harbour walls which would result in increased flooding at this location.

4.6.8 There is an area of flooding in the historic flood map along the coastline to the south of the harbour entrance (area 4 on Figure 4-9) that is not predicted to flood during the model verification event. The coastal wall which was present in 2013 is higher than the peak tidal level for the 2013 event this suggests that any flooding in this area was potentially from a different flood source or the flooding shown on the historic flood map occurred during the 1953 event and the current defences were not in place at that time. Further information was provided by the EA during the consultation process that stated that the 2013 flooding did not solely occur because of overtopping from Lake Lothing. It was found that water was able to flow through a broken tidal flap on one of the outfalls into Lake Lothing and this may explain why the modelled flood extent differs from the historic flood outline.

4.6.9 The model predicts more flooding near to Mutford Bridge (area 5 shown on Figure 4-9) than is shown on the historic flood map. One explanation for this could be that part of the area is park land and it is unlikely that there would be much information on flooding in this location during a flood event.

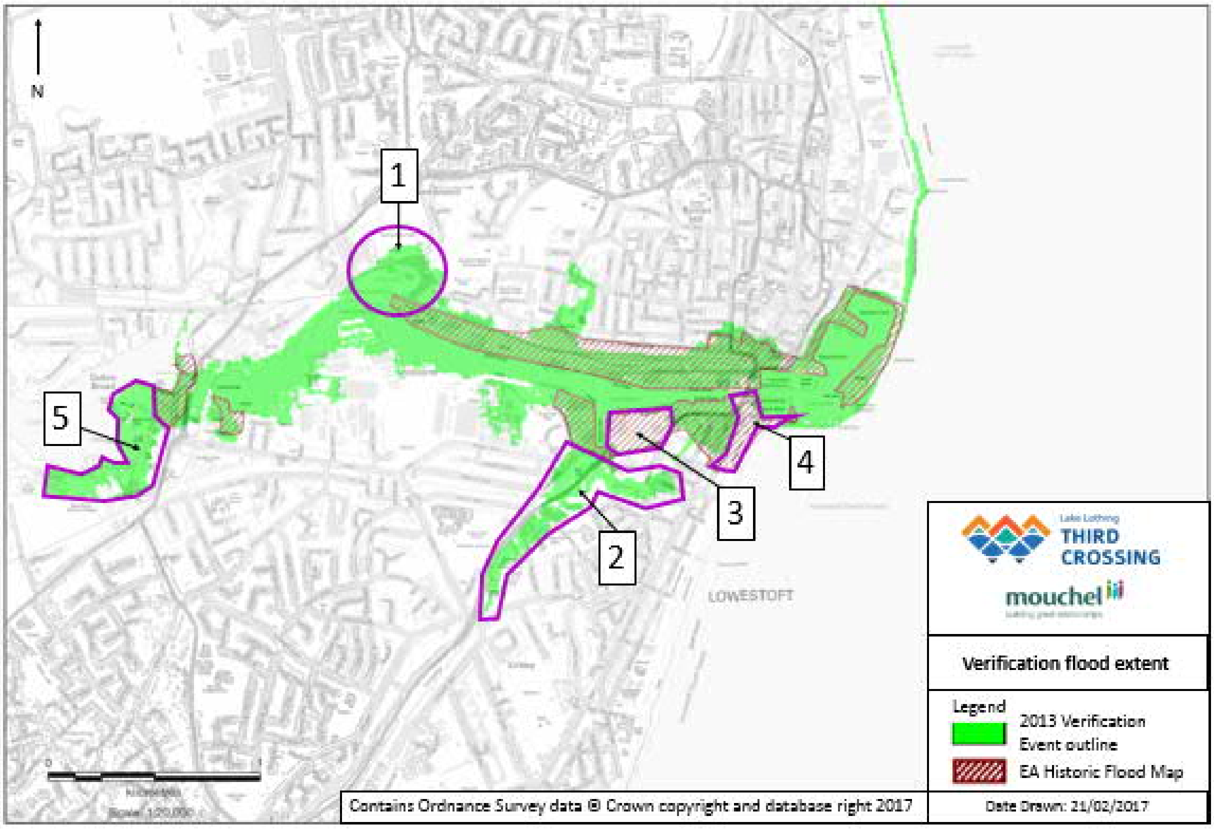


Figure 4-9 - Verification event flood extent compared to historic flood map

4.6.10 Following the flooding event in 2013, the EA collected photographs which have been made available for use in this model verification process. The photos are taken at a number of locations where flooding was evident. The depth of flood water at each photograph location has been estimated by the EA. The water depths can only be used as a guide because the water has not been measured explicitly during the event therefore there is a possibility that the measure does not show the exact depth and it is not known whether the photographs were taken at the peak of the flood event. The dataset has been deemed sufficient for use in this verification process, although it should be noted that modelled flood depths are unlikely to exactly match those estimated..

4.6.11 Figure 4-10 shows the modelled flood extent and the 2013 estimated flood extent as recorded by the EA on the south side of Lake Lothing along the A12 near St Johns Road. The EA recorded flood extent shows areas where flooding was witnessed and the modelled flood extent includes all of these areas. Figure 4-10 includes the predicted water depths from the model and the site estimated depth for the 2013 event at each photograph location. In most cases the model predicts the water depths across the area well, differences between modelled depths and recorded depths are as little at 0.05m at two locations (points 3 and 5). Points 1, 4 and 6 show differences of up to 0.2m. This has been considered reasonable in a tidal model of this size. One reason for the differences could be local elevation differences that are not picked up in the LiDAR data used to represent the floodplain in the model. At point 2, the model shows a predicted water depth of 1.09m, this is approximately 0.51m higher than the water depth estimated from the photograph in this location. The photograph at point 2 shows a chain link fence and the flood depth measurement is taken to a patch of debris caught in the fence. It is possible that the peak flood level was greater and no evidence was found of a higher water level. Another possible explanation for the difference is a local high spot in the topography that the LiDAR does not pick up. It should be noted that the estimated flood depth at point 2 appears low compared to the rest of the levels estimated across the floodplain.

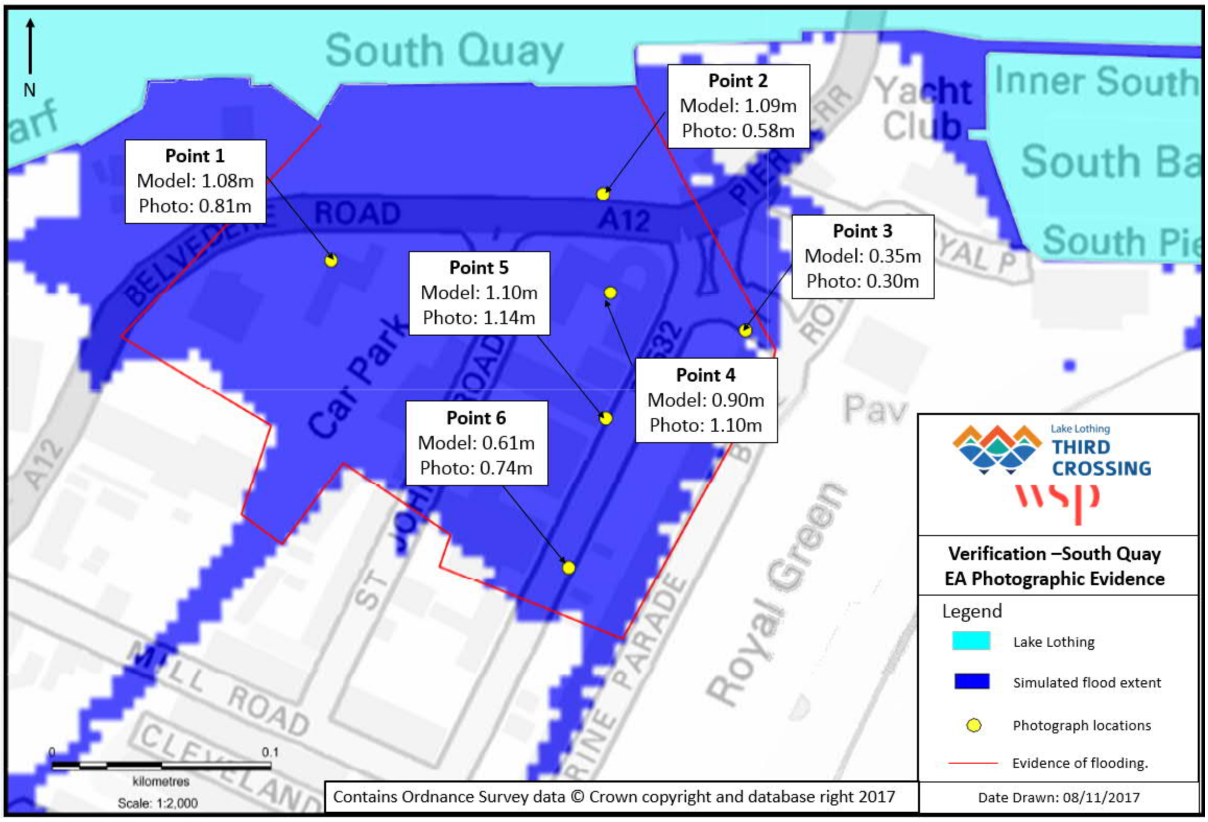


Figure 4-10 - South quay verification points

4.6.12 Figure 4-11 shows the modelled flood extent and the 2013 estimated flood extent as recorded by the EA on the north side of Lake Lothing in Lowestoft town centre. The modelled flood extent mostly matches the EA observed flood extent, although there are some areas where the modelled flood extent does not extend as far as the observed flood event. A reason for the differences may be that local flow patterns are not represented within the model resolution, however the difference in flood extent can be considered small and overall the model predicts the flood extent well. The depths taken from the photographs on the north side of Lake Lothing (shown on Figure 4-11) differ from the model predicted flood depths by approximately 0.2 metres. This is considered a good fit when considering the total water depth through the area during the 2013 event.

4.6.13 Although it has not been possible to calibrate the hydraulic model developed for this assessment, the sensitivity testing and model verification procedure undertaken have shown that the model results are realistic and can be considered robust for the purpose of assessing the flood risk associated with the Scheme.

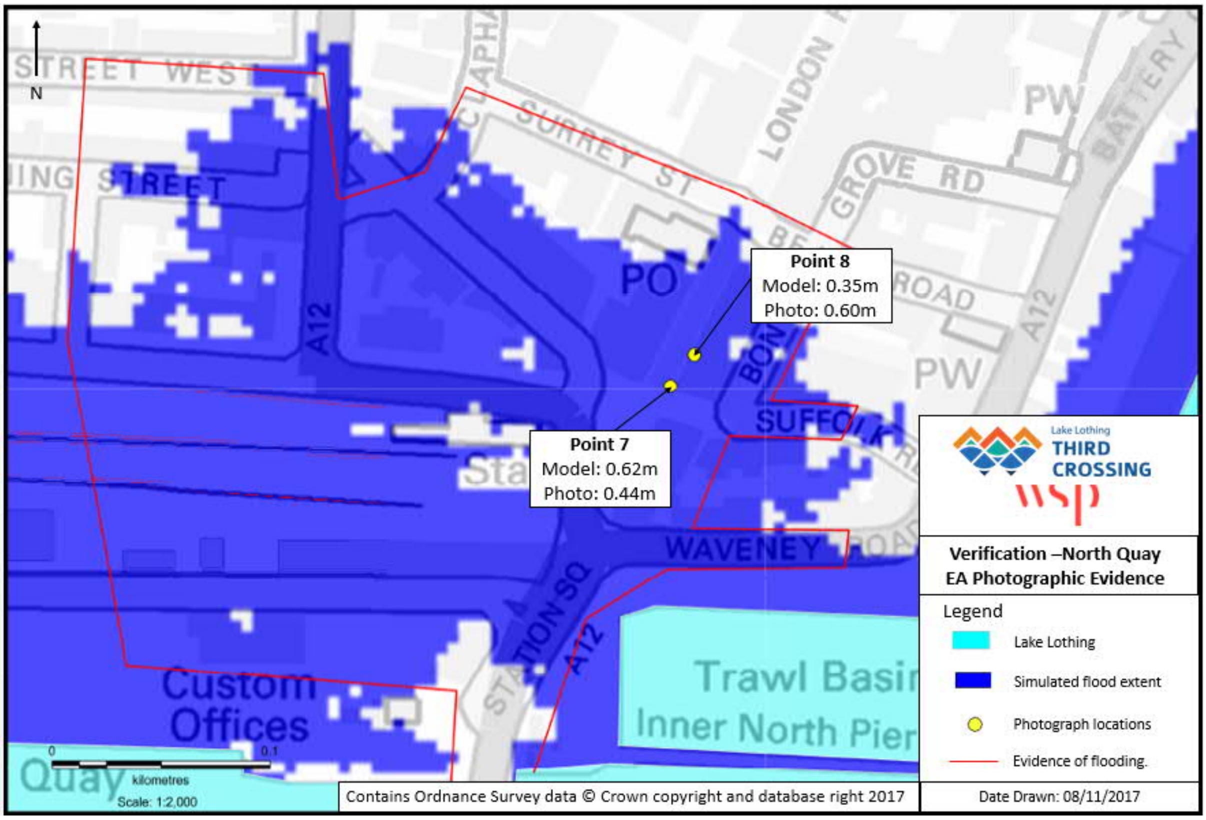


Figure 4-11 - Lowestoft centre (north quay) verification points

5 Hydraulic Modelling Results

5.1 Model Runs

5.1.1 A total of 21 model runs have been undertaken as part of this assessment. Three return periods have been simulated in the present day and two climate change scenarios for the Baseline and Scheme scenarios. Additional model runs have been undertaken for the 0.5% AEP event to understand the impact of the Scheme if the bridge piers were 50% larger than the current design. As explained in 4.2.14, a 10% blockage of the total cross-sectional area underneath the bridge deck has been used to represent the bridge piers for the Scheme scenario. A 'Scheme Worst Case' scenario has been developed whereby a 15% blockage of the total cross-sectional area underneath the bridge deck was applied to represent a reasonable worst case scenario if the bridge piers were increased in size by approximately 150%. Table 5-1 shows all the model runs that have been undertaken as part of this assessment.

Table 5-1 - Model Simulations

Scenario	Return Period	Present Day 2017	Climate Change 2140	H++ (UKCP09 high risk, low probability scenario)
Baseline	5% AEP	Lowestoft_baseline_20	Lowestoft_baseline_20cc	Lowestoft_baseline_20cc+
	0.5% AEP	Lowestoft_baseline_200	Lowestoft_baseline_200cc	Lowestoft_baseline_200cc+
	0.1% AEP	Lowestoft_baseline_1000	Lowestoft_baseline_1000cc	Lowestoft_baseline_1000cc+
Scheme	5% AEP	Lowestoft_scheme_20	Lowestoft_scheme_20cc	Lowestoft_scheme_20cc+
	0.5% AEP	Lowestoft_scheme_200	Lowestoft_scheme_200cc	Lowestoft_scheme_200cc+
	0.1% AEP	Lowestoft_scheme_1000	Lowestoft_scheme_1000cc	Lowestoft_scheme_1000cc+
Scheme Worst Case (limits of deviation sensitivity test)	0.5% AEP	Lowestoft_scheme_worst_case_200	Lowestoft_scheme_worst_case_200cc	Lowestoft_scheme_worst_case_200cc+

5.2 Baseline Results

5.2.1 Figure 5-1 shows the flood extents predicted by the model for the present day baseline scenario. The results show that parts of Lowestoft are at risk during a 5% AEP event, particularly near to Oulton Broad and there is a small amount of flooding predicted immediately west of the A47 Bascule Bridge. The predicted flooding to Lowestoft during the 0.5% AEP is larger than that shown for the 5% AEP event with the majority of the north bank of Lake Lothing flooded and a large area to the south also flooded. As expected the 0.1% AEP event shows an even larger extent of flooding with a large area to the south of Lake Lothing additionally flooded in this scenario compared to the 0.5% AEP event.

5.2.2 The predicted flood extents in the baseline scenario with the climate change allowances added are significantly increased for the 5% AEP and 0.5% AEP events and are similar in extent to the present day 0.1% AEP event outline. The 0.1% AEP climate change event outline is only slightly larger than the present day outline. For the H++ scenario, all of the design events modelled show a significant increase in flood extent. The flood maps for the climate change and H++ scenarios are provided in Section 7.4 – Supporting Documents.

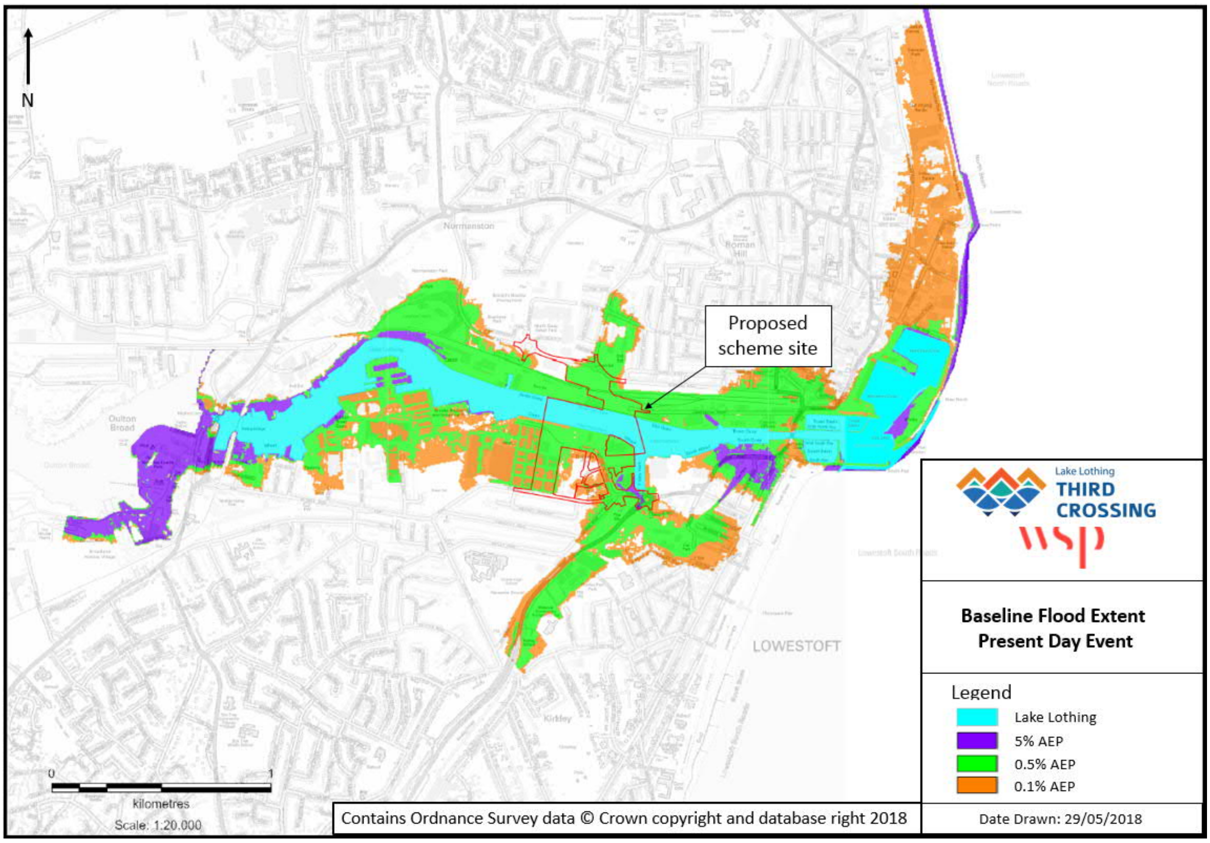


Figure 5-1 - Baseline present day design flood extent

5.3 Scheme Results

5.3.1 The results of the model runs representing the Scheme scenario have been compared to the baseline model results for each simulation. In order to assess the impact of the Scheme on flood risk, water levels predicted for the different model runs have been compared at the comparison points shown on Figure 4-4. For the 0.5% AEP event, the Scheme Worst Case scenario results have also been compared to the Scheme scenario results to determine the impact of increasing the pier sizes underneath the bridge deck.

Present Day Events

5.3.2 Table 5-2 shows the baseline and post-development water levels predicted by the model in Lake Lothing for the present day scenario at each of the comparison points on Figure 4-4 (highlighted points are those closest to the Scheme). The results in Table 5-2 shown that within Lake Lothing, the Scheme has a minimal impact on peak water levels for the present day scenario. There is no change in water levels predicted within Lake Lothing with the Scheme in place during the 5% AEP present day event. For the 0.5% AEP present day event, no increase in water levels within Lake Lothing is predicted, there is a decrease in water levels predicted to the west of the Scheme. During the 0.1% AEP event, there is an increase (up to 0.01m) in water levels on the eastern side of the new bridge and a slight decrease in water levels on the western side (up to 0.03m). There is no increase in predicted water levels for the 0.5% AEP present day event for the Scheme Worst Case scenario compared to the Scheme scenario.

5.3.3 It is also necessary to assess the impact of the Scheme on water levels on the floodplain. For the 5% AEP present day event, there is no change in flood levels on the floodplain between the baseline and Scheme scenarios. For the 0.5% AEP present day event (Figure 5-2) an increase in water level (up to 0.01m) compared to the baseline is predicted on the floodplain to the east of the Scheme and there is a decrease in water levels of up to 0.06m to the west of the Scheme. During the 0.1% AEP present day an increase of up to 0.02m is predicted across the floodplain on the eastern side of the Scheme. There is a small anomaly within the model results for this event where an increase of 0.06m is predicted in the Scheme scenario compared to the baseline but this covers a small number of cells within the model and corresponds with a low point in the LiDAR within the carpark of Asda and Dunelm near the A12.

Table 5-2 – Present Day 2017 Hydraulic Modelling Results

Present Day	Baseline (mAOD)			Difference (Proposed – Baseline (m)		
Point	5%	0.5%	0.1%	5%	0.5%	0.1%
P1	2.74	3.39	3.91	0.00	0.00	0.00
P2	2.74	3.39	3.90	0.00	0.00	0.00
P3	2.74	3.39	3.91	0.00	0.00	0.01
P4	2.74	3.39	3.91	0.00	0.00	0.00
P5	2.73	3.35	3.82	0.00	0.00	0.01
P6	2.73	3.33	3.77	0.00	0.00	0.00
P7	2.74	3.34	3.76	0.00	0.00	0.01
P8	2.74	3.34	3.76	0.00	0.00	0.01
P9	2.74	3.34	3.76	0.00	0.00	0.01
P10	2.74	3.34	3.76	0.00	0.00	0.01
P11	2.74	3.34	3.76	0.00	-0.02	-0.03
P12	2.74	3.34	3.76	0.00	-0.02	-0.03
P13	2.74	3.34	3.76	0.00	-0.02	-0.02
P14	2.74	3.34	3.76	0.00	-0.02	-0.03
P15	2.74	3.32	3.73	0.00	-0.02	-0.03
P16	2.73	3.28	3.63	0.00	-0.02	-0.03

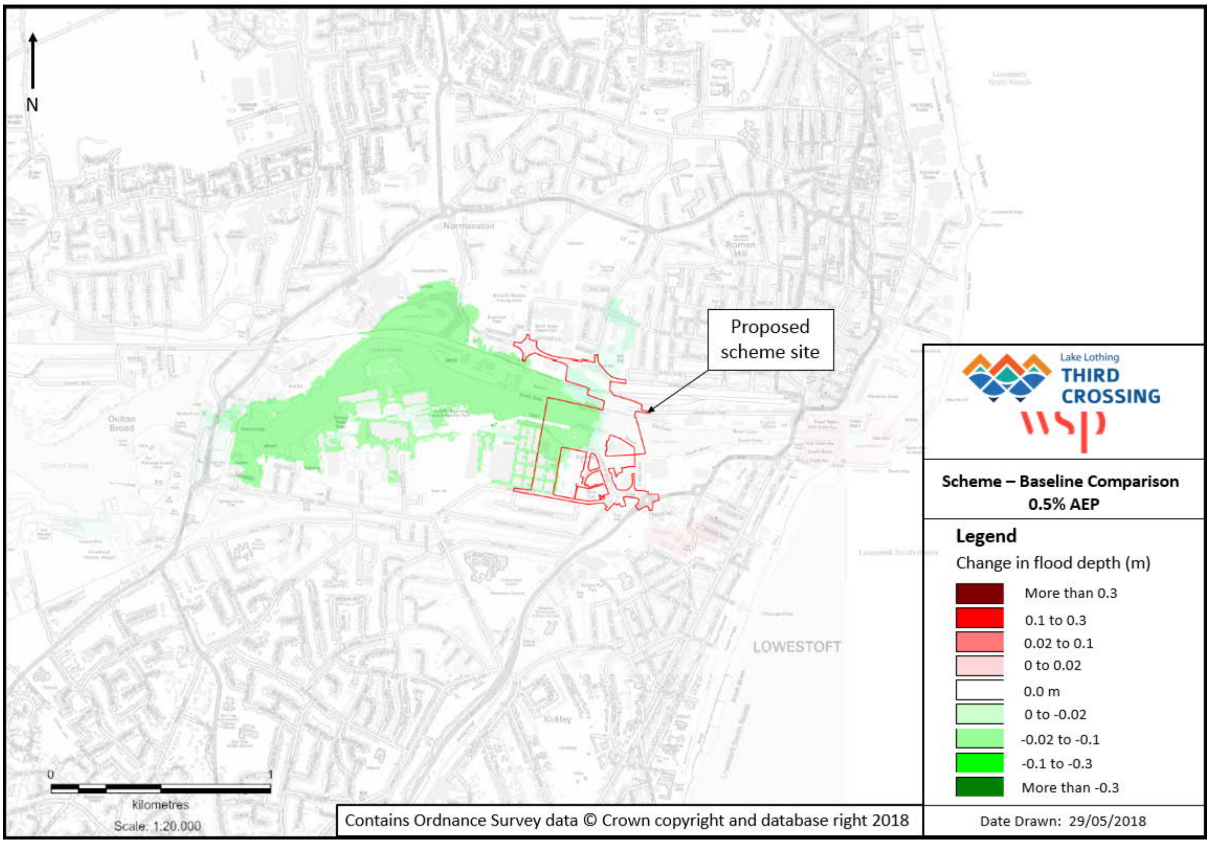


Figure 5-2 - Scheme - Baseline comparison for 0.5% AEP present day design event

Climate Change Events

5.3.4 Table 5-3 shows the peak water levels predicted by the model in the baseline and Scheme scenarios at the comparison points within Lake Lothing (Figure 4-4) for the climate change events modelled (highlighted points are those closest to the Scheme). For both the 5% and 0.5% AEP climate change events, there is an increase of up to 0.02m in water levels predicted within Lake Lothing with the Scheme in place on the eastern side of the bridge. A decrease in water levels within Lake Lothing is predicted to the west of the Scheme for both the 5% and 0.5% AEP climate change events. The Scheme has a greater impact during the climate change events due to the higher tidal levels for these events compared to the present day events. The tidal levels during all of the climate change events are high enough for a small head loss to be generated across the bridge in the Scheme model. There is no increase in predicted water levels for the 0.5% AEP climate change event for the Scheme Worst Case scenario compared to the Scheme scenario.

5.3.5 For the 5% AEP climate change event, water levels on the floodplain to the east of the Scheme are predicted to increase by up to 0.02m with the Scheme in place compared to the baseline scenario. To the west of the Scheme, decreases of up to 0.04m are predicted compare to the baseline scenario. In the 0.5% AEP climate change event (Figure 5-3) floodplain water levels are predicted to increase by up to 0.02m to the east of the Scheme above the baseline scenario and water levels are predicted to decrease by up to 0.06m to the west of the Scheme. The 0.1% AEP plus climate change events shows water level increases of up to 0.05m on the floodplain in the Scheme scenario. Predicted water levels to the west of the Scheme decrease by up to 0.08m during the 0.1% AEP Scheme scenario. Figure 5-3 shows at the Kirkley Stream boundary, the water levels predicted for the Scheme scenario in this location are up to 0.02m higher than the water levels predicted for the baseline scenario. This is a negligible increase and there is no increase in flood extent near to the Kirkley Stream boundary, therefore explicit simulation of the impacts further upstream within the Kirkley Stream catchment was not deemed necessary for this assessment.

Table 5-3 – Climate Change 2140 Hydraulic Modelling Results

Climate Change	Baseline (mAOD)			Difference (Proposed – Baseline (m)		
Point	5%	0.5%	0.1%	5%	0.5%	0.1%
P1	4.27	4.93	5.45	0.00	0.00	0.00
P2	4.26	4.92	5.44	0.00	0.00	0.00
P3	4.27	4.93	5.45	0.00	0.00	0.00
P4	4.27	4.93	5.46	0.00	0.00	0.00
P5	4.16	4.75	5.25	0.01	0.01	0.01
P6	4.05	4.63	5.11	0.01	0.01	0.02
P7	4.03	4.56	5.01	0.01	0.02	0.02
P8	4.03	4.57	5.01	0.02	0.02	0.04
P9	4.03	4.57	5.01	0.01	0.02	0.03
P10	4.03	4.58	5.01	0.02	0.02	0.04
P11	4.03	4.57	5.01	-0.03	-0.04	-0.04
P12	4.03	4.58	5.01	-0.03	-0.04	-0.05
P13	4.03	4.57	5.01	-0.03	-0.04	-0.04
P14	4.03	4.57	5.01	-0.04	-0.06	-0.07
P15	3.99	4.52	4.95	-0.04	-0.05	-0.07
P16	3.84	4.27	4.58	-0.03	-0.04	-0.05

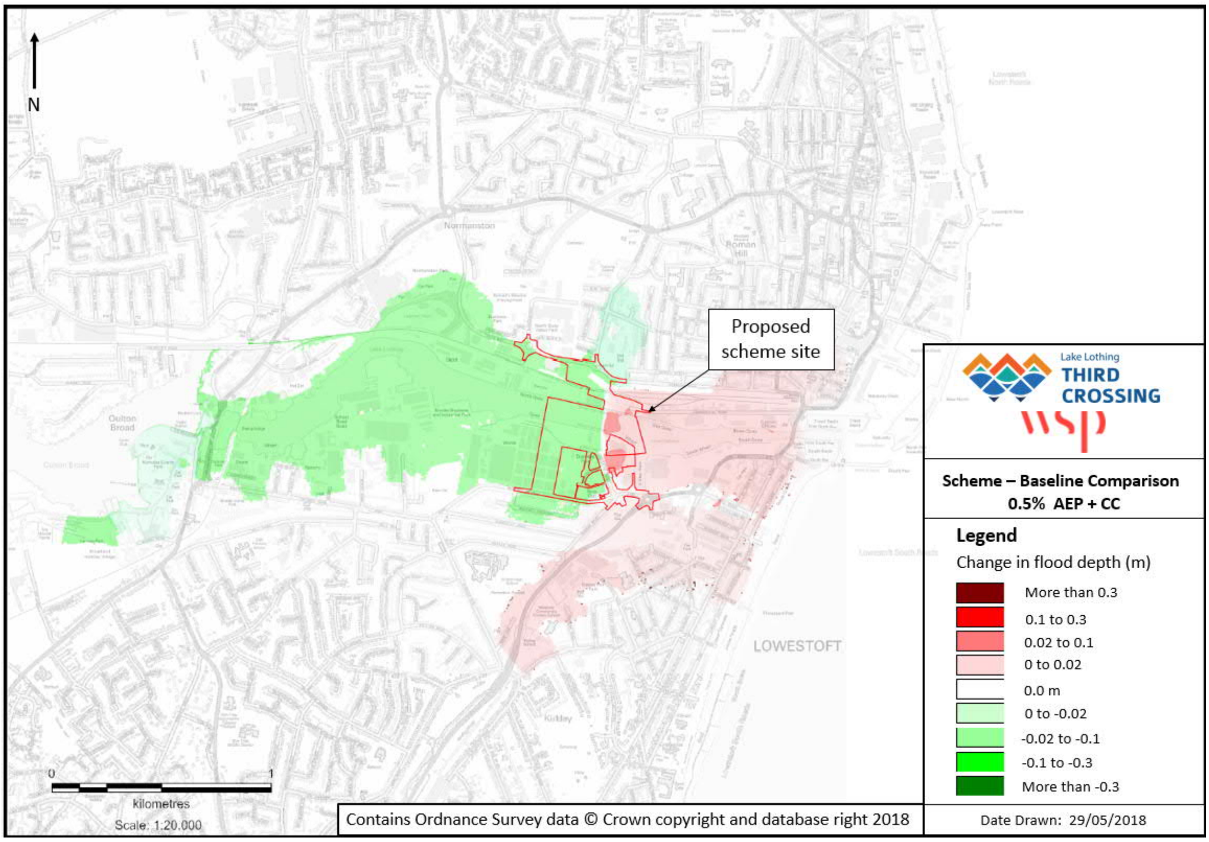


Figure 5-3 - Scheme - Baseline comparison for 0.5% AEP climate change event

5.3.6 Table 5-4 shows the peak water levels predicted by the model in the baseline and Scheme scenarios at the comparison points within Lake Lothing (Figure 4-4) for the H++ events modelled (highlighted points are those closest to the Scheme). The Scheme is predicted to have a greater impact on water levels within Lake Lothing during the H++ events due to significantly increased tidal levels. An increase in water levels in Lake Lothing with the Scheme in place is predicted for each event modelled. The maximum increase in water levels predicted within Lake Lothing is 0.14m during the 0.1% H++ event. In the Scheme Worst Case scenario, there is an increase of 0.01m in the predicted flood level at comparison point 4 in the outer harbour compared to the Scheme scenario. To the west of the Scheme, the Scheme Worst Case scenario actually shows 0.01m lower water levels than the Scheme scenario due to increased blockage at the new bridge location. The increase in blockage underneath the bridge deck (from 10% to 15%) between the Scheme and Scheme Worst Case scenario has a negligible impact on the model results even in the 0.5 % AEP H++ event and the only negative impact is shown within the outer harbour.

5.3.7 On the floodplain for the 5% AEP H++ event, water levels are predicted to increase up to 0.09m. There are areas where the water level has decreased by 0.1m to the west of the Scheme. The predicted increases in water level on the floodplain for the 0.5% AEP H++ event (Figure 5-4) are up to 0.1m and decreases of up to 0.1m are predicted to the west of the Scheme. The 0.1% AEP H++ event shows an increase of up to a 0.14m in predicted water depths on the floodplain. There are decreases of up to 0.16m predicted to the west of the Scheme during the 0.1% AEP H++ event.

Table 5-4 - H++ Scenario Hydraulic Modelling Results

H++	Baseline (mAOD)			Difference (Proposed – Baseline (m)		
Point	5%	0.5%	0.1%	5%	0.5%	0.1%
P1	5.83	6.51	7.06	0.00	0.00	0.01
P2	5.82	6.49	7.02	0.00	0.00	0.00
P3	5.83	6.52	7.06	0.00	0.00	0.00
P4	5.85	6.57	7.04	0.00	0.00	0.00
P5	5.67	6.32	6.85	0.01	0.01	0.02
P6	5.56	6.20	6.71	0.02	0.02	0.03
P7	5.40	5.96	6.40	0.03	0.04	0.06
P8	5.40	5.95	6.38	0.05	0.08	0.10
P9	5.40	5.95	6.38	0.04	0.06	0.08
P10	5.40	5.95	6.39	0.06	0.11	0.14
P11	5.40	5.95	6.38	-0.07	-0.06	-0.07
P12	5.40	5.95	6.38	-0.07	-0.06	-0.07
P13	5.40	5.95	6.38	-0.07	-0.05	-0.07
P14	5.40	5.94	6.37	-0.10	-0.11	-0.13
P15	5.33	5.85	6.25	-0.10	-0.10	-0.13
P16	4.85	5.22	5.49	-0.07	-0.07	-0.08

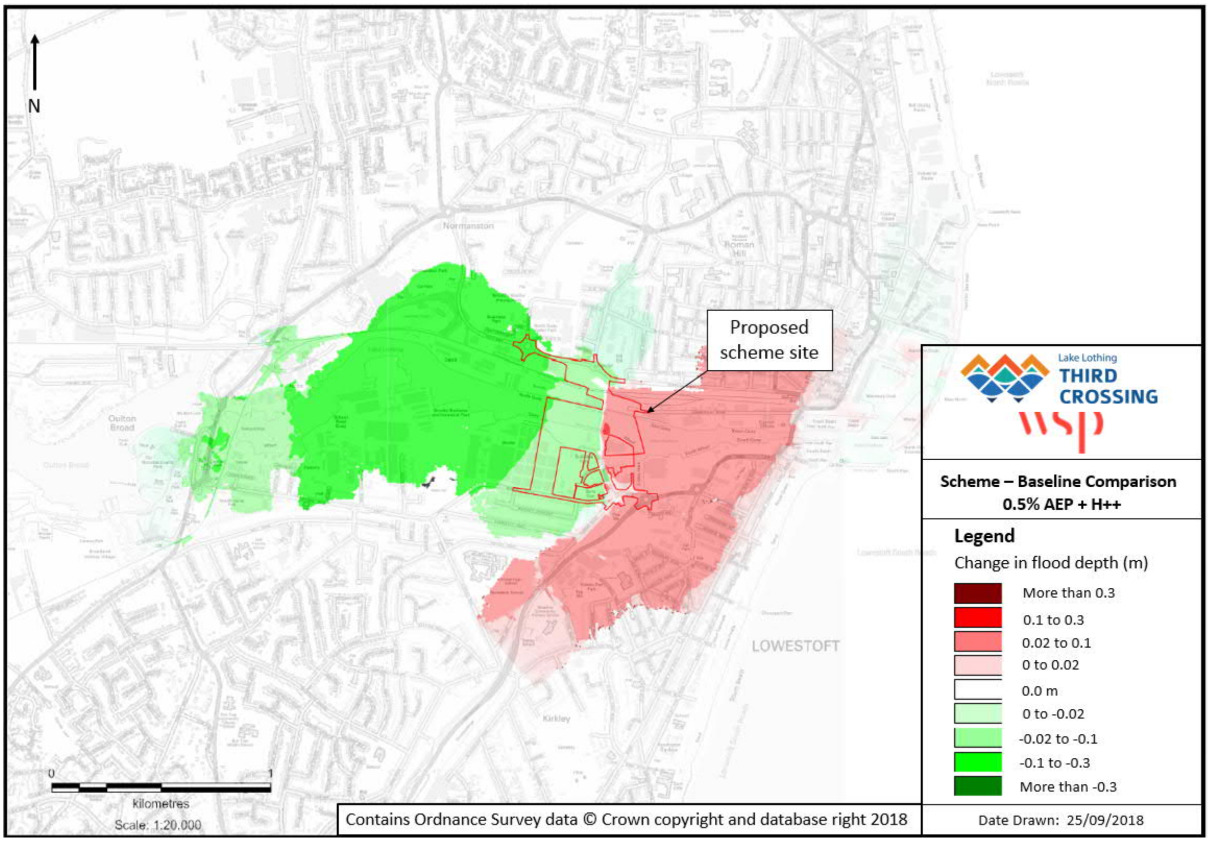


Figure 5-4 - Scheme - Baseline comparison for 0.5% AEP H++ event.

5.3.8 In conclusion, the results from the model have been found to be reasonable. The floodplain extents are in the expected range, this shows the model domain is acting as expected for each return period. The simulated water depths and impacts increase as the event increases. In the Scheme scenario, the water depths increase to the east and decrease to the west of the Scheme. This is as expected because the bridge creates a flow constriction leading to energy losses and afflux at the structure. The impacts are shown to be higher closer to the Scheme location, this is expected when simulating a bridge in a watercourse. The level of impact is relatively low compared to the tidal level, this is expected because the design of the Scheme has been developed to cause the minimum amount of impact on water levels. The model results have been assessed and considered suitable for use in the FRA for the Scheme.

6 Summary

6.1.1 A 2D hydraulic model of Lake Lothing and the outer harbour has been developed to assess the risk of flooding to the Scheme and the impact of the Scheme on flood risk elsewhere. It was necessary to develop a model as part of the FRA for the Scheme as the order limits are within Flood Zone 3.

6.1.2 A large amount of data was collected and reviewed for use in this study. A key part of the data review process was a review of the existing hydraulic model of Lake Lothing and the outer harbour provided by CH2M Hill on behalf of WDC for use in this assessment. The outcome of the model review was that, as the existing model was developed for a different purpose, it was necessary to develop a separate model for this assessment. The focus of this assessment is the local hydraulic effects of the Scheme, therefore there is a need to use the most recent and accurate data, particularly close to the Scheme site. The CH2M Hill model was developed for a different purpose and is still valid but it is necessary to refine and incorporate more detail into the model developed for this assessment to determine the impacts of the Scheme on the hydraulics within Lake Lothing.

6.1.3 The hydrology of Lake Lothing has been analysed and the EA have specified the design events and climate change scenarios to be considered in this study. Tidal levels have been derived to define the eastern boundary of the hydraulic model that represents sea levels along the Lowestoft coast. EA guidance on estimating design sea levels has been used to derive the tidal boundary used in the model. Fluvial flows have been calculated on the three watercourses that discharge into Lake Lothing to allow the fluvial inputs to be included in the hydraulic model. Fluvial inflows to the model have been estimated following the EA Flood Estimation Guidelines. However, sensitivity testing later showed that it was not necessary to include the fluvial flows in the hydraulic model developed for this assessment as the main flood risk to Lowestoft is tidal.

6.1.4 A 2D model of Lake Lothing and the outer harbour has been developed for this assessment, baseline and Scheme versions of the model have been created. Following the model build, sensitivity tests were carried out to ensure the suitability of the model for this assessment and understand the uncertainty in the model. The model was found to be most sensitive to the tidal boundary condition.

6.1.5 The 2D model has been reviewed by the EA, two updates were implemented as a result. The stubby building method for simulating buildings on the floodplain was included and the resolution of the model was increased from 10m to 5m. Wave overtopping has been discounted on the basis that the wave overtopping only has an impact prior to tidal inundation at the coast. The sensitivity testing has shown that the tidal boundary has the greatest impact of maximum flood depths and any increase in water level due to wave action would be insignificant. The site itself is situated over 1km inland from the coast and is therefore outside the influence of any coastal wave overtopping effects. Due to the fetch length in Lake Lothing, it is unlikely any significant wave heights will be generated within Lake Lothing.

6.1.6 A verification process has been carried out for the baseline model by simulating the 2013 tidal event which caused significant flooding in Lowestoft. It was not possible to calibrate the model as there is only one level gauge within Lake Lothing and this has been used to define the tidal boundary for the verification model run. A check against the EA historic flood map showed that the model developed for this study compares reasonably well with the historic outline. A comparison between photographic evidence of flood extents and depths has shown that the model performs well and predicts the flood extent accurately. Overall the flood depths compare well with those observed on the photographs provided by the EA, although there are some discrepancies. It is not known whether the photographs were taken at the peak of the flood event and this may explain some of the differences in the estimated and modelled flood depths.

6.1.7 A comparison of the results from the baseline and Scheme scenarios has shown that for the present day (2017) events (5%, 0.5% and 0.1% AEP), there are small water level increases (≤0.01m) within Lake Lothing and on the floodplain with the Scheme in place. For the climate change scenario (2117), increases of up to 0.04m (0.1% AEP event) are predicted with the Scheme in place compared to the baseline scenario. The H++ model runs that have been used to assess the credible maximum scenario show an increase of up to 0.14m during the 0.1% AEP event with the Scheme in place.

6.1.8 A Scheme Worst Case scenario has been modelled for the 0.5% AEP event to understand the impact of an increase in bridge pier size underneath the bridge deck compared to the current design. The increase in blockage underneath the bridge deck (from 10% to 15%) between the Scheme and Scheme Worst Case scenario has a negligible impact on the model results even in the 0.5 % AEP H++ event and the only negative impact is shown within the outer harbour (0.01m increase in Scheme Worst Case scenario compared to the Scheme scenario).

6.1.9 In conclusion, the model has undergone a comprehensive sensitivity, verification and review process to ensure it is robust and accurate. It is considered suitable for use in the FRA for the Scheme.

7 Appendix 1 to Annex B

7.1 CH2M Hill model review

1 Introduction

1.1 Background to this review

Item:	Comment:
1.1.1 Review title:	Lake Lothing Existing Hydraulic Model Review
1.1.2 Review purpose:	The Lake Lothing Third Crossing has been designated a Nationally Significant Infrastructure Project (NSIP) and is a key objective in regeneration of the harbour area of Lowestoft. . An existing hydraulic model of Lake Lothing, the outer harbour and part of Oulton Broad was provided for use in the FRA for the Scheme. The existing model was developed by CH2M Hill on behalf of Waveney District Council as part of the Lowestoft Flood Risk Management Strategy. The purpose of this review is to determine the suitability of the existing model for use in the FRA.
1.1.3 Review scope:	Model hydraulics and hydrology
1.1.4 Review undertaken for:	Suffolk County Council (SCC)
1.1.5 Review undertaken by:	Daniel Eddon/Julia Hunt
1.1.6 Date of review:	August 2016
1.1.7 Review version (s):	Lowestoft Tidal Model – Supply model to EA – Lowestoft_01.ief (The lock at Mutford Bridge open scenario)
1.1.8 Model produced by:	CH2M Hill
1.1.9 Action levels	Recommendations are made with three priority levels as described below: Must be addressed as part of the current study Please follow recommendation if time allows Not strictly necessary in this case but good practice to consider for future studies na No action required
1.1.10 Study aims & objectives:	The aim of the FRA is to determine the impacts of the Scheme on flood risk to Lowestoft. Any adverse impacts of flood risk are identified and reported on in the FRA document.
1.1.11 Area of interest:	Lowestoft including Lake Lothing and the outer harbour

1.2 Supporting documents / files reviewed

Subject document / file	Description	Version/Date	Filename	Reviewer's comments
1.2.1 Lowestoft Tidal Defences Additional Modelling Studies	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. As part of the study, a hydraulic model covering Lake Lothing, the outer harbour and Oulton Broads was developed.	October 2014	Lowestoft_Tidal_Defences_final_draft_03.pdf	Report provides an overview of the model development. Provides sufficient details to review to current setup of the model. Some details regarding the tidal curve derivation are referred in Appendix D_rev2.pdf. Further details are in the report 'Lowestoft Estuary Inception Study, Final Project Report' which was not provided. It must be noted that the report refers to results from the full Broadlands rivers catchment model.
1.2.2 Lowestoft tidal barrier – outer harbour water level modelling investigation	Using the model developed as part of the 2014 study, the outer harbour water levels were investigated further for a number of flood defence options.	July 2016	Lowestoft_Outer_Harbour_Modelling_v3A.pdf	Report builds on work completed in the 2014 study. Three options were explored in more detail and minor updates were made to the model as part of this study.

1.3 Model summary

Issue	Summary	Reviewer comments	Action
1.3.1 Software used, including versions	Flood Modeller Pro = 4.2.6050.22474 TUFLOW = 2016-03-AA-w64	Software versions up to date at time of study. Software applied suitable for assessment.	Latest versions of software should be used in any modelling going forward
1.3.2 Return periods provided for review	100yr tidal inflow was provided. An arbitrary fluvial inflow to 1D model was included to prevent the 1D model running dry.	One return period is sufficient for review purposes but the model needs to be run for a range of return periods as part of the interim assessment of flooding.	Must do
1.3.3 Scenarios provided for review	Baseline	na	na
1.3.4 Model version reviewed	Lowestoft_01.dat and all associated 1D and 2D files As part of the 2014 study, CH2M Hill linked the 1D BESL model that represents the entire Oulton Broads fluvial system including the River Waveney and Yare and their associated tributaries to a 2D model of Lake Lothing and the outer harbour at Lowestoft. The 1D BESL model 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. The 1D BESL 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 provided for use in this study by CH2M Hill included a small extract from the 1D BESL model (representing approximately a 630m reach of Oulton Broad) but not the entire 1D domain. All of the components of the 2D domain for the baseline scenario were supplied.	na	na
1.3.5 All model files provided for review?	Yes	na	na
1.3.6 Does the model run as provided?	Yes	na	na

2 Hydrology

Issue	Summary	Reviewer comments	Action
2.1 Hydrology – Methodology	The methodology used to derive the tidal curve is commented upon in Appendix D_rev2.pdf. The document states that the design curves remain unchanged from the original Lowestoft Estuary Inception Study, 2012. No details of the specific method used to derive the tidal curves has been provided. The climate change scenarios are derived using the DEFRA 2006 climate change guidance. The hydrology within the original 1D BESL model that represents the entire Broadlands river system is complicated. The model provided by CH2M Hill for use in this assessment has a nominal inflow at the upstream of the short 1D section included (representing part of Oulton Broad). The 1D inflow is only used to prevent the 1D model running dry.	A review/update of the tidal curve derivation is recommended using the most up to date guidance document and climate change allowances. Decision to be made regarding fluvial inflows to Oulton Broad.	Must do
2.2 Gauging stations	There are 2 level gauges in the area of interest. Lowestoft harbour tidal gauge at the A47 Bascule Bridge and Oulton Broads level gauge at the lock at Mutford Bridge.	The Lowestoft harbour tidal gauge has 9 years of daily averaged data. Daily average is not sufficient resolution to produce a tidal curve, however it can be used as a check. The level gauge in Oulton Broads is upstream of Mutford Bridge and has 15 years of daily average data.	na
2.3 Catchment delineation and catchment characteristics	No catchment inflows are used in this model – the inflow to the 1D model is a nominal QT boundary.	na	na
2.4 Flood Peak Estimation	The Extreme Sea Level (ESL) data provided by the EA has been used to define the peak tidal level for the 1 in 100 year tidal event supplied with the model.	A review/update of the tidal curve derivation is recommended using the most up to date guidance document and climate change allowances.	**Must do**
2.6 Oulton Broads initial conditions	An initial inflow into the 1D domain is applied to prevent the cross section from becoming dry during the simulation.	This is a reasonable approach to use in this case.	Na

Issue	Summary	Reviewer comments	Action
2.8 Model inflows	The 100 yr event hydrograph simulated a number of tidal peaks over 100 hours with the highest level occurring at 45 hours.	There are no fluvial inflows within the 2D domain, despite there being tributaries that discharge into Lake Lothing. The inclusion of fluvial inflows in the model should be investigated.	**Useful**

3 1D Domain – General

Issue	Summary	Reviewer comments	Action
3.1 Length of 1D domain(s)	0.62km	na	na
3.2 Node summary and model extent	There are a total of four nodes in the 1D model provided for use in this assessment. The model contains one structure representing the lock as an orifice and a spill to represent the boundary between the 1D and 2D domains within the model. The spill is located across Mutford Bridge. Representing the lock in 1D allows the lock to be simulated in the open and closed position. The 1D model is dynamically linked to the 2D floodplain along the southern bank to the lock. The dummy spill at the lock uses the Mutford Bridge deck elevations as the spill level and simulates the losses of the flow under the structure in the orifice unit. It is unclear from the report whether LiDAR data or survey data has been used to set the 1D cross section elevations.	The representation of the lock and Mutford Bridge appears more complicated than necessary for the third crossing study. It is recommended that a more simplistic method should be used to represent the lock.	**Must Do**
3.3 Naming convention	Naming convention on river sections is based on chainage of the larger Broadlands rivers catchment model (1D BESL model)	na	na
3.4 Topographic survey	No survey of Oulton Broads was made available for use in this review.	Topographical data to the check the elevation in the 1D cross sections should be considered if available, however it is not necessary to request a survey specifically for this application.	**Useful**

4 Hydraulics

<table>
<tr><th>Issue</th><th>Summary</th><th>Reviewer comments</th><th>Action</th></tr>
<tr><td>4.1 Boundaries</td><td>The model has one HT boundary where the tidal curve is applied representing tidal levels in the North Sea.

Between the 1D and 2D models, a SX link is used to convey the water over the spill across Bridge Road. There are four HX links connecting the 4 river sections on the southern side of Oulton Broads to the 2D domain.

Upstream of the 1D domain is a QT boundary providing an arbitrary flow in the domain.</td><td>An investigation of the impact of having no upstream boundary in the 1D domain is recommended. Currently the water in the model pools in this area. This is because the extract obtained from CH2M Hill does not fully represent Oulton Broad and the larger river network it is connected to.

The HT boundary is appropriately applied at the harbour entrance, which simulates the worst case scenario.</td><td>Must Do</td></tr>
<tr><td>4.2 1D Channel geometry</td><td><table><tr><th>Node</th><th>Width (m)</th></tr><tr><td>OD2960</td><td>600</td></tr><tr><td>OD3140</td><td>675</td></tr><tr><td>OD3310</td><td>261</td></tr><tr><td>OD3580</td><td>420</td></tr></table>Table 7-1: 1D CHANNEL WIDTHS
Figure 1 shows the cross sectional profile of node OD2960.

The 1D sections were found to show the right bank (south bank) of Oulton Broad on the left hand side of the screen and the left bank (north bank) of Oulton Broad on the right hand side of the screen.</td><td>The cross-sections are sufficient width and extend onto the floodplain (Table 1) on the northern side of the Oulton Broad to represent the floodplain. On the southern bank, the 1D sections are connected to 2D to allow flow exchange between the two domains.

According to convention and to ensure the 1D and 2D domains are consistent, the 1D cross sections should be plotted from left to right bank.

A check of elevations in the DTM of the model shows that the cross sections should be flipped to ensure the left bank is represented on the left hand side of the screen.</td><td>Must Do</td></tr>
</table>

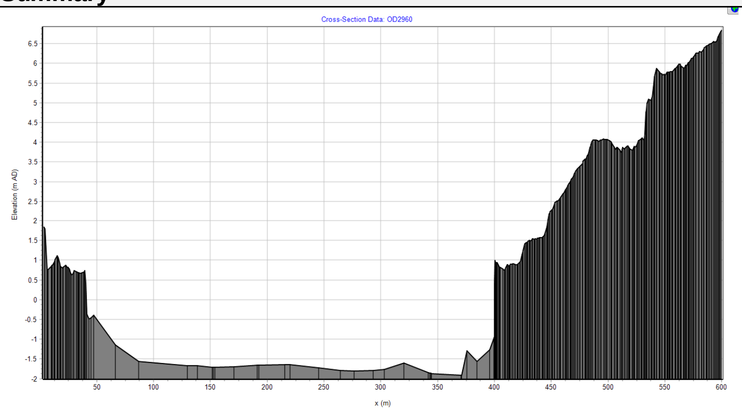
<table>
<tr><th>Issue</th><th>Summary</th><th>Reviewer comments</th><th>Action</th></tr>
<tr><td></td><td>

FIGURE 7-1 – NODE OD2960</td><td></td><td></td></tr>
<tr><td>4.3 Manning's N</td><td>The modelling reports supplied do not discuss the manning's n values used within the model.

A Manning's n value of 0.035 is used in the 1D model for the cross sections.

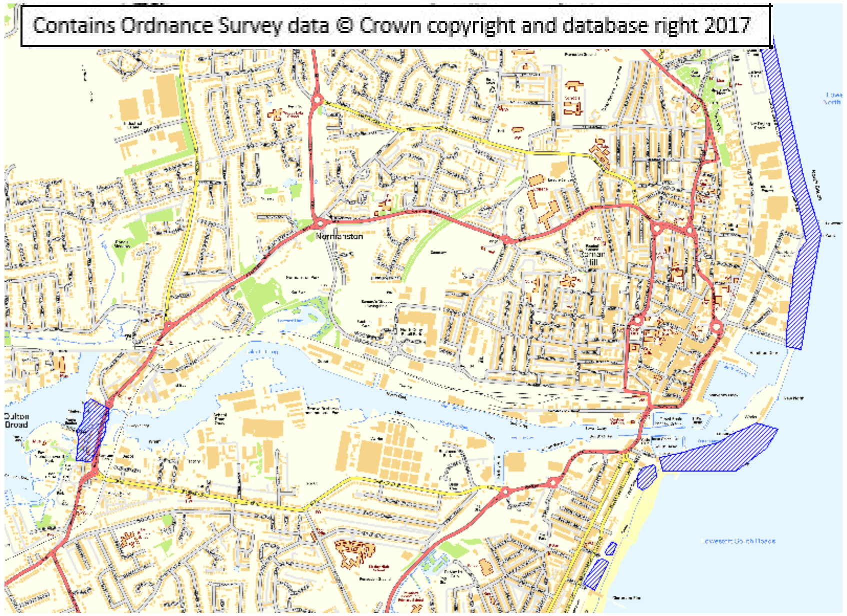
The Manning's n values used on the floodplain are listed in Table 2. The Manning's n values are applied to the floodplain using OS mastermap to define the different land uses.

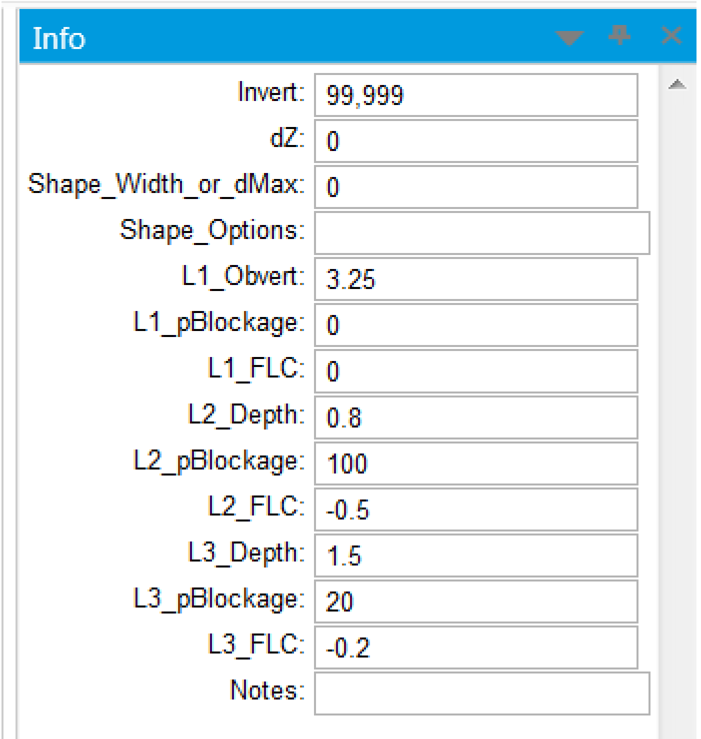
<table>
<tr><th>Surface</th><th>Manning's n</th></tr>
<tr><td>Buildings</td><td>1.000</td></tr>
<tr><td>General surface</td><td>0.033</td></tr>
<tr><td>Glasshouse</td><td>1.000</td></tr>
<tr><td>Inland water</td><td>0.030</td></tr>
<tr><td>Inland water, natural environment</td><td>0.030</td></tr>
<tr><td>Landform</td><td>0.035</td></tr>
<tr><td>Landform, historic interest</td><td>0.035</td></tr>
<tr><td>Natural environment</td><td>0.100</td></tr>
<tr><td>Path</td><td>0.016</td></tr>
</table>
TABLE 7-2: 2D FLOODPLAIN MANNING'S N VALUES
There are a significant number of roughness patches within the model. They are generally positioned in areas where sudden inundation is expected. Figure 2 shows the location of all the roughness patches.</td><td>Manning's n value of 0.035 is reasonable for a channel.

There is no consideration for the floodplain roughness on the north bank in the 1D domain. This review recommends a roughness sensitivity to be carried out before the 1D domain is used for this study.

On the 2D floodplain, the Manning's n values are within acceptable limits, however they are generally low. For example, the typical value for 'General Surface' is 0.04 or 0.05. There is also a significant amount of repetition and overlap in the surface types.

A review of the Manning's n values on the floodplain is required using the OS mastermap.</td><td>Must do</td></tr>
</table>

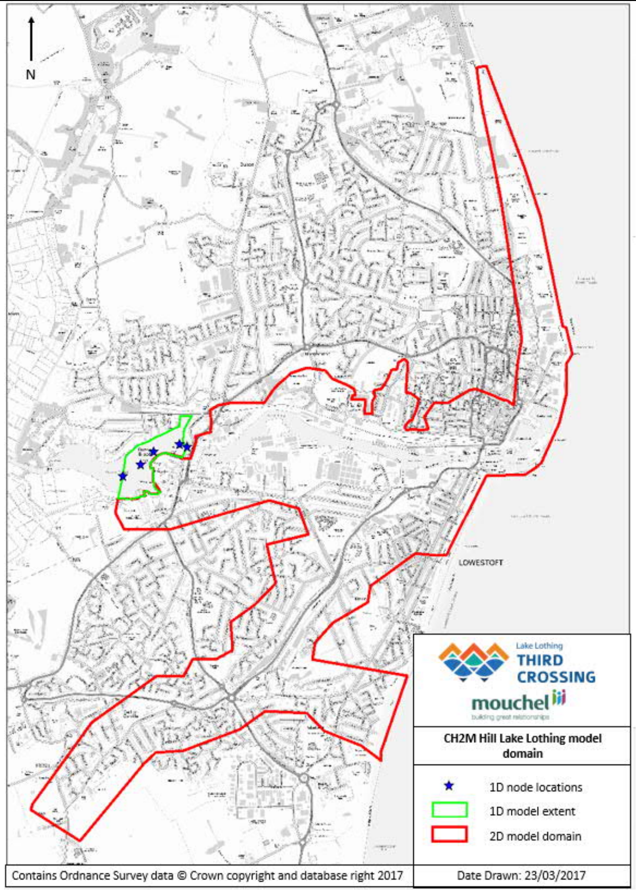
Issue	Summary	Reviewer comments	Action
	 **FIGURE 7-2 – ROUGHNESS PATCHES**	Roughness patches are acceptable if all other methods of model stabilisation have been tried. This review recommends roughness patches are not used if the model will run without them.	
4.4 Structures	The 1D model contains one orifice unit representing the Lock. The Lock is represented as open in the version of the model received. The throat soffit level is 2.48mAOD, the throat invert level -1.5mAOD with a bore area of 31.944m2. The weir flow coefficient = 1.5 and surcharged flow coefficient = 1 and the modular limit is 0.7. The 1D/2D boundary is at Mutford Bridge and the model simulates the losses at Mutford Lock and the opening under Mutford Bridge in the orifice unit. The spill uses the topography at Mutford bridge as the spill onto the 2D domain.	This approach appears to half simulate the lock and Mutford Bridge in 1D and half in the 2D domain. This review recommends that Lock at Mutford bridge should be simulated fully in the 2D domain in the closed position. This would require the SX link to be moved upstream of lock onto Oulton Broad and the Mutford bridge could be represented in the 2D domain as a flow constriction unit.	**Must Do**

Issue	Summary	Reviewer comments	Action
	The A47 Bascule bridge is represented in the 2D domain as a flow constriction unit. The parameters used to simulate the bridge are shown in Figure 3. No survey of the bridge was available therefore the elevations has been estimated using topographical survey of the levels on the north and south approaches and site photographs. Point data has been used to overlap the general elevations and representing the arched nature of the bridge.  **FIGURE 7-3 – A47 BASCULE BRIDGE**	It is recommended that detailed elevations for all the structures in Lake Lothing should obtained and included in the model. Sensitivity testing should be carried out to access the impact on the maximum water level.	

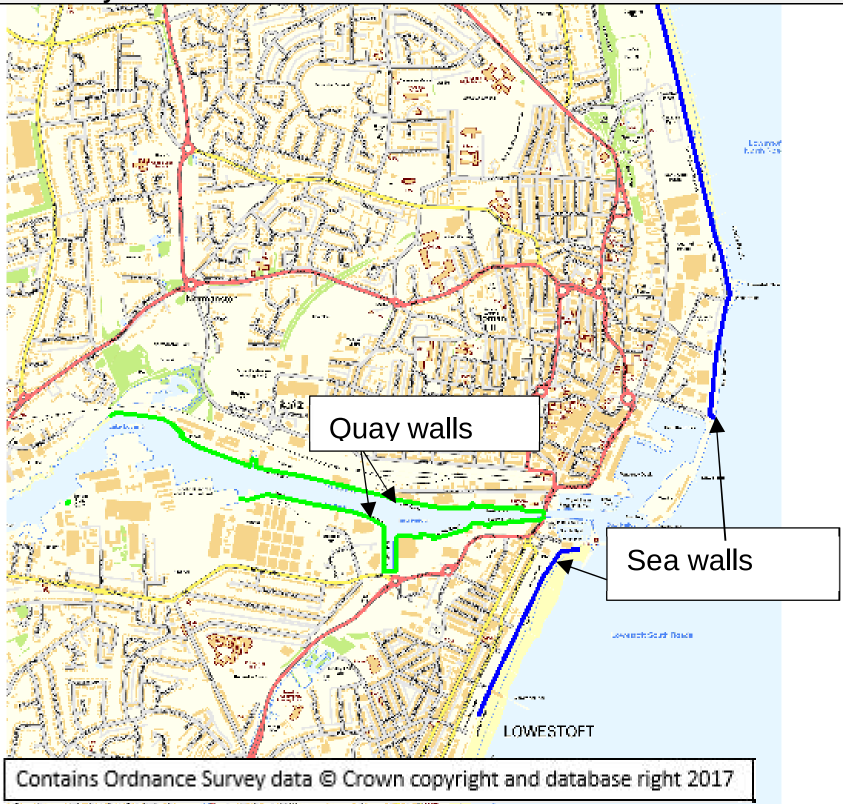
Issue	Summary	Reviewer comments	Action
	There is no representation of the railway bridge over Lake Lothing approximately 100m from Mutford Bridge.		

5 2D Domain – General

Issue	Summary	Reviewer comments	Action
5.1 General Cell size(s): Suitable for study objectives?	10m	This is considered suitable for the model of this size, however it would be beneficial to reduce if model stability allows for this.	Useful
5.2 Base topography	As highlighted in the 2016 modelling note, 2015 LiDAR has been used to define the base topography within the model. Figure 4 shows the 2D model extent. A significant proportion of the Kirkley Stream catchment is simulated in the 2D domain. There are two locations where the tidal inflow is applied, at the harbour and on the south beach (where the domain reaches the coast). The bed level of Lake Lothing is represented using a standard value of -1.5mAOD.	It is recommended that the most up to date LiDAR available is used in any future assessments. Bathymetry data could be used to represent the bed of Lake Lothing in order to more accurately predict tidal levels within the channel.	Useful

Issue	Summary	Reviewer comments	Action
	 **FIGURE 7-4- 2D MODEL DOMAIN**		

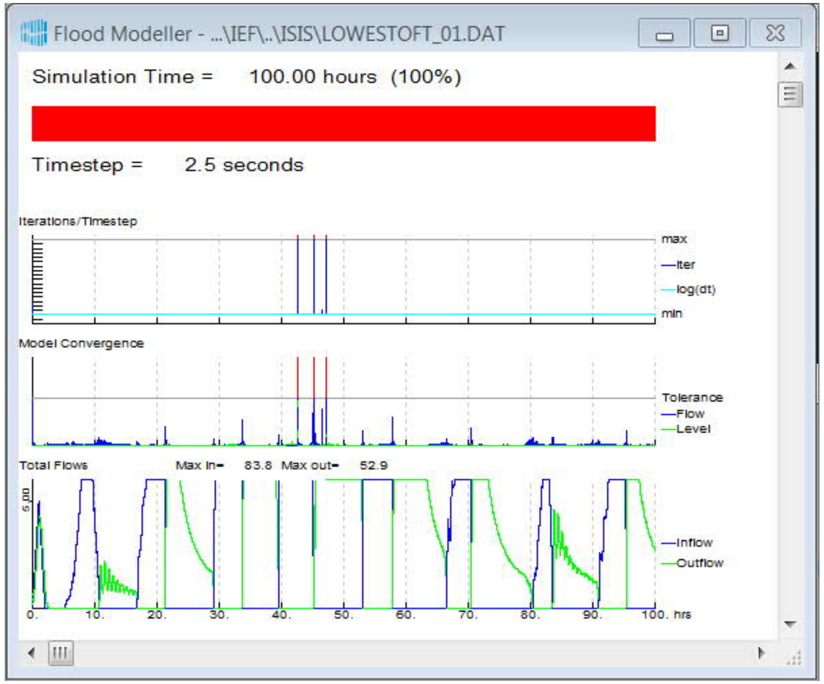
Issue	Summary	Reviewer comments	Action
5.3 Topographical Adjustment	The following adjustments were made to the base topography: - Stamped inner harbour walls (green line, Figure 5) representing the elevation of the quay walls in Lake Lothing. - Sea defences (blue line, Figure 5) representing the elevation of the existing coastal sea walls.	The elevations appear to be reasonable, however a check against LiDAR or survey data is recommended before use in this study.	**Useful**

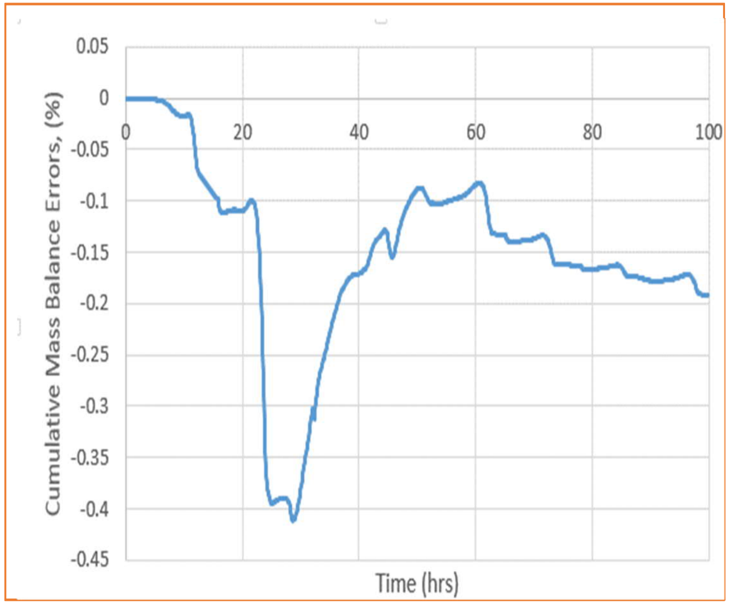
Issue	Summary	Reviewer comments	Action
	 **FIGURE 7-5 – LOCATIONS OF ADJUSTED TOPOGRAPHY**		
5.4 Buildings representation	Buildings are represented with roughness value of 1.000.	This is considered a suitable approach to represent buildings on the floodplain.	NA

Issue	Summary	Reviewer comments	Action
5.5 1D-2D linking	HX linking applied to link the 1D and 2D domains along the southern bank of Oulton Broad in the 2d_bc_Broads_link_002_tuflow.mif code layer. A SX link connects Oulton Broad to Lake Lothing over the lock and Mutford Bridge crossing in the 2d_bc_MutfordLock_link_tuflow_07.mif code layer.	The need to include the short section of 1D in the model used in the interim assessment of flooding should be investigated.	**Must Do**

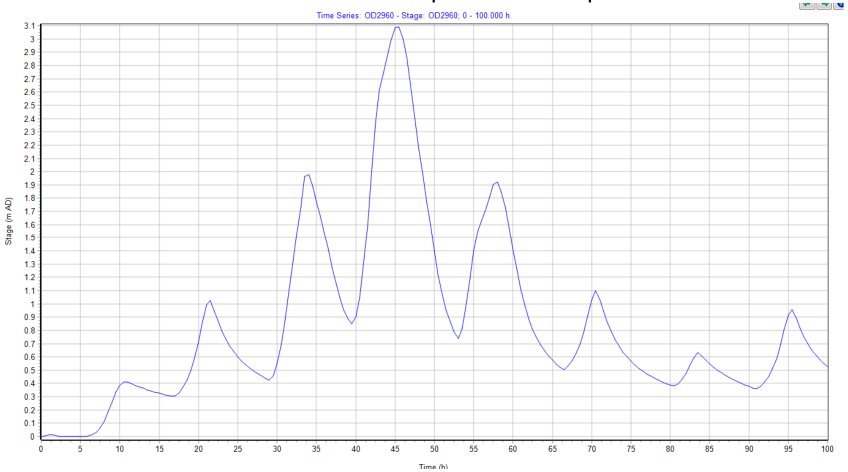
6 Model Run Parameters and Model Performance

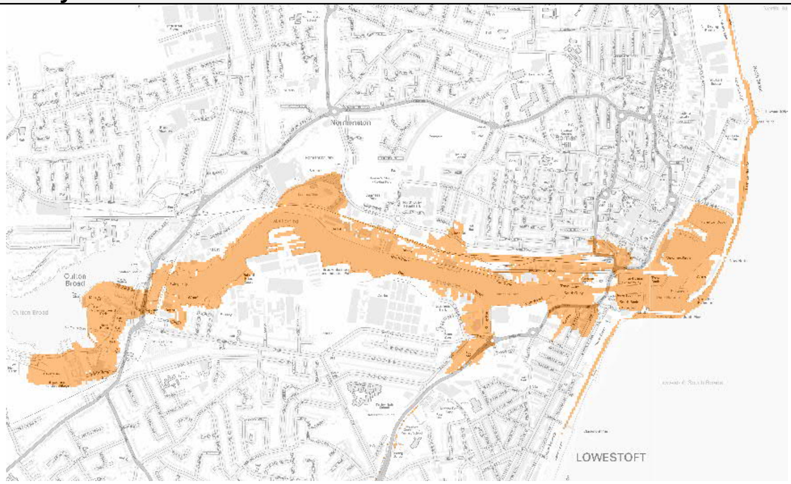
Issue	Summary	Reviewer comments	Action
6.1 Timestep	2.5s in 1D and 5s in 2D.	This is considered suitable for model configuration. Typically 2D timestep is twice 1D timestep. A reduced timestep is recommended. This may reduce some of the numerical instabilities and potentially eliminate the need for the roughness patches within the model.	**Useful**
6.2 Run parameters (amended from default)	Automated Priessmann slots applied to river sections Qtol = 0.1 Maxitr = 19 Theta = 0.55 Other parameters are as default	Automated Priessmann slots are applied in the simulations provided for review. This option can mask errors in input data. Whilst these are not evident in data provided for this review, if the model runs without this option applied then it is recommended that this option is unchecked. Qtol and Maxitr have both been increased from default. These values are within acceptable limits for a tidally influenced model. However, it is good practice to have the parameters as low as possible therefore if the model runs with lower Qtol and Maxitr values then it is recommended that these parameters are reduced.	**Good Practice**

Issue	Summary	Reviewer comments	Action
		Theta is set at 0.55, this is the recommended value for tidal models.	
6.3 Convergence	ISIS model runs show that there are some instances of poor model convergence as shown in Figure 6.  **FIGURE 6: MODEL CONVERGENCE**	The model has poor convergence at the high tidal peak. This is because of the sudden influx of water into the 1D domain. This review recommends reducing the poor convergence if possible.	Useful

Issue	Summary	Reviewer comments	Action
6.4 Mass errors (target ± 1%)	The cumulative mass error is within the ± 1% acceptable range during the whole simulation period. See Figure 7 below.  **FIGURE 7-6: MASS BALANCE ERROR**	na	na

7 Model Results

Issue	Summary	Reviewer comments	Action
7.1 1D water surface profile	The 1D water surface profile looks reasonable. Figure 8 shows that the water level follows the trend of the tidal curve input which is expected.  **FIGURE 8 – NODE OD2960 WATER LEVEL**	na	na
7.2 2D results	Figure 9 shows the flood map for the 100 year flood event. The flood extent shows flooding to a number of areas in the floodplain. It must be noted that the 100 yr flood event shown is from the larger model used in the CH2M Hill study of which only an extract was provided for use in this study.	The verification process written in the report compares the tidal arrival times between Lowestoft and Great Yarmouth which is suitable for the larger model. There is a reference to the 2013 flood event and 'indicative flood locations', however it is unclear how the flood locations have been arrived at. It is also not clear from the report whether a comparison of modelled outputs to indicative flood locations or gauge data in Lowestoft has been carried out.	**Must Do**

Issue	Summary	Reviewer comments	Action
	 **FIGURE 7-7: 100YR FLOOD EXTENT** A verification process is carried out to verify the method of tidal curve application in the model. This was carried out by comparing the tidal gauges at Lowestoft and Great Yarmouth for December 2013 flood event and concluded that the peak tide arrived at Lowestoft 15 minutes after Yarmouth. The modelling report discusses the proposed tidal barrier and the Lock open and closed scenario. Principally, the modelling results suggest Lake Lothing can be used to store up to a 1 in 200 year flood event with minor flooding of Lowestoft if the lock and the proposed tidal barrier is closed. Any higher magnitude events generate greater flooding because the tidal barrier is overtopped.	The review recommends that a verification process is carried out on the 2D flood map using all available data including level gauge data, EA historic flood map and if available, photographic evidence of flooding.	

8 Audit Trails

Issue		Summary	Reviewers comments	Action
8.1 Logbook provided?	No	No, a report that explained the updates to the model has been provided.	The model report does not contain enough information to confidently use the model without a number of modifications and checks	**Must do**
8.2 Suitable file naming, structure & management?	No	File structure is not in the standard format recommended by TUFLOW however the file names do refer to their content.	A rearrangement of the model files is recommended by this review. It is recommended that the standard TUFLOW file structure is used.	**Best Practice**
8.3 Check files provided	No	na	A model run was required to obtain the check files therefore the check files report on the extract model only, not the full 1D BESL and 2D Lowestoft model.	na
8.4 Comments provided within model?	Yes	Some comments provided at spill units in 1D	na	**Useful**

9 Conclusions

Conclusions
This review note presents comments noted during the review and recommendations for required actions. The key recommendations are summarised below. Recommendations are made with three priority levels: **Must do** Must be addressed as part of the current study Produce a range of tidal event curves using the most up-to-date data and guidance Assess the impact of the Lock and Mutford Bridge with an aim to simplify the representation of these structures Determine whether a 1D domain and representation of the Lock in 1D is required Ensure any 1D sections are displayed left bank to right bank on screen Assess the Manning's n floodplain roughness and undertake sensitivity testing Stabilise the model and remove roughness patches Obtain any survey data/as built information for all the existing structures in Lake Lothing Validate/Verify the model results using all available information **Useful** Make use of most up to date LiDAR data Use bathymetric data to accurately represent bed levels in Lake lothing Check the derived tidal curve with the gauge data in Lake Lothing Define tributary catchments that discharge directly into Lake Lothing and perform a fluvial hydrological analysis Use survey data to check the cross sections in the 1D domain Reduce the 2D cell size Check existing harbour wall and coastal defence levels Reduce the timestep Reduce the model poor convergence **Good Practice** Remove the Automated Priessmann Slots if model runs without them Reduce Qtol value to default Reduce Maxitr value to default

8 Appendix 2 to Annex B

8.1 Tidal calculations record

CALCULATION CONTROL SHEET
PROJECT: Lake Lothing, Third Crossing
PART OF PROJECT: Design Sea Level Calculations
CALCULATION TITLE: Design Sea Level Calculations record
FILE LOCATION: G:\1403\7.0 Projects\7.05 Live Projects\1073877 Lake Lothing\09 Documents\Hydrology\Report

CALCULATION SUMMARY
This report provides a record of the calculations and decisions made during the derivation of the tidal boundary inflows using the recommendations in SC060064/TR4: Practical Guidance design sea levels. Following the review of the model by the Environment Agency (EA), the extreme sea levels from Open Coast (CFBD) Flood Risk Study (JBA, 2014) have been used.
Purpose of Calculations To derive design tidal inflow for the sea boundary in the Lowestoft tidal model.

CHECKING AND REVIEW STATUS					
Rev	**Purpose**	**Author**	**Reviewed**	**Authorised**	**Date**
1	Draft for model build	DE	JH	TJ	20/04/2017
2	Update following EA model review	DE	JH	TJ	08/11/2017

REVISION HISTORY			
Revision Ref./ Date Issued	**Date**	**Purpose and description of Amendments**	**Issued to**
1	14/12/2016	Draft for model build	
2	03/11/2017	Update following EA model review	

1 Introduction

This document provides a record of the calculations and decisions made during design sea level estimation. It will often be complemented by more general hydrological information given in a project report. This version of the report is for when a single tidal boundary is required.

2 Method Statement

Item	Comments
Purpose of study Give an overview which includes: Purpose of study Approx. no. of tidal boundaries required	The Lowestoft Lake Lothing and Outer Harbour Area Action Plan was adopted in 2012 and identifies Waveney District Council's long term ambition for a third vehicular crossing of Lake Lothing. The Lake Lothing, Third Crossing has been designated a Nationally Significant Infrastructure Project (NSIP) and is a key objective in regeneration of the harbour area of Lowestoft. This document presents the tidal curve calculation for the sea boundary in Lake Lothing. This is achieved by combining extreme water level, astronomical tide profile and a surge shape. Each component is derived following the SC060064/TR4: Practical Guidance Design Sea Levels (Environmental Agency (EA), 2011) using the extreme sea levels from Open Coast (CFBD) Flood Risk Study (JBA, 2014).
Description of catchment Brief description of catchment, or reference to section in accompanying report	Lowestoft is a seaside town in Suffolk on the east coast of England. The harbour, known as Lake Lothing is one of the sea boundaries for the Broadlands rivers catchment. Lake Lothing is a tidal driven lake which has a boundary with the North Sea downstream and Mutford Lock upstream. The lake is split into two areas, the inner harbour and the outer harbour. The downstream end of Lake Lothing is subject to approximately a 12 hour tidal cycle from the North Sea which causes changes in water levels in the lake basin.
Flood estimates required	Flow hydrographs / peak flow estimates are required for present day (2017) scenario, climate change and H++ as request by the EA (Appendix A in the Interim Assessment of Flooding): • 5% Annual Exceedance Probability (AEP), 0.5% AEP, 0.1% AEP; • 5% AEP plus climate change, 0.5% AEP plus climate change, 0.1% AEP plus climate change; • 5% AEP plus H++ Scenario, 0.5% AEP plus H++ Scenario, 0.1% AEP plus H++ Scenario.

Table 1: Overview of Study

What is the source of the sea level data? • Admiralty Tidal Time Charts • Gauge Data	Gauge data situated at the A47 Bascule Bridge in Lowestoft harbour (NGR: 652127 292785)

Table 2: Source of Sea Level Data

Watercourse	Station Name	Gauging authority number	Grid reference	Period of available data	Type of Data
Lake Lothing Harbour	LAKE LOTHING	T341907	TM5212792785	9 years	Tidal (Level)
Comments	Data for the gauge is provided in two formats, checked daily average sea levels from the EA and 15 minute 'live data' from the National Tidal and Sea Level Facility[8], (NTSLF) which has not been quality checked and is extracted at 4hr intervals from an online graph meaning it is labour intensive and prone to human error.				

Table 3: Site information

Item	Comments
Other Flow / levels gauging sites	Level gauge at the lock at Mutford Bridge records levels within Oulton Broads
Historic flood data	Tidal flooding of properties on and near the coastline in Lowestoft and Lake Lothing. (2013 and 1953). A shape file showing the flood extent in an event is provided in the Environmental Agency's Historic flood maps. As the time or date information for the event is unavailable, it was assumed that the extent is the 2013 event because shapefiles were not available in 1953.
Flow data for events	No flow data available, level only gauges at Lake Lothing and Oulton Broad.
Results from previous studies / models	Lowestoft Tidal defences: Additional Modelling Studies, 2014 Lowestoft Estuary Inception Study, 2013 Lowestoft Tidal flood Study, 2013 1D BESL model (simulates Oulton broads fluvial system)
Other data (e.g. Groundwater, tidal	Photographs taken during 2013 flood event published in a local newspaper.

Table 4: Other Data Available

[8] http://www.ntslf.org/data/realtime?port=Lowestoft

Item	Comments
Outline the method	The conceptual method chosen here follows the guidance; *SC060064/TR4: Practical Guidance design sea levels.* In April 2008, the EA undertook a strategic overview of the coasts in England. The guidance was created for the EA project, *Coastal flood boundary conditions for UK mainland and Islands* (SC060064/TR2: Design sea levels[9]), with the aim to update and consolidate the outdated methods for producing tidal curves suitable for Flood Risk Assessments. The aims of the project were to: • Provide a consistent set of extreme sea levels around the coasts of England, Wales and Scotland. • Provide a means of generating total storm tide curves for use with the extreme sea levels. • Offer practical guidance on how to use these new datasets. This method is acknowledged as the best method for calculating the tidal curves in the UK using the most up-to-date method and the best data available. EA recommends its use for tidal curve derivation when undertaking Flood Risk Assessments.

Table 5: Sea Level Derivation Method

[9] Coastal flood boundary conditions for UK mainland and islands SC060064/TR2: Design sea levels, Environmental Agency, 2011

3 Tidal Curve Calculations

The extreme tidal curves are derived using the guidance from *SC060064/TR4: Practical Guidance Design Sea Levels.* All decisions and reasons are presented.

Ten Step procedure
• Check study location is outside of estuary boundaries
• Select an appropriate chainage point for extreme sea levels
• Select an annual exceedance probability peak sea level
• Consider allowance for uncertainty
• Identify base astronomical tide
• Convert levels to Ordnance Datum
• Identify surge shape to apply
• Produce the resultant design tide curve
• Sensitivity testing
• Apply allowance for climate change

Table 6: Guidance

The guidance is part of the larger project, *Coastal flood boundary conditions for UK mainland and islands, (Environmental Agency, 2011)* and is the best method currently available for tidal curve derivation in UK waters. As part of this project a number of additional datasets are provided:

Additional Data
Estuary Boundaries
Extreme Sea Levels
Gauge Sites
Confidence Interval
Surge Shapes.

Table 7: Additional Data sets

Since the guidance was published, there has been an update to the extreme sea levels by JBA for the EA. Following the guidance and the updated extreme sea levels, the event tidal curves are generated.

3.1 Check Study Location is Outside of Estuary Boundaries

The guidance is valid only for areas outside of estuaries, and as such the first check is to make sure the boundary is not in a major estuary. As part of the *SC060064/TR4 guidance,* a shape file is provided with all major estuary locations highlighted, Figure 1 shows a comparison between the Lowestoft estuary boundary and the Lowestoft model tidal boundary.

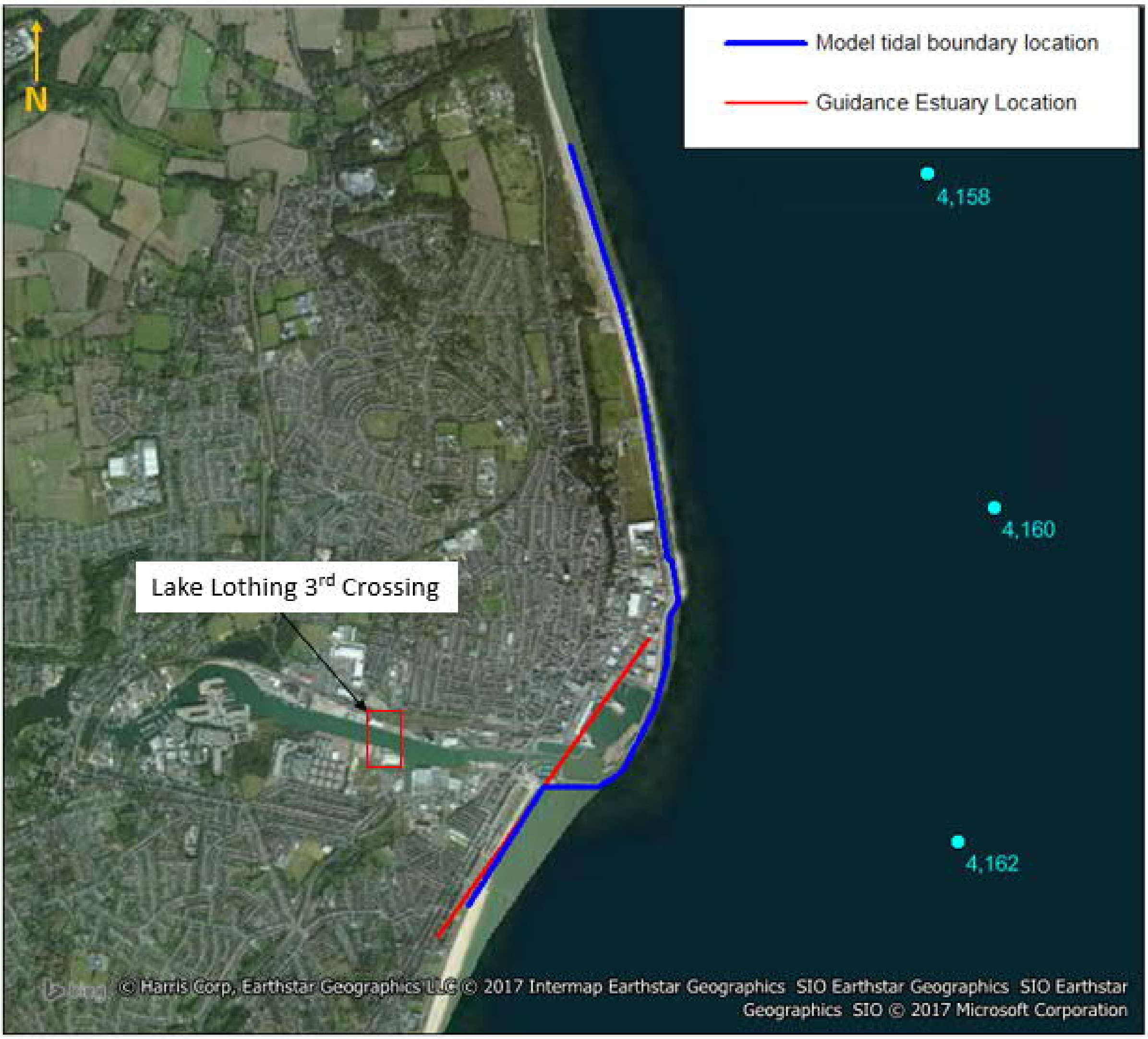


Figure 1: Estuary Boundary Check

Figure 1 shows the estuary boundary of Lake Lothing in red and the proposed tidal boundary of the Lowestoft tidal model in blue. The location of the model boundary is close to the estuary location in the guidance. At most locations, the tidal boundary is outside of the estuary however there is a small section which is on the estuary line because it follows the coastline. In this model, this is deemed acceptable because Lowestoft has an engineered harbour and in reality the estuary discharges north of the area where the tidal boundary touches the estuary line. Based on this assessment, this guidance is deemed appropriate for use to generate the tidal curve.

3.2 Select the Appropriate Chainage Point for Extreme Sea Levels

The guidance recommends that the extreme sea level node nearest to a perpendicular line drawn from the tidal boundary should be used to define the extreme sea levels for the site of interest. A perpendicular line drawn from the Lowestoft tidal boundary passes closest to 4162 chainage node as shown on Figure 2.

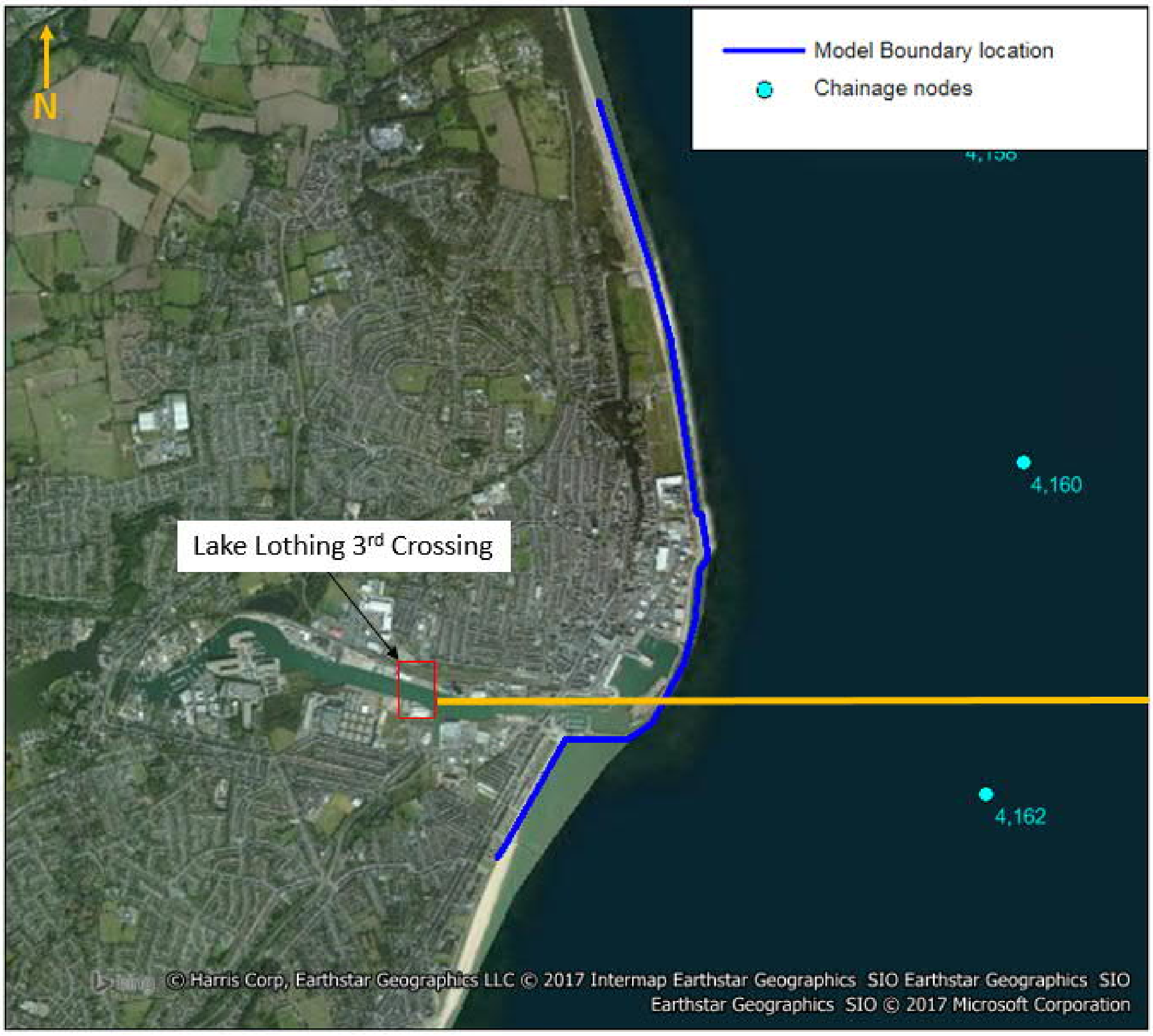


Figure 2: Chainage

3.3 Select an Annual Exceedance Probability Peak Sea Level

For each chainage node, an extreme sea level for the full range of return periods is provided in the additional data supplied alongside the guidance. The extreme sea levels provided in the Open Coast (CFBD) Flood Risk Study by JBA for the EA at node 4162 are provided in Table 8 for the events considered in this study.

AEP	Extreme sea levels (m AOD)
5%	2.74
0.5%	3.4
0.1%	3.92

Table 8: Extreme Sea Levels

3.4 Consider Allowance for Uncertainty

As part of the *SC060064/TR4* project, confidence in the extreme sea levels are provided as shown in Table 9 for the events considered in this study. The confidence levels are a measure of the potential error in the EA extreme sea level modelled results. The uncertainty is considered acceptable for this project. The EA require the Scheme to be assessed against the high impact, low probability (H++) event. Modelling of the H++ event will demonstrate the sensitivity of the model to the levels forced at the tidal boundary.

AEP	Uncertainty (+/- m)
5%	0.2
0.5%	0.3
0.1%	0.4

Table 9: Uncertainty levels (node 4162)

3.5 Identify Base Astronomical Tide

The next stage of the tidal curve derivation is to identity the base astronomical tide. *SC060064/TR4* guidance states that the astronomical tide used for the tidal curve should have a peak between the Highest Astronomical Tide (HAT) and the Mean High Water Springs (MHWS). Table 10 shows the HAT and MHWS values for Lowestoft from the National Tidal and Sea Level Facility[10] (NTSLF). The tidal levels are provided in chart datum in Lowestoft harbour. Conversion to ordnance datum is to add -1.5m, this is carried out in part 3.6.

HAT (mCD)	MHWS (mCD)
2.98	2.58

Table 10: HAT and MHWS for Lowestoft

The SC060064/TR4 guidance states that the Admiralty tidal tables should be used to estimate the astronomical tide. This step is unnecessary because Lowestoft has a tidal gauge in the harbour meaning that an astronomical tide can be obtained from recorded data.

Browsing the gauge data, a tidal profile with a peak tide of 2.85mCD was found. The NTSLF website publishes tidal levels on an interactive graph. The numerical dataset is not available, therefore a sample was taken from the graph at approximately a four hour resolution.

As part of the Lake Lothing Third Crossing study, WSP received the 1D-2D hydraulic model developed for the Lowestoft Tidal Defences study[11] carried out by CH2M Hill on behalf of Waveney District Council. The tidal curve for the original 1% AEP event was provided with the CH2M Hill model.

The data from the NTSLF is too coarse to be used for the tidal curve, therefore the CH2M Hill tidal curve data was considered for use in this study. In order to test the suitability of the CH2M Hill tidal curve, it was scaled to a peak of 2.85mCD and compared to the NTSLF data as shown in Figure 3.

[10] http://www.ntslf.org/tgi/portinfo?port=Lowestoft

1.1.1 [11] Lowestoft Tidal defences: Additional Modelling Studies, 2014

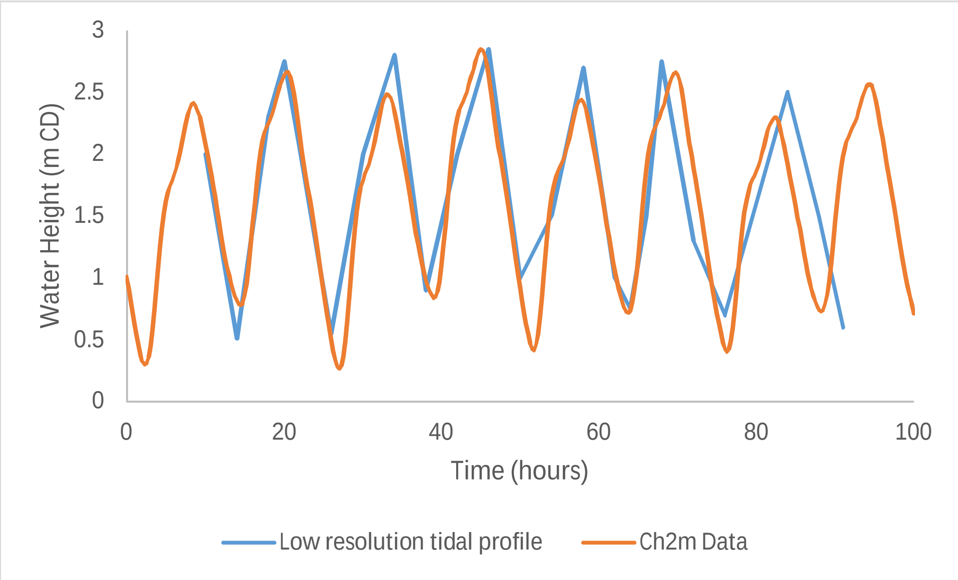


Figure 3: Astronomical tidal profile comparison

Figure 3 shows the CH2M Hill scaled tidal curve and the low resolution tidal profile taken from NTSLF graph. The peaks and troughs of both profiles align and are comparable. The largest peak, 2.85mCD is identical because of the scaling procedure. Some of the other peaks are different, this is a consequence of the scaling. However, for the Lake Lothing Third Crossing study the maximum water level is most important and the other peaks are less relevant. Therefore, due to the good comparison between the two data sets, it was deemed appropriate to use the CH2M Hill tidal curve to define the astronomical tide for the Lowestoft model tidal boundary.

3.6 Convert Levels to Ordnance Datum

The tidal levels are quoted in chart datum and need to be converted to ordnance datum. A chart datum conversion is provided at key ports around the UK. Lowestoft chart datum conversion is -1.5m. The data from the gauge site in Lowestoft is quoted in chart datum therefore this needs to be converted to ordnance datum to be comparable with the extreme sea levels and suitable for use in the hydraulic model.

3.7 Identify Surge Shape

As part of the *SC060064/TR4* project surge shapes were derived for key locations around the UK, the Lowestoft surge shape is number 9 in the Design_Surge_Shapes.xls provided with the guidance documentation.

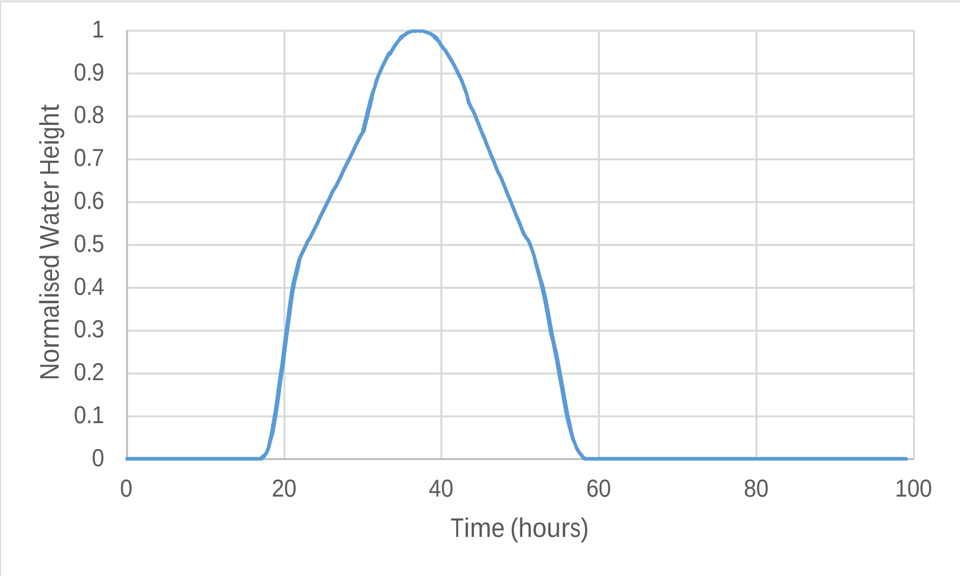


Figure 4: Shape 9 – Lowestoft Surge

Figure 4 shows the normalised surge shape at Lowestoft which is combined with the CH2M Hill model curve to derive the design tide curve.

3.8 Produce the Resultant Design Tide Curve

The guidance states that the resultant design tide curve is derived by combining the extreme sea level, base astronomical tide and surge shape. The first process is to align the astronomical tide and surge shape peaks, in this case this is at 45 hours in line with the CH2M Hill tidal curve.

Once the CH2M Hill tidal curve and surge shape are aligned, it is necessary to scale the astronomical tide to the required extreme sea level. To explain this procedure, the 0.5% AEP event will be used as an example. Firstly the difference between the required extreme sea level (3.4m AOD) and the peak CH2M Hill (3.11m AOD) is calculated which in this example is 0.29m. As the surge shape is aligned with the peak water level time in the CH2M Hill tidal curve, the maximum surge value of 1.0 occurs at the same time as the peak water level. The surge shape can now be scaled by the coefficient 0.19/1.0 = 0.19m AOD, thus creating a surge height which can be added to the CH2M Hill tidal curve resulting in the required peak water level for the event.

This procedure is carried out of each return period, scaling to the extreme sea level for a given design event (Table 8)

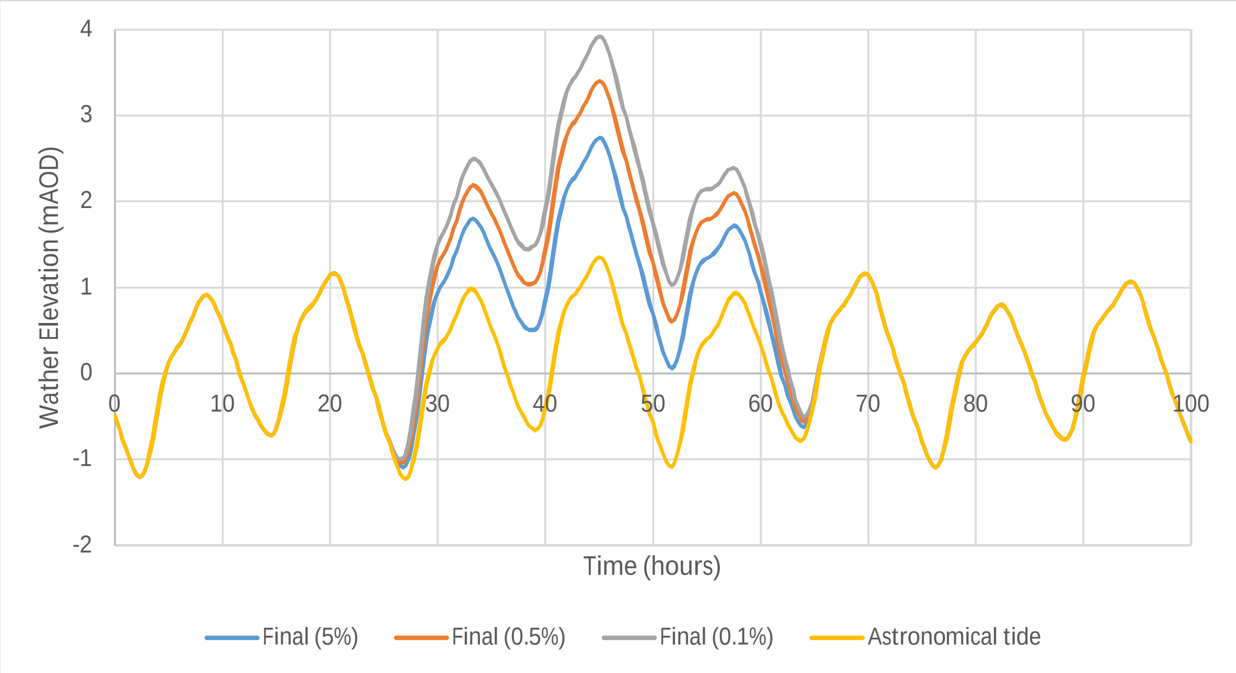


Figure 5: Final design event tidal curves

Figure 5 shows the final tidal curves for the 5% AEP, 0.5% AEP and 0.1% AEP events used in the model simulations.

3.9 Sensitivity Test

The guidance, *SC060064/TR4* requires the surge shape to be offset. This is to see the impacts of the surge arriving at a different time on the tidal curve. This is unnecessary for this study because the extreme tidal level remains at the same level which is the driving factor in tidal flooding. Other tests will be undertaken to determine the sensitivity of the model to certain parameters.

3.10 Climate Change Calculations

As the development is classed as Nationally Significant Infrastructure Project (NSIP) and 'safety critical' with a design life of 120 years, the EA have requested that the impact of the development is tested for climate change events. Following the advice presented in the National Policy Statement for National Networks[12] which states that if transport infrastructure has safety-critical elements and the design life of the asset is 60 years or greater, climate change should be considered.

Following consultation, the EA have requested testing the development against a climate change sea level rise. They have recommended a comparison between five different guidance's and the worst case to be considered. The five guidance datasets/tables are:

- National Planning Policy Framework (NPPF) - Table 3
- UK Climate Change Projections, (UKCP09) 50% high emissions
- UKCP09 95% high Emissions
- UKCP09 95% medium emissions
- Upper End allowance, Table 5 (Adapting to climate change).

The information for the NPPF – Table 3 and Upper End allowance- Table 5 are available on the internet. The UKCP09 website uses an online portal which gives access to all the datasets. As the design life is beyond 2100, the high emissions sea level rise is calculated by extrapolating to the required year by extending the current data to 2140. This is achieved by extending using a linear method as agreed with

[12] National Policy Statement for National Networks, Department for Transport, 2014

the EA. An assumption has been made that the Lowestoft Third Crossing is unlikely to be constructed before 2020; therefore for the climate change calculations it was deemed appropriate to calculate sea level rise between 2020 and 2140. Table 11 shows the expected extreme sea level rise based on each guidance.

Guidance table/dataset	Predicted sea level rise
NPPF - Table 3	1.539m
UKCP09 50% HE	0.863m
UKCP09 95% HE	1.345m
UKCP09 95% ME	1.104m
Upper End	1.529m

Table 11 - Climate change assessment

Following the assessment, the NPPF – Table 3 returned the largest increase. The estimated sea level rise used in the simulation is 1.54m. This will be added to the astronomical tidal curve and the extreme sea level prior to the scaling process described in section 3.8.

As the development is considered safety critical, the EA have requested that the Scheme is assessed against the high risk, low probability event (H++) scenario. However, mitigation for this scenario is not required (Appendix A of the Interim Assessment of Flooding) Table 11 shows the sea level rise in mm per year for the H++ scenario from *Adapting to Climate Change*[13]. As the guidance provides values up to 2115, the data is extrapolated using a linear approach to calculate the rate of sea level rise from 2116 to 2140 to cover the design life of the Scheme.

Change to relative mean sea level	Sea level rise mm/yr up to 2025	Sea level rise mm/yr 2026 to 2050	Sea level rise mm/yr 2051 to 2080	Sea level rise mm/yr 2081 to 2115	Sea level rise mm/yr 2116 to 2140
H++ Scenario	6	12.5	24	33	40

Table 12 - Sea level rise, H++ scenario

Using Table 12, the total sea level rise for the H++ scenario is 3.1m based on 120 years from 2020-2140.

The climate change sea level increases are added to the astronomical tidal curve prior to the scaling process discussed above.

4 Conclusions

The extreme tidal levels in Table 13 have been derived following the guidance, SC060064/*TR4* and discussed in the previous section.

Event	5% AEP (m AOD)	0.5% AEP (m AOD)	0.1% AEP (m AOD)
Present day extreme sea level (2017)	2.74	3.40	3.92
Climate change Scenario (based on the NPPF-Table 3)	4.28	4.94	5.46
H++ event climate change	5.84	6.50	7.02

Table 13 - Final calculated tidal peaks

The final tidal curves generated will be used as the inflow boundary to the hydraulic model developed for the Lake Lothing Third Crossing FRA. For the tidal curves for all events see section 5.

[13] Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities

4.1 Limitations

There are a number of limitations highlighted in the guidance documents. These are presented in table 14.

Limitation	Description
Extreme sea levels are considered accurate to one decimal place.	The extreme sea levels are considered accurate to one decimal place, two decimal places are provided only to differentiate between nodes on the chainage.
Extreme sea levels do not consider wave impacts	The sea level values presented include effects from the storm surge but do not include any impact on local sea level due to onshore wave action.

Table 14: Limitations of the tidal curve derivation method

The guidance document recognises flaws in the data used to produce the extreme sea levels, this is due to difficulty recording long-term sea level data. However, it is stated that this is the best possible method currently available and uses the most accurate initial conditions available. The limitations are considered acceptable for the accuracy required in a flood risk assessment therefore the extreme sea level curves will be used to assess flooding in Lowestoft due to the Third Crossing Development.

5 Figures

Final tidal curves

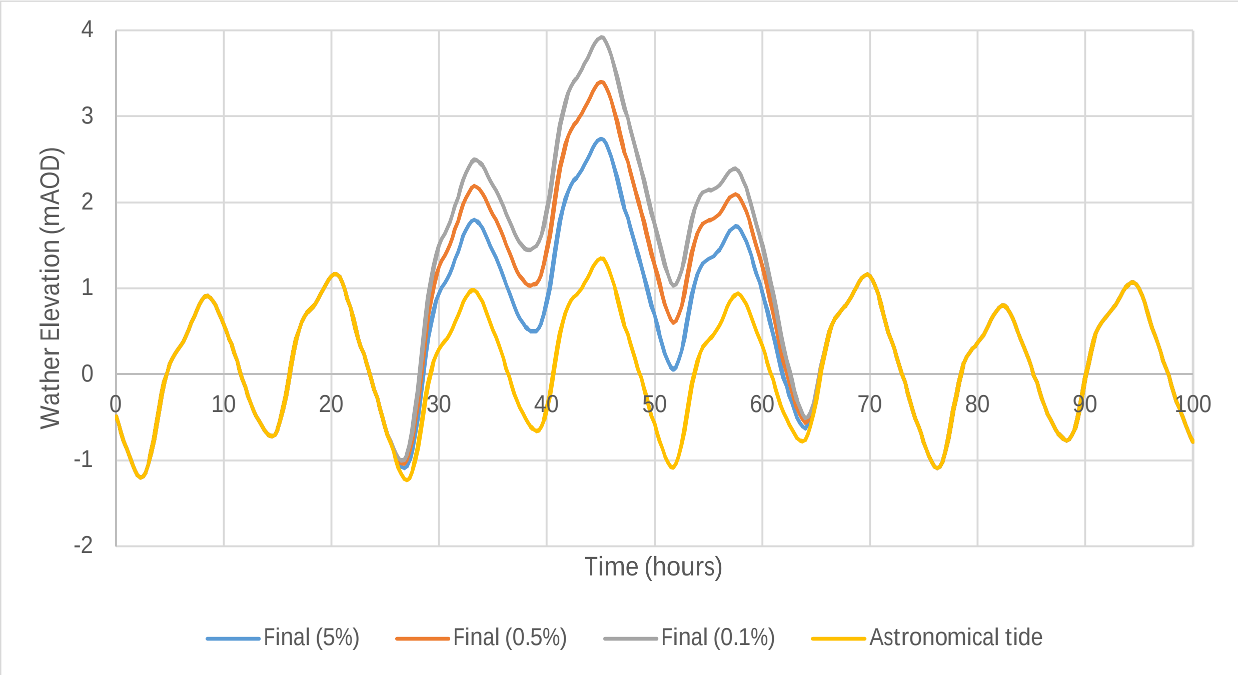


Figure A1: Final design event tidal curves

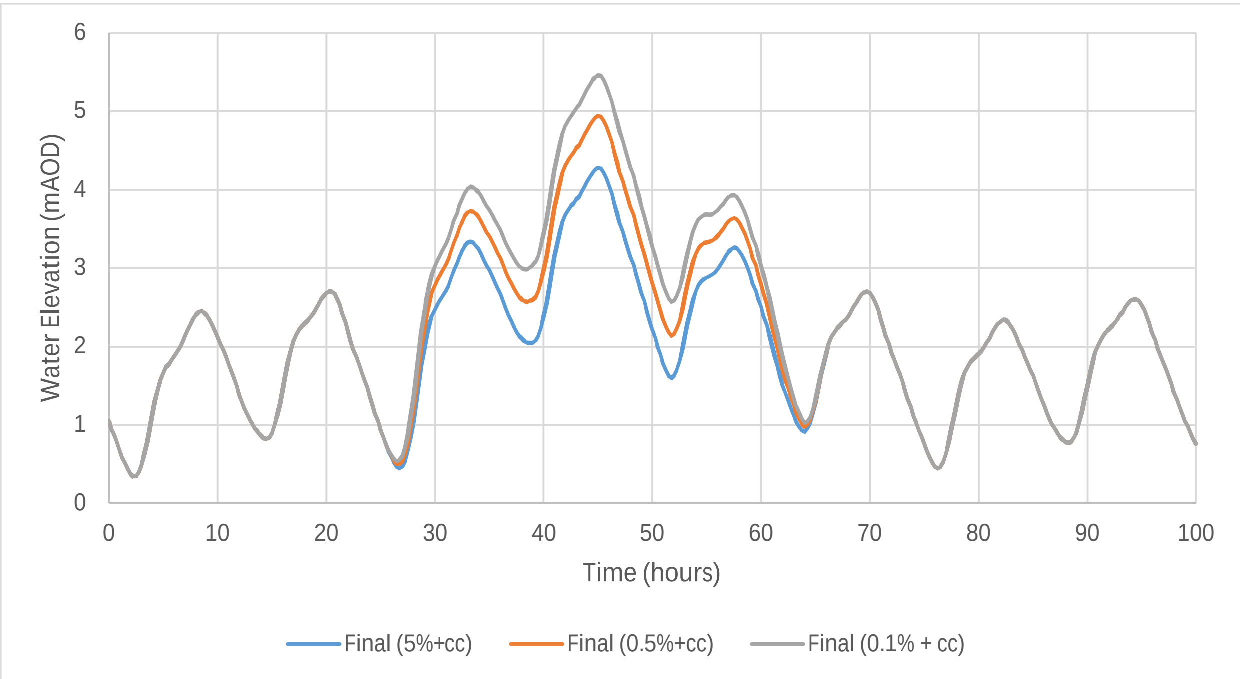


Figure A2: Final present day climate change scenario tidal curves (based on NPPF-Table 3 probability scenario)

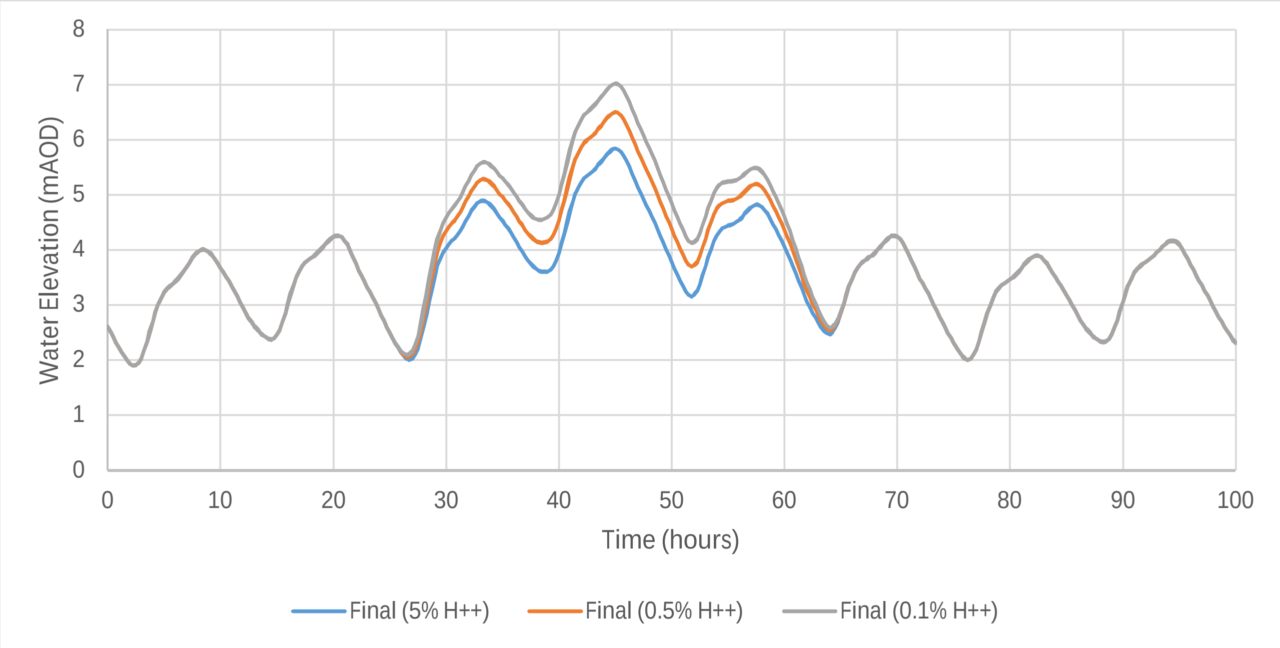


Figure A3: Final H++ scenario tidal curves

9 Appendix 3 to Annex B

9.1 Fluvial calculations record

CALCULATION CONTROL SHEET
PROJECT: Lake Lothing, Third Crossing
PART OF PROJECT: Hydrology calculations
CALCULATION TITLE: FEH Calculation Record
FILE LOCATION: G:\1403\7.0 Projects\7.05 Live Projects\1073877 Lake Lothing\09 Documents\Hydrology\Report

CALCULATION SUMMARY
This report provides a record of the calculations and decisions made during design flood estimation using the techniques of the Flood Estimation Handbook (Institute of Hydrology, 1999).
Purpose of Calculations To derive design hydrographs and peak flows for three catchments that flow into Lake Lothing in Lowestoft.

CHECKING AND REVIEW STATUS					
Rev	**Purpose**	**Author**	**Reviewed**	**Authorised**	**Date**
1	Draft for model build	DE	JH	TJ	29/03/17

REVISION HISTORY			
Revision Ref./ Date Issued	**Date**	**Purpose and description of Amendments**	**Issued to**
1	03/2017	Draft version for hydraulic model update	

Abbreviations

AM .... Annual Maximum

AREA............................ Catchment area (km^2)

BFI................................ Base Flow Index

BFIHOST .... Base Flow Index derived using the HOST soil classification

CD .... Catchment Descriptors

CFMP .... Catchment Flood Management Plan

CPRE .... Council for the Protection of Rural England

FARL .... FEH index of flood attenuation due to reservoirs and lakes

FEH .... Flood Estimation Handbook

FSR .... Flood Studies Report

HOST .... Hydrology of Soil Types

NRFA............................ National River Flow Archive

POT .... Peaks Over a Threshold

QMED........................... Median Annual Flood (with return period 2 years)

RaDAR .... Radio Detection and Ranging

ReFH .... Revitalised Flood Hydrograph method

SAAR............................ Standard Average Annual Rainfall (mm)

SPR .... Standard percentage runoff

SPRHOST .... Standard percentage runoff derived using the HOST soil classification

Tp(0)............................. Time to peak of the instantaneous unit hydrograph

UAF .... Urban Adjustment Factor

URBAN......................... Flood Studies Report index of fractional urban extent

URBEXT1990 .... FEH index of fractional urban extent

URBEXT2000 .... Revised index of urban extent, measured differently from URBEXT1990

WINFAP-FEH .... Windows Frequency Analysis Package – used for FEH statistical method

1. Introduction

This calculation record document provides a record of the calculations and decisions made during flood estimation. It will often be complemented by more general hydrological information given in a project report. The information given here should enable the work to be reproduced in the future. This version of the record is for studies where flood estimates are needed at multiple locations.

2. Method Statement

Table 2.1: Overview of study

Item	Comments
Purpose of study Give an overview which includes: Purpose of study Approx. no. of flood estimates required Peak flows or hydrographs?	***Standard introduction*** This document will present the flood estimation calculations for three small tributaries that discharge directly into the Lake Lothing. Peak flows and hydrographs are required.
Description of catchment Brief description of catchment, or reference to section in accompanying report	Lake Lothing is a tidally influenced, salt water lake in Lowestoft through which part of the Norfolk Broads discharges into the North Sea. The largest fluvial inflow source is from Mutford Lock which controls flow into Lake Lothing from Oulton Broad. This lock is in daily use as it provides access to the Norfolk Broads for sailing vessels. There are 3 smaller catchments flowing directing into Lake Lothing Harbour. Kirkley stream (National Grid Reference: 653900, 292650) and two smaller, unnamed catchments (National Grid Reference: 653400 292750 and 654050 292850).
Flood estimates required	Flow hydrographs / peak flow estimates are required for: 20 (5% AEP), 200 (0.5% AEP), 1000 (0.1% AEP) , 20+cc, 200+cc, 1000+cc years flood design events.

Table 2.2: Source of flood peak data

Was the HiFlows UK dataset used? If so, which version? If not, why not? Record any changes made	Yes – As part of the pooling group analysis (HiFlows, v4.1).

Table 2.3: Gauging Stations (flow or level data available at sites or nearby donor catchments)

Watercourse	Station Name	Gauging authority number	NWA number (used in FEH)	Grid reference	Catchment Area (km^2)	Rating?	Period of available data
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

No suitable Gauge Station was found in the vicinity of the study catchments.

Table 2.4: Data available at each Gauging Station

Station Name	Start & end of data in Hi Flows UK	Update from EA for this study? Dates?	Suitable for QMED?	Suitable for pooling?	Data Quality Check needed?
N/A	N/A	N/A	N/A	N/A	N/A
Comments on data quality (inc. rating) and any checks made	N/A				

Table 2.5: Rating Equations

Station Name	**Type of rating** e.g. theoretical, empirical; degree of extrapolation	Rating review needed?	**Reasons** e.g. availability of recent flow gaugings, amount of scatter in the rating.
N/A	N/A	N/A	N/A

Table 2.6: Other data available

Item	Comments
Flow / level gauges	Level gauge at the Lock records levels within Oulton Broads Level gauge at A47 Bascule Bridge (eastern end of Lake Lothing) Data for both gauges within the study area has been supplied by the Environment Agency for the period January 2007 – August 2016.
Historic flood data	Tidal flooding of properties on and near the coastline.
Extra data for other sites in pooling groups	none
Flow data for events	none
Rainfall data for events	none
Potential evaporation data / MORECS data	none
Results from previous studies / models	Lowestoft Tidal defences: Additional Modelling Studies, 2014 Lowestoft Estuary Inception Study, 2013 Lowestoft Tidal flood Study, 2013 1D BESL model (simulates Oulton broads fluvial system)

Table 2.6: Other data available

Item	Comments
Other data (e.g. Groundwater, tidal	Lake Lothing is predominately tidally driven.

Table 2.7: Initial choice of approach

Item	Comments
Outline the conceptual model, addressing questions such as: • Where are the main sites of interest? • What is likely to cause flooding at those locations? (peak flows, flood volumes, combinations of peaks, groundwater, snowmelt, tides…) • Might those locations flood from runoff generated on part of the catchment only, e.g. downstream of a reservoir? • Is there a need to consider temporary debris dams that could collapse?	The study area for the hydraulic assessment covers three small tributaries which flow into Lake Lothing in Lowestoft harbour. These will be used as point inflows into an existing 2D Lake Lothing model to simulate the fluvial inflow. While the main source of flow in Lake Lothing is tidal, including the riverine inflows will allow the 'worst case' flood scenario to be modelled. Standard FEH approach – ReFH and FEH Statistical method will be used to derive the flow estimated for the small catchments. A preferred method will be chosen based on the analysis of the methods used.

Table 2.7: Initial choice of approach

Item	Comments
Any unusual catchment features to take into account? e.g. 6 highly permeable – avoid ReFH if BFIHOST>0.65, consider permeable catchment adjustment for statistical method if SPRHOST<20% 7 highly urbanised – avoid standard ReFH if URBEXT1990>0.125; consider FEH Statistical or other alternatives; consider method that can account for differing sewer and topographic catchments 8 pumped watercourse – consider lowland catchment version of rainfall-runoff method **9** major reservoir influence (FARL<0.90) – consider flood routing, extensive floodplain storage – consider choice of method carefully	For Kirkley stream (11.07km² catchment area) 1 BFIHOST is 0.638 and SPRHOST is 30.59%. The catchment is therefore permeable. 2 URBEXT1990 and 2000 are 0.1547 and 0.1549 respectively. This relates to the 'Heavily Urbanised' category. 3 FARL is 1 for Kirkley Stream so no extensive floodplain storage. For Catchment 1, 653400 292750 (0.56km² catchment area) 4 BFIHOST is 0.721 and SPRHOST is 27.02%. The catchment is therefore highly permeable and the ReFH method is likely to be unsuitable. ♦ URBEXT1990 and 2000 are 0.4219 and 0.4799 respectively. This relates to the 'Very heavily urbanised' category. ♦ FARL is 1 for Catchment 1 so no extensive floodplain storage. For Catchment 2, 654050 292850 (0.71 km² catchment area) 5 BFIHOST is 0.755 and SPRHOST is 22.32%. The catchment is therefore highly permeable. ♦ URBEXT1990 and 2000 are 0.5158 and 0.5193 respectively. This relates to the 'Very heavily urbanised' category. ♦ FARL is 1 for Catchment 2 so no extensive floodplain storage.
Is FEH appropriate? (it may not be for very small, heavily urbanised or complex catchments) **Outline the choices available and whether appropriate for the sites of interest:** 10 FEH Statistical (single site or pooled?) 11 FEH rainfall-runoff 12 Revitalised rainfall runoff 13 IoH124 14 Rational Method **15** Hybrid approach?	Small catchments (0.71km² and 0.56km²) for the two unnamed catchments therefore FEH may not be appropriate however calculations are carried out to confirm. High BFIHOST for two unnamed catchments therefore ReFH may not be appropriate however calculations are carried out to confirm. Urbanisation has been taken into account in ReFH and FEH Statistical methods. Choices to be used are: 1 FEH Statistical Pooled analysis 2 ReFH

Table 2.7: Initial choice of approach

Item	Comments
Initial choice of method(s) and reasons 16 Will the catchment be split into sub-catchments? If so, how?	ReFH and FEH Statistical Pooled analysis to be undertaken for 3 catchments flowing into Lake Lothing. These are: • Kirkley Stream • Catchment 1, 653400 292750 Catchment 2, 654050 292850
Software to be used (with version numbers)	FEH CD_ROM v3.0[14] WINFAP-FEH v3[15] (with HiFlows v4.1)

3. Locations where flood estimates are required

The table below lists the locations of hydrological points of interest (subject sites). The site codes listed below are used in all subsequent tables to save space. A map showing the hydrological boundaries and downstream points of interest is shown in Figure 3.1.

Table 3.1: Summary of hydrological points of interest (all subject sites)

Site code	Watercourse	Site	Grid Reference		Catchment area from FEH WEB (km^2)	Revised area if required (km^2)
1	Kirkley Stream	Kirkley Stream	653900	292650	11.07	-
2	Unnamed Catchment	Catchment 1	653400	292750	0.56	-
3	Unnamed Catchment	Catchment 2	654050	292850	0.71	-
Reasons for choosing hydrological points of interest (subject sites)	Kirkley Stream is the point of confluence with Lake Lothing and the area represents the full catchment. Catchment 1 is the point of confluence with Lake Lothing and the area represents the full catchment. Catchment 2 is the point of confluence with Lake Lothing and the area represents the full catchment.					
How catchment descriptors were checked	Catchment area was checked by inspection of Ordnance Survey maps and LiDAR data. Checks of soil types and drainage show that the soil type are sandy (Kirkley and Catchment 1) and loamy (catchment 2) with natural drainage. This correlates with the BFIHOST values for the catchments.					

[14] FEH CD-ROM v3.0 © NERC (CEH). © Crown copyright. © AA. 2009. All rights reserved.

[15] WINFAP-FEH v3 © Wallingford HydroSolutions Limited and NERC (CEH) 2016.

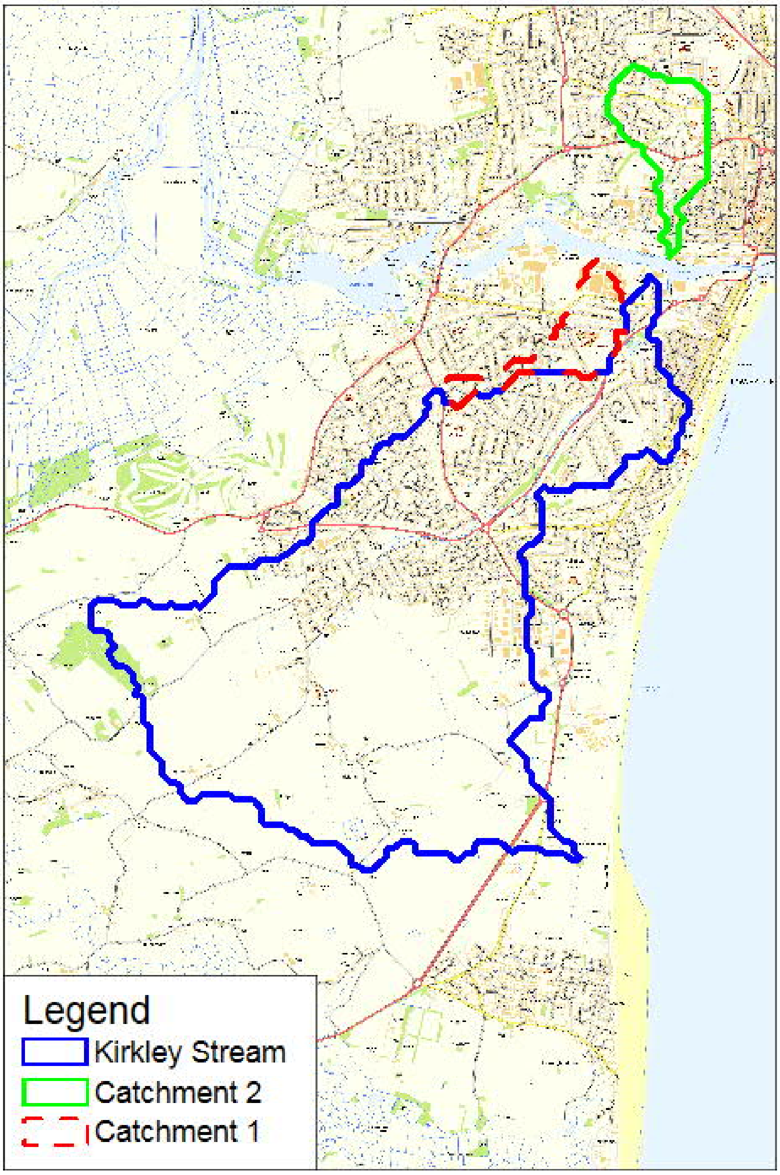


Figure 3-1: Map of catchments

Catchment Descriptors from FEH CD ROM Version 3 at the five hydrological points of interest have been extracted for use on this study.

For the design runs, the URBEXT 2000 values were updated to 2016 for each sub-catchment. The method used to adjust QMED for urbanisation, for both subject sites and donor sites, is that published in Kjeldsen (2010)[16] in which PRUAF (percentage runoff urban adjustment factor) is calculated from BFIHOST. The result will differ from that of WINFAP-FEH v3.0.003 which does not correctly implement the urban adjustment of Kjeldsen (2010). Significant differences will occur only on urban catchments that are highly permeable.

[16] Kjeldsen, T. R. (2010). Modelling the impact of urbanization on flood frequency relationships in the UK. Hydrol. Res. 41. 391-405.

$PRUAF = 1 + 0.47 * URBEXT_{2000}(BFIHOST/(1-BFIHOST))$

N.B. The FEH CD-ROM Version 3 provides URBEXT values for the year 2000 ($URBEXT_{2000}$). $URBEXT_{2000}$ is not simply an update of $URBEXT_{1990}$ but it is based on new data produced using different mapping techniques.

Table 3.2 shows the re-statement of the categories of urbanisation distinguished in the FEH according to their URBEXT 1990 values, together with 'equivalent' URBEXT 2000 values.

Table 3.2: Categories of catchment urbanisation related to FEH CDROM (2007)

Category	URBEXT1990	URBEXT2000
Essentially rural	0.000 <_ $URBEXT_{1990}$ < 0.025	0.000 <_ $URBEXT_{2000}$ < 0.030
Slightly urbanised	0.025 _ $URBEXT_{1990}$ < 0.050	0.030 _ $URBEXT_{2000}$ < 0.060
Moderately urbanised	0.050 _ $URBEXT_{1990}$ < 0.125	0.060 _ $URBEXT_{2000}$ < 0.150
Heavily urbanised	0.125 _ $URBEXT_{1990}$ < 0.250	0.150 _ $URBEXT_{2000}$ < 0.300
Very heavily urbanised	0.250 _ $URBEXT_{1990}$ < 0.500	0.300 _ $URBEXT_{2000}$ < 0.600
Extremely heavily urbanised	0.500 _ $URBEXT_{1990}$ _ 1.000	0.600 _ $URBEXT_{2000}$ _ 1.000

In addition to updating URBEXT to 2015 values, URBEXT values were checked and no adjustments were made based on visual inspection of Ordnance Survey maps and neighbouring catchment descriptors. The final values of URBEXT 2015 (and all other catchment descriptors) used in the analysis and reason for any adjustments are provided in Table 3.3.

Table 3.3 shows the catchment descriptors to be used for each point of interest.

Table 3.3: Catchment descriptors used in analysis

CD			
Grid Ref	Kirkley Stream	Catchment 1	Catchment 2
AREA	11.07	0.56	0.71
ALTBAR	11	7	18
ASPBAR	2	22	185
ASPVAR	0.2	0.58	0.71
BFIHOST	0.638	0.721	0.755
DPLBAR	5.33	1.02	1.14
DPSBAR	8.4	5.3	27
FARL	1	1	1

FPEXT	0.391	0.3482	0.0912
FPDBAR	3.081	1.138	0.323
FPLOC	0.858	0.84	0.478
LDP	8.51	2.44	1.88
PROPWET	0.27	0.27	0.27
RMED-1H	11.1	10.9	11
RMED-1D	30.2	28.7	28.8
RMED-2D	38	36.3	35.6
SAAR	602	599	600
SAAR4170	610	605	600
SPRHOST	30.59	27.02	22.32
$URBCONC_{1990}$	0.844	0.881	0.924
$URBEXT_{1990}$	0.1547	0.4219	0.5158
$URBLOC_{1990}$	0.549	1	0.912
$URBCONC_{2000}$	0.84	0.94	0.964
$URBEXT_{2000}$	0.1549	0.4799	0.5193
$URBLOC_{2000}$	0.586	0.947	0.961
C	-0.02436	-0.02489	-0.02484
D1	0.32889	0.31713	0.31822
D2	0.36447	0.3667	0.35466
D3	0.22802	0.2359	0.23607
E	0.31795	0.31713	0.31925
F	2.46533	2.45479	2.45752
C(1km)	-0.024	-0.025	-0.024
D1(1km)	0.31	0.322	0.31
D2(1km)	0.372	0.346	0.372
D3(1km)	0.237	0.231	0.237
E(1km)	0.317	0.318	0.317
F(1km)	2.46	2.461	2.46
Adjusted URBEXT[17] $_{2016}$	0.1602	0.4964	0.5372
Adjusted URBEXT[18] $_{2016}$	0.1667	0.4546	0.5558
Notes on changes made:	$URBEXT_{2000}$ factor used = 1.034 $URBEXT_{1990}$ factor used = 1.077	$URBEXT_{2000}$ factor used = 1.034 $URBEXT_{1990}$ factor used = 1.077	$URBEXT_{2000}$ factor used = 1.034 $URBEXT_{1990}$ factor used = 1.077

4. Statistical method

The FEH statistical method constructs a flood frequency curve based on the estimation of QMED, which is then used to calculate peak flow estimates for each return period. FEH methods should not normally be applied on heavily urbanised catchments (with an URBEXT value greater than 0.5) or catchments smaller than 0.5km². Catchment 2 has a URBEXT was of greater than 0.5, in this case the ReFH urban method is favoured.

The statistical method was carried out for the three locations at the points of hydrological interest mentioned in Section 2.

For this study, the sub-catchments are un-gauged, therefore the QMED value has been estimated based on catchment descriptors extracted from FEH CD-ROM 3 and the most recent equation published by CEH for QMED estimations. No potential donor catchments were found close to the

[17] $URBEXT_{2000}$ Adjustment

[18] $URBEXT_{1990}$ Adjustment

subject sites. Statistical pooling analysis was undertaken using FEH WINFAP software to produce a growth curve and calculate flood flows for range of return periods.

The final FEH statistical method flow estimates for the sub-catchments are presented at the end of the section in Table 4.7 for the following range of return periods: 20, 20+cc, 200, 200+cc, 1000 and 1000+cc

The initial estimates of QMED are displayed in Table 3.3. They are based on catchment descriptors alone and use the following equation:

$$QMED = 8.3062 AREA^{0.8510} 0.1536^{\left(\frac{1000}{SAAR}\right)} FARL^{3.4451} 0.0460^{BFIHOST^2}.$$

Table 4.1: Search for Donor Sites (if applicable)

Comment on potential donor sites: 17 Number of potential donor sites available 18 Distances from subject site 19 Similarity in terms of AREA, BFIHOST, FARL and other catchment descriptors 20 Quality of flood peak data **21** Include a map if necessary. Note that donor catchments should usually be rural.	No Donor sites are applicable for the catchments in this report.

Methods:
AM – Annual maxima; POT – Peaks over threshold; DT – Data transfer; CD – Catchment descriptors alone.
When QMED is estimated from POT data, it should also be adjusted for climatic variation.

Table 4.2: Donor sites chosen and QMED adjustment factors

NWA number	Watercourse	Station	Reason	AM or POT	QMED from flow data (A)	QMED from CDs (B)	Adj ratio (A/B)
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
If a spreadsheet has been used to calculate QMED insert link here: G:\1403\7.0 Projects\7.05 Live Projects\1073877 Lake Lothing\09 Documents\Hydrology\Calculations\Qmed Calculation.xls							

The data transfer procedure is the revised one from Science Report SC050050. The QMED adjustment factor A/B for each donor site is given in Table 4.3. This is moderated using the power term, a, which is a function of the distance between the centroids of the subject catchment and the donor catchment. The final estimate of QMED is $(A/B)^a$ times the initial estimate from catchment descriptors.

$$a = 0.4598*\exp(-0.020*d_{ij})+(1-0.4598)*\exp(-0.4785*d_{ij})$$

If more than one donor has been used, use multiple rows for the site and give the weights used in the averaging. Record the weighted average adjustment factor in the penultimate column.

Table 4.3: Estimation of QMED at subject sites

Site Code	Method	Initial QMED from CD's (m^3/s)	Initial QMED from CD's (m^3/s)				If more than one		Final estimate of QMED (m^3/s)
			NRFA no. used	Distance between centroids d_{ij}	Power term, a	Moderated QMED adjustment factor, $(A/B)^a$	Weight	Weighted ave. adjustment	
Kirkley Stream	CD	0.99	-	-	-	-	-	-	0.99
Catchment 1	CD	0.08	-	-	-	-	-	-	0.08
Catchment 2	CD	0.10	-	-	-	-	-	-	0.10
Are the values of QMED consistent, for example at successive points along the watercourse and at confluence?					Successive QMED is not appropriate for this study as all catchments flow into Lake Lothing independent of each other				

Pooling groups were derived using the revised procedures from Science Report SC050050 (2008). Several subject sites may use the same pooling group. The composition of the edited pooling groups is given in the Appendix.

Table 4.4: Derivation of pooling groups

Name of Group	**Site code for which group initially derived**	**Subject site treated as gauged?** (enhanced single site analysis)	**Changes made to default pooling group with reasons.** Note also any sites that were investigated but retained in the group.	**Weighted average L-moments,** L-CV and L-skew (before urban adjustment)
Kirkley	**Kirkley Stream**	No	Four stations removed due to low SPRHOST values. One station removed due to low FARL value. Four sites added to edited pooling group to total 526 years.	$L\text{-}CV_{initial} = 0.231$ $L\text{-}Skew_{initial} = 0.061$ $L\text{-}CV_{final} = 0.244$ $L\text{-}Skew_{final} = 0.106$
C1	**Catchment 1**	No	One station removed for short record. Three stations removed due to low SPRHOST values. One station removed due to low FARL value. One station removed for high discordancy. Four sites added to edited pooling group to total 520 years.	$L\text{-}CV_{initial} = 0.218$ $L\text{-}Skew_{initial} = 0.199$ $L\text{-}CV_{final} = 0.237$ $L\text{-}Skew_{final} = 0.243$
C2	**Catchment 2**	No	One station removed for short record. Four stations removed due to low SPRHOST values. One station removed due to low FARL value. One station removed for high discordancy. Six sites added to edited pooling group to total 533 years.	$L\text{-}CV_{initial} = 0.231$ $L\text{-}Skew_{initial} = 0.234$ $L\text{-}CV_{final} = 0.219$ $L\text{-}Skew_{final} = 0.228$

If a spreadsheet has been used for pooling group growth curves insert link here:
G:\1403\7.0 Projects\7.05 Live Projects\1073877 Lake Lothing\09 Documents\Hydrology\Calculations:

- kirkley stream_Results_FEH statistical.xls
- catchment 1_Results_FEH statistical.xls
- catchment 2_Results_FEH statistical.xls
-

Notes:
The weighted average L-moments, before urban adjustment, can be found at the bottom of the Pooling-group details window in WINFAP-FEH.

Table 4.5: Derivation of flood growth curves at each subject site

Site code	**Method:**	**Distribution(s) chosen and reason, include goodness of fit parameters**	**Any urban adjustment or permeable adjustment?**	**Parameters of chosen distribution(s)**
Kirkley	P	GL and GEV recommended by FEH, with GL producing a steeper growth curve that is more conservative at higher return periods	V3 (Kjeldsen, 2010) applied to growth curve	Location: 1.000 Scale: 0.227 Shape: -0.131 Bound: -0.741
C1	P	GL and GEV recommended by FEH, with GL producing a steeper growth curve that is more conservative at higher return periods	V3 (Kjeldsen, 2010) applied to growth curve	Location: 1.000 Scale: 0.163 Shape: -0.331 Bound: -0.005

Site code	Method:	Distribution(s) chosen and reason, include goodness of fit parameters	Any urban adjustment or permeable adjustment?	Parameters of chosen distribution(s)
C2	P	GL and GEV recommended by FEH, with GL producing a steeper growth curve that is more conservative at higher return periods	V3 (Kjeldsen, 2010) applied to growth curve	Location: 1.000 Scale: 0.147 Shape: -0.324 Bound: 0.547
Notes: Methods: SS – Single site; P – Pooled; ESS – Enhanced single site; J – Joint analysis A pooling group (or ESS analysis) derived at one gauge can be applied to estimate growth curves at a number of ungauged sites. Each site may have a different urban adjustment, and therefore different growth curve parameters. Urban adjustments are all carried out using the v3 method: Kjeldsen (2010). Growth curves were derived using the revised procedures from Science Report SC050050 (2008).				

Table 4.6: Growth Curves

Site Code	Growth Curve Factor for the following return periods	
	20	200
Kirkley	1.82	2.73
C1	1.82	3.36
C2	1.72	3.06

Table 4.7 provides the final peak flow estimates calculated using the statistical method with an urban adjustment factor (UAF) of 1.036 applied to the $QMED_{rural}$ and urban adjustment applied to the growth curves utilising Kjeldsen, Version 3 (2010).

Table 4.7: Statistical Method Estimate of Peak Flows

Name	Flood peak (m³/s) for the following return periods in years								
	20	20cc (25%)[19]	20cc (65%)[20]	200	200cc (25%)[6]	200cc (65%)[7]	1000	1000cc (25%)[6]	1000cc (65%)[7]
Kirkley	1.79	2.24	2.95	2.7	3.38	4.46	5.08	6.35	8.38
C1	0.15	0.19	0.25	0.27	0.34	0.45	0.54	0.68	0.89
C2	0.17	0.21	0.28	0.3	0.38	0.5	0.65	0.81	1.07

Table 4.7 provides the peak flow estimates calculated using the statistical method with an urban adjustment factor (UAF) applied to the $QMED_{rural}$; Kirkley = 1.21, Catchment 1 = 1.79, Catchment 2 = 2.04.

[19] Based on Anglian river basin district for a design life of 100 years – central value. (*Adapting to climate change – Guidance 2016)*

[20] Based on Anglian river basin district for a design life of 100 years – upper value. (*Adapting to climate change – Guidance 2016)*

5. Revitalised FSR/FEH rainfall runoff method

The Revitalised Flood Hydrograph (ReFH) method was developed by CEH to provide a more realistic representation of flood hydrology. This method is generally believed to perform reasonably well on most catchments. However, this method is not currently appropriate for either 'heavily urbanised' or 'very heavily urbanised' based on the values of URBEXT2000 extracted from FEH CD-ROM 3 because its summer design event was only calibrated on seven urban catchments, and further research to improve the ReFH method has been recommended.

The ReFH Urban is an enhancement of the existing ReFH rainfall-runoff technique in order to better estimate design flows in heavily or very heavily urbanised catchments. This alternative method which is based on the study published by Kjeldsen (2009) can be applied when there is a difference between the boundaries of the topographic and sewer catchments.

Peak flow estimates from the Revitalised FEH rainfall-runoff model calculated without using urban subdivisions for this heavily urbanised watercourse, however these flows will be calculated separately to determine the impact of using these extra calculations on flow estimates compared to those calculated without urban subdivisions.

Parameters used to derive the ReFH method hydrographs are provided in Table 5.1 and 5.2. For this study, the critical storm duration of each sub-catchment has been calculated in order to generate the maximum peak flow estimate each catchment individually.

The ReFH method flow estimates for each sub-catchment are presented in Table 5.3.

Table 5.1: Parameters for ReFH model

Site Code	**Method** OPT: Optimisation BR: Baseflow Recession Fitting CD: Catchment Descriptors DT: Data Transfer	T_p (hours)	C_{max} (mm) Maximum storage capacity	BL (hours) Baseflow lag	BR Baseflow Recharge
Kirkley	CD	6.053	533.1	38.011	1.441
C1	CD	1.275	598.78	15.213	1.644
C2	CD	0.698	625.573	13.13	1.728
Brief description of any flood event analysis carried out (further details should be or in a project report)					

Table 5.2 Design events for Standard ReFH method

Site Code	Urban or Rural	**Season of design** (summer or winter)	Storm Duration (hours)	**Storm area for ARF** (if not catchment area)
Kirkley	Urban	Summer	29.5	-
C1	Urban	Summer	3.5	-
C2	Urban	Summer	1.7	-
Are the storm durations likely to be changed in the next stage of the study? (e.g. by optimisation within a hydraulic model?)			Storm duration have been optimised for 100 year event.	

Table 5.3: Peak flow estimates from the Revitalised FEH rainfall-runoff model

Site code	Flood peak (m^3/s) for the following return periods in years								
	20	20cc (25%)	20cc (65%)	200	200cc (25%)	200cc (65%)	1000	1000cc (25%)	1000cc (65%)
Kirkley	3.03	3.79	5	5.51	6.89	9.09	9.52	11.9	15.71
C1	0.29	0.36	0.48	0.57	1.72	0.94	1.1	1.38	1.82
C2	0.47	0.59	0.78	0.99	1.23	1.62	2	2.51	3.3

Table 5.4 shows the parameters for the ReFH Urban method for each of the catchments.

Table 5.4: Parameters for ReFH urban model

Site Code	Undeveloped area (km^2))	Paved, draining away from the watercourse (km^2))	Paved, draining towards the watercourse (km^2))	Sewer Capacity (yr RP)	Runoff (%)
Kirkley	8.68	0	2.39	70	70
C1	0.02	0	0.54	30	70
C2	0.67	0	0.04	30	70
Brief description of any flood event analysis carried out (further details should be or in a project report)					

Table 5.5: Design events for ReFH urban model

Site Code	Urban or Rural	Season of design (summer or winter)	Storm Duration (hours)	Storm area for ARF (if not catchment area)
Kirkley	Urban	Winter	11.01	-
C1	Urban	Summer	5.01	-
C2	Urban	Summer	1.03	-
Are the storm durations likely to be changed in the next stage of the study? (e.g. by optimisation within a hydraulic model?)			Storm duration have been optimised for 100 year event.	

The ReFH Urban method combines a flow prediction for paved and unpaved areas within the catchment to create a more realistic flow hydrograph for an urban catchment. This typically results in the combination of a short flashy peak (urban flow) and longer slower peak (rural flow). Appendix A shows the hydrographs for 100 year return period in three catchments.

Table 5.6 shows the peak flows for each of the catchments.

Table 5.6: Peak flow estimates from the revitalised FEH rainfall runoff urban model

Site code	Flood peak (m^3/s) for the following return periods in years								
	20	20cc (25%)	20cc (65%)	200	200cc (25%)	200cc (65%)	1000	1000cc (25%)	1000cc (65%)
Kirkley	3.09	3.86	5.09	5.50	6.88	9.08	8.45	10.57	13.95
C1	0.49	0.61	0.81	0.93	1.16	1.53	1.5	1.87	2.47
C2	1.70	2.12	2.81	3.56	4.44	5.87	5.95	7.43	9.81

6. Summary of results

Peak discharges were calculated for each sub-catchment for the following range of return periods: 20, 20+cc, 200, 200+cc, 1000 and 1000+cc. The following methods were investigated: FEH Statistical and ReFH. Table 6.1 summarises the 200 year peak flows for both methods for all sub-catchments.

Table 6.1: Summary of 100 year return period peak flow estimated for the different methods

Site code	Site name	Peak flow for 200 year return period (m³/s)		
		FEH Statistical	ReFH	ReFH-Urban
Kirkley	Kirkley Stream	2.7	5.51	15.42
C1	Catchment 1	0.27	0.57	0.33
C2	Catchment 2	0.3	0.99	0.62

Table 6.2: Choice of method

Item	Comments
Final choice of method and reasons Include: 10 Reference to type of study 11 Nature of catchment 12 Type of data available	For all catchments a hybrid method for the hydrograph will be adopted. This will use the ReFH Urban hydrograph shape and fit it to the statistical peak. This is because the statistical method is the most suitable method for a catchment of this size and by using the ReFH Urban method for the shape then the short storm periods typical of an urban area is somewhat accounted for.

Table 6.3: Assumptions, limitations and uncertainty

Item	Comments
List the main assumptions made (specific to this study)	
Discuss any particular limitations, e.g. applying methods outside the range of catchment types or return periods for which they were developed	There is a number of limitations with the methods used of the hydrograph derivation. Neither the statistical or standard ReFH methods are suitable for small, heavily urbanised catchments, therefore the use of ReFH Urban for the hydrograph shape negated some of the issues. Using the hybrid method for the catchments (ReFH Urban scaled of statistical peak) negates some of the issues with using the ReFH urban method in a catchment with less urban area whilst still showing a realistic hydrograph shape and storm period.

Item	Comments
Give what information you can on uncertainty in the results – e.g. confidence limits for the QMED estimates using FEH 3 12.5 or the factorial standard error from Science Report SC050050 (2008).	The ReFH urban method is designed to improve the performance of the standard ReFH method in urban catchments therefore there is confidence with this method in catchment 1 and 2.
Comment on the suitability of the results for future studies, e.g. at nearby locations or for different purposes.	The results have made use of the most up-to-date data and methods and could be applied to future studies within Lake Lothing
Give any other comments on the study, for example suggestions for additional work.	N/A

Table 6.4: Checks

Item	Comments
Are the results consistent, for example at confluences?	N/A
What do the results imply regarding the return periods of floods during the period of record?	There are no gauges within the catchments, (only within Lake Lothing itself) therefore it is not possible at this stage to determine the return period of previous flood events within the catchment.
What is the 100-year growth factor? Is this realistic? (The guidance suggests a typical range of 2.1 to 4.0)	The 100-year growth factor • Kirkley stream = 2.43 • Catchment 1 = 2.77 • Catchment 2 = 2.55
If 1000-year flows have been derived, what is the range of ratios for 1000-year flow over 100-year flow?	The 100/1000 year ratio is: • Kirkley stream = 2.12 • Catchment 1 = 2.42 • Catchment 2 = 2.61

Item	Comments
What range of specific runoffs (l/s/ha) do the results equate to? Are there any inconsistencies?	The specific runoff rates: • Kirkley stream = 2.44 • Catchment 1 = 4.82 • Catchment 2 = 4.22
How do the results compare with those of other studies? Explain any differences and conclude which results should be preferred.	There is a Kirkley stream study which shows localised flooding upstream in the catchment. This is consistent with the water levels derived here. There are no previous studies for catchment 1 and 2 that can be used as a comparison.
Are the results compatible with the longer-term flood history? **Are there any amendments to parameters after verification / Calibration?**	There is some flooding due to fluvial sources upstream of Kirkley stream however the main source of flooding in the area is from the tidal levels. There is no flooding events attributed to catchment 1 and 2.
Describe any other checks on the results	

Supporting Information

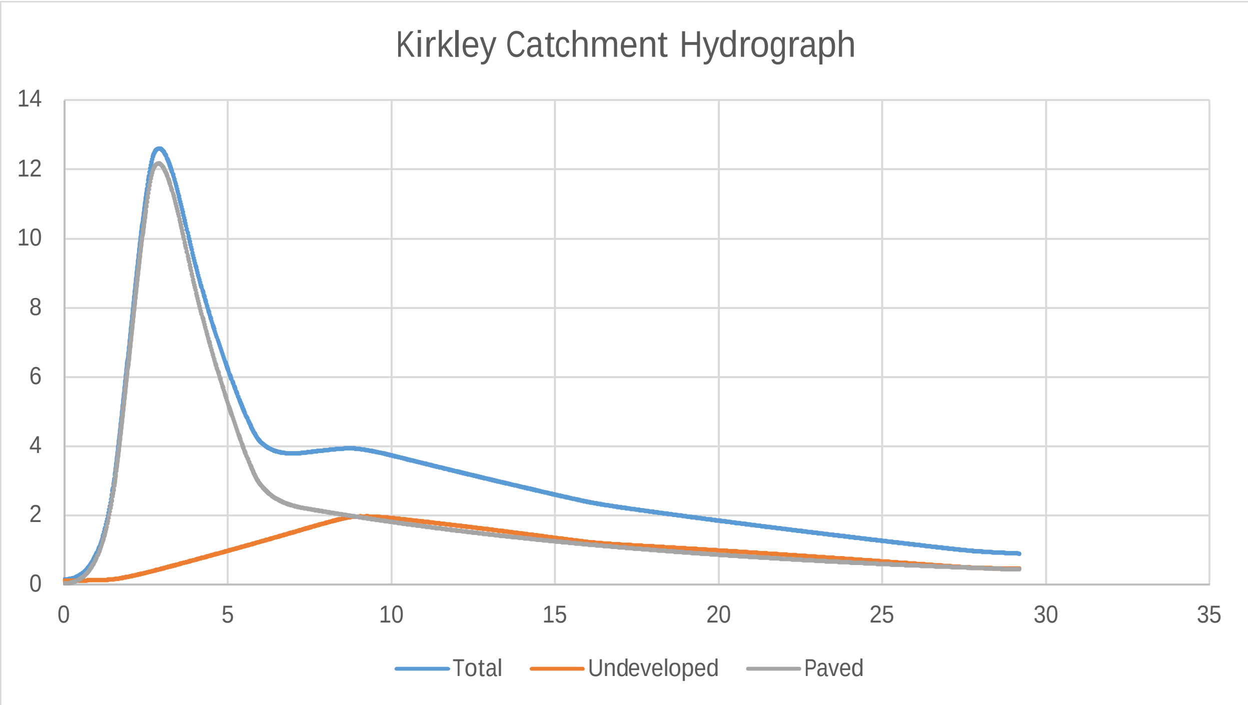


Figure 1A, Kirkley stream hydrograph

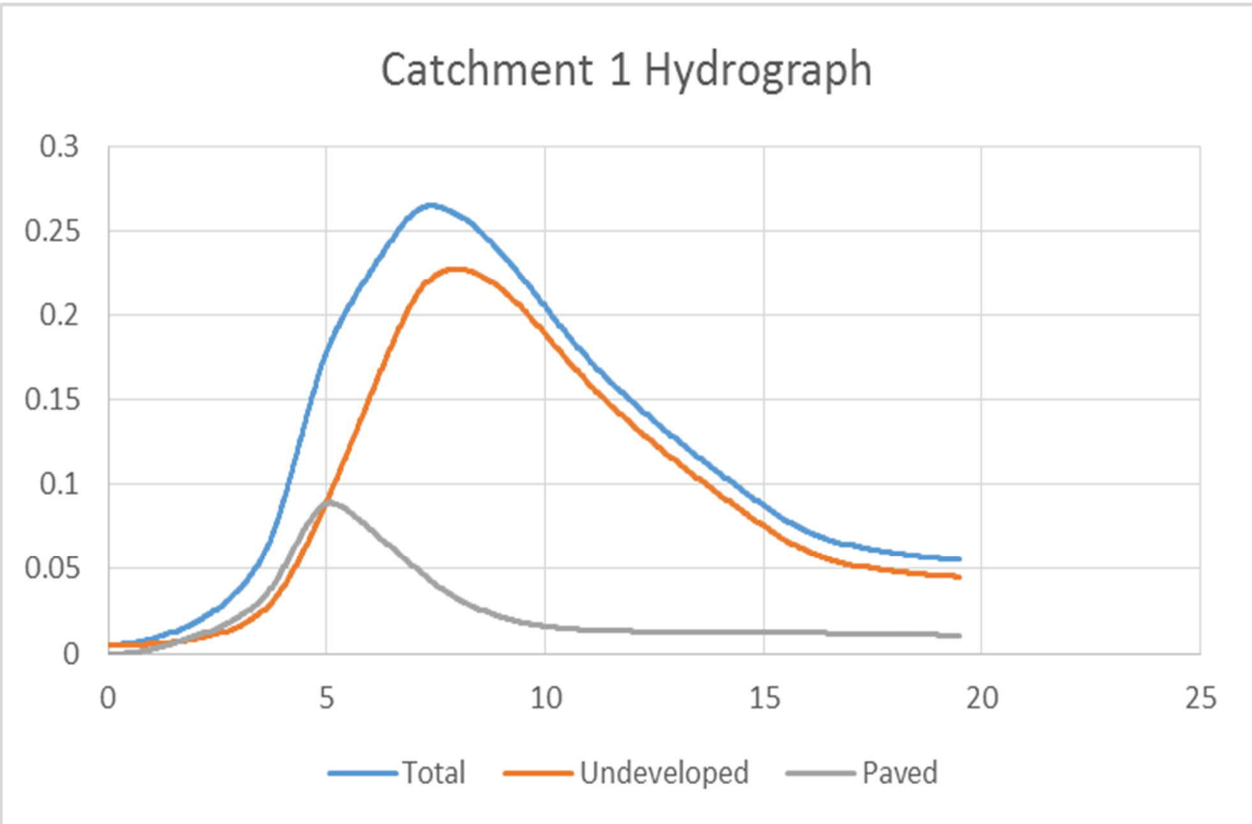


Figure 2A, Catchment 1 Hydrograph

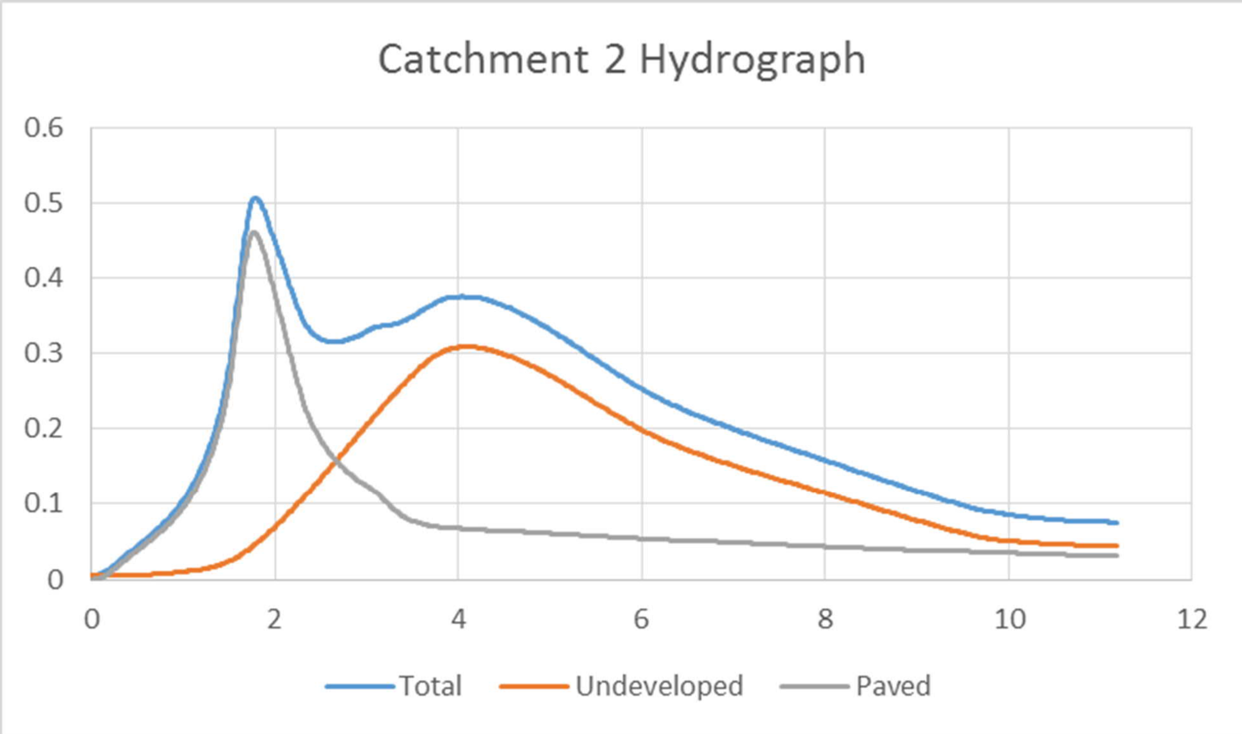


Figure 3A, Catchment 2 Hydrograph

10 Appendix 4 to Annex B

7.4 Flood maps

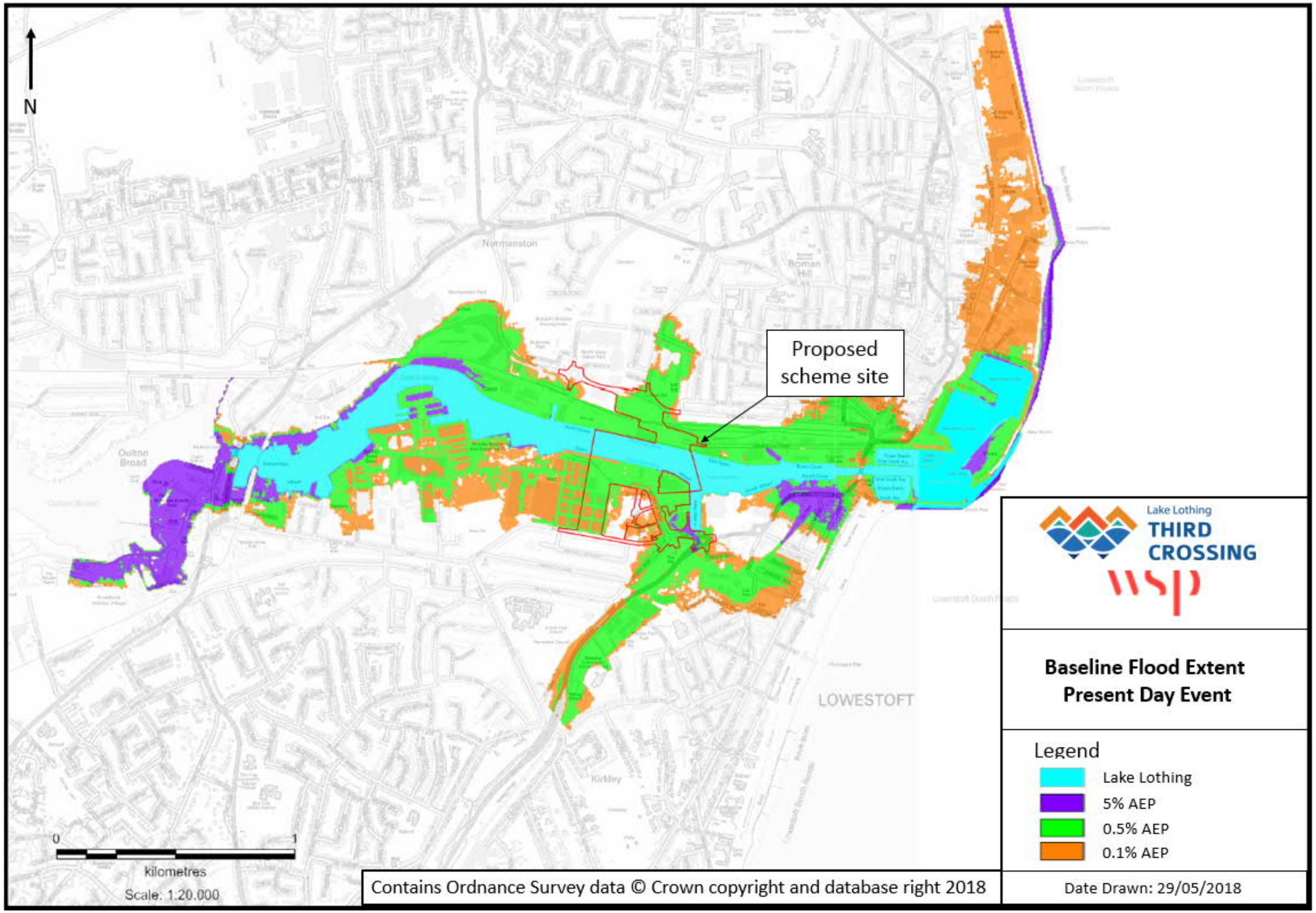


Figure FM1 – Present day baseline events (5% AEP, 0.5% AEP and 0.1% AEP) flood extent

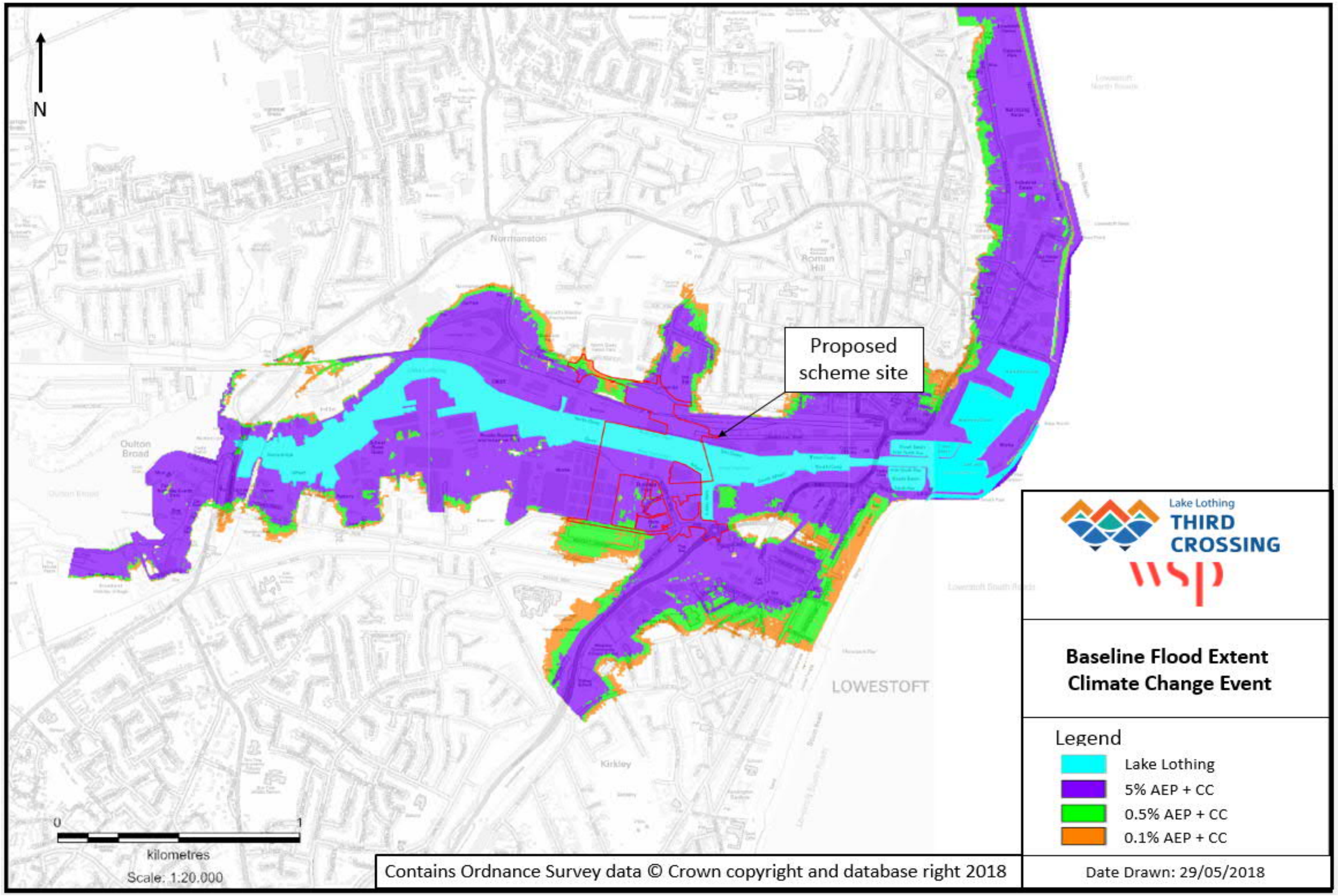


Figure FM2- Climate change baseline events (5% AEP, 0.5% AEP and 0.1% AEP) flood extent

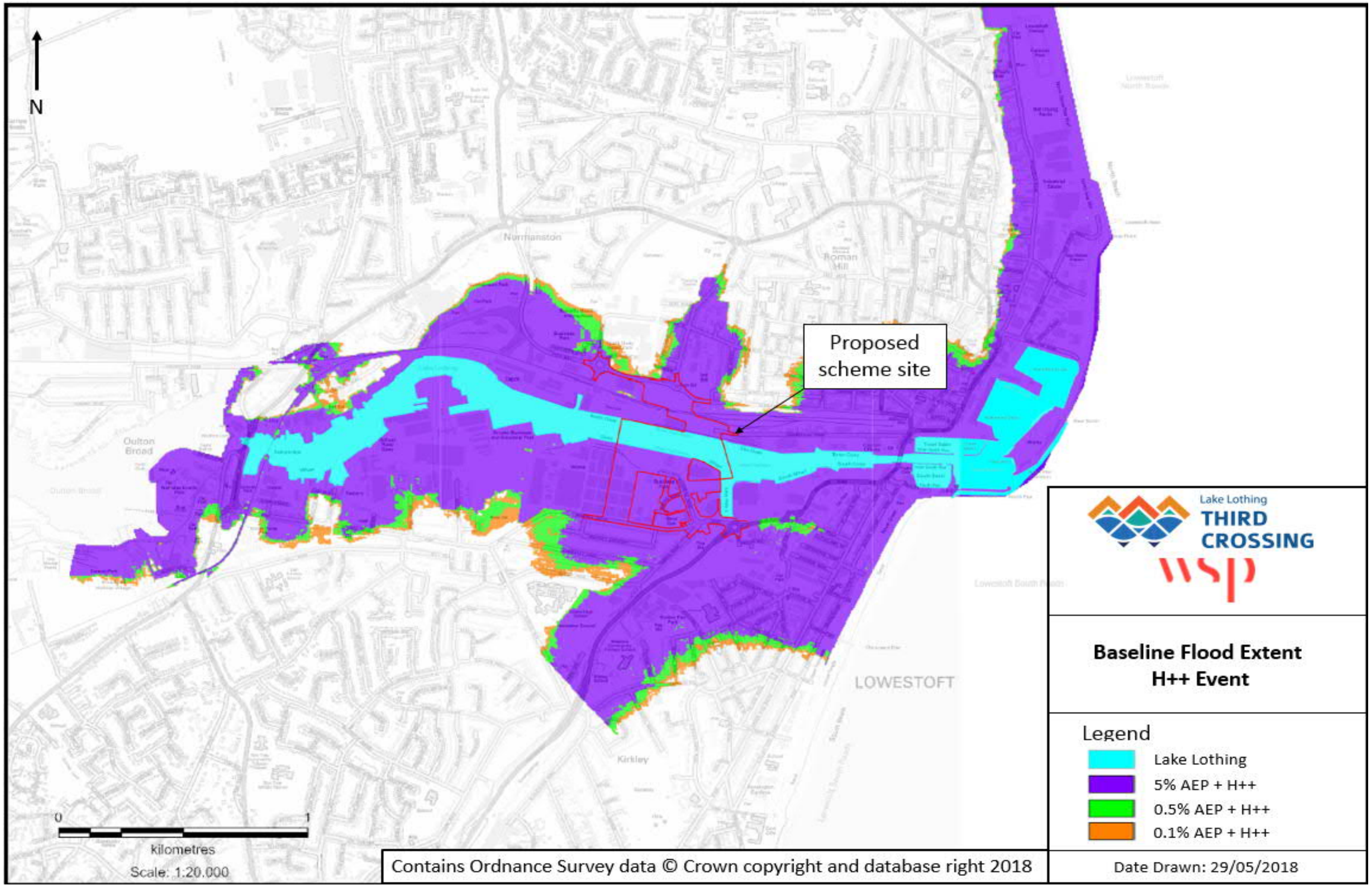


Figure FM3 - H++ baseline events (5% AEP, 0.5% AEP and 0.1% AEP) flood extent

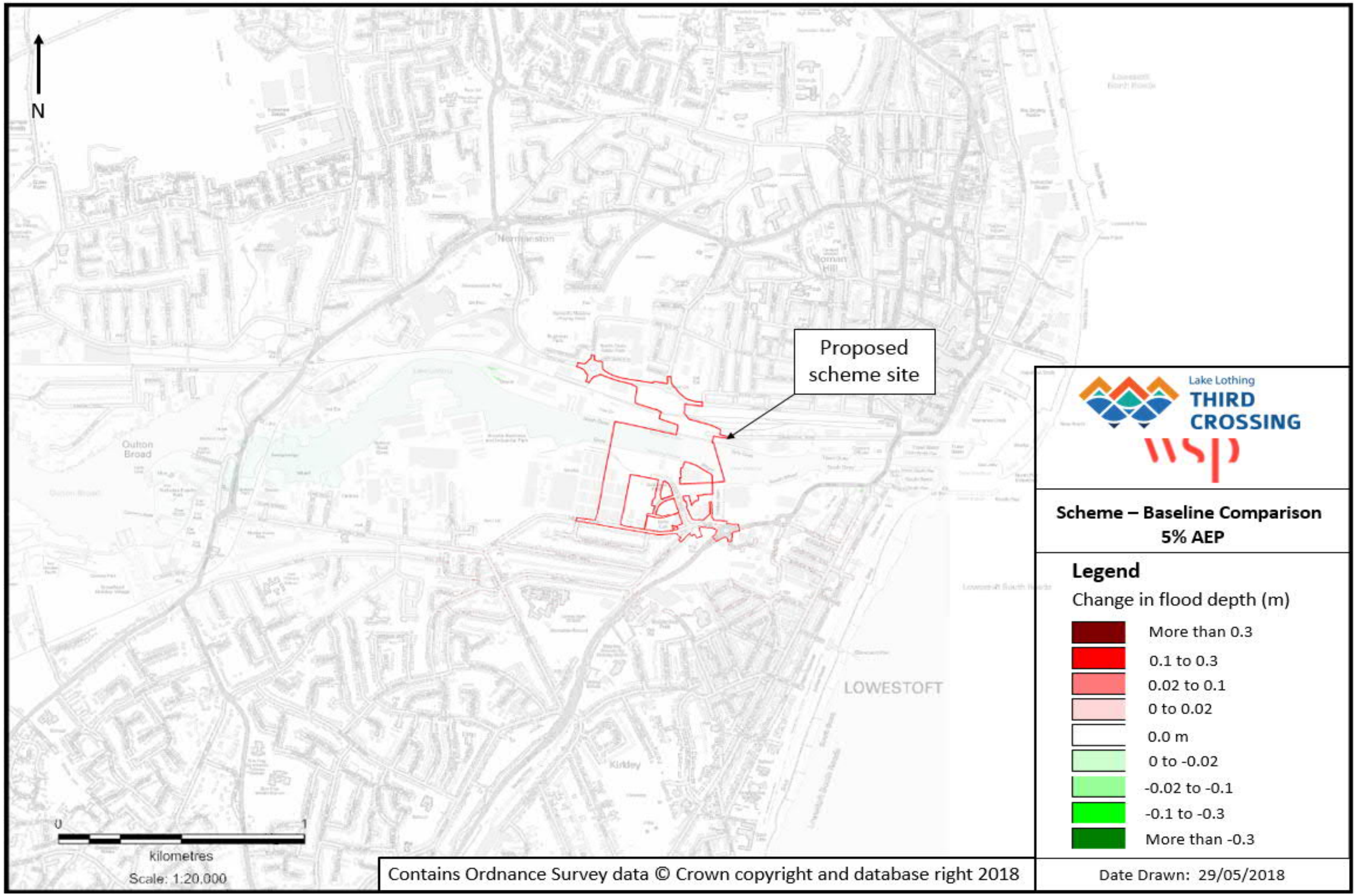


Figure FM4 - 5% AEP present day event comparison (Scheme - Baseline)

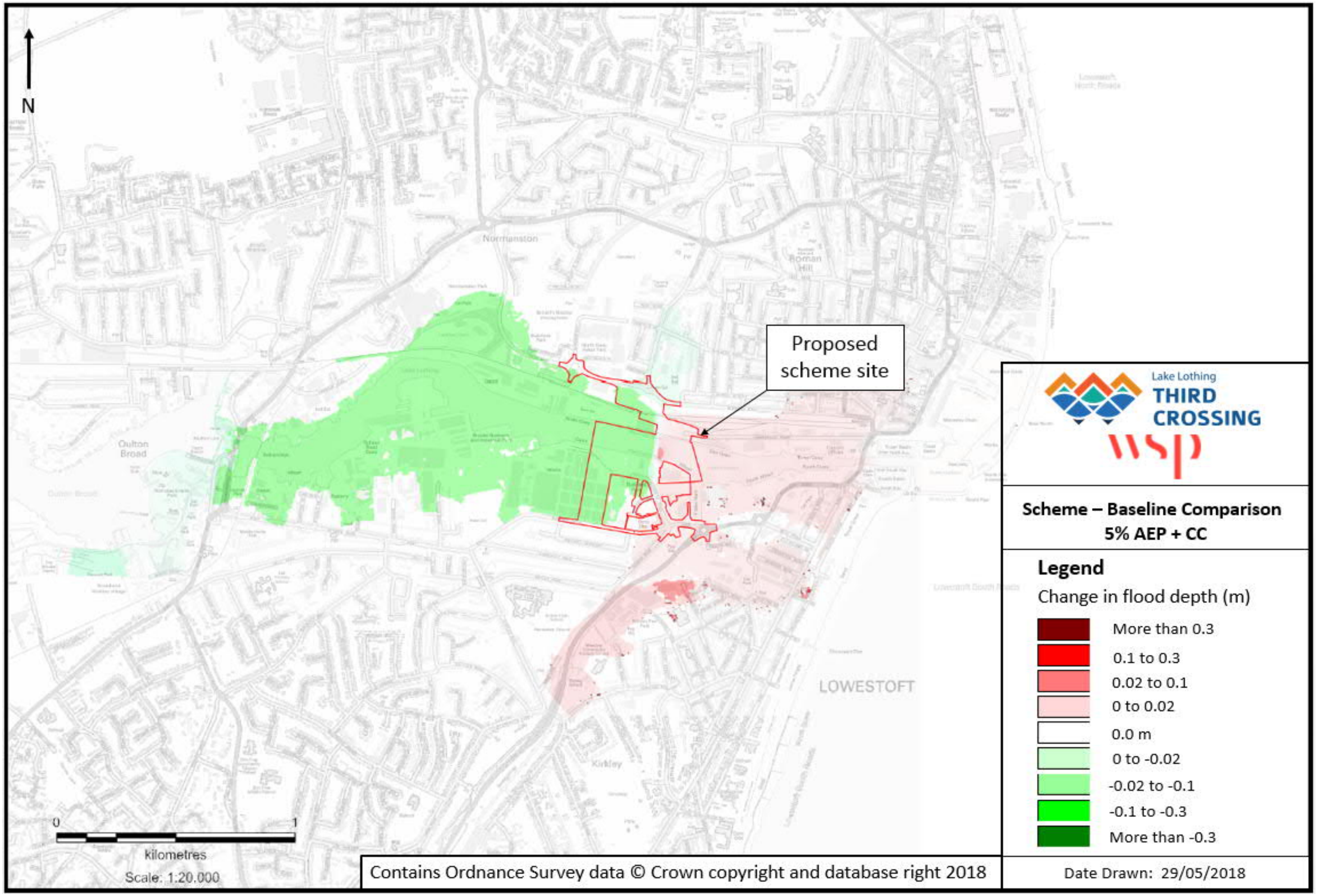


Figure FM5 - 5% AEP climate change event comparison (Scheme - Baseline)

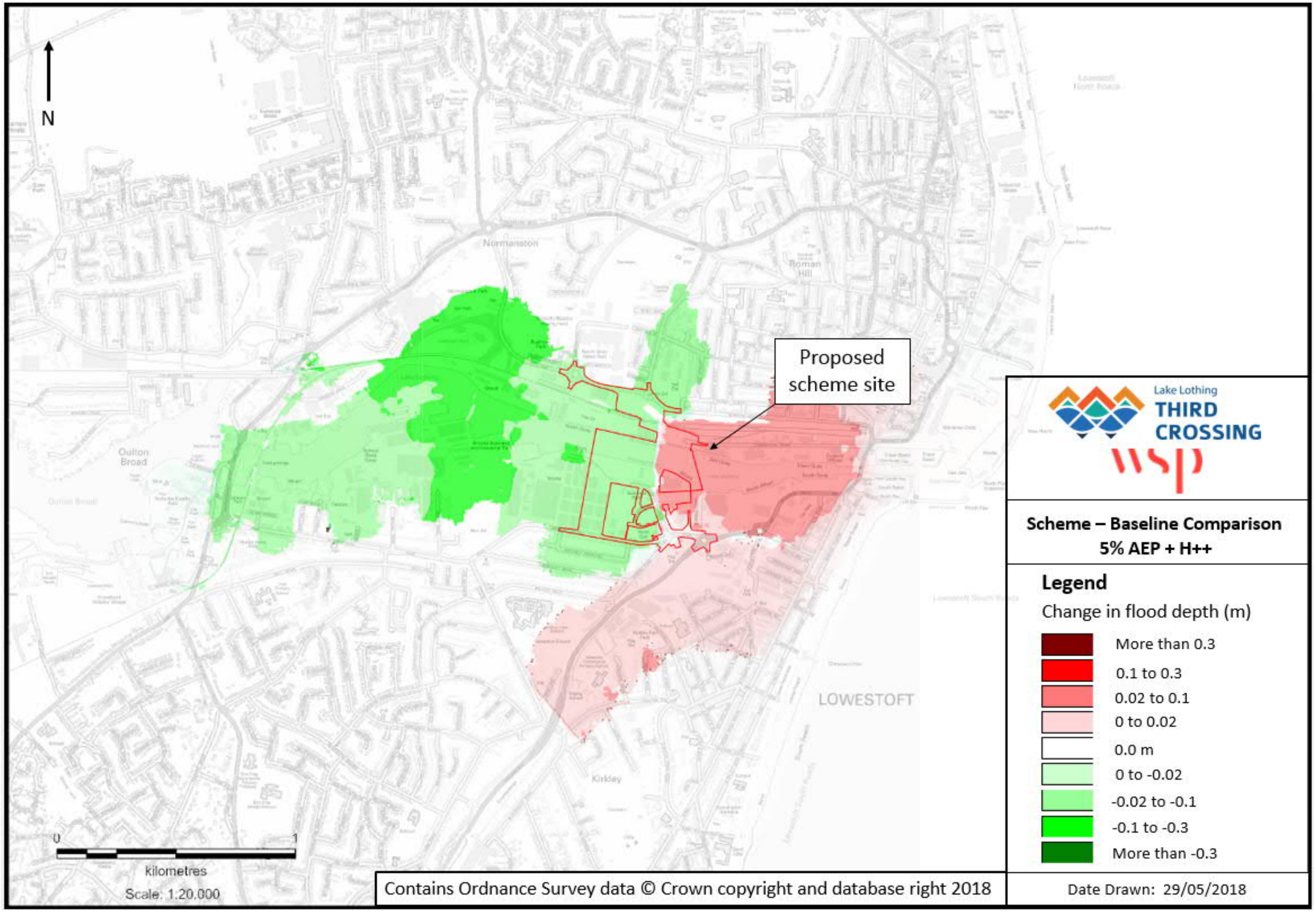


Figure FM6- 5% AEP H++ event comparison (Scheme - baseline)

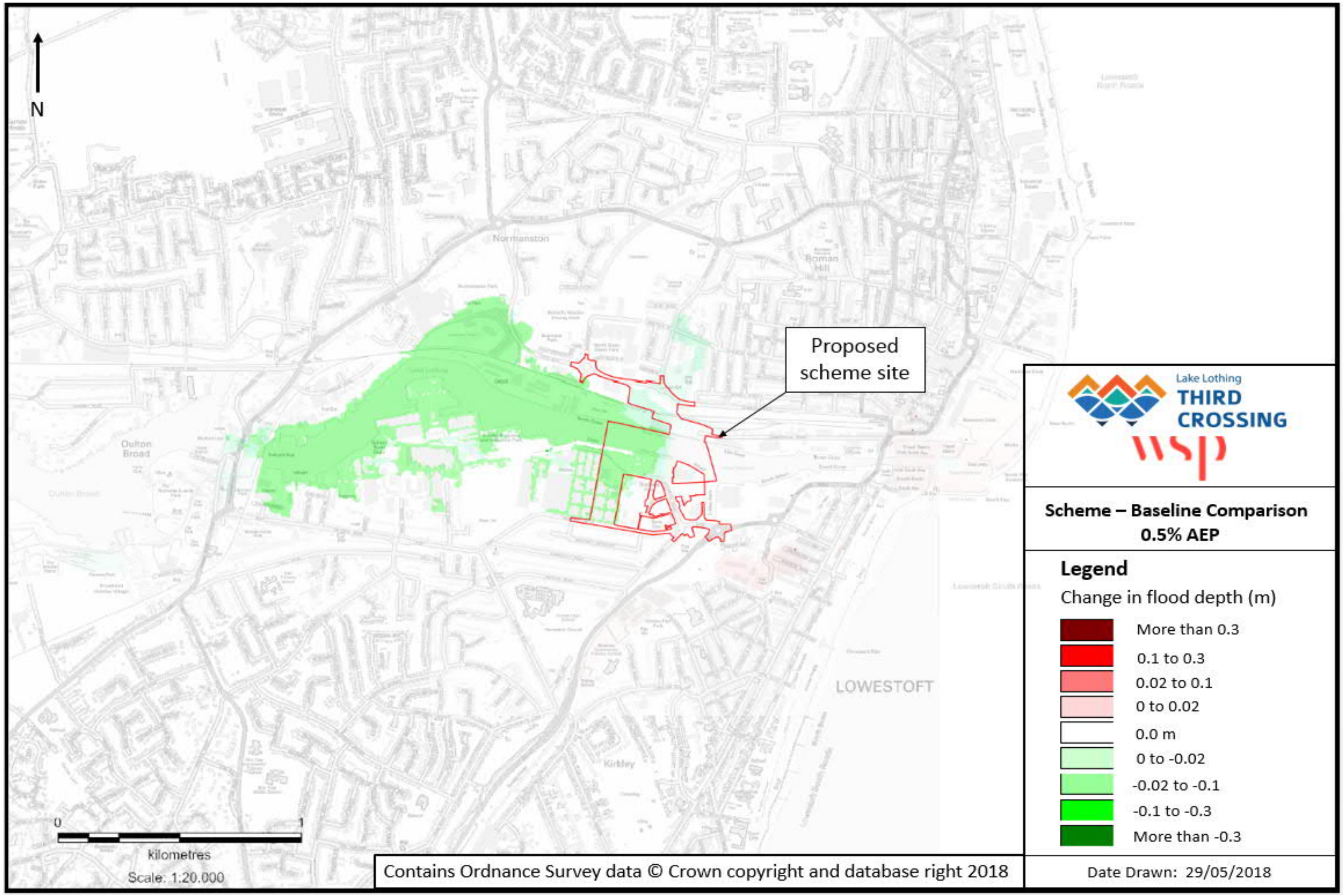


Figure FM7– 0.5% AEP present day event comparison (Scheme - Baseline)

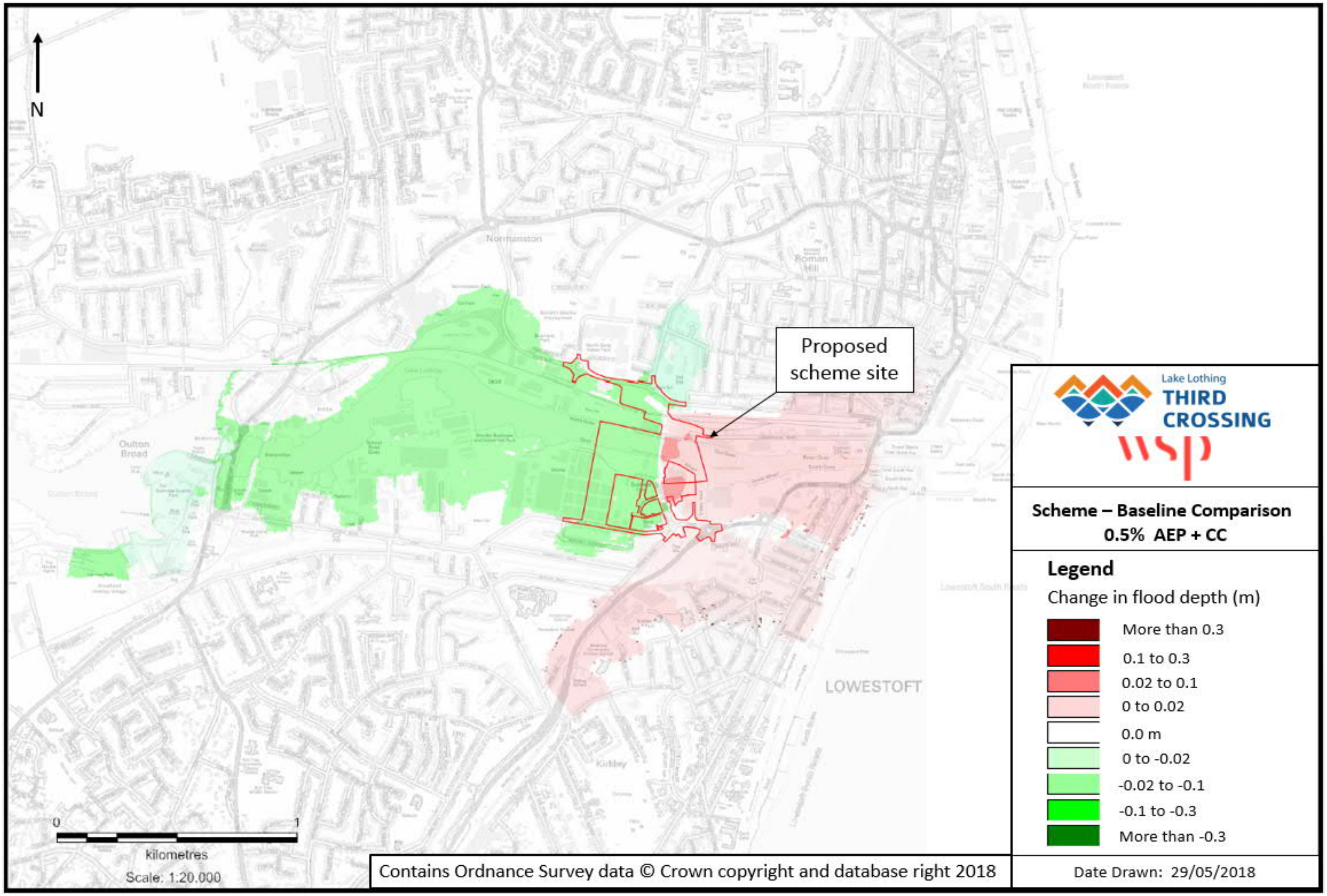


Figure FM8 - 0.5% AEP climate change event comparison (Scheme - Baseline)

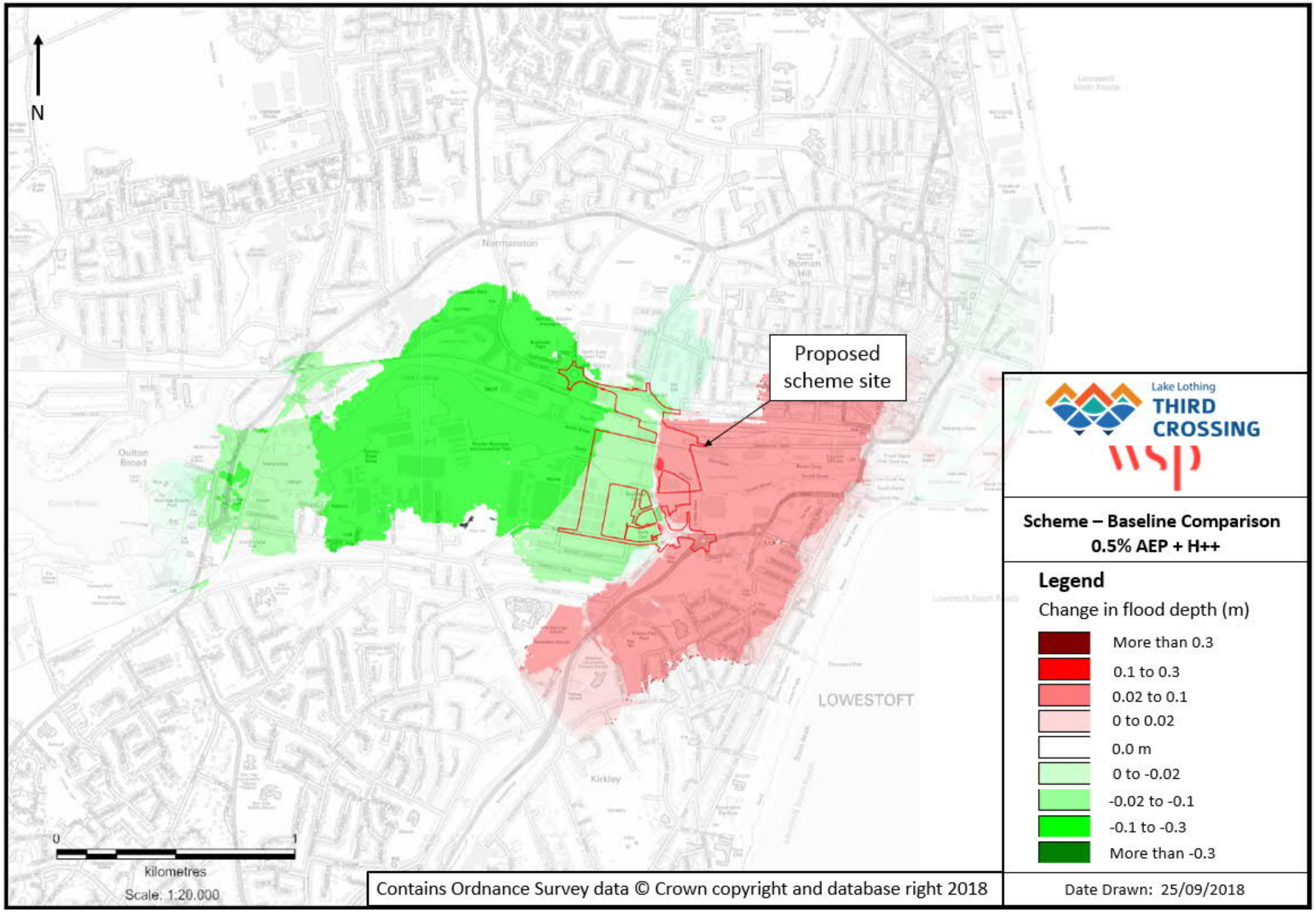


Figure FM9 - 0.5% AEP H++ event comparison (Scheme - Baseline)

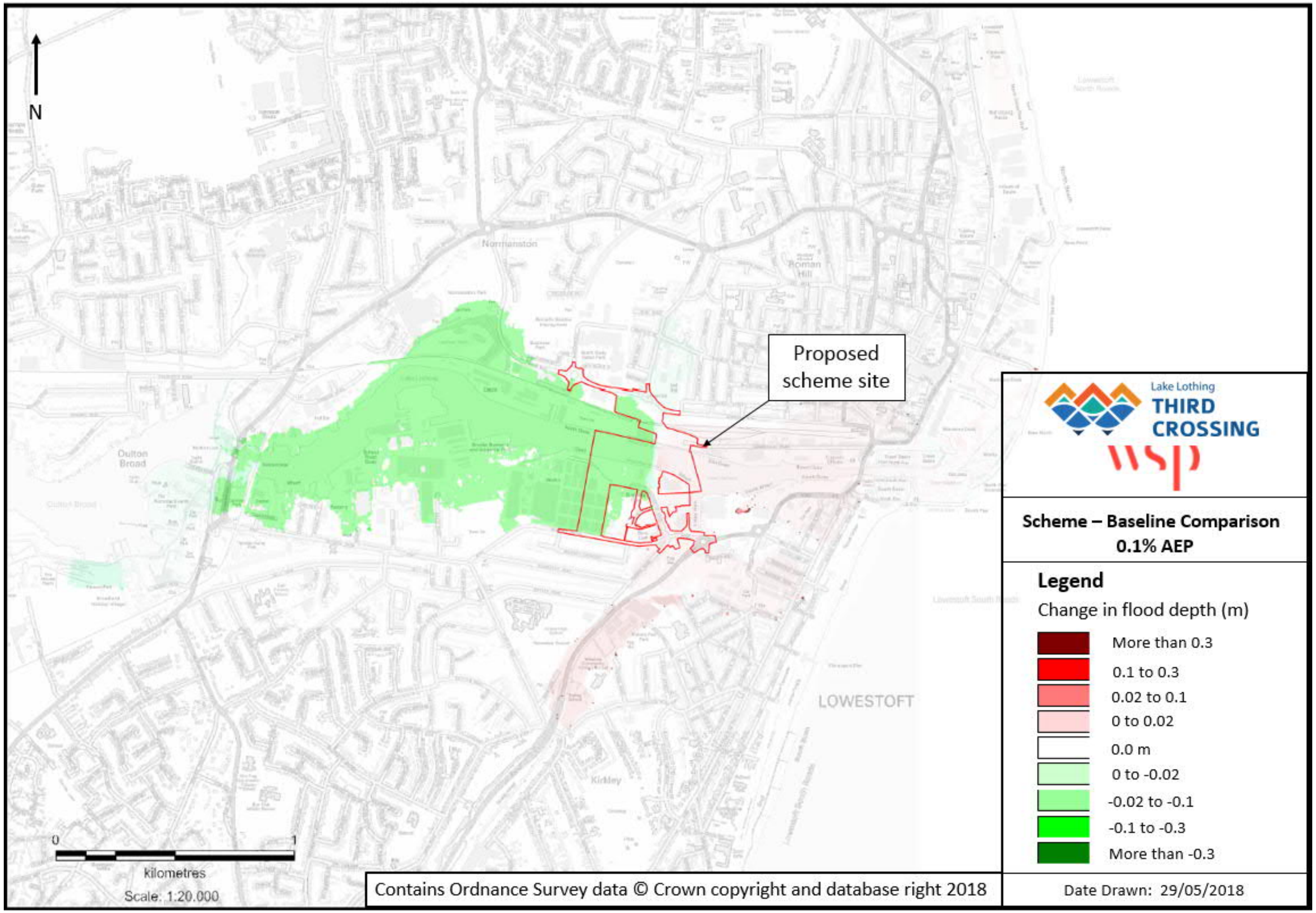


Figure FM10 - 0.1% AEP present day event comparison (Scheme - baseline)

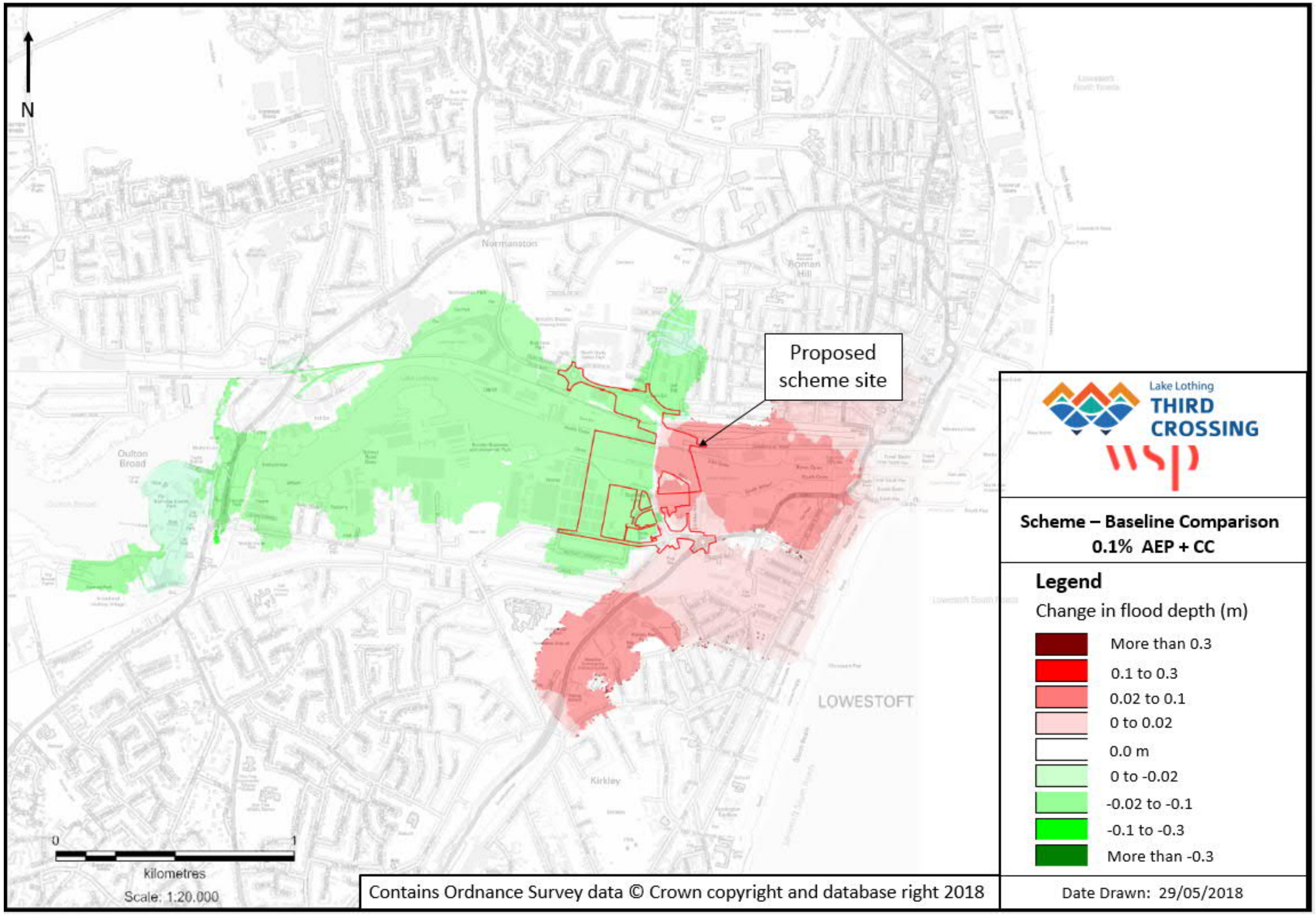


Figure FM11 - 0.1% AEP climate change event comparison (Scheme - baseline)

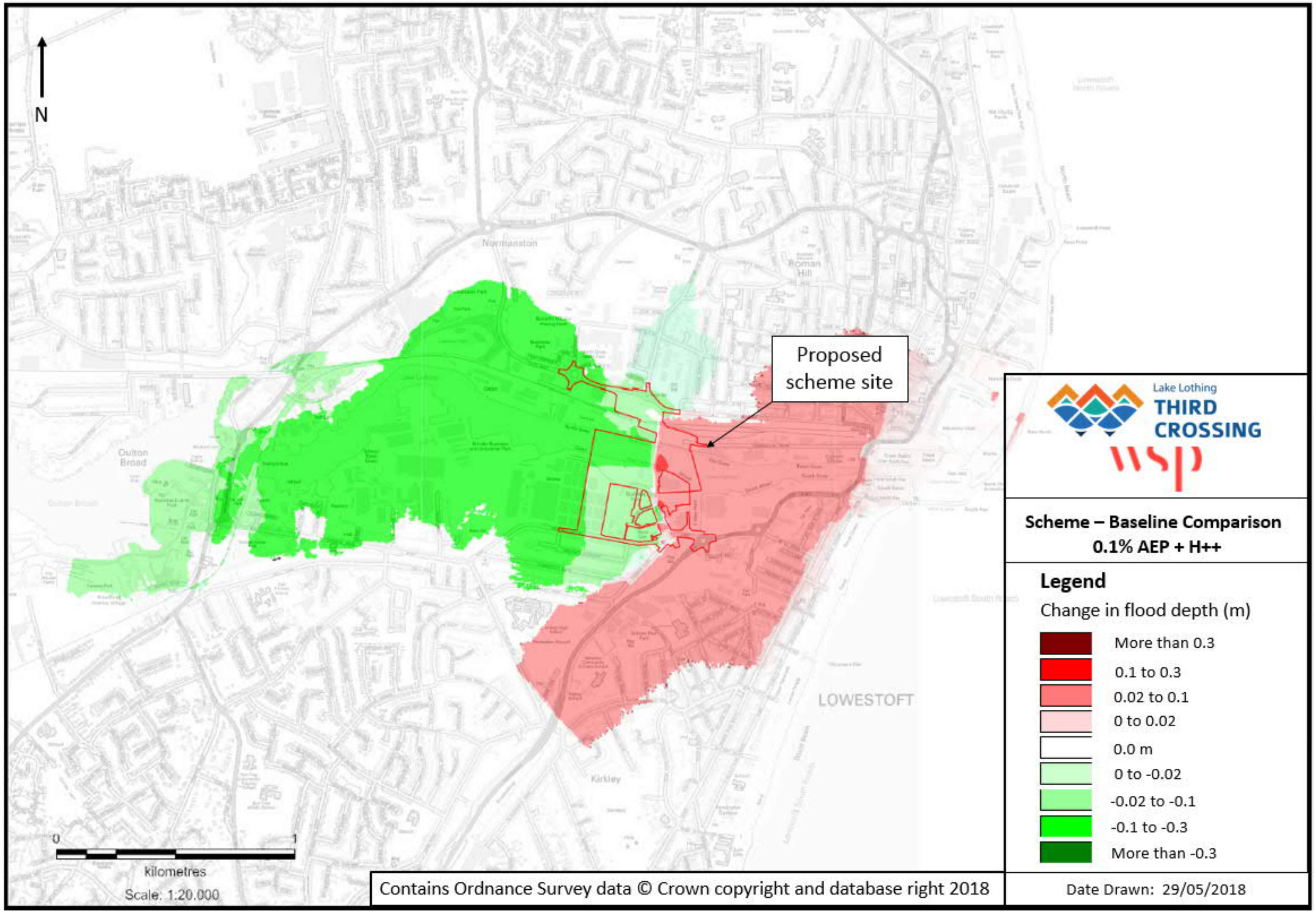


Figure FM12 - 0.1% AEP H++ event comparison (Scheme - baseline)

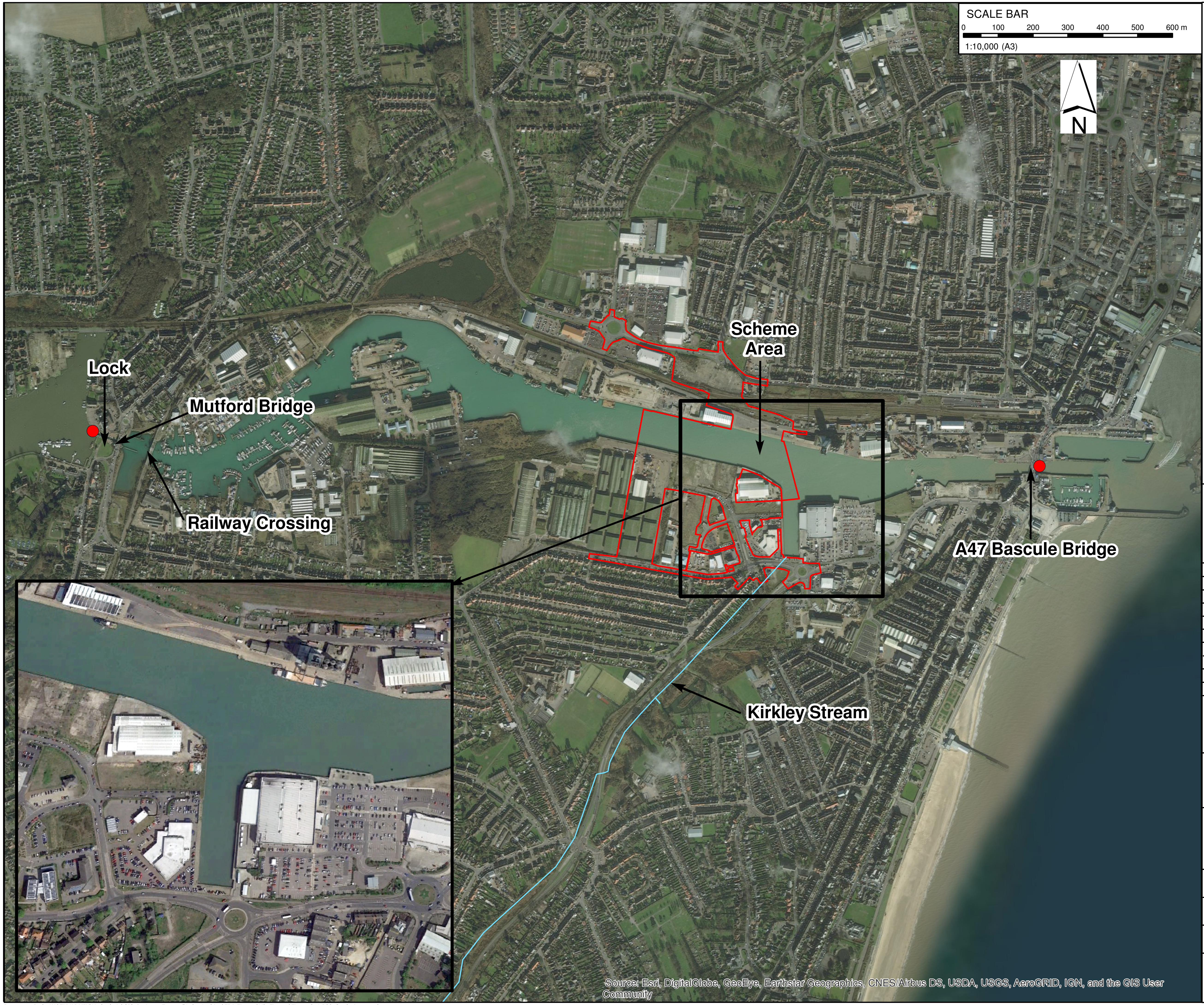
The Lake Lothing (Lowestoft)
Third Crossing Order 201[*]

Document 6.3: Environmental Statement
Volume 3 Appendices

Appendix 18A

Annex C - Figures

Author: Suffolk County Council



KEY

- Level Gauge
- Order Limits

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DESCRIPTION

Suffolk County Council

PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Scheme Location
Figure 2-1

DRAWING STATUS

For DCO Submission

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IW	JH	HR	JB	S4

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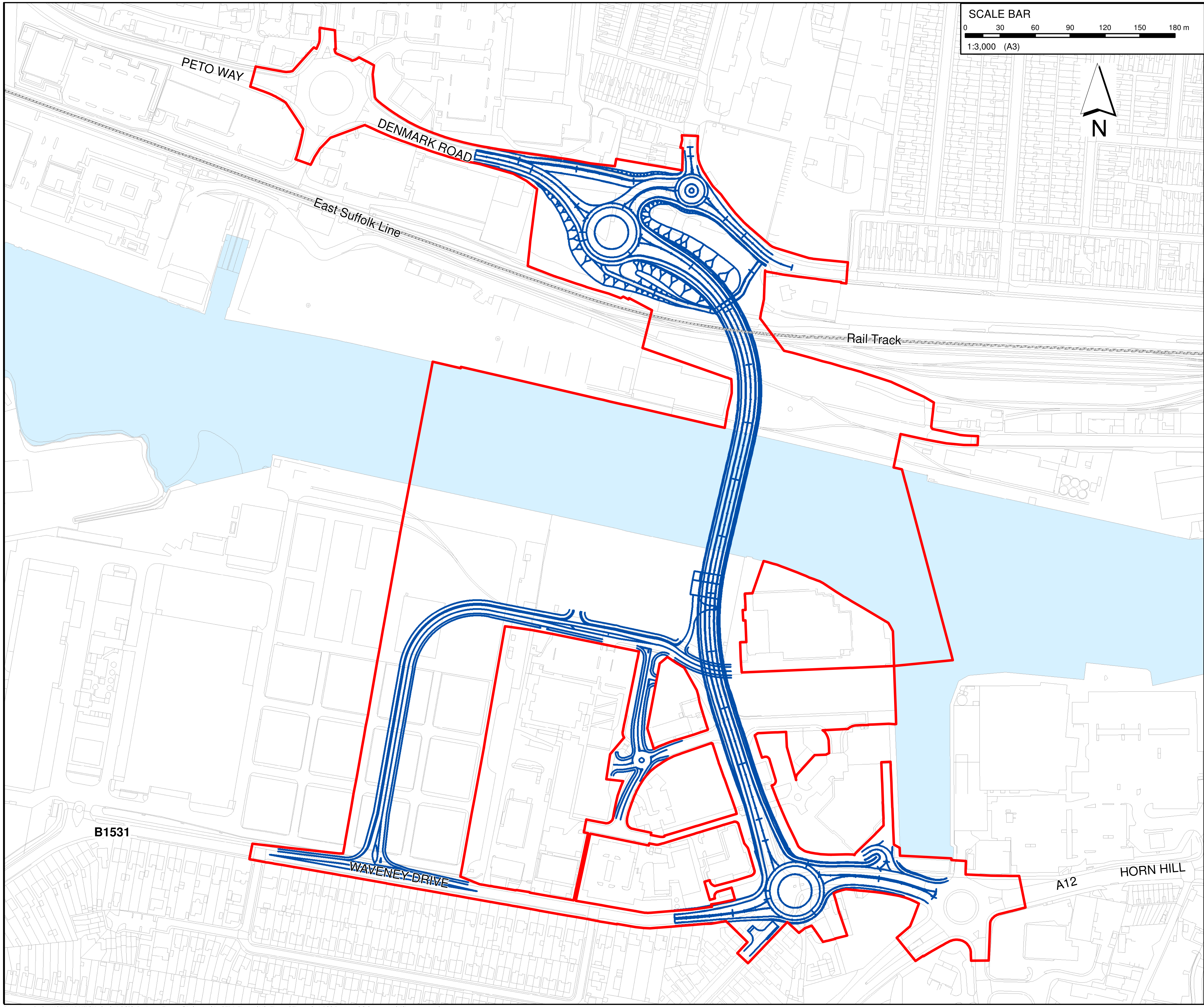

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- The Scheme (illustrative)

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PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

The Scheme
Figure 3-1

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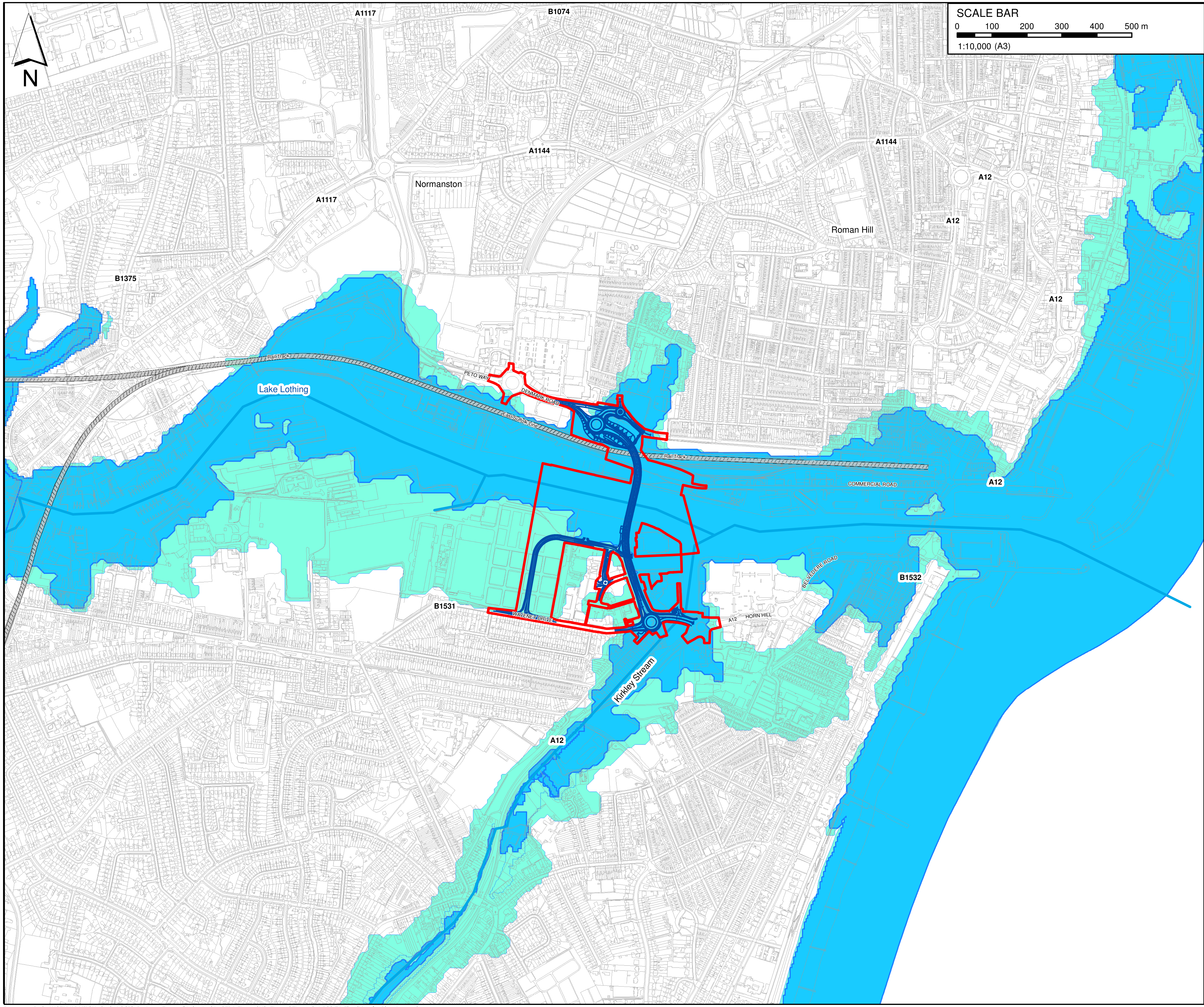

KEY

- The Scheme (illustrative)
- Main River
- Order Limits
- Existing Rail Track
- Floodzone 3
- Floodzone 2

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Lake Lothing THIRD CROSSING

DRAWING TITLE

EA Flood Maps for Planning
Figure 6-1
(source : www.gov.uk)

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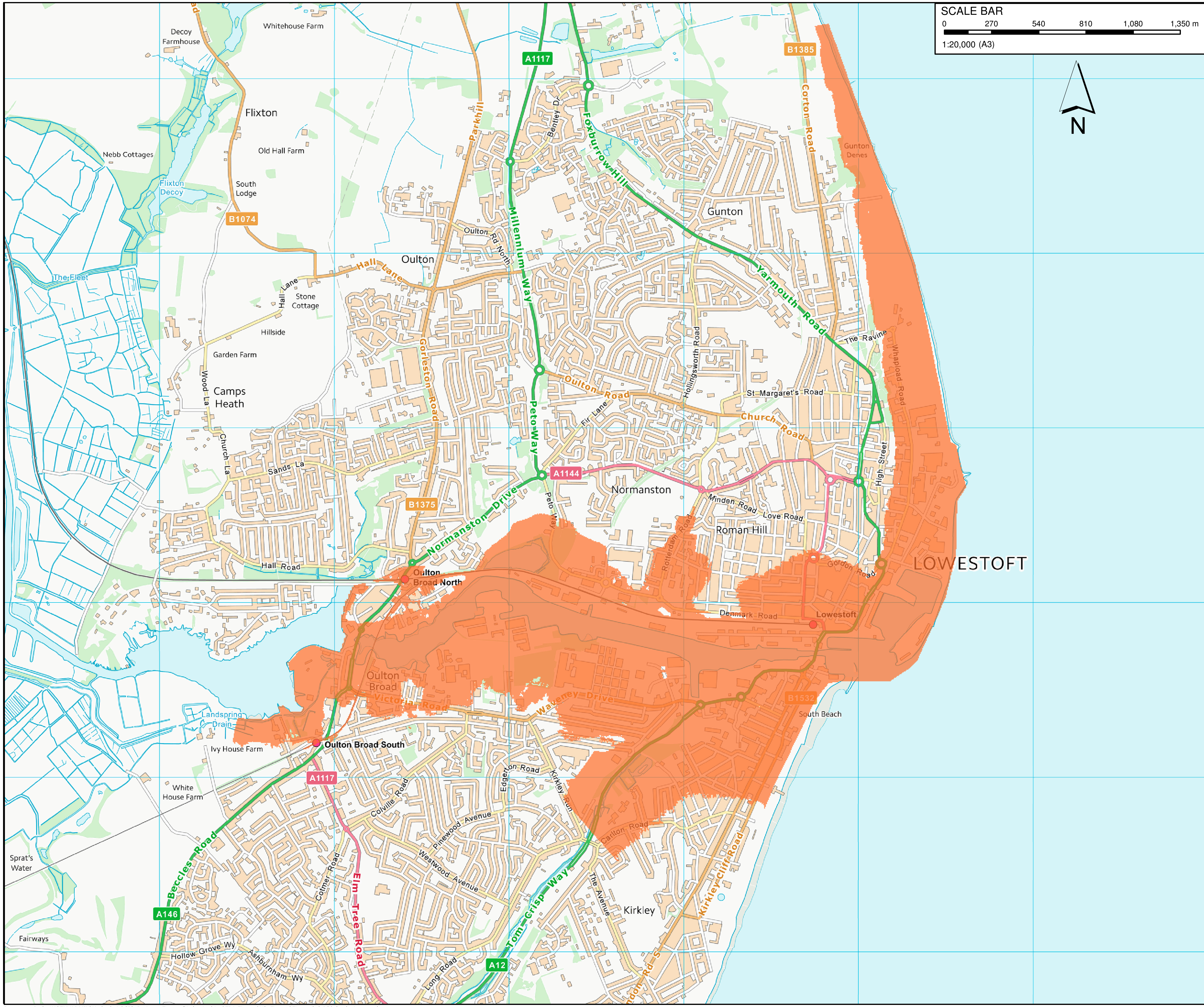

KEY

Study Area

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PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Assessment Study Area
Figure 6-2

DRAWING STATUS

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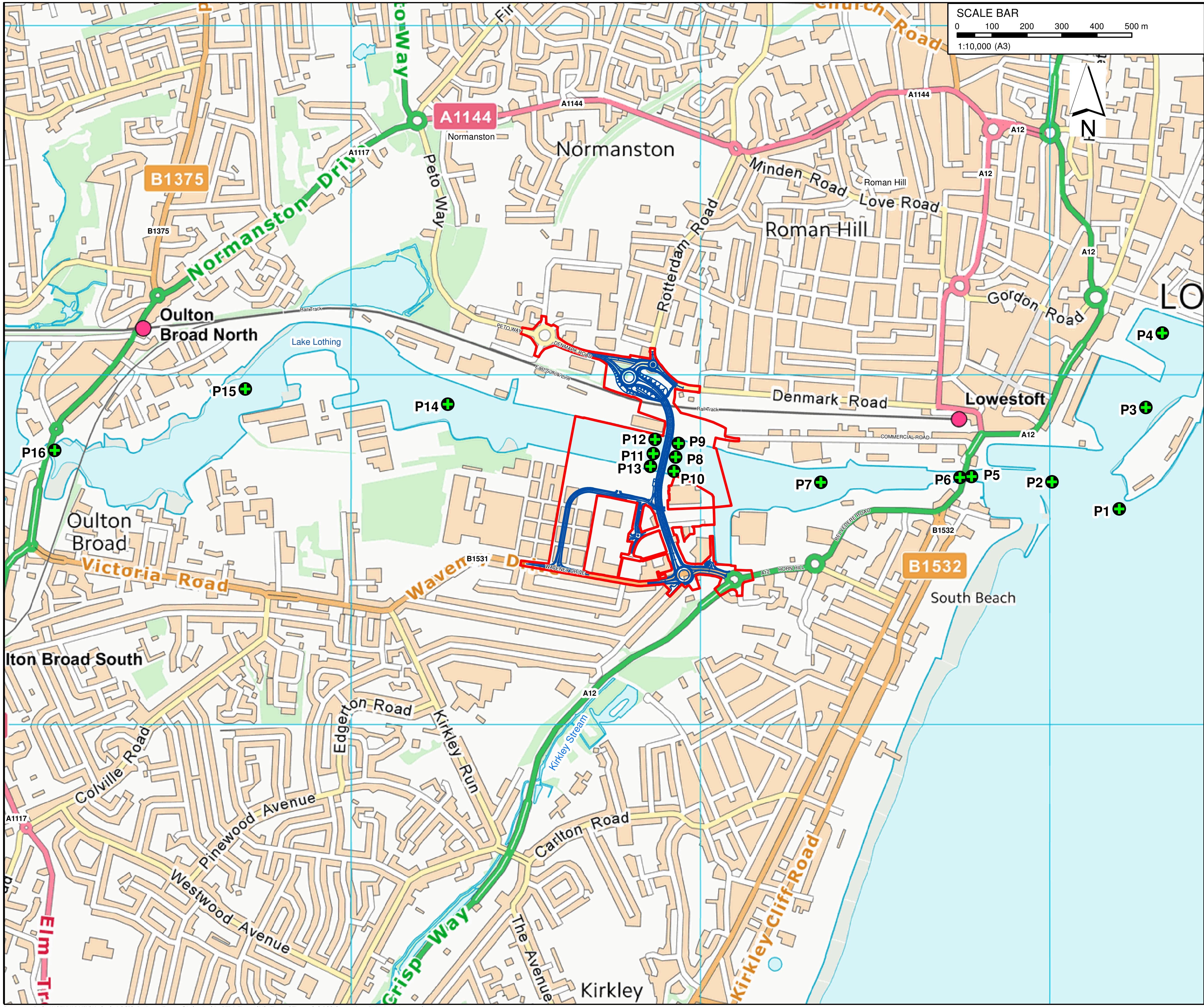

KEY

- The Scheme (illustrative)
- Comparison Point Locations
- Order Limits

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PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Comparison Point Locations
Figure 6-3

DRAWING STATUS

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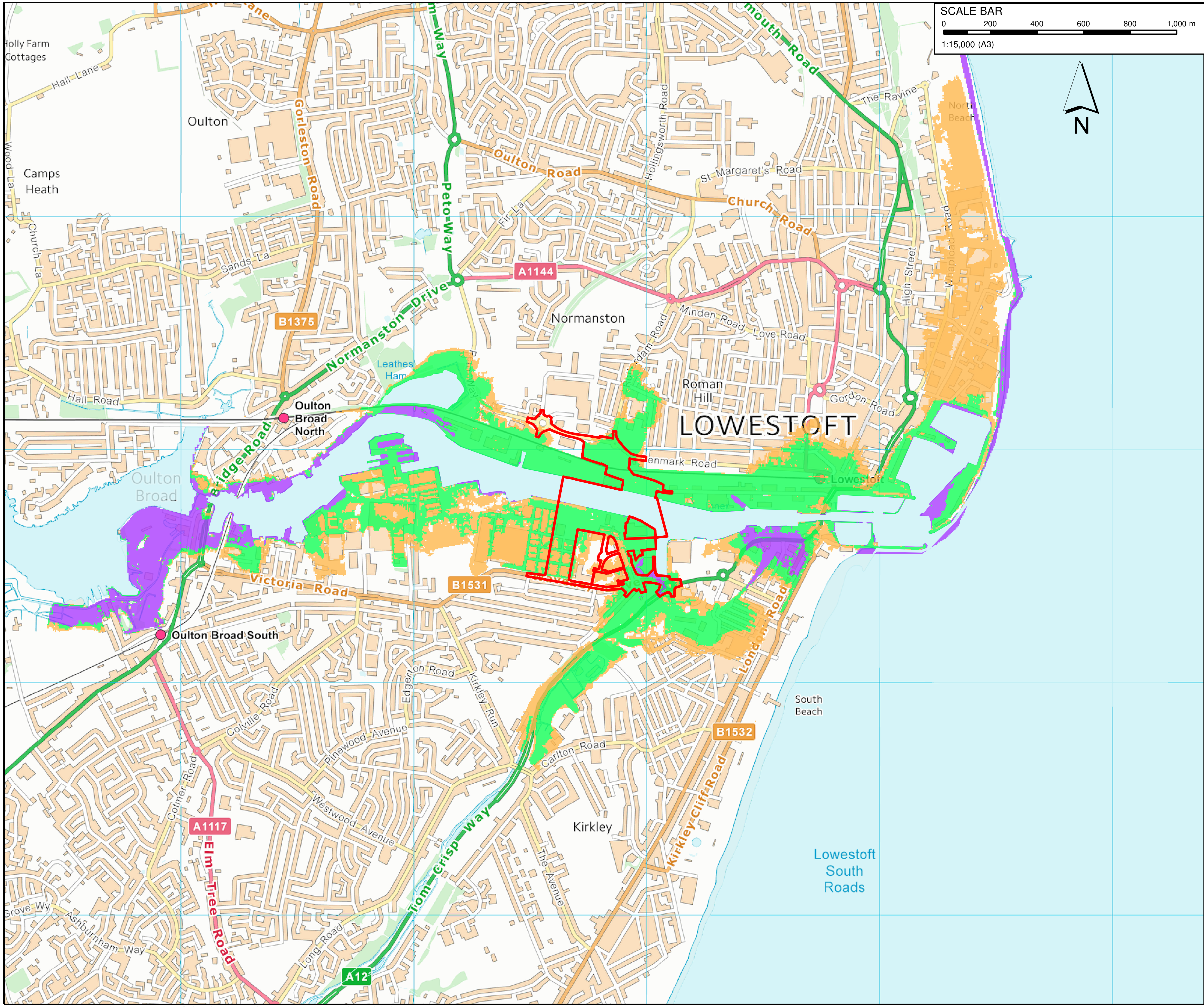

KEY

- Order Limits
- Lake Lothing

Baseline Flood Extent

- 5% AEP
- 0.5% AEP
- 0.1% AEP

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Lake Lothing THIRD CROSSING

DRAWING TITLE

Baseline Model Flood Map
Figure 6-4

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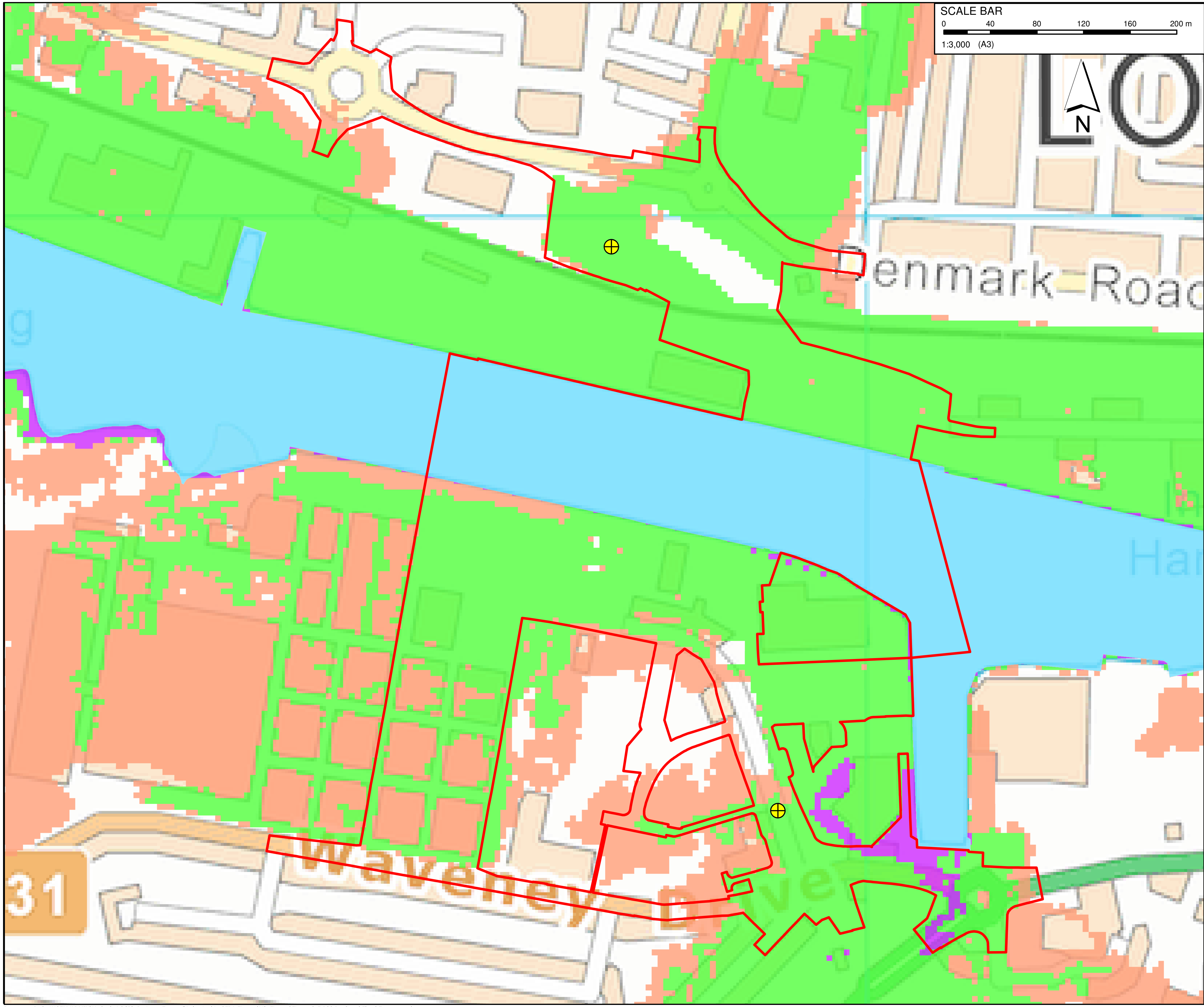

KEY

- Order Limits
- Lake Lothing
- Observation Points

Scheme Flood Extent Present Day

- 5% AEP
- 0.5% AEP
- 0.1% AEP

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Lake Lothing THIRD CROSSING

DRAWING TITLE

Predicted Flood Extents for the Scheme Present Day Scenarios
Figure 6-5

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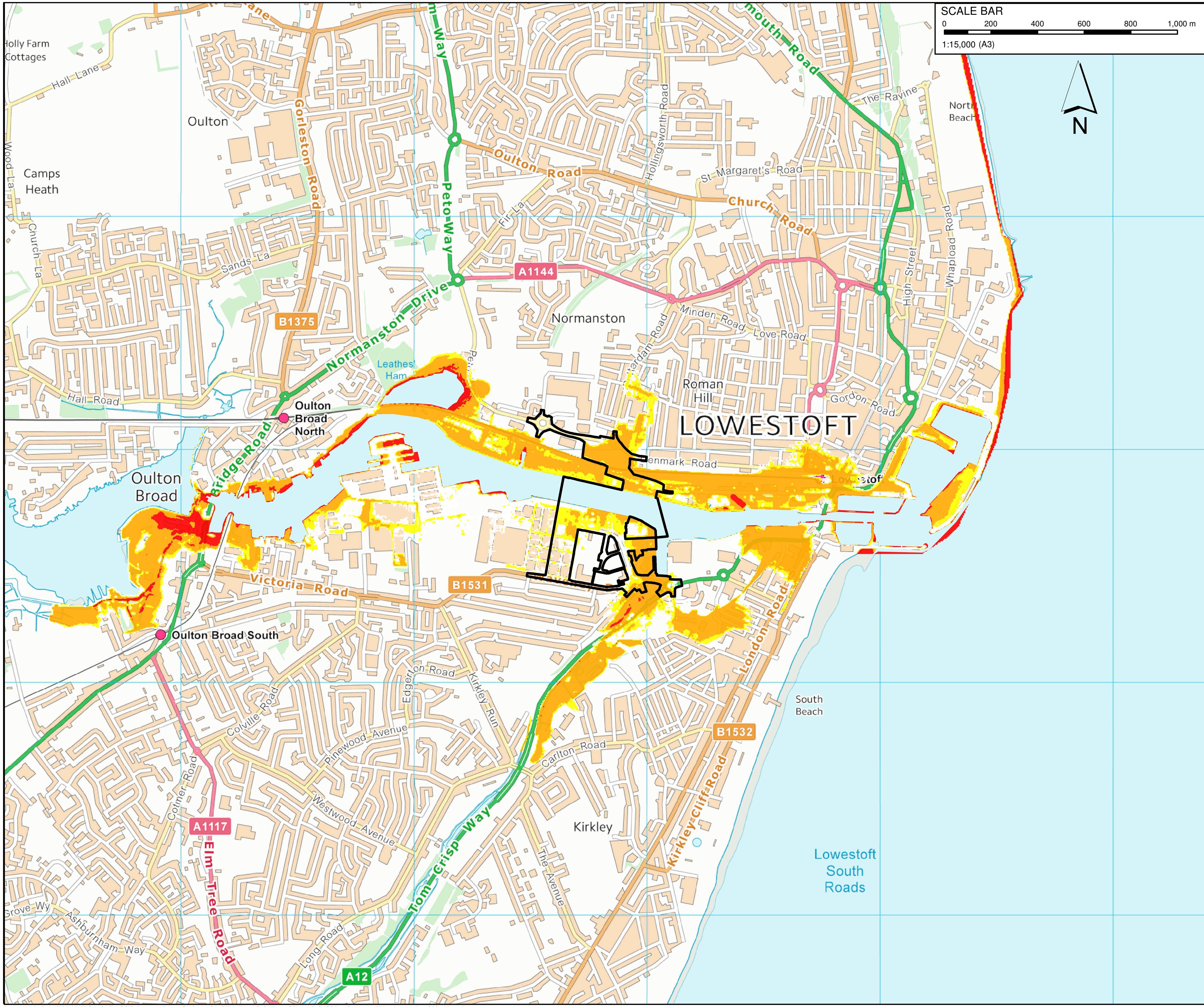

KEY

Order Limits

Hazard to People

- Anywhere outside of the modelled flood extent
- Danger for some - includes children, the elderly and the infirm
- Danger for most - includes the general public
- Danger for all - includes the emergency services

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PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Baseline Hazard Map
Present Day, 200yr RP
Figure 6-6

DRAWING STATUS

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Project | Originator | Volume

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Location | Type | Role | Number

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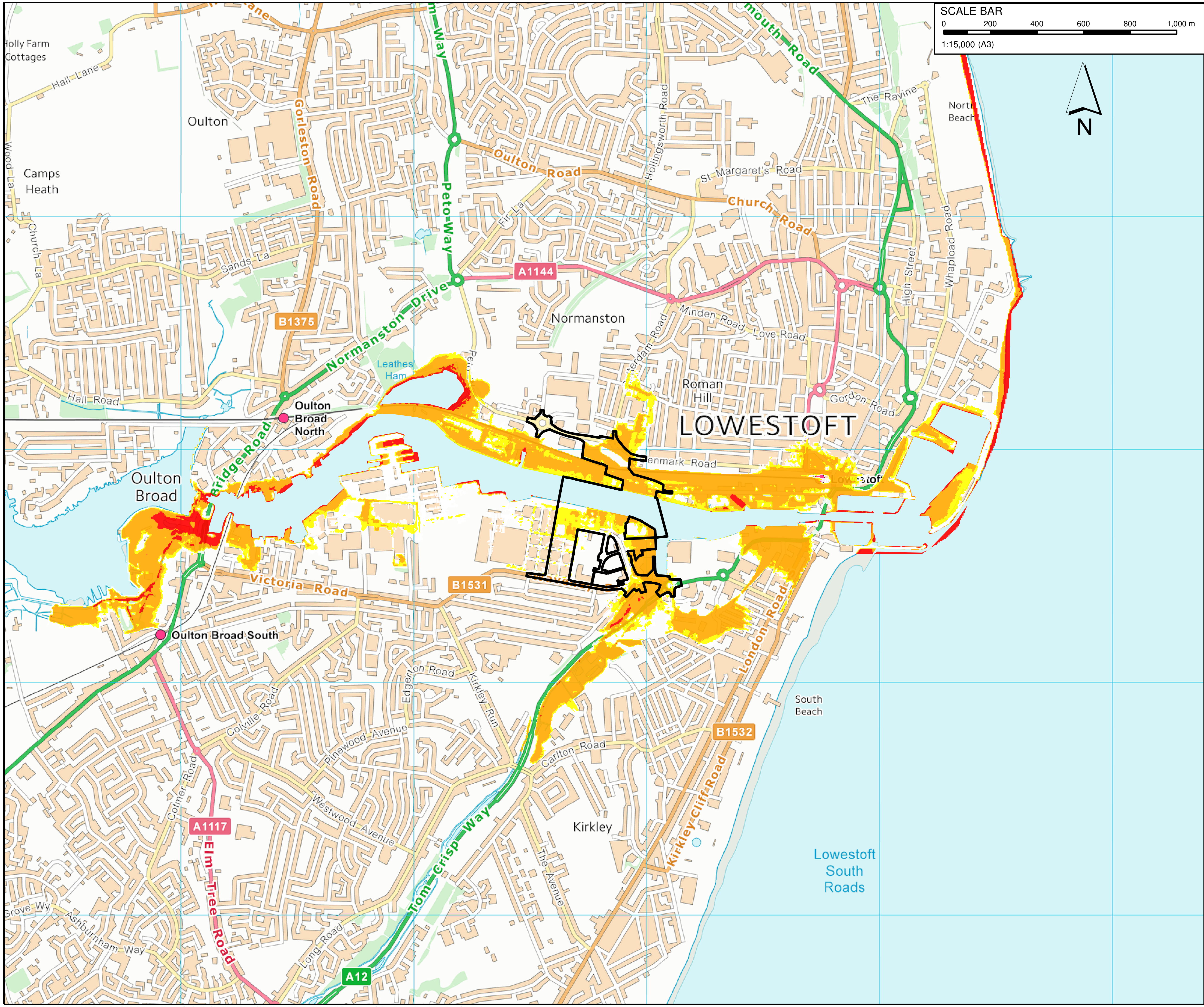

KEY

Order Limits

Hazard to People

- Anywhere outside of the modelled flood extent
- Danger for some - includes children, the elderly and the infirm
- Danger for most - includes the general public
- Danger for all - includes the emergency services

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Lake Lothing THIRD CROSSING

DRAWING TITLE

Scheme Hazard Map
Present Day, 200yr RP
Figure 6-7

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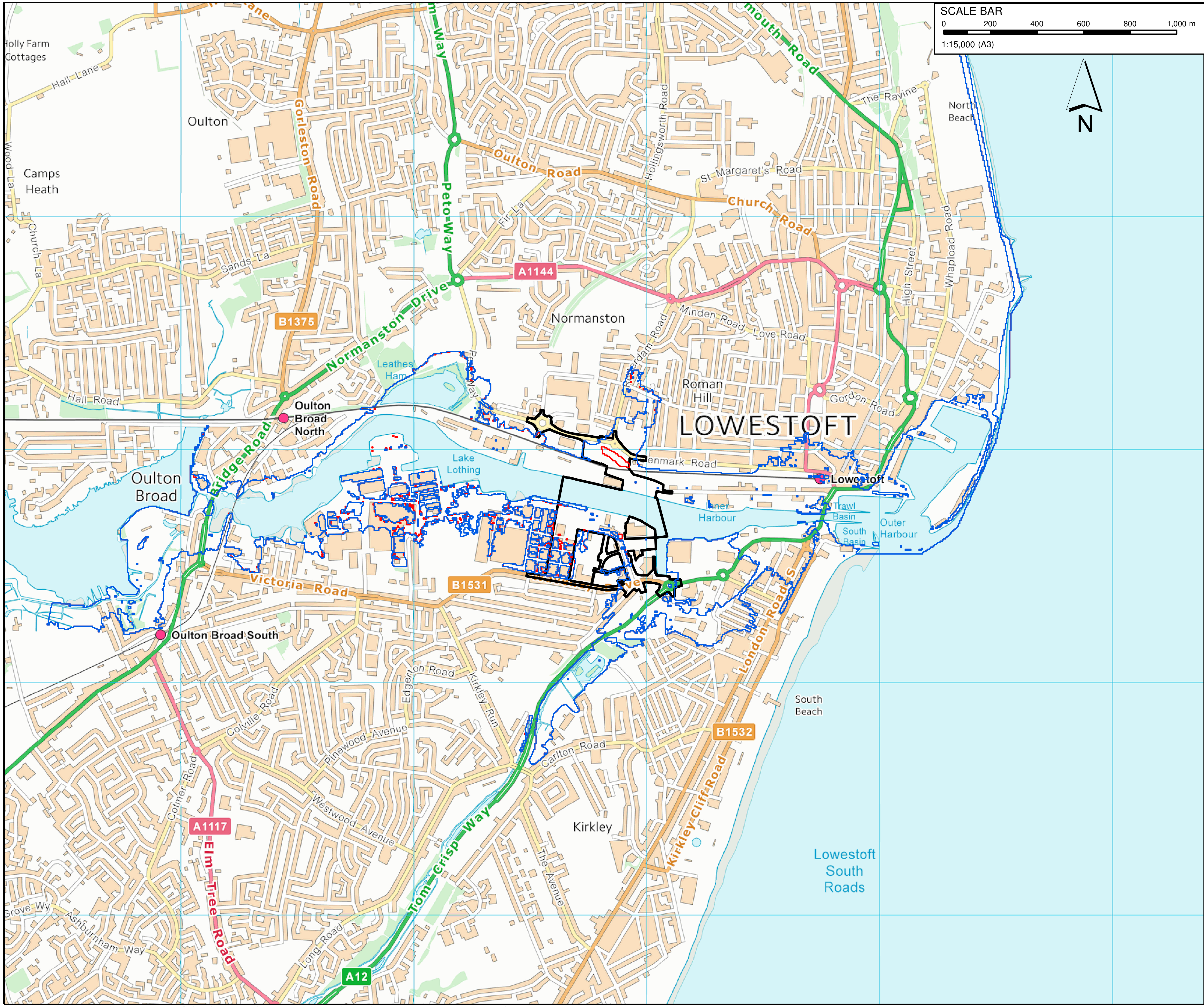

KEY

- Order Limits
- Scheme extents - present day
- Baseline extents - present day

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REVISION	DRAWN	CHECKED	APPROVED	DATE

DESCRIPTION

Suffolk County Council

PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Scheme – Baseline extent comparison
Present Day, 200yr RP
Figure 6-8

DRAWING STATUS

For DCO Submission

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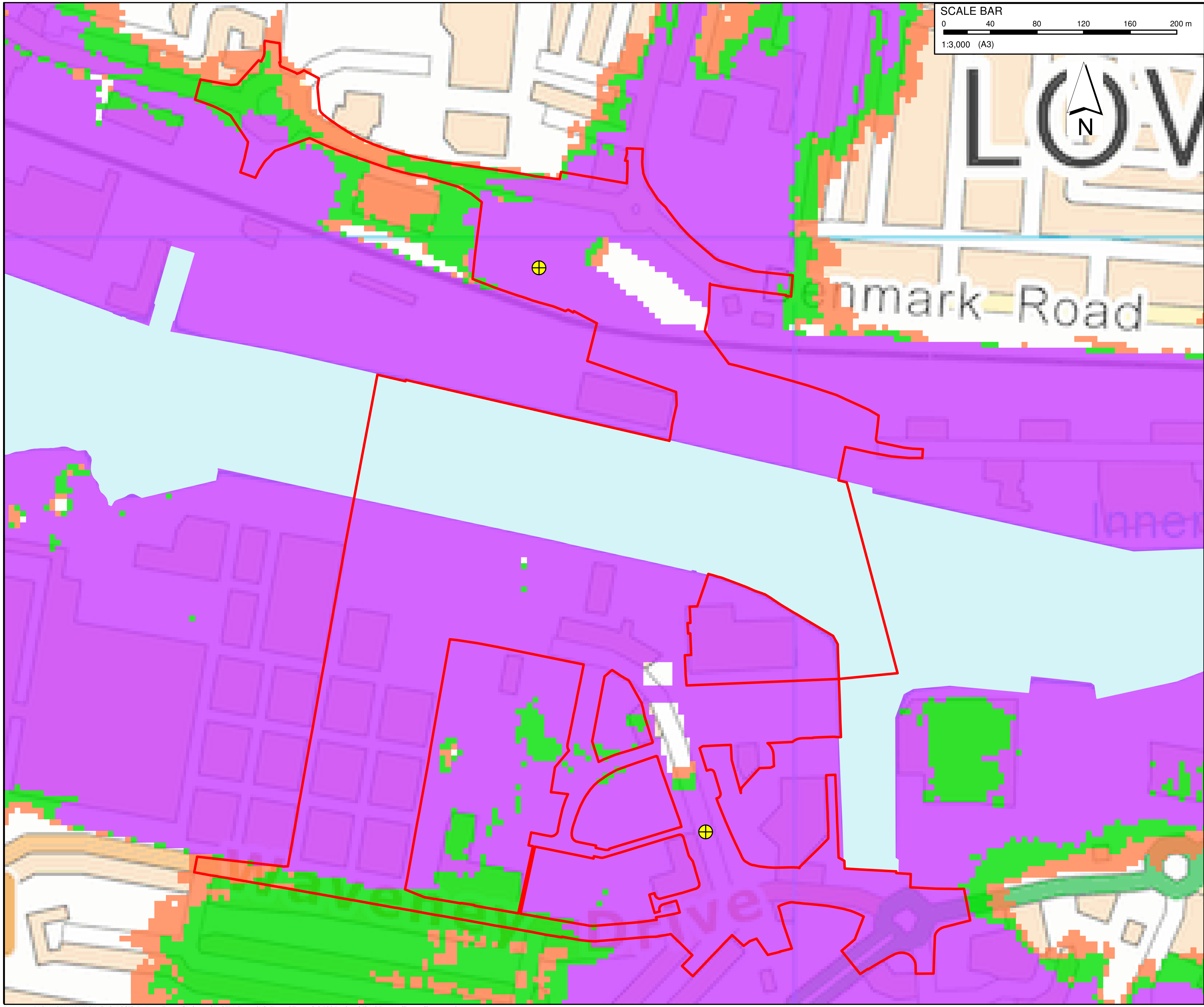
Project | Originator | Volume

1069948-WSP-EGN-LL-SK-LE-0014

Location | Type | Role | Number



KEY

- Order Limits
- Lake Lothing
- Observation Points

Scheme Flood Extent Climate Change

- 5% AEP
- 0.5% AEP
- 0.1% AEP

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DESCRIPTION

Suffolk County Council

PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Predicted Flood Extents for the Scheme Climate Change Scenarios
Figure 6-9

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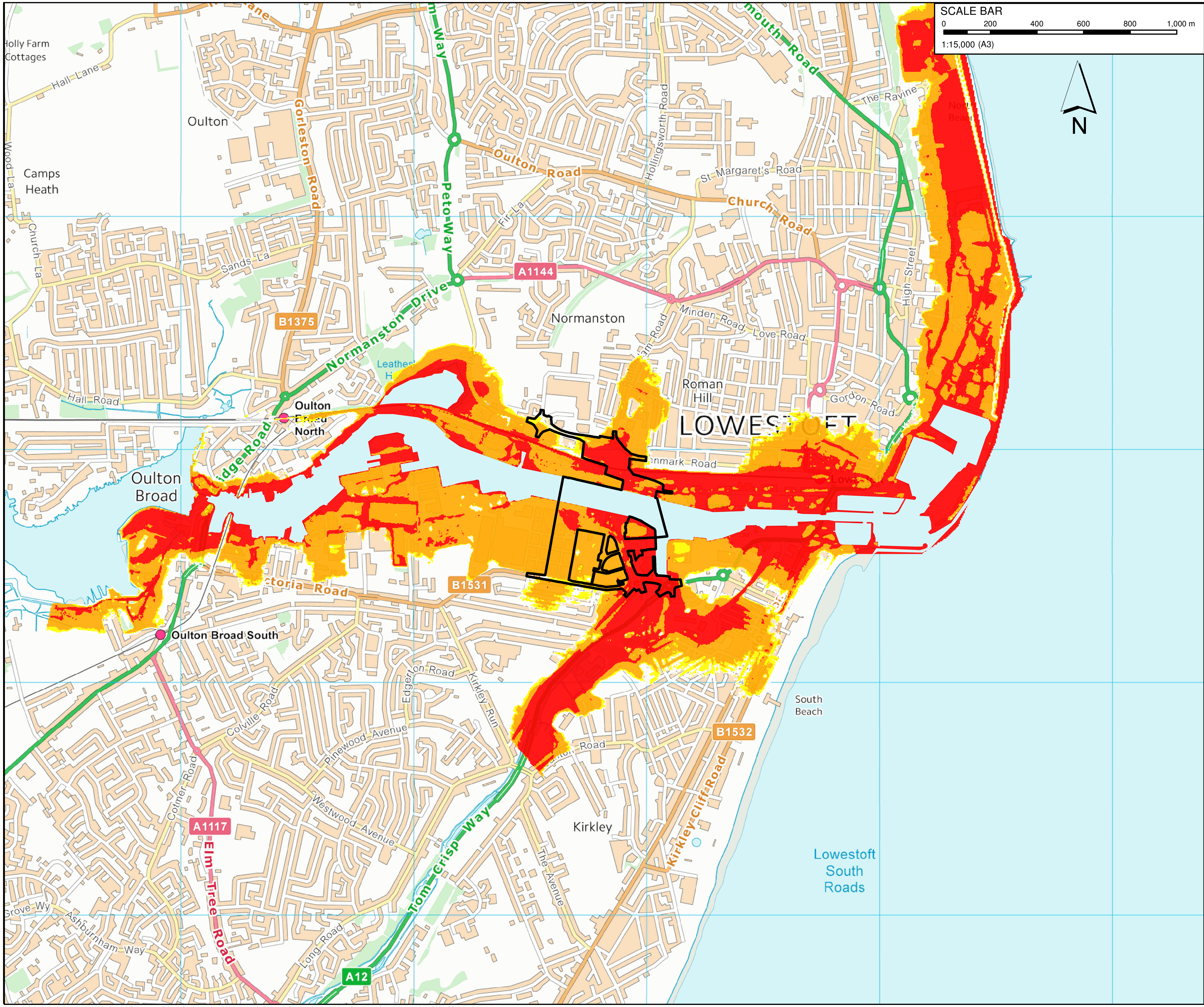

KEY

Order Limits

Hazard to People

- Anywhere outside of the modelled flood extent
- Danger for some - includes children, the elderly and the infirm
- Danger for most - includes the general public
- Danger for all - includes the emergency services

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PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Baseline Hazard Map
Present Day, 200yrCC RP
Figure 6-10

DRAWING STATUS

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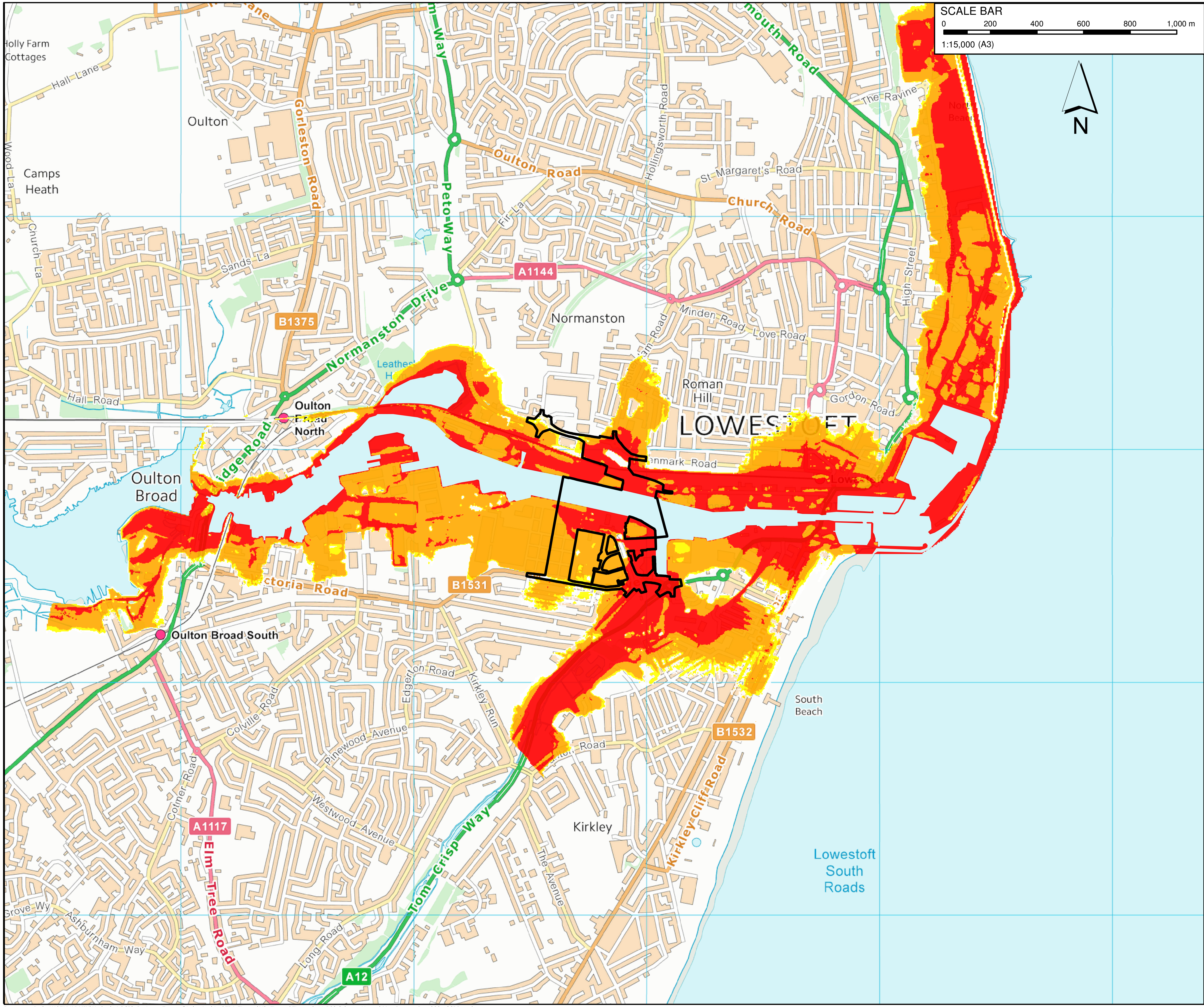
1069948-WSP-EGN-LL-SK-LE-0015

Location | Type | Role | Number



KEY

Order Limits

Hazard to People

- Anywhere outside of the modelled flood extent
- Danger for some - includes children, the elderly and the infirm
- Danger for most - includes the general public
- Danger for all - includes the emergency services

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PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Scheme Hazard Map
Present Day, 200yrCC RP
Figure 6-11

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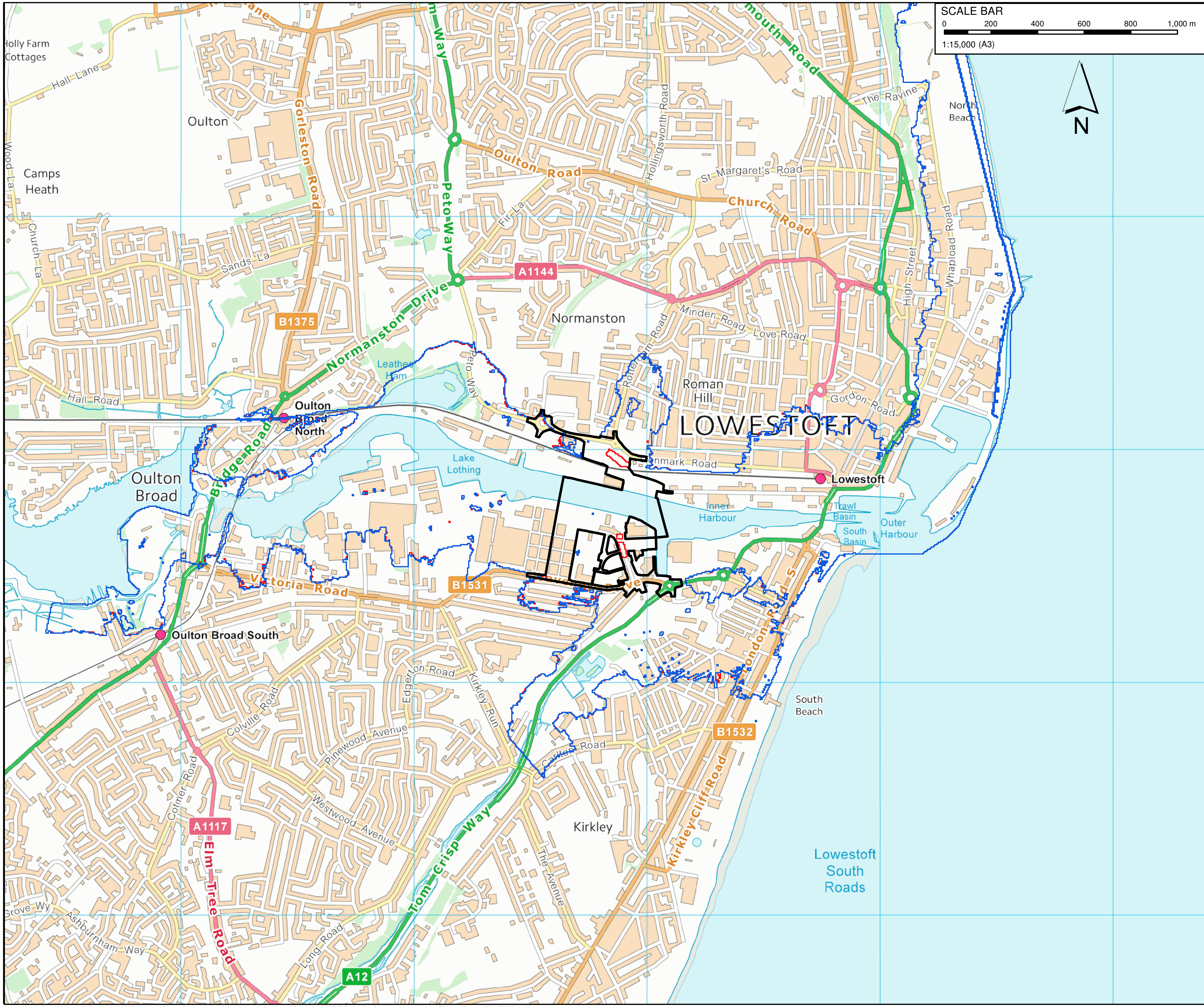
Location | Type | Role | Number



KEY

- Order Limits
- Scheme extents - climate change
- Baseline extents - climate change

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Suffolk County Council

PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Scheme – Baseline extent comparison
Climate Change, 200yr RP
Figure 6-12

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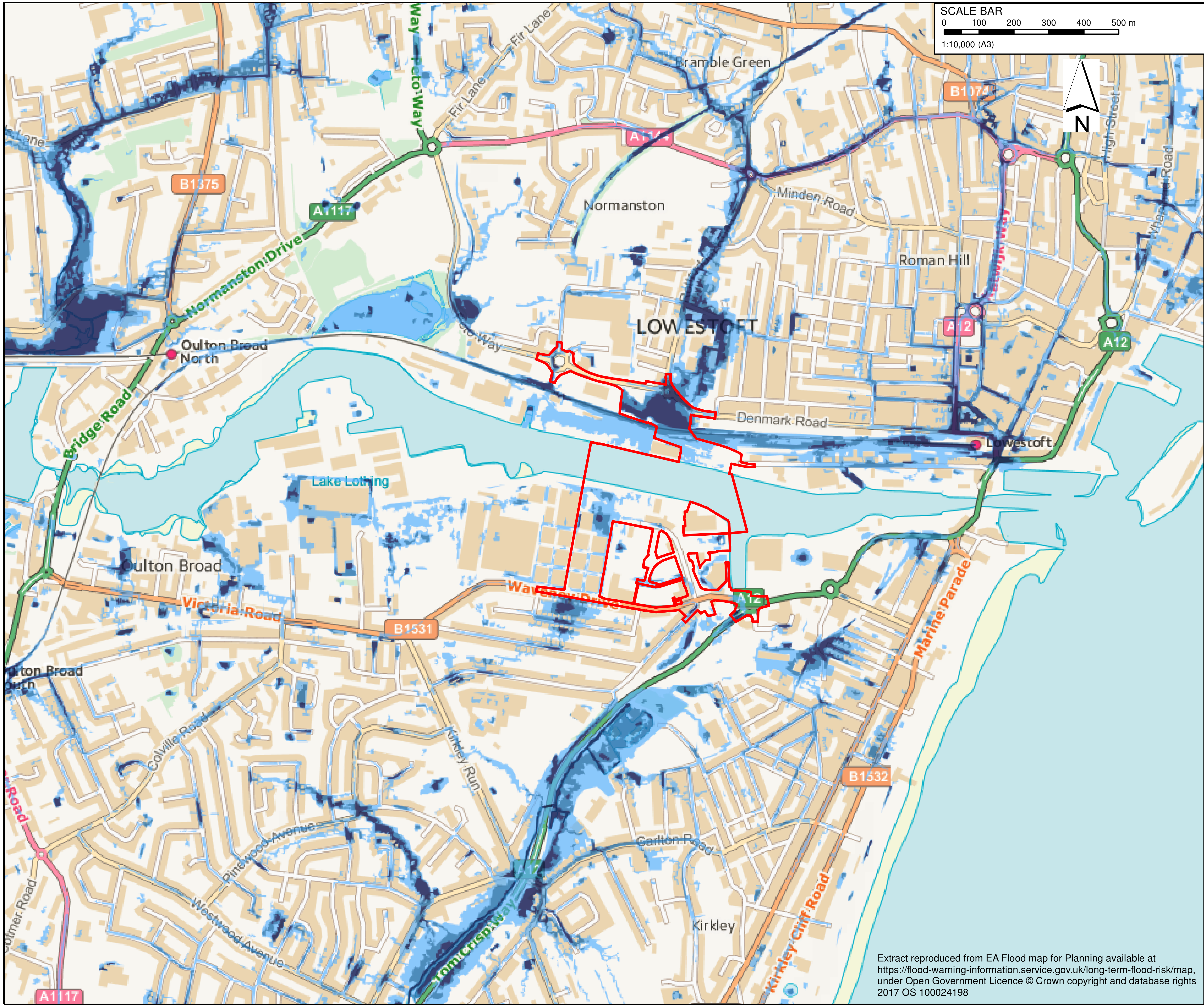

KEY

- Order Limits

Flood Risk from Surface Water

- High
- Medium
- Low
- Anywhere outside of the modelled flood extent

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PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Extract from EA Risk of Surface Water Flooding Map
Figure 6-13

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Location | Type | Role | Number

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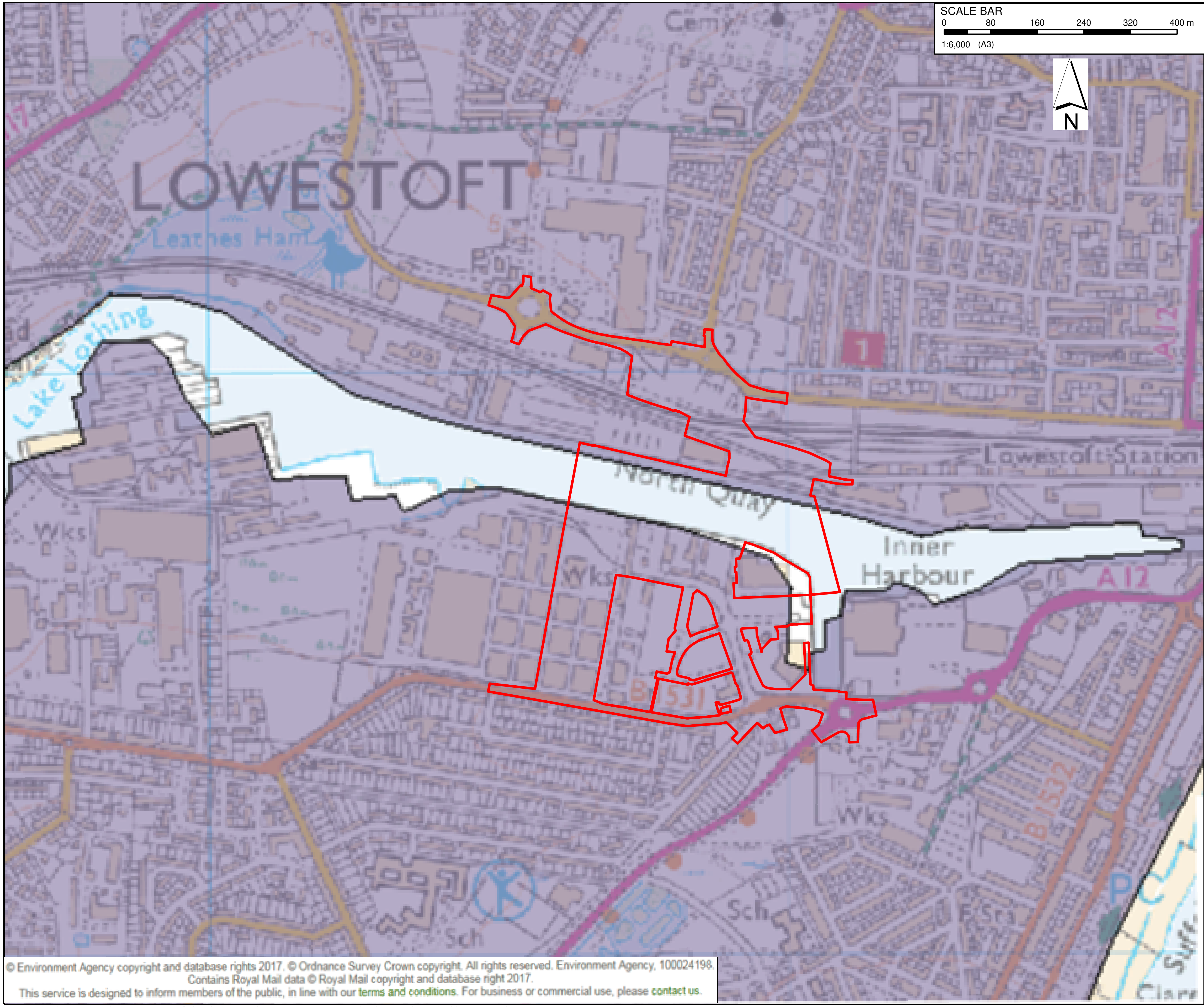

KEY

Order Limits

Groundwater Vulnerability Zones

Major Aquifer High

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DESCRIPTION

Suffolk County Council

PROJECT TITLE

Lake Lothing THIRD CROSSING

DRAWING TITLE

Extract from the EA Groundwater Vulnerability Zones Map (scale 1:15000)
Figure 6-14

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