Great Yarmouth Third River Crossing

Application for Development Consent Order

Document 6.2: Environmental Statement Volume II: Technical Appendix 12B: Flood Risk Assessment

Planning Act 2008

The Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009 (as amended) ("APFP")

APFP regulation Number: 5(2)(a)

Planning Inspectorate Reference Number: TR010043

Author: Norfolk County Council

Document Reference: 6.2 – Technical Appendix 12B

Version Number: 0 – Revision for Submission

Date: 30 April 2019

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Glossary of Abbreviations and Defined Terms

AAP	Area Action Plan
AEP	Annual Exceedance Probability
AOD	Above Ordnance Datum
BGS	British Geological Society
CFMP	Catchment Flood Management Plan
DMRB	Design Manual for Roads and Bridges
EA	Environment Agency
FRA	Flood Risk Assessment
GYBC	Great Yarmouth Borough Council
IDB	Internal Drainage Board
LFRMS	Local Flood Risk Management Strategy
MHWST	Mean High Water Spring Tide
MLWST	Mean Low Water Spring Tide
NCC	Norfolk County Council
NPPF	National Planning Policy Framework
NPS NN	National Policy Statement for National Networks
NPS	National Policy Statement
NSIP	Nationally Significant Infrastructure Project
PPG	Planning Practice Guidance
PFRA	Preliminary Flood Risk Assessment
SFRA	Strategic Flood Risk Assessment
SMP2	Shoreline Management Plan 2
SuDS	Sustainable Drainage Systems

1 Introduction

1.1 Scope of the Assessment

1.1.1 This Flood Risk Assessment (FRA) has been prepared for the proposed Great Yarmouth Third Crossing (hereinafter referred to as “the Scheme”) within the town of Great Yarmouth on the East Anglian coast of England. The FRA is supported by figures in Volume 3 of the ES (document reference 6.3).

1.1.2 The Great Yarmouth Local Plan was adopted in December 2015 and identifies Great Yarmouth Borough Council’s (GYBC) long-term ambition for a third vehicular crossing of the River Yare and the Scheme has been designated a Nationally Significant Infrastructure Project (NSIP).

1.1.3 The National Policy Statement for National Networks (NPS NN) (Ref 12B.1) paragraph 5.94 states that in preparing an FRA, the applicant should:

- “consider the risk of all forms of flooding arising from the project (including in adjacent parts of the United Kingdom), in addition to the risk of flooding to the project, and demonstrate how these risks will be managed and, where relevant, mitigated, so that the development remains safe throughout its lifetime;
- take the impacts of climate change into account, clearly stating the development lifetime over which the assessment has been made;
- consider the vulnerability of those using the infrastructure including arrangements for safe access and exit;
- include the assessment of the remaining (known as ‘residual’) risk after risk reduction measures have been taken into account and demonstrate that this is acceptable for the particular project;
- consider if there is a need to remain operational during a worst-case flood event over the development’s lifetime; and
- provide the evidence for the Secretary of State to apply the Sequential Test and Exception Test, as appropriate”.

1.1.4 More comprehensive guidance regarding the FRA process is provided in the NPPF (Ref 12B.2) and PPG (Ref 12B.3), this FRA has been carried out in accordance with the requirements of these documents as well as the NPS NN.

1.1.5 The aim of this assessment is to establish the flood risk associated with the Scheme, during the construction phase and the operational phase. The objectives of this FRA are summarised as follows:

- Assess the risk to the Scheme from all potential sources of flooding (both during construction and operation);
- Establish the existing and future flood risk to the Scheme;
- Assess the potential impacts of the Scheme on flood risk elsewhere (both during construction and operation); and
- Determine appropriate mitigation measures to manage flooding issues during operation in a sustainable way.

1.2 Policy and Guidance

1.2.1 All legislation, policy and guidance relevant to this FRA are summarised in Appendix 12A. Key policy and guidance documents followed to develop this FRA are summarised below.

National Planning Policy Framework

1.2.2 The NPPF (Ref 12B.2) sets out the framework for planning decisions made by local, regional and national government and the Environment Agency (EA). The NPPF advises that FRAs are required for all developments in Flood Zones 2, 3a and 3b and for all development sites in Flood Zone 1 that are 1 hectare (ha) or greater. The definitions of these zones are provided in Section 4 of this FRA. The majority of the Application site lies in Flood Zone 3 (3a) (refer to Table 2), therefore a FRA is required.

Design Manual for Roads and Bridges

1.2.3 The Design Manual for Roads and Bridges (DMRB) (Ref 12B.4) provides guidance on the assessment and management of the impacts that road projects may have on the water environment.

1.2.4 A general theme in this manual identifies that development within floodplains should be restricted to essential transport and utilities infrastructure, and further adds that the design and construction of such infrastructure should allow for full operation, even in times of flood. As a result of construction there should be no net loss of floodplain storage, flood flows should not be impeded and the infrastructure should not increase the flood risk elsewhere.

1.2.5 Paragraph 3.30 states that “roads should only be located within functional floodplains.... if there is no acceptable alternative and restricted to the shortest practical crossing, avoiding extensive construction within the floodplain. Where this is unavoidable, the level of the road should be above the level of the predicted event....an event with a 1% annual probability of occurrence for river floodplains, or the 0.5% annual event for tidal floodplains”.

Sustainable Drainage Systems (SuDS) Manual (C753)

1.2.6 The SuDS Manual (C753), produced by CIRIA in November 2015 (Ref 12B.5), provides best practice guidance on the planning, design, construction, operation and maintenance of sustainable drainage systems (SuDS) to facilitate their effective implementation within developments.

1.2.7 Refer to Section 7.2 of this FRA for more information.

1.3 Information Provided

1.3.1 The following information has informed this study:

- General Arrangement Plans (document reference 2.2);
- Engineering Plans, Drawings and Sections (document reference 2.10);
- OS Mastermap (provided by NCC);
- As-built construction drawings for Haven Bridge (provided by NCC);
- Bathymetric survey data for the River Yare through Great Yarmouth (collected by Peel Ports Great Yarmouth in 2017;
- 0.5m LiDAR covering Great Yarmouth (flown in 2105 by the EA);
- 1m LiDAR covering Great Yarmouth (flown in 2009 by the EA);
- Extreme Sea Level (ESL) data (provided by the EA);
- 15-minute resolution recorded water level data from gauges at Haven Bridge, Gorleston, Three Mile House and Burgh Castle (provided by the EA);
- Existing 1D/2D hydraulic model covering Great Yarmouth developed for the Great Yarmouth Reporting and Mapping Study, 2011 (provided by the EA);
- Existing 1D/2D hydraulic model covering Great Yarmouth developed for Great Yarmouth Flood Defence – Epoch 2 – 2016 to 2021, (Outline Business Case), 2018 (provided by EA); and
- Existing 1D/2D hydraulic model representing baseline scenario in Great Yarmouth, JBA 2018 with latest defence crest levels included (provided by EA).

1.3.2 The following documents have been used to gather information for this FRA:

- Great Yarmouth Strategic Flood Risk Assessment (SFRA), November 2017 (Ref 12B.6);

- Broadlands Rivers Catchment Flood Management Plan (CFMP), December 2009 (Ref 12B.7);
- Kelling to Lowestoft Ness Shoreline Management Plan 6 (SMP), August 2012 (Ref 12B.8);
- NCC Preliminary Flood Risk Assessment Report (PFRA); July 2011 (Ref 12B.9);
- Norfolk Local Flood Risk Management Strategy (LFRMS), July 2015 (Ref 12B.10);
- EA data and web based mapping; and
- Broads Authority web based mapping.

2 Existing Site

2.1.1 Great Yarmouth is a seaside town in Norfolk on the east coast of England. The River Yare flows through the centre of the town creating a commercial port with a number of large ship berths. Tidal defences line the river edge, providing protection from coastal flooding to the town. The river flows in a southerly direction, under two existing bridges before turning at almost a right angle to discharge in an easterly direction into the sea.

2.1.2 The River Yare is one of the sea boundaries of the Broadlands Rivers catchment and is tidally driven; the main flooding mechanism to Great Yarmouth is tidal. Tidal levels drive the levels in the River Yare and across the Norfolk Broads. Great Yarmouth currently has two road bridge crossings over the River Yare; the A47 Bridge and Haven Bridge as shown in Figure 12.1. These are the only two ways for traffic to cross the River Yare currently.

2.1.3 The River Bure is a tributary of the River Yare that flows into the River Yare approximately 240m downstream of the A47 Bridge. Upstream of the A47 Bridge, the River Yare forms a lake known as Breydon Water.

2.1.4 There are a number of Environment Agency (EA) defence assets throughout Great Yarmouth, which consist of a mixture of embankments, quays, bridge abutments, demountable defences, flood gates and walls. The condition of these assets varies. Much of the town is dependent on flood defences to protect it from tidal flooding.

3 The Scheme

3.1.1 The full Scheme description is contained within Chapter 2 of the ES (document reference 6.1). The features of the Scheme that are relevant to the FRA are discussed here. The 17.33 hectare (ha) Application Site is made up of the Principal Application Site (proposed bridge location) and Satellite Application Sites (variable message signs, or VMS). The Scheme includes a bridge deck spanning the watercourse, for this assessment an invert level of 4.5mAOD and a deck height of 9.6mAOD in the centre of the bridge have been assumed and are within the Limits of Deviation for the Scheme. These values have been included in the assessment and a Rochdale Envelope approach has been used to consider a feasible worst-case Scheme design in terms of flood risk. The soffit level of the bridge is not likely to be less than 5.36mAOD but the 4.5mAOD level has been used in the modelling in order to be conservative as this will cause a greater constriction in the channel. The bridge deck level will potentially be higher than 9.6mAOD but a higher deck level would not have an impact on the findings of this assessment as the 9.6mAOD level is above the highest tidal flood level considered in this assessment as discussed in Section 6.

3.1.2 Knuckles would span approximately a quarter of the way across the channel from both banks and their combined impact would restrict the channel width by up to approximately 50% to 50m (limit of deviation). It has been assumed for this assessment that each knuckle ties into the bridge deck and therefore both knuckles have a deck height of 9mAOD. Each side of the bridge has an approach road sloping from 9.6mAOD on the bridge deck to the existing ground level on either side of the river. The approach roads have been represented as solid embankments in the flood model developed for the assessment but there is an opening in them on either side of the river to allow roads to run alongside the river underneath the approach roads to the bridge.

3.1.3 The Scheme consists of a new dual carriageway road across the River Yare in Great Yarmouth linking the A47 at Harfrey's Roundabout on the western side of the river to the A1243 South Denes Road on the eastern side.

3.1.4 The Scheme is considered a nationally significant infrastructure project (NSIP) and deemed 'Safety Critical' meaning it should remain accessible/functional in an emergency event. The design life of the Scheme is 120 years and, assuming the Scheme would not be constructed before 2020, it was deemed appropriate to use the year 2140 for future flood scenarios taking into account climate change as requested by the EA.

3.1.5 The area of the Application Site is 17.33ha but this is split over seven discrete areas as shown in the General Arrangement Plans (document reference 2.2) Approximately 70% of the total Scheme area (12.13ha) has been identified using aerial imagery and site walkovers as being impermeable in nature. The remaining 5.2ha (approximately 30%) of the Scheme area has therefore been identified as having permeable surfaces. The area within the Application Site is predominately brownfield land which is mostly impermeable concrete surfaces that are the remnants of former dockside developments. At the Satellite Application Sites, the Scheme will not change the ratio of permeable to impermeable surfaces. At the Principal Application Site, there will be an increase of 1.78ha in the impermeable surface area compared to the existing surfaces within this area. This will have an impact on the surface water runoff from the site and this is discussed in Section 6.

3.1.6 The Scheme is located within Flood Zone 3 (3a), which means there is a 0.5% Annual Exceedance Probability (AEP) of flooding from the sea or a 1% AEP chance of flooding from fluvial sources in any given year.

4 Planning Policy

4.1 National Policy Statement for National Networks

4.1.1 The NPS NN (Ref 12B.1) sets out the government policies for NSIPs on the road and rail networks in England and provides planning guidance for promoters. The Secretary of State uses the NPS NN as the primary basis for making decisions on development consent applications for NSIPs in England. The Scheme is an NSIP and has safety-critical elements, therefore the NPS NN is relevant to this assessment.

4.1.2 The NPS NN recognises that as a result of climate change, the risk of flooding will increase within the lifetime of NSIPs. Section 4.41 of the NPS NN 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. An updated version of the UK Climate Projections, UKCP18, was released in November 2018. The use of climate change allowances from UKCP09 and UKCP18 in this assessment is discussed in Section 6.

4.1.3 In line with the NPS NN, this FRA has been undertaken as the Scheme is within Flood Zone 3. The NPS NN (paragraph 5.93) states that the FRA:

'should identify and assess the risks of all forms of flooding to and from the project and demonstrate how these flood risks will be managed, taking climate change into account.'

4.1.4 The NPS NN advises that early pre-application meetings with the EA (and any other relevant flood risk management bodies) should be held for projects which may be affected by or may add to flood risk. If the EA has concerns about the proposal on flood risk grounds, these should be discussed with the EA and the applicant should look to amend their proposal or provide additional information in order to satisfy the concerns of the EA.

4.1.5 For local flood risk (surface water, groundwater and ordinary watercourse flooding), the NPS NN recommends that local flood risk management strategies and surface water management plans provide useful information.

4.1.6 In order to grant development consent, the Secretary of State must be satisfied that the application is supported by an appropriate FRA and the Sequential Test (NPPF) and, if required, the Exception Test (NPPF) has been applied.

4.1.7 The Sequential Test sets out that preference should be given to location projects in Flood Zone 1 and if there is no reasonably available site in Flood

Zone 1, projects can be located in Flood Zone 2. If there is no reasonably available site in Flood Zones 1 and 2, then national networks infrastructure projects can be located in Flood Zone 3, subject to the Exception Test.

4.1.8 The Exception Test provides a method of managing flood risk while still allowing necessary development to occur. The Exception Test is discussed further in Section 4.2.

4.1.9 The NPS NN states that the FRA should be carried out with reference to the guidance from the NPPF and accompanying Planning Practice Guidance (PPG). With regard to linear infrastructure, Paragraph 5.102 of the NPS NN states:

The Secretary of State should expect that reasonable steps have been taken to avoid limit and reduce the risk of flooding to the proposed infrastructure and others. However, the nature of linear infrastructure means that there will be cases where:

- *upgrades are made to existing infrastructure in an area at risk of flooding;*
- *infrastructure in a flood risk area is being replaced;*
- *infrastructure is being provided to serve a flood risk area; and*
- *infrastructure is being provided connecting two points that are not in flood risk areas, but where the most viable route between the two passes through such an area.*

4.2 National Planning Policy Framework

Flood Zone Definition

4.2.1 Table 4.1 shows the various Flood Zones as defined in the PPG (Ref 12B.3). These Flood Zones refer to the probability of the river and sea flooding and they disregard the effect of any flood defences that may be present. The scheme is predominantly located in Flood Zone 3 (3a), with smaller areas of the Order limits falling within Flood Zones 1 and 2 as shown on Figure 12.2. Section 6.1 discusses this in greater detail.

Table 4.1: Flood Zone Definitions (Extracted from the PPG)

Flood Zone 1	This zone comprises land assessed as having a less than 1 in 1,000 annual probability of river or sea flooding (<0.1%).	Low Probability
Flood Zone 2	This zone comprises land assessed as having between a 1 in 100 and 1 in 1,000 annual probability of river flooding (1% – 0.1%), or between a 1 in 200 and 1 in 1,000 annual probability of sea flooding (0.5% – 0.1%) in any year.	Medium Probability
Flood Zone 3a	This zone comprises land assessed as having a 1 in 100 or greater annual probability of river flooding (>1%), or a 1 in 200 or greater annual probability of flooding from the sea (>0.5%) in any year.	High Probability
Flood Zone 3b	This zone comprises land where water has to flow or be stored in times of flood. The identification of functional floodplain should take account of local circumstances but land which would flood with an annual probability of 1 in 20 (5%) or greater in any year, or is designed to flood in an extreme (0.1%) flood, should provide a starting point for consideration.	Functional Floodplain

Flood Risk Vulnerability

4.2.2 In the PPG, developments are classified according to their ‘Flood Risk Vulnerability’ as presented in the extract from the PPG in Table 4.2. The Scheme is classified as ‘Essential Infrastructure’ under the PPG as this covers ‘essential transport infrastructure (including mass evacuation routes) which has to cross the area at risk’.

Table 4.2: Flood Risk Vulnerability (Extracted from the PPG (Ref 12B.3))

Vulnerability Classification	Description
Essential Infrastructure	• Essential transport infrastructure (including mass evacuation routes) which has to cross the area at risk. • Essential utility infrastructure which has to be located in a flood risk area for operational reasons, including electricity generating power stations and grid and primary substations; and water treatment works that need to remain operational in times of flood. • Wind turbines.
Highly vulnerable	• Police and ambulance stations; fire stations and command centres; telecommunications installations required to be operational during flooding. • Emergency dispersal points. • Basement dwellings. • Caravans, mobile homes and park homes intended for permanent residential use.

Vulnerability Classification	Description
	• Installations requiring hazardous substances consent. (Where there is a demonstrable need to locate such installations for bulk storage of materials with port or other similar facilities, or such installations with energy infrastructure or carbon capture and storage installations, that require coastal or water-side locations, or need to be located in other high flood risk areas, in these instances the facilities should be classified as 'Essential Infrastructure').
More vulnerable	• Hospitals • Residential institutions such as residential care homes, children's homes, social services homes, prisons and hostels. • Buildings used for dwelling houses, student halls of residence, drinking establishments, nightclubs and hotels. • Non–residential uses for health services, nurseries and educational establishments. • Landfill and sites used for waste management facilities for hazardous waste. • Sites used for holiday or short-let caravans and camping, subject to a specific warning and evacuation plan.
Less vulnerable	• Police, ambulance and fire stations which are not required to be operational during flooding. • Buildings used for shops; financial, professional and other services; restaurants, cafes and hot food takeaways; offices; general industry, storage and distribution; non-residential institutions not included in the 'more vulnerable' class; and assembly and leisure. • Land and buildings used for agriculture and forestry. • Waste treatment (except landfill and hazardous waste facilities). • Minerals working and processing (except for sand and gravel working). • Water treatment works which do not need to remain operational during times of flood. • Sewage treatment works, if adequate measures to control pollution and manage sewage during flooding events are in place.
Water-compatible development	• Flood control infrastructure. • Water transmission infrastructure and pumping stations.

Vulnerability Classification	Description
	• Sewage transmission infrastructure and pumping stations. • Sand and gravel working. • Docks, marinas and wharves. • Navigation facilities. • Ministry of Defence defence installations. • Ship building, repairing and dismantling, dockside fish processing and refrigeration and compatible activities requiring a waterside location. • Water-based recreation (excluding sleeping accommodation). • Lifeguard and coastguard stations. • Amenity open space, nature conservation and biodiversity, outdoor sports and recreation and essential facilities such as changing rooms. • Essential ancillary sleeping or residential accommodation for staff required by uses in this category, subject to a specific warning and evacuation plan.

Appropriate Development

Sequential Test

4.2.3 The Scheme was initially subject to the Sequential Test. Drawing on previous optioneering work undertaken, Chapter 3 of the ES (document reference 6.1) explains the reasons for the choice of location for the Scheme, concluding that it is the most appropriate location. As the Scheme involves a bridge crossing a river, there are no viable alternative sites within Flood Zone 1 or Flood Zone 2 as the infrastructure has to cross the floodplain.

Exception Test

4.2.4 The Scheme is classified as 'Essential Infrastructure' in accordance with the PPG and is predominantly located in Flood Zone 3 (3a). Applying the flood risk vulnerability and Flood Zone 'compatibility' table from the PPG as shown in

4.2.5 Table *6.1* shows that the Exception Test is required for the Scheme in this location.

4.2.6 As set out in the NPS NN, the Exception Test is only appropriate for use where the Sequential Test alone cannot deliver an acceptable site, thus taking into account the need for national networks infrastructure to remain operational during floods.

4.2.7 The NPS NN also states that both elements of the test will have to be passed for the development to be consented. For the Exception Test to be passed the following must be met (paragraph 5.108):

- *It must be demonstrated that the scheme development provides wider sustainability benefits to the community that outweigh flood risk; and*
- *A flood risk assessment must demonstrate that the scheme development will be safe for its lifetime, without increasing flood risk elsewhere and, where possible, will reduce flood risk overall.*

4.2.8 Part one of the Exception Test is addressed in Appendix A of the Case for the Scheme (document reference 7.1), which details how the wider sustainability benefits of the Scheme outweigh flood risk. The wider benefits of the Scheme include improving connectivity and resilience for port activities, supporting the delivery of existing and potential renewable energy NSIPs and supporting the port's role as an international gateway. This FRA has been prepared to address part two of the Exception Test only. The Application site is predominantly in Flood Zone 3a and is essential infrastructure, therefore the Exception Test is required as indicated by the red text in Table 4.3.

Table 4.3: Flood Risk Vulnerability and Flood Zone "Compatibility" (Recreated from the PPG)

Flood Risk Vulnerability Classification		Essential Infrastructure	Water Compatible	Highly Vulnerable	More Vulnerable	Less Vulnerable
Flood Zone	Zone 1	✓	✓	✓	✓	✓
	Zone 2	✓	✓	Exception Test required	✓	✓
	Zone 3a	Exception Test required	Exception Test required	X	Exception Test required	✓

	Zone 3b	Exception Test required	✓	X	X	X

Key: ✓ Development is appropriate
X Development should not be permitted

4.3 Local Planning Policy

Great Yarmouth Local Plan: Core Strategy 2013-2030

4.3.1 The Great Yarmouth Local Plan was adopted in 2015 by GYBC. The plan details the future development ambitions for the Great Yarmouth area during the years 2013-2030. It sets out in strategic terms, the council's overall approach to future development; where it should take place and the key factors that need to be taken into account when considering proposals for development.

4.3.2 Although emerging Great Yarmouth Waterfront Area Action Plan (AAP) documents were drafted in 2007 and 2010, they are yet to be adopted as Supplementary Planning Documents. Policy CS17 supersedes the draft AAPs and until such time that a Supplementary Planning Document for the area is adopted, which is an ambition of Policy CS17, proposals relating to the development of individual buildings and/or sites within the Waterfront Area must demonstrate conformity with it. The ambitious growth expectations for the area (although it is acknowledged that not all are intended to be within the current plan period) includes the identification of sites for:

- 1,000 new dwellings of a mix of types (at least 300, or 350 according to Policy CS3, to be delivered in the plan period);
- 16,500m^2 of employment space (7,700m^2 anticipated to be delivered in the plan period);
- 14,200m^2 of retail and leisure floorspace (5,050m^2 of which is anticipated to be delivered in the Plan period).

4.3.3 There is a specific policy on flood risk within the First Draft Local Plan (Policy CS13, Ref 12B.11) which sets out how development proposals should take flood risk into account. The policy also states that the Strategic Flood Risk Assessment (SFRA) (Ref 12B.6) should be the starting point in assessing whether a proposal is at risk from flooding, furthermore seeking the use of Sustainable Drainage Systems (SuDS) in all new developments.

5 Previous Studies and Historic Flood Risk

5.1 Previous Studies

5.1.1 In line with the recommendation in paragraph 5.97 of the NPS NN (Ref 12B.1), the following local documents have been considered as part of this FRA:

- Great Yarmouth Strategic Flood Risk Assessment (SFRA), November 2017 (Ref 12B.6);
- Broadlands Rivers Catchment Flood Management Plan (CFMP), December 2009 (Ref 12B.7);
- Kelling to Lowestoft Ness Shoreline Management Plan 6 (SMP), August 2012 (Ref 12B.8);
- NCC Preliminary Flood Risk Assessment Report (PFRA), July 2011 (Ref 12B.9);
- Norfolk Local Flood Risk Management Strategy (LFRMS), July 2015 (Ref 12B.10);
- Anglian River Basin Flood Risk Management Plan (FRMP) December 2015 (Ref 12B.12); and
- NCC Investigation Report into flooding across Great Yarmouth Borough, June 2015 (Ref 12B.13).

Great Yarmouth Strategic Flood Risk Assessment

5.1.2 The Great Yarmouth SFRA was undertaken in November 2017 on behalf of GYBC. This document provides an overview and guidance on the flood risk for the Great Yarmouth Borough, taking into account the latest flood risk information and the current state of national planning policy.

5.1.3 The SFRA states that due to the low-lying nature of the authority area, the Principal Application Site is at risk of fluvial flooding. The River Yare, a main river located within the Principal Application Site, is subject to tidal influences at the downstream end of its catchment. Consequently, its tidal influence is powerful enough to reverse the flow of the rivers and hold back water within the surrounding drainage system. This ‘tide-locking’ effect raises levels further up the catchments and in adjoining tributaries increasing the flood risk over a broad area.

5.1.4 Tidal flooding in the area is caused by extreme tide levels exceeding ground and / or defence levels. Tidal flooding in Great Yarmouth usually occurs by waves overtopping existing defences. The SFRA also states that flood zones 1, 2 and 3 delineate areas at low risk, medium risk and high risk respectively from both tidal and fluvial flooding. However, the flood zones do not take tidal defences into account tidal defences, flood zones 3 and 2 represent the area that would be flooded in the 0.5% AEP and 0.1% AEP tidal event in the absence of defences, respectively. It should be noted that the consideration of climate change may influence current flood zones in the future.

5.1.5 According to the SFRA (Ref 12B.6), tidal flooding is the most significant flood risk in the borough as Great Yarmouth is bound to the east by the North Sea and is entirely located within the tidally influenced area of the Broadlands Rivers catchment. Additionally, the CFMP (Ref 12B.7) states that there is acute risk of tidal flooding in Great Yarmouth and across the Broads within the study area; there are defences throughout Great Yarmouth to protect the town from tidal flooding.

5.1.6 Tidal / coastal inundation along the sea front is shown to affect properties along and in the vicinity of South Beach Parade, Marine Parade and North Drive. These affected properties are within close reach of the Scheme, with South Beach Parade at a distance of 0.6km, Marine Parade at 2.5km and North Drive at 2.1km.

5.1.7 Tidal locking has the potential to increase levels upstream in the River Yare and River Bure due to the watercourses not being able to discharge effectively during high tide. In addition, high levels in the River Yare may result in the River Bure being unable to discharge effectively, causing levels near the confluence to rise.

5.1.8 There are a variety of EA assets located in the Great Yarmouth borough. The assets comprise a mixture of embankments, quays, bridge abutments, demountable defences, flood gates and walls.

5.1.9 Flood defences within Great Yarmouth are predominantly formed of walls, as shown in Plate 5.1. A number of bridge abutments, flood gates and demountable defences are located along the walls. Embankments surround the south-east of Breydon Water. A quay is located along Riverside Road and to the south-west of the port in Great Yarmouth town.

5.1.10 The SFRA classified the condition of the current defences as either very good, good, fair, poor or very poor condition as illustrated in Plate 5.2.

5.1.11 In 2016, the Environment Agency finished the first phase of work to replace over 500 metres of tidal defences, which reduces the risk of flooding to the Southtown and Cobham areas of Great Yarmouth. Over the coming decades, the EA intend to refurbish the tidal defences in 5-year phases. The EA scheme is intended to reduce the risk of tidal flooding from the River Yare to over 6,000 properties, including 5,000 homes over 12km of flood defences.

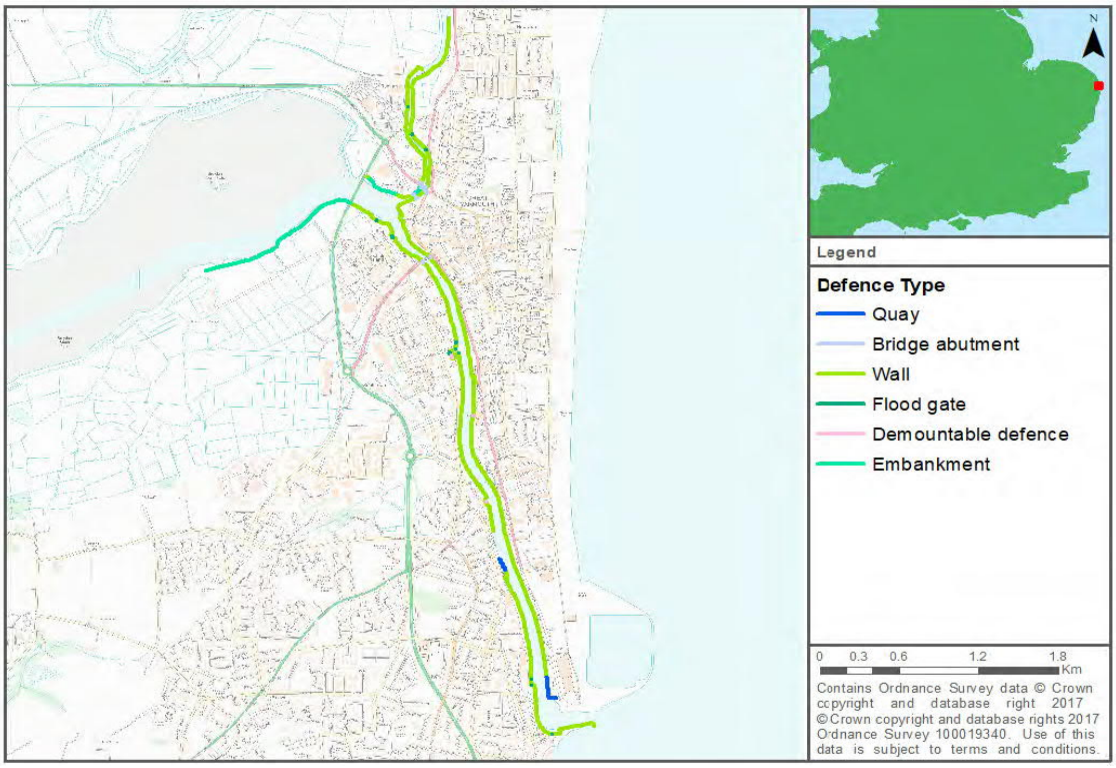

Plate 5.1: EA Flood Defence Type in Great Yarmouth Town (Extract from SFRA)

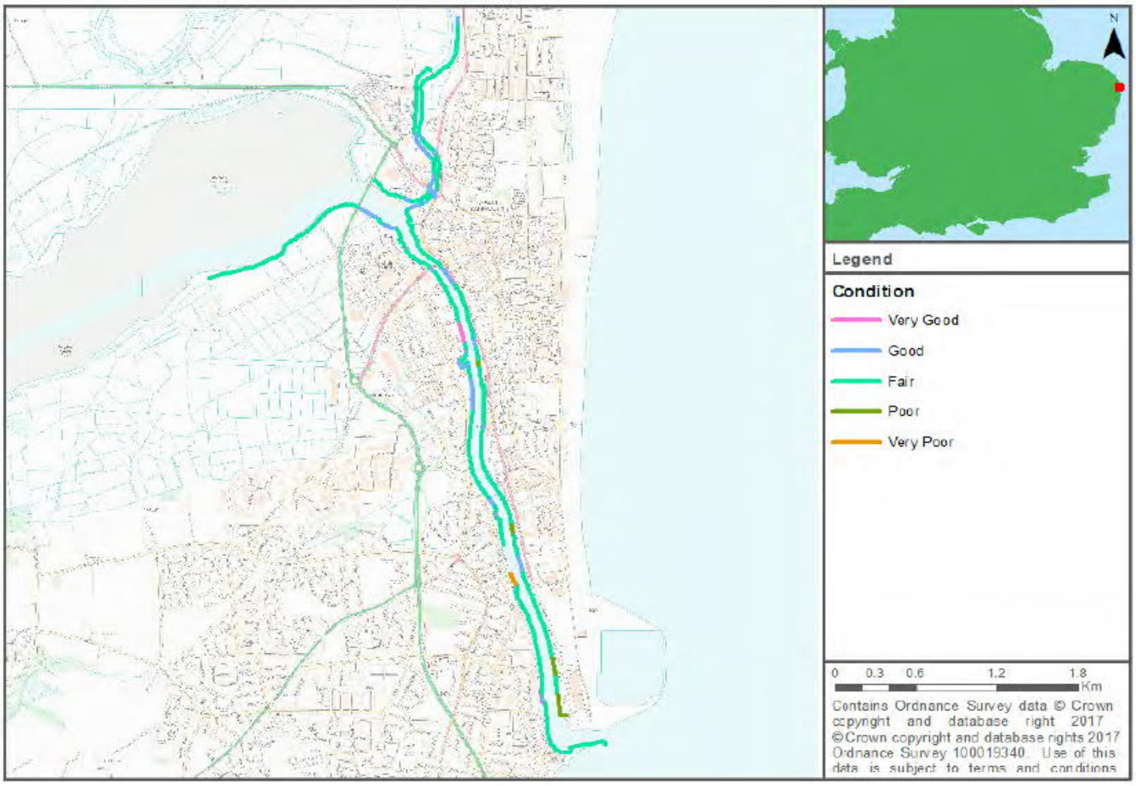

Plate 5.2: EA Flood Defence Condition in Great Yarmouth Town (Extract from SFRA)

5.1.12 The SFRA references the 2012 Kelling to Lowestoft Ness SMP. This document describes the high-level strategy and coastal policies within the study area. The coastal flood risk in Great Yarmouth is high, and may result in flooding of the beaches and undefended areas, or cause overtopping of defences within the town.

5.1.13 Surface water flood risk is shown to affect large areas in Great Yarmouth. As stated in the SFRA:

'In the 3.3% AEP event, surface water is generally restricted to roadways and gardens. However, around Burgh Road property is shown to be affected by surface water extents. In the 1% AEP event, surface water extents continue to increase, with additional properties affected throughout the settlements; properties off Wren Drive are notably affected. In the 0.1% AEP event, surface water flooding is shown to be widespread across the settlements with the areas shown to be most at risk including properties off Oxford Avenue, Yallop Avenue, Primrose Way, Lord's Lane as well as numerous other locations across the settlements.'

5.1.14 The roads referenced in the above quote are located on the outer suburbs of Great Yarmouth, and therefore are not associated with the Scheme.

5.1.15 Historic surface water flooding is mainly attributed to heavy rainfall events which have caused pumping stations to fail and the drainage capacity to be exceeded. This is further explored in Section 6.2.

5.1.16 As identified in the SFRA (para 5.2.3) "Great Yarmouth borough is partially covered by the Waveney, Lower Yare and Lothingland IDB and the Water Management Alliance. The Water Management Alliance covers five IDBs; the Broads IDB partially covers the borough." Plate 6.2 shows these areas.

5.1.17 Extracted from the SFRA (para 6.3.3), the IDB policy statements of flood protection and flood management are summarised as follows:

- "The Waveney, Lower Yare and Lothingland IDB policy statement discusses that the Board will seek to maintain a general standard of protection against flooding of 1 in 25-years for developed areas and 1 in 15-year for agricultural land. The policy statement acknowledges that the standards cannot be taken literally and that some over-spilling from the systems may occur during these events.
- The Broads IDB policy statement discusses that the Board will seek to maintain a general standard of protection against flooding of 1 in 10-years with 600mm of freeboard to agricultural land and 1 in 100-year with 300mm freeboard to developed areas. The policy statement acknowledges that the standards cannot be taken literally and that some over-spilling from the systems may occur during these events."

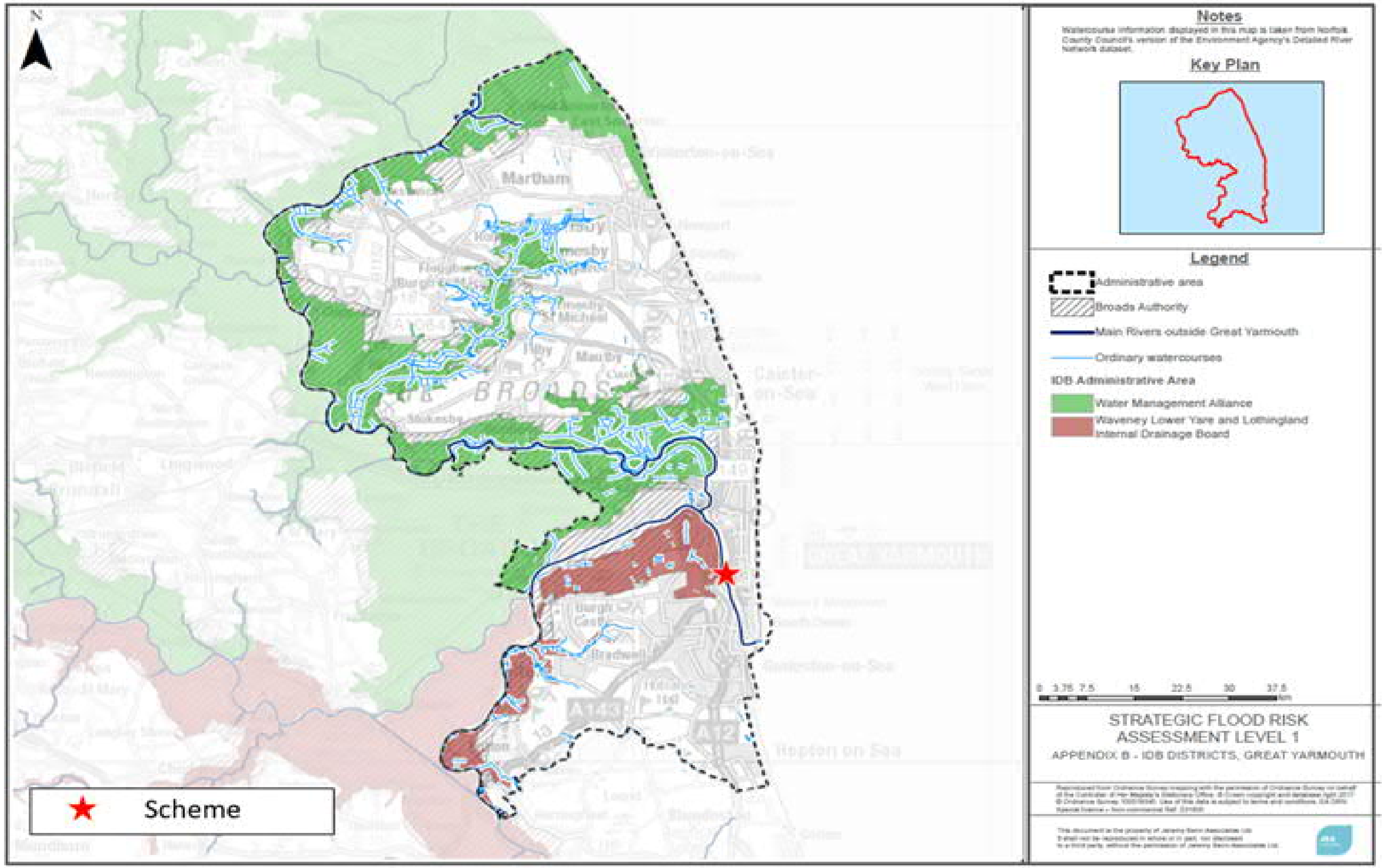

Plate 6.2: IDBs covering Great Yarmouth and the Norfolk Broads (extracted from the Great Yarmouth SFRA)

Broadlands Rivers Catchment Flood Management Plan

5.1.18 The Broadlands Rivers CFMP was published in December 2009 by the EA (Ref 12B.7). Its purpose is to provide an overview of the flood risk for the Broadlands Rivers catchment and sets out the preferred plan for sustainable flood risk management over the next 50-100 years. Produced through a wider consultation and appraisal process, it identifies flood risk management policies to assist all key decision makers in the catchment.

5.1.19 The Broadlands Rivers catchment includes five major rivers: The Rivers Ant, Bure, Wensum, Yare and Waveney. These catchments drain into the tidally dominated area of inland waterways known as The Broads, and finally out to sea through the mouth of the River Yare at Great Yarmouth.

5.1.20 The topography of the Broadland Rivers catchment is predominately flat. The area upstream of Norwich is relatively hilly, however as the rivers reach the Broads, they become wide and flat. Here the land is mostly below sea level and as such is mostly tidal in nature.

5.1.21 The Scheme is located within Great Yarmouth Sub-area 5 where the preferred policy option is 5; ‘Areas of moderate to high flood risk where we can generally take further action to reduce flood risk’. This policy applies to those areas where the case for further action to reduce flood risk is most compelling, for example where there are many people at high risk, or where changes in the environment have already increased risk. Taking further action to reduce risk will require additional appraisal to assess whether there are socially and environmentally sustainable, technically viable and economically justified options.

5.1.22 The CFMP states that the main source of flooding in Great Yarmouth is from tidal sources, with eight properties at risk during the 0.5% AEP, however there is also a risk from surface water and sewer flooding. The key messages for Great Yarmouth (pages 22 and 23 of CFMP), Sub-area 5 area are:

- "*Continue with improvement works to the defences in Great Yarmouth;*
- *Develop a study to look at options to manage residual flood risk in the future;*
- *Organisations need to take an integrated approach to managing river, tidal and surface water flooding;*
- *Any redevelopment of floodplain areas is an opportunity to increase their flood resilience;*
- *Emergency response and flood awareness plans will be used to manage flood risk from the flood defences failing or being overwhelmed".*

5.1.23 The proposed actions to implement the preferred policy are as follows:

- "*Continue with the current flood risk management activities, including works to improve the existing defences;*
- *Develop a flood risk study to investigate how we can manage the future flood risk through improving flood risk management activities. This may be to develop a flood risk study to investigate how we can manage the residual future flood risk through improving flood risk management activities. This may be through creating new flood defences and also the possibility of a tidal barrier on the River Yare;*
- *Work with partners to develop a Surface Water Management Plan for Great Yarmouth;*
- *Encourage planners to develop policies for regeneration to follow the principles of PPS25, incorporate resilience measures so that the location, layout and design of development can help to mitigate persistent flood risk and provide opportunities to persistent flood risk and provide opportunities to improve the environment and make space for water;*
- *Improving public awareness and encouraging people to sign up to, and respond to, flood warnings. Flood awareness plans will inform people about the risk of defences breaching and actions they can take to protect themselves;*
- *Emergency response plans to manage flood risk from the defences failing or being overwhelmed, and work with partners to manage flood risk to critical infrastructure".*

5.1.24 Plate 5.3 taken from the CFMP shows that there are currently up to 25 properties at risk from river flooding, and also up to 25 properties at risk from tidal flooding along the River Yare in Great Yarmouth. Plate 5.3 displays flood risk to properties located in the Broadlands River catchment. Taking into account a 1% annual probability river flood, 0.5% annual probability and combined flooding, also factoring in current flood defences.

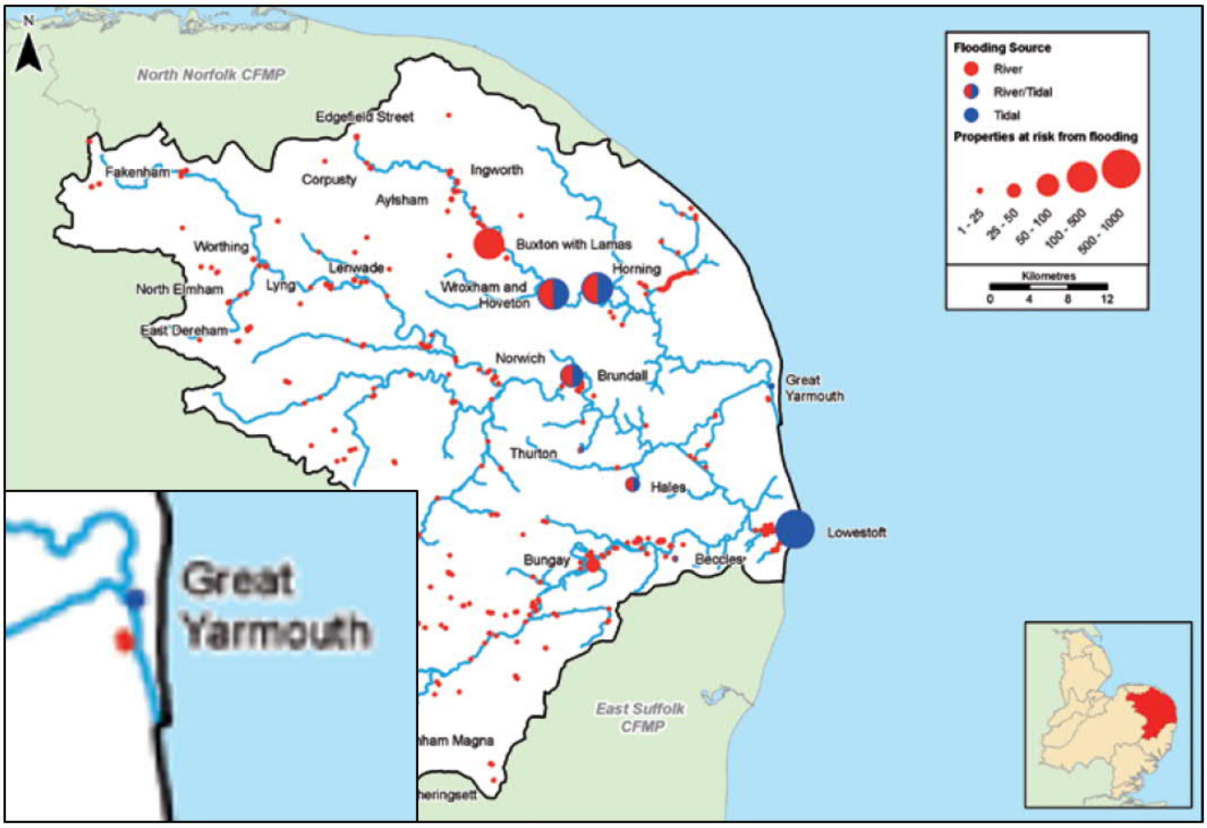

Plate 5.3: Flood Risk to Property (Extract from CFMP)

Kelling to Lowestoft Ness Shoreline Management Plan

5.1.25 The Kelling to Lowestoft Ness SMP (Ref 12B.8) aims to minimise exposure of people and property to the risks of coastal change by encouraging new development away from areas at risk of coastal change.

5.1.26 The SMP provides a large-scale assessment of the risks associated with coastal evolution and presents a policy framework for various different areas. The Scheme lies within the Eccles to Great Yarmouth policy. Under that policy the beach is expected to continue to provide ample protection without the need for any intervention.

5.1.27 The SMP identified that *"the longer-term plan has to allow for some realignment of the shoreline to take place northwards from Caister Point to enable improved material movement along this coastline. This will still result in the protection of most development at Caister, whilst helping to ensure the protection of all assets in Great Yarmouth and maintaining the nature conservation interests here also"*.

Norfolk County Council Preliminary Flood Risk Assessment Report

5.1.28 The NCC PRFA (Ref 12B.9) was published in July 2011. There is limited information regarding historical fluvial and tidal flooding events in this document. However, various future flood risk maps were produced. Plate 5.4 identified that 1,000 to 10,000 properties are susceptible to ground-water flooding in Great Yarmouth.

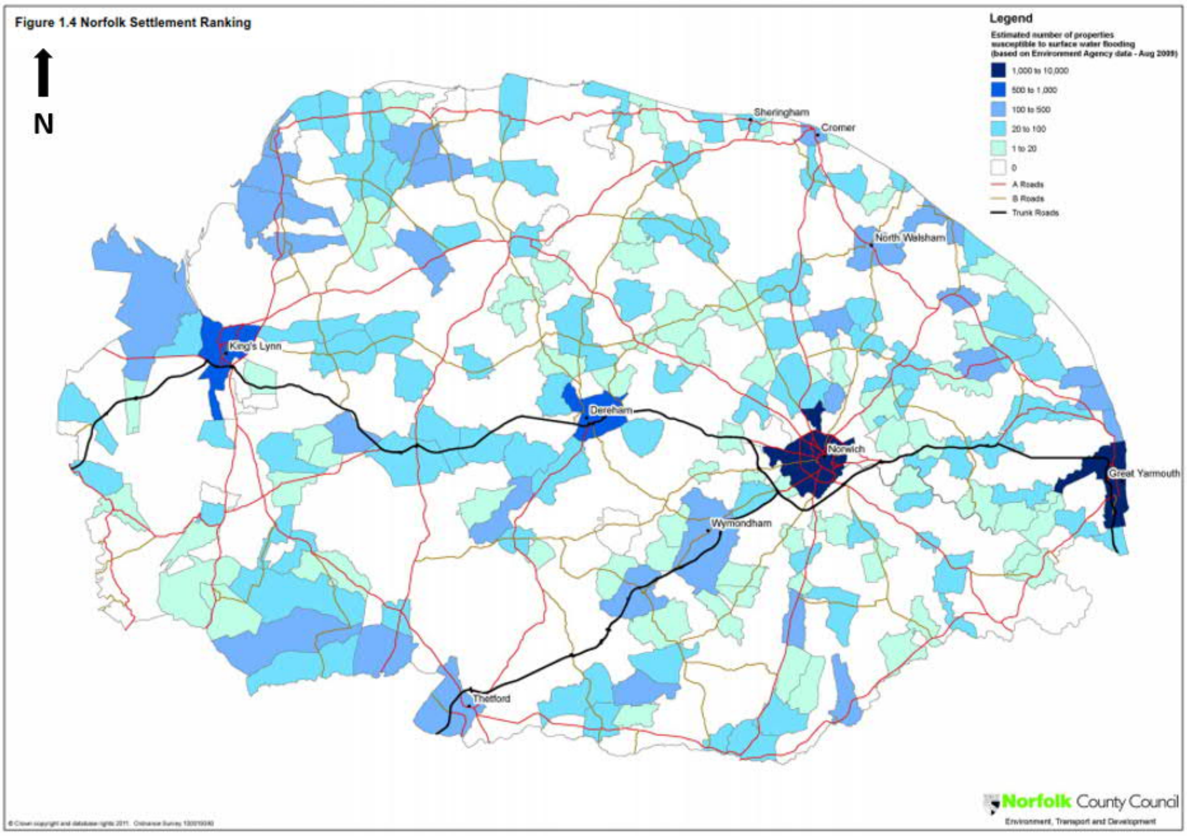

Plate 5.4: Norfolk Settlement Ranking (Extract from PFRA)

Norfolk Local Flood Risk Management Strategy

5.1.29 The Norfolk LFRMS identified that the most significant flood risk in the Great Yarmouth borough is that of coastal inundation (approx. 24km of coastline) and fluvial flooding. Although the frequency of such events is considered low and in most circumstances flood defences are likely to be effective in preventing such flooding. It stated that a coastal flood event has the potential to be catastrophic, with deep, fast flowing water and a spread of water that would affect a very large area.

5.1.30 A network of flood defences has been constructed to reduce flood risk within the borough, and drainage features are currently being used to manage water discharge. These measures are, in normal circumstances, expected to prevent the spread of flood water. However, there remains the potential for the flood defence infrastructure or pumping stations to fail, sustaining a residual risk of flooding in these areas.

5.1.31 The key messages (para 12.31-12.41) outlined in the LFRMS are:

- "Tidal flooding in Great Yarmouth and Gorleston is a medium probability but high consequence event (para 12.31);
- Drainage and surface water issues in Great Yarmouth result in generally less severe but more frequent flooding (para 12.32);
- There is a risk of foul sewer flooding that results from the misconnection of surface water drainage to the foul sewer network. In order to address this issue opportunities to disconnect surface water from foul sewers need to be explored (para 12.35);
- The high levels of residual flood risk and the predicted additional flood risk from climate change, highlight the importance of locating development away from vulnerable areas and the potential of developments to increase flood risk elsewhere (para 12.36);
- There is a need to introduce more sustainable drainage systems into the area, which can facilitate storage and re-use of water while slowing water down (para 12.40);
- Locating new development away from the most vulnerable flood risk areas would minimise the cost of installing and maintaining new flood defences and land drainage measures" (para 12.41).

Anglian River Basin Flood Risk Management Plan (FRMP)

5.1.32 The Anglian River Basin consists of 11 catchments, covering 27,890km² from Lincolnshire in the north to Essex in the south, and from the Northamptonshire in the west to the East Anglian coast (Ref 12B.12). Of the 6 million people living in the river basin district, there are over 55,000 people at high risk of flooding from rivers or the sea (more than a 1 in 30 chance of being flooded in any year (3.3%)).

5.1.33 Great Yarmouth is located in the Broadland Rivers catchment. The FRMP states that the main outlet to the sea is the mouth of the Yare at Great Yarmouth, which controls the flow of tidal waters into the Broads as below:

"The characteristics of the rivers in Broadland mean they are susceptible to flooding from tidal surges which penetrate up the rivers. The scale is significant. It can take up to 5 hours for the tide to travel from Gorleston to Stalham. Furthermore, the low-lying nature of the land means that once defences are overtopped, water can travel significant distances, putting settlements at flood risk that are some distance from the channel. The River Bure and Yare are both affected by tidal and river flooding."

5.1.34 Appendix B of the FRMP (Ref 12B.12) provides detailed information on the various sub-areas and flooding statistics. It also provides catchments based on Water Framework Directive (WFD) management catchments, Flood Risk Areas (identified through the PFRA) and other strategic areas across the river basin district.

5.2 Historic Flooding

5.2.1 Great Yarmouth borough has a history of documented flood events with the main source being from tidal surges.

5.2.2 Historical incidents of flooding are detailed by Anglian Water in their DG5 register. This database records incidents of flooding relating to public foul, combined or surface water sewers and identifies which properties have suffered flooding. A total of 144 recorded flood incidents have been identified on the DG5 register for the Great Yarmouth borough.

5.2.3 It was reported in the Section 19 Flood Investigation Report (Ref 12B.13) that at least 59 properties in Great Yarmouth were flooded internally by heavy rainfall in the months of May, June and July 2014. On the 27 June 2014 in Ormesby St Margaret 32.2mm was recorded as falling in 30 minutes by the Ingham Radar station. The intensity of rainfall for this duration equates to a 1:146-year rainfall event. For a 1-hour return period this equates to a 1:56 year event calculated using the Flood Estimation Handbook (FEH) (Ref 12B.14).

5.2.4 There is a long history of property flooding in the Great Yarmouth area. One of the most consequential floods occurred in 1953, whereby the east coast of England was devastated by a significant tidal surge, which left 307 people dead and 40,000 homeless. This storm surge damaged infrastructure, such as power stations, gasworks, roads, railways, sewage services and water services.

5.2.5 Flooding occurred in Great Yarmouth on the 5th and 6th of December 2013 when a tidal surge combined with a high tide along the east coast of England. Prior to this event, residents were evacuated from the Gorleston area. It was reported in 2013 that emergency services pumped out flood water at Suspension Bridge Tavern near the A149 Bridge crossing over the River Bure.

5.2.6 The CFMP identified that in 2009 there were currently eight properties at risk in Great Yarmouth during a 0.5% annual probability tidal flooding, taking into account flood defences. Notably, in the future (2100) this number is predicted to rise exponentially to 5,600 properties. The EA is currently designing upgrades to the existing tidal flood defences through Great Yarmouth to provide a higher standard of protection in the future. The current programme for the EA defence upgrades is for construction to begin in December 2019 with completion in September 2020.

6 Flood Risk Assessment

6.1 Overview

6.1.1 Flood risk from rivers and sea, surface water, sewers, groundwater and artificial sources is assessed in this section. This section is mainly focussed on flood risk to the Scheme and the impact of the Scheme on flood risk elsewhere during the operational phase. Flood risk during construction is specifically addressed in Section 8. Where flood risk to the Scheme or an increase in flood risk as a result of the Scheme has been identified, mitigation measures are discussed in Section 7.

6.2 Flood Risk from Rivers and the Sea

6.2.1 The EA Flood Map for Planning (Figure 12.2) shows that the Principal Application Site lies predominantly within Flood Zone 3 (3a). This is land assessed as having a 0.5% AEP or greater risk of flooding from the sea or a 1% AEP or greater risk of flooding from rivers in any given year. Based on the information available, the Scheme is considered to be at high risk of tidal flooding and is not considered to be at risk of flooding from rivers.

6.2.2 The Principal Application Site lies predominantly within Flood Zone 3 (3a) but is in proximity of Flood Zones 1 and 2, and is associated with two distinct EA main rivers, the River Yare and the River Bure (Refer to Figure 12.1). The Scheme lies within an EA Flood Warning Area.

6.2.3 As part of the FRA, a detailed hydraulic assessment of tidal flood risk from the River Yare to the Scheme and the impact of the Scheme on flood risk elsewhere has been undertaken. The hydraulic modelling work undertaken for this FRA is summarised in this section and full details are provided within the hydraulic modelling report in Annex A.

Consultation

6.2.4 As the River Yare is designated as a Main River, the EA has been consulted as part of this assessment. The EA has reviewed the methodology for this assessment in contribution to the Scoping Opinion (document reference 6.7). The consultation responses from the EA (Table 12.3 and Table 12.4, Chapter 12), including their requirements for this assessment, have been taken into account.

Hydraulic Model Development

6.2.5 A 1D/2D Flood Modeller-TUFLOW model of the River Yare and its surrounding floodplain in Great Yarmouth has been developed for this assessment. Following review of the existing hydraulic model of Great

Yarmouth (2011) provided by the EA at the outset of this assessment, it was concluded that a new model should be developed for this assessment using the latest topographic and hydrological data.

6.2.6 The updated EA model of Great Yarmouth, developed by JBA in 2018, was received once the model for this assessment was already built. As such, information on defence heights through Great Yarmouth has been taken from the latest EA model and used to ensure the current defence levels are represented in the model developed for this assessment.

6.2.7 The model domain extends from the western edge of Breydon Water to the mouth of the River Yare where the river discharges into the sea. The River Yare through Great Yarmouth itself has been included in the 2D model domain in order to model flow routes through the town. It was not considered necessary to include the upper reaches of the River Yare within the 2D domain but the storage potential of Breydon Water and the northern floodplain has been included in a 1D domain linked to the 2D domain. It should be noted that the 1D domain is not an accurate physical representation of Breydon Water. Using this method, the model represents the function of the storage area without significantly increasing model runtimes as would happen if Breydon Water and the northern floodplain were included in the 2D model domain. This approach does not affect the robustness of the modelling results within the River Yare as the major flow mechanisms of Breydon Water and the northern floodplain are accounted for without causing unreasonable model run times, which would happen if the entire area was simulated in 2D.

6.2.8 This section of the FRA presents a summary of the model scenarios and results of the hydraulic modelling undertaken. Full details of the hydraulic model build are provided in the hydraulic modelling report in Annex A.

6.2.9 A baseline model was developed to represent the existing flood risk within Great Yarmouth. The baseline model was subject to sensitivity testing to ensure the model was robust and could be used to undertake hydraulic assessments as part of the FRA process. For the model calibration, the 5th-6th December 2013 tidal surge event was simulated in the model. Recorded data at Gorleston gauge has been used to define the tidal boundary in the model and the predicted water level results at Haven Bridge gauge have been compared to recorded data for the event. The model calibration is discussed in full in the Hydraulic Modelling Report (refer to Annex A).

6.2.10 Following the development of the baseline model, a version of the model was created to represent the Scheme post-construction scenario by representing the bridge (including the knuckles in the channel) and its approach roads within the model. The flood risk during construction has also been considered as part of this assessment but the footprint during construction within the River Yare channel is no larger than the post-construction footprint. The knuckles in the channel will be created by building a coffer dam on either side of the channel, which will then be back filled. Therefore, it has not been necessary to create a ‘during construction’ version of the hydraulic model as it would be the same as the Scheme post-construction version.

6.2.11 The model has been used to assess the risk of flooding in Great Yarmouth for the present-day scenario and, 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 (based on allowances for the year 2140, 120 years in the future). The EA stated in their stage 2 consultation response that if the design life of the Scheme is 60 years or greater, the UK Climate Projections 2009 (UKCP09) high emissions scenario against the 2080s projections at the 50% probability level should be applied. The UKCP18, which will eventually supersede UKCP09, were released in November 2018 and have been considered in this assessment as they contain an update to future sea level rise estimates as a result of climate change. It should be noted that some of the projections in UKCP09 are still valid for other applications.

6.2.12 The EA also stated in the stage 2 consultation response that if the Scheme is considered safety critical, the Scheme should also be assessed against the H++ estimates for sea level rise (high risk, low probability) to assess a credible maximum scenario. However, the EA has stated that mitigation is not required for the H++ scenario; it is used to fully understand the risks associated with the Scheme. UKCP18 does not include an update to the H++ estimates for future sea level rise, therefore the H++ estimates from UKCP09 have been used in this assessment.

6.2.13 In summary, the scenarios considered in this assessment are:

- Baseline present day
- Future baseline climate change
- Future baseline H++
- Scheme present day
- Future scheme climate change
- Future scheme H++

6.2.14 The hydrology of the River Yare has been analysed to derive inflows to the hydraulic model. Tidal levels have been derived to define the eastern boundary of the hydraulic model that represents sea levels along the Great Yarmouth coast. Tidal curves have been derived for three design flood events; 5% AEP, 0.5% AEP and 0.1% AEP based on present day sea levels.

6.2.15 For each of the design events, an allowance for sea level rise representing the impact of climate change has been applied to the present day tidal curves to calculate the future climate change scenario. There are a range of methods to determine climate change allowance in terms of sea level rise and, following consultation, the EA recommended reviewing all of the scenarios and selecting the highest potential future sea level rise calculated for use in this FRA. Sea level rise at Great Yarmouth 120 years in the future was calculated using the following methods:

- Flood Risk Assessments – Climate Change Allowances (Ref 12B.16) – Table 3;
- UKCP18 50% Representative Concentration Pathways (RCP) 8.5;
- UKCP18 95% RCP8.5;
- UKCP18 95% RCP4.5; and
- Upper End Allowance, Table 5 - Adapting to Climate Change (Ref 12B.15).

6.2.16 The highest sea level rise was calculated using UKCP18 95% RCP8.5 scenario (a rise of 1.83m by 2140) and this value has been used in this assessment to represent climate change as it is a conservative increase derived in line with the EA's recommendation.

6.2.17 To develop tidal curves representing the future H++ scenario, the H++ sea level rise estimates from UKCP09 were added to the present day tidal curves for the 0.5% AEP design event.

6.2.18 The impact of fluvial flows on flood risk to the Scheme was considered as part of the hydraulic assessment but these were found to have a negligible impact on flooding. Therefore, only tidal flooding has been modelled as part of this assessment as agreed with the EA. Table 6.1 provides a summary of each of the model runs undertaken for this assessment.

6.2.19 Flood risk to the Scheme has been identified using the Scheme scenario model and the results of the baseline and Scheme scenarios have been compared to ascertain the impact of the Scheme on flooding elsewhere.

Table 6.1: Modelled Scenarios

Baseline	Scheme
Present Day (2019)	
5% AEP	5% AEP
0.5% AEP	0.5% AEP
0.1% AEP	0.1% AEP
Future Baseline	**Future Scheme**
5% AEP + Climate Change (2140)	5% AEP + Climate Change (2140)
0.5% AEP + Climate Change (2140)	0.5% AEP + Climate Change (2140)
0.1% AEP + Climate Change (2140)	0.1% AEP + Climate Change (2140)
0.5% AEP H++	0.5% AEP H++

Methodology for Assessing Results

6.2.20 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 12.4. Changes in water level across the floodplain have also been assessed by comparing water depths predicted by the model for the baseline and Scheme scenarios.

6.2.21 In order to understand the significance of any change in flood risk between the baseline and scheme scenarios, the approach has been based on that published in the DMRB (HA 205/08) (Ref 16B.17), updated as necessary to take account of the 2017 EIA Regulations and the NPPF (PPG). The sensitivity of receptors to changes in flood risk has been classified as shown in Table 6.2, this is based on Table 2 of the Flood Risk and Coastal Change PPG (Ref 12B.3).

Table 6.2: Receptor Sensitivity Classification

Sensitivity	Description
Essential Infrastructure	• Essential transport infrastructure (including mass evacuation routes) which has to cross the area at risk. • Essential utility infrastructure which has to be located in a flood risk area for operational reasons, including electricity generating power stations and grid and primary substations; and water treatment works that need to remain operational in times of flood.

Sensitivity	Description
	• Wind turbines.
Highly vulnerable	• Police and ambulance stations; fire stations and command centres; telecommunications installations required to be operational during flooding. • Emergency dispersal points. • Basement dwellings. • Caravans, mobile homes and park homes intended for permanent residential use. • Installations requiring hazardous substances consent. (Where there is a demonstrable need to locate such installations for bulk storage of materials with port or other similar facilities, or such installations with energy infrastructure or carbon capture and storage installations, that require coastal or water-side locations, or need to be located in other high flood risk areas, in these instances the facilities should be classified as 'Essential Infrastructure').
More vulnerable	• Hospitals • Residential institutions such as residential care homes, children's homes, social services homes, prisons and hostels. • Buildings used for dwelling houses, student halls of residence, drinking establishments, nightclubs and hotels. • Non–residential uses for health services, nurseries and educational establishments. • Landfill and sites used for waste management facilities for hazardous waste. • Sites used for holiday or short-let caravans and camping, subject to a specific warning and evacuation plan.
Less vulnerable	• Police, ambulance and fire stations which are not required to be operational during flooding. • Buildings used for shops; financial, professional and other services; restaurants, cafes and hot food takeaways; offices; general industry, storage and distribution; non-residential institutions not included in the 'more vulnerable' class; and assembly and leisure. • Land and buildings used for agriculture and forestry. • Waste treatment (except landfill and hazardous waste facilities). • Minerals working and processing (except for sand and gravel working).

Sensitivity	Description
	• Water treatment works which do not need to remain operational during times of flood. • Sewage treatment works, if adequate measures to control pollution and manage sewage during flooding events are in place.
Water-compatible development	• Flood control infrastructure. • Water transmission infrastructure and pumping stations. • Sewage transmission infrastructure and pumping stations. • Sand and gravel working. • Docks, marinas and wharves. • Navigation facilities. • Ministry of Defence defence installations. • Ship building, repairing and dismantling, dockside fish processing and refrigeration and compatible activities requiring a waterside location. • Water-based recreation (excluding sleeping accommodation). • Lifeguard and coastguard stations. • Amenity open space, nature conservation and biodiversity, outdoor sports and recreation and essential facilities such as changing rooms. • Essential ancillary sleeping or residential accommodation for staff required by uses in this category, subject to a specific warning and evacuation plan.

6.2.22 The magnitude of impact in terms of flooding has been classified as shown in Table 6.3. The magnitude of change is a deviation from the baseline flood depth predicted for a given location.

Table 6.3: Magnitude of Impact

Magnitude of Impact	Change in flood depth
Major	0.3+ OR flooding in areas that were previously not flooded
Moderate	>0.1 - <=0.3
Minor	>0.02 - <=0.1
Negligible	0 - <=0.02

6.2.23 Using the level of sensitivity and the magnitude of impact, the significance of a change in flood risk can be determine using the Significance Matrix shown in Table 6.4. The significance categories are described in Table 6.5.

Table 6.4: Significance of a Change in Flood Risk

		Magnitude of Impact				
		No change	**Negligible**	**Minor**	**Moderate**	**Major**
Sensitivity	**Highly Vulnerable**	Neutral	Slight	Moderate or Large	Large or Very Large	Very Large
	More Vulnerable	Neutral	Slight	Slight or Moderate	Moderate or Large	Large or Very Large
	Less Vulnerable	Neutral	Neutral or Slight	Slight	Moderate	Moderate or Large
	Water Compatible	Neutral	Neutral or Slight	Neutral or Slight	Slight	Slight or Moderate

Table 6.5: Description of Significance Categories

Significance Category	Typical Descriptors of Effect
Very Large	Only adverse effects are normally assigned this level of significance. They represent key factors in the assessment process. These effects are generally, but not exclusively, associated with sites or features of international, national or regional importance that are likely to suffer a most damaging impact and loss of resource integrity. However, a major change (e.g. loss or severe damage to key characteristics) in a site or feature of local importance may also enter this category.
Large	These beneficial or adverse effects are considered to be very important considerations and are likely to be material in the decision-making process.
Moderate	These beneficial or adverse effects may be important but are not likely to be key decision-making factors. The cumulative effects of such factors may influence decision-making if they lead to an increase in the overall adverse effect on a particular resource or receptor.

Significance Category	Typical Descriptors of Effect
Slight	These beneficial or adverse effects may be raised as local factors. They are unlikely to be critical in the decision-making process but are important in enhancing the subsequent design of the Scheme.
Neutral	No effects or those that are beneath levels of perception, within normal bounds of variation or within the margin of forecasting error.

6.2.24 Receptors within Great Yarmouth have been classified using Ordnance Survey (OS) Address Base Data, which classifies all properties based on the Local Land and Property Gazetteers and OS large-scale data (Ref 12B.18). A summary of the receptors identified within the study area for this assessment is provided in Table 6.6*: Flood Risk Receptors Identified within Assessment Study Area*

6.2.25 with particularly sensitive receptors listed individually. Figure 12B.1 shows the location of the receptors within the study area. The impact of the Scheme on flooding at the receptors listed in Table 6.6*: Flood Risk Receptors Identified within Assessment Study Area*

6.2.26 has been assessed by calculating the change in flood level to each of the receptors between the Baseline and Scheme scenarios for each flood event considered in this assessment (

6.2.27 Table *6.1*), the significance of change at each receptor has then been classified using Table 6.4.

Table 6.6: Flood Risk Receptors Identified within Assessment Study Area

Receptor	Sensitivity (from Table 6.2)	Location
Residential (including residential care homes)	More Vulnerable	Throughout majority of study area except on agricultural land immediately south of Breydon Water and to south of Principal Application Site on east bank of River Yare
Commercial	Less Vulnerable	Throughout majority of study area
Commercial water compatible	Water Compatible	Along west and east banks of River Yare through Great Yarmouth (port infrastructure)
Great Yarmouth Fire Station	Highly Vulnerable	NGR: 652593, 306812
Police Investigation Centre	Highly Vulnerable (assumed required to be operational during flooding)	NGR: 651805, 306445
A47	Essential Infrastructure	Crosses River Yare at eastern end of Breydon Water and runs north-south to the west of the River Yare through Great Yarmouth

6.2.28 In order to understand the impact of the Scheme on flood risk to people, flood hazard has been analysed. Flood hazard is a measure of the level of danger posed by a flood event to people and describes the flood conditions in which people are likely to be swept over or drown in a flood. Flood hazard is a combination of flood depth, velocity and the presence of debris. Flood hazard is calculated by the hydraulic model (TUFLOW) directly, the model has been configured to record the UK hazard rating as proposed in the Flood Risks to People Guidance (Ref 12B.19). The formula used to calculate flood hazard rating is:

$$D(V + 0.5) + DF$$

Where, D = Depth, V = velocity and DF = Debris Factor

6.2.29 The debris factor can be set in a number of ways but the most recent guidance (Ref 12B.20) is to use a depth varying debris factor with a non-zero value at low flood depths. Following the guidance, the debris factors (conservative method) that have been used in this assessment are provided in Table 6.7.

Table 6.7: Debris Factors Applied in the Model to Calculate Flood Hazard

Depth	Debris Factor
0 to 0.25m	0.5
0.25 to 0.75m	1
d>0.75m and/or v>2m/s	1

6.2.30 Values of the flood hazard rating are calculated for each grid cell within the model using the formula shown above, the values for flood hazard rating are then classified as shown in Table 6.8 to show the risk to people for a particular flood event across the modelled area.

Table 6.8: Flood Hazard Rating

Flood Hazard Rating	Hazard to People Classification
0	No hazard
<0.75	Very low hazard
0.75 – 1.25	Danger for some
1.25 – 2.0	Danger for most
>2.0	Danger for all

6.2.31 The flood hazard rating has been calculated for each of the events modelled in this assessment and a comparison of the hazard ratings across the study area between the Baseline and Scheme scenarios for each flood event has been made to identify whether the Scheme acts to increase flood hazard within Great Yarmouth.

Hydraulic Modelling Results – Present Day Scenario

6.2.32 Figure 12.3 shows the flood extents predicted by the model for the Baseline Present Day event. The results show that there is no risk during a 5% AEP Present Day event to Great Yarmouth in the Baseline scenario. The modelling has shown that the urban area of Great Yarmouth floods during the 0.5% AEP and larger events. The 0.5% Baseline Present Day event shows a significant flood extent caused due to water levels overtopping the raised defences through the town. As expected the 0.1% AEP Baseline Present Day event shows extensive flooding throughout the catchment. In addition to the significant flooding in the town centre, the water levels are sufficient to overtop the defences along the southern edge of Breydon Water in the 0.1% AEP Baseline Present Day event.

6.2.33 Table 6.9 shows the Baseline and Scheme water levels predicted by the model in channel for the Present Day scenario for different return periods at each of the comparison points on Figure 12.4. Table 6.9 shows that in the channel during the 5% AEP Present Day event, to the south of the Scheme there is a negligible adverse impact as water levels increase by up to 0.02m. To the north of the Scheme during the same event, there is a minor beneficial impact as water levels in the channel are reduced by up to 0.09m. The negligible increase in water levels in the channel can be attributed to the narrowing of the channel by the bridge knuckles, which reduce the width of the channel under the bridge by approximately 50% compared to its current width.

6.2.34 Within the channel, the differences between the Baseline and Scheme scenarios for the 0.5% AEP and 0.1% AEP Present Day events show the same pattern as the 5% AEP event. For the 0.5% AEP Present Day event there is a negligible adverse impact in water levels south of the Scheme of up to 0.02m. However, there is a minor beneficial reduction in water levels north of the Scheme of up to 0.08m. During the 0.1% AEP Present Day event, there is a minor adverse impact south of the Scheme with increases in water level predicted up to 0.06m and to the north of the Scheme there is a minor beneficial impact with reductions in water level of up to 0.05m. These results show that the general effect of the Scheme in the channel is to increase water levels south of the site and decrease north of the site. This is because of the constriction in the channel caused by the knuckles used to support the Scheme. This reduces the overall capacity of the channel between the supports slowing the flow rate through the area reducing the amount of water that can transit up the channel from the tidal boundary.

Table 6.9: Present Day Hydraulic Modelling Results

Present Day	Baseline (mAOD)			Scheme (mAOD)			Difference (Scheme – Baseline (m))		
Point (Figure 12.4)	**5%**	**0.5%**	**0.1%**	**5%**	**0.5%**	**0.1%**	**5%**	**0.5%**	**0.1%**
US1	2.38	2.99	3.16	2.33	2.96	3.15	-0.05	-0.04	-0.01
US2	2.40	3.01	3.27	2.34	2.97	3.25	-0.06	-0.05	-0.02
US3	2.44	3.04	3.31	2.37	2.99	3.28	-0.07	-0.06	-0.03

US4	2.48	3.07	3.35	2.40	3.01	3.32	-0.08	-0.06	-0.03
US5	2.52	3.12	3.41	2.44	3.05	3.37	-0.08	-0.07	-0.04
USW	2.55	3.15	3.44	2.46	3.07	3.40	-0.09	-0.07	-0.04
USE	2.55	3.14	3.44	2.46	3.07	3.40	-0.09	-0.07	-0.04
C1	2.57	3.17	3.46	2.48	3.08	3.42	-0.09	-0.08	-0.05
C2	2.58	3.18	3.48	2.59	3.20	3.54	0.02	0.02	0.06
C3	2.59	3.20	3.50	2.61	3.22	3.56	0.02	0.02	0.06
DSW	2.61	3.22	3.53	2.63	3.24	3.58	0.02	0.02	0.05
DSE	2.61	3.22	3.53	2.62	3.24	3.58	0.02	0.02	0.05
DS5	2.64	3.26	3.60	2.65	3.28	3.65	0.02	0.02	0.04
DS4	2.67	3.30	3.68	2.69	3.32	3.72	0.01	0.01	0.04
DS3	2.72	3.36	3.79	2.73	3.37	3.82	0.01	0.01	0.02
DS2	2.78	3.43	3.91	2.78	3.43	3.92	0.01	0.00	0.01
DS1	2.82	3.48	4.00	2.83	3.48	4.01	0.00	0.00	0.00

6.2.35 It is also necessary to assess the impact of the Scheme on water levels on the floodplain and the different receptors within Great Yarmouth. For the 5% AEP Present Day event, there is no change in flood levels on the floodplain between the Baseline and Scheme scenarios as all the water is retained in the channel for this event and no out of bank flooding occurs.

6.2.36 Figure 12.5 shows a comparison of the predicted water levels for the Baseline and Scheme Present Day scenarios for the 0.5% AEP event showing the magnitude of impact with the Scheme in place. A negligible increase in flood extent on an area of grassland between South Denes Road and Great Yarmouth Power Station is predicted with the Scheme in place because the Scheme water levels are 0.02m higher than the Baseline water levels in this area. There is also a minor increase in flood extent at Southtown Common with the Scheme in place due to a minor increase in water levels of up to 0.1m compared to the Baseline scenario affecting the Common itself and a section of the open channel of the watercourse that flows through the Common. To the south of the Scheme, on the eastern bank of the River Yare water levels are increased by up to 0.08m (minor adverse impact) in the Scheme Present Day scenario compared to the Baseline Present Day scenario. On the west bank of the River Yare to the south of the Scheme, water levels are increased by up to 0.1m (minor adverse impact) at Southtown Common.

6.2.37 Table 6.10 lists the receptors within the study area (shown on Figure 12B.1) predicted by the hydraulic model to be flooded for the 0.5% AEP Present

Day event and details the change in flood depth between the Baseline and Scheme scenarios for this event. A receptor is assumed to be flooded if the modelled flood extent covers any part of the building footprint, it has been assumed in the model that all buildings within the study area have a threshold level of 0.2m (in the absence of detailed survey information), therefore buildings are shown to be internally flooded where the modelled flood depths are greater than 0.2m. Based on the sensitivity of each receptor and the change in flood depth between the Baseline and Scheme scenarios predicted by the hydraulic model, the significance of the change in flood risk for each receptor has been classified based on Table 6.4.

Table 6.10: Impact of Scheme on flooding to receptors during 0.5% AEP Present Day scenario

Receptor	Sensitivity	Baseline Flood Depth	Change in Flood Depth Scheme – Baseline	Significance of Change in Flood Risk
Police Investigation Centre, Thamesfield Way **(Emergency/Rescue Service shown on Figure 12B.1)**	**Highly Vulnerable** (assumed required to be operational during flooding)	0.22m	-0.22m (flooded in Baseline scenario, not flooded in Scheme scenario)	Large beneficial
Great Yarmouth Fire Station **(northern fire station shown on Figure 12B.1)**	**Highly Vulnerable**	1.1m	-0.14m (flooded in both Baseline and Scheme scenario)	Large beneficial
Residential properties on west bank of River Yare to south of Scheme (Queen Anne's Road)	**More Vulnerable**	0.3m	Up to +0.13m (flooded in both Baseline and Scheme scenario)	Moderate adverse
Residential properties to north of Scheme **(Southtown area on west bank and between Sutton**	**More Vulnerable**	West bank: between 0.2m and 0.56m	Up to -0.3m (flooded in both Baseline and Scheme scenario)	Moderate beneficial

Receptor	Sensitivity	Baseline Flood Depth	Change in Flood Depth Scheme – Baseline	Significance of Change in Flood Risk
Road and Alma Road on east bank of River Yare)		East bank: between 0.4m and 0.9m		
Commercial properties on west bank of River Yare to south of Scheme	**Less Vulnerable**	0.3m	Up to +0.03m (flooded in both Baseline and Scheme scenario)	Slight adverse
Commercial properties to north of Scheme **(Southtown area on west bank and between Sutton Road and Alma Road on east bank of River Yare)**	**Less Vulnerable**	West bank: between 0.2m and 0.56m East bank: between 0.4m and 0.9m	Up to -0.3m (majority flooded in both Baseline and Scheme scenario but a number of commercial properties are removed from flooding with the Scheme in place)	Moderate beneficial
Water compatible commercial properties to south of Scheme on east bank of River Yare (within port area)	**Water compatible**	Between 0.2m and 0.6m	Up to +0.08m (flooded in both Baseline and Scheme scenario)	Slight adverse
Water compatible commercial properties to south of Scheme on west	**Water compatible**	1.3m	Up to +0.02m (flooded in both Baseline	Slight adverse

Receptor	Sensitivity	Baseline Flood Depth	Change in Flood Depth Scheme – Baseline	Significance of Change in Flood Risk
bank of River Yare (within port area)			and Scheme scenario)	

6.2.38 The impact of the Scheme on flood hazard in the 0.5% AEP Present Day event has also been assessed to understand whether any receptors move to a higher flood hazard category compared to the Baseline scenario. For this event, the changes in flood hazard predicted by the model are small and the pattern of change is in line with the change in water levels seen between the Baseline and Scheme scenarios. The flood hazard ratings across the study area for the Baseline 0.5% AEP Present Day event and Scheme 0.5% AEP Present Day Event are shown in Figure 12.6 and Figure 12.7, respectively. To the south of the Scheme on the east bank of the River Yare (where water levels are increased with the Scheme in place), the extent of the 'Danger for most' hazard rating category increases slightly with the scheme in place compared to the Baseline but no properties in this area move into a higher hazard category as a result. To the south of the Scheme on the west bank of the River Yare, where water levels increased moderately with the Scheme in place, the areas shown as 'Danger for some' and Danger for most' increase slightly but no properties are impacted by this. There are no areas on the floodplain in the 0.5% AEP Present Day event in either the Baseline or Scheme scenario that are classified as 'Danger for all', the channel is classified in this category due to its depth.

6.2.39 To the north of the Scheme on both sides of the river, as the water levels are predicted to reduce for the 0.5% AEP Present Day event with the Scheme in place compared to the Baseline scenario, the flood hazard rating improves for a number of properties with some being moved to a lower hazard category with the Scheme in place.

6.2.40 In terms of flood risk to the Scheme itself and its operability and safety requirements, the level of the bridge deck assumed for this assessment (9.6mAOD) is above the maximum flood level considered in this assessment, as the 0.1% AEP H++ event peak tidal level is 7.13mAOD. However, the approach roads to the bridge are impacted by flooding.

6.2.41 The approach road on the embankment on the western side of river is not predicted to flood during the 0.5% AEP Present Day Scheme scenario, however there is ponding of flood water on the southern side of the embankment leading to increased flooding to houses with the Scheme in place. The approach road on eastern side of the river is predicted to flood during 0.5% AEP Present Day event with the Scheme in place but the flood depths in this area are up to 0.13m lower than in the Baseline scenario for the same event. Ideally, the approach road would be raised above the 0.5% AEP Climate Change flood level but given the location of the approach road adjacent to the river and the fact that it is essential infrastructure that has to cross the area of risk, it would be impractical to raise the road above the flood level in this area. In the 0.5% AEP Present Day Baseline scenario, the whole area surrounding the approach road on the eastern side of the river is flooded to a depth of approximately 2.9m.

Hydraulic Modelling Results – Climate Change Scenario

6.2.42 Figure 12.8 shows the flood extents predicted by the model for the Baseline Climate Change event. The results show that all three climate change events modelled predict flooding to a large part of the study area with a large part of the urban area flooded in each event.

6.2.43 Table 6.11 shows the Baseline and Scheme water levels predicted by the model in channel for the Climate Change scenario for different return periods at each of the comparison points on Figure 12.4. Table 6.11 shows that in the channel during the 5% AEP Climate Change event, to the south of the Scheme, water levels are raised by up to 0.12m with the largest increase at the location of the bridge (moderate adverse impact). The impact of the Scheme in the Climate Change scenario is actually less during the 0.5% AEP and 0.1% AEP as the peak tidal level for each of these events is above all of the current defence heights through the town. Therefore, the increases seen in the channel are less than for the 5% AEP event, for which some of the defence heights are higher than the peak water level. There is a minor adverse impact in the channel for the 0.5% AEP event with water levels increased by up to 0.1m in the Scheme scenario compared to the Baseline. The increases in the channel with the Scheme in place for the 0.1% AEP event are negligible (up to 0.02m).

6.2.44 As for the Present Day scenario, each of the climate change scenarios show a beneficial impact in terms of flood risk to the north of the Scheme with reductions predicted within the channel. For each flood event, the reduction in water levels has a minor beneficial impact.

Table 6.11: Climate Change Hydraulic Modelling Results

Climate Change	Baseline (mAOD)			Scheme (mAOD)			Difference (Scheme – Baseline (m))		
Point (Figure 12.4)	**5%**	**0.5%**	**0.1%**	**5%**	**0.5%**	**0.1%**	**5%**	**0.5%**	**0.1%**
US1	3.34	4.09	4.93	3.33	4.04	4.87	-0.01	-0.05	-0.05
US2	3.42	4.11	4.93	3.41	4.06	4.87	-0.01	-0.05	-0.06
US3	3.47	4.12	4.93	3.46	4.07	4.87	-0.01	-0.05	-0.06

US4	3.54	4.13	4.92	3.52	4.08	4.87	-0.02	-0.05	-0.06
US5	3.62	4.15	4.92	3.60	4.09	4.88	-0.02	-0.06	-0.04
USW	3.68	4.17	4.95	3.64	4.11	4.90	-0.03	-0.06	-0.04
USE	3.67	4.17	4.94	3.64	4.11	4.90	-0.03	-0.06	-0.04
C1	3.71	4.18	4.96	3.66	4.12	4.91	-0.04	-0.06	-0.05
C2	3.73	4.19	4.97	3.85	4.22	5.00	0.12	0.04	0.02
C3	3.76	4.20	4.99	3.87	4.25	5.01	0.11	0.05	0.02
DSW	3.81	4.23	5.02	3.91	4.30	5.03	0.09	0.07	0.01
DSE	3.81	4.23	5.02	3.91	4.30	5.03	0.09	0.07	0.01
DS5	3.96	4.38	5.14	4.03	4.48	5.16	0.07	0.10	0.02
DS4	4.12	4.63	5.33	4.18	4.70	5.34	0.05	0.07	0.02
DS3	4.31	4.89	5.52	4.35	4.93	5.54	0.04	0.04	0.01
DS2	4.51	5.16	5.74	4.52	5.18	5.75	0.02	0.02	0.01
DS1	4.66	5.36	5.88	4.66	5.36	5.88	0.00	0.00	0.00

6.2.45 The impact of the Scheme on water levels on the floodplain and receptors within Great Yarmouth has been assessed for the Climate Change scenario. The impact of the Scheme in the Climate Change scenarios is less than for the Present Day scenario as the water levels for each event are higher in the Climate Change scenario and flooding on the floodplain is more extensive during the Climate Change Baseline scenario meaning that the Scheme has less of an impact overall. Figure 12.9 shows a comparison of the predicted water levels for the Baseline and Scheme Climate Change scenarios for the 0.5% AEP event showing the magnitude of impact with the Scheme in place. The difference in extent of flooding between the Baseline and Scheme scenarios for the 0.5% AEP Climate Change event is negligible. As for the Present Day scenario, there is an increase in water levels to the south of the Scheme and a reduction in water levels to the north. On the floodplain to the south of the Scheme, the maximum increase in water level with the Scheme in place is 0.1m, a moderate adverse impact. Near to the harbour at the end of the River Yare, there is a negligible adverse impact with increases in water level of up to 0.02m with the Scheme in place.

6.2.46 Table 6.12 lists the receptors within the study area predicted to be flooded by the hydraulic model for the 0.5% AEP Climate Change event and details the change in flood depth between the Baseline and Scheme scenarios for this event. A receptor is assumed to be flooded if the modelled flood extent covers any part of the building footprint, it has been assumed in the model that all buildings within the study area have a threshold level of 0.2m (in the absence of detailed survey information), therefore buildings are shown to be internally flooded where the modelled flood depths are greater than 0.2m. Based on the sensitivity of each receptor and the change in flood depth between the Baseline and Scheme scenarios predicted by the hydraulic model, the significance of the change in flood risk for each receptor has been classified based on Table 6.4.

Table 6.12: Impact of Scheme on flooding to receptors during 0.5% AEP Climate Change scenario

Receptor	Sensitivity	Baseline Flood Depth	Change in Flood Depth Scheme – Baseline	Significance of Change in Flood Risk
Police Investigation Centre, Thamesfield Way **(Emergency/Rescue Service shown on Figure 12B.1)**	**Highly Vulnerable** (assumed required to be operational during flooding)	3.7m	-0.05m (flooded in both Baseline and Scheme scenario)	Moderate beneficial
Great Yarmouth Fire Station **(northern fire station shown on Figure 12B.1)**	**Highly Vulnerable**	1.2m	-0.01m (flooded in both Baseline and Scheme scenario)	Slight beneficial
Residential properties on west bank of River Yare to south of Scheme (Queen Anne's Road)	**More Vulnerable**	3m	Up to +0.07m (flooded in both Baseline and Scheme scenario)	Slight adverse
Residential properties to north of Scheme **(Southtown area on west bank and between Sutton Road and Alma Road on east bank of River Yare)**	**More Vulnerable**	West bank: 3.8m East bank: between 2m and 3m	Up to -0.05m (flooded in both Baseline and Scheme scenario)	Slight beneficial
Commercial properties on west	**Less Vulnerable**	3m	Up to +0.05m	Slight adverse

Receptor	Sensitivity	Baseline Flood Depth	Change in Flood Depth Scheme – Baseline	Significance of Change in Flood Risk
bank of River Yare to south of Scheme			(flooded in both Baseline and Scheme scenario)	
Commercial properties to north of Scheme **(Southtown area on west bank and between Sutton Road and Alma Road on east bank of River Yare)**	**Less Vulnerable**	West bank: 3.8m East bank: between 2m and 3m	Up to -0.05m (majority flooded in both Baseline and Scheme scenario but a number of commercial properties are removed from flooding with the Scheme in place)	Slight beneficial
Water compatible commercial properties to south of Scheme on east bank of River Yare (within port area)	**Water compatible**	Between 1.6m and 2.4m	<+0.01m (flooded in both Baseline and Scheme scenario)	Neutral
Water compatible commercial properties to south of Scheme on west bank of River Yare (within port area)	**Water compatible**	Between 2m and 3.2m	Up to +0.07m (flooded in both Baseline and Scheme scenario)	Slight adverse

6.2.47 The impact of the Scheme on flood hazard in the 0.5% AEP Climate Change event has also been assessed to understand whether any receptors move to a higher flood hazard category compared to the Baseline scenario. For this event, there is a negligible change in flood hazard predicted between the Baseline and Scheme scenarios. The flood hazard ratings across the study area for the Baseline 0.5% AEP Climate Change event and Scheme 0.5% AEP Climate Change Event are shown in Figure 12.10 and Figure 12.11, respectively. For both the Baseline and Scheme scenario, a large proportion of the study area is classified as 'danger to all' incorporating a large number of properties.

6.2.48 Whilst the bridge deck is above the 0.1% AEP Climate Change flood level, the approach roads to the bridge are predicted to flood during each of the Climate Change events modelled. On the western side of the river, the new roundabout that the approach road leads to is predicted to flood to a depth of up to 3m in the 0.5% AEP Climate Change event. However, this is not as a result of the Scheme as the Baseline flood depth in this area is approximately 3m as well (there is actually a slight reduction in flood levels predicted in the Scheme scenario compared to the Baseline in the 0.5% AEP Climate Change event). The eastern approach road to the bridge is predicted to flood up to a depth of approximately 2.5m in the 0.5% AEP Climate Change event but flood levels in this location even in the Baseline scenario are up to 2.5m in this event.

Hydraulic Modelling Results – H++ Scenario

6.2.49 Figure 12.12 shows the flood extents predicted by the model for the Baseline and Scheme 0.5% AEP H++ events. The results show that for both scenarios a large part of the study area and urban area of Great Yarmouth is predicted to flood.

6.2.50 Table 6.13 shows the Baseline and Scheme water levels predicted by the model in channel for the 0.5% AEP H++ scenario at each of the comparison points on Figure 12.4. Table 6.13shows that in the channel during the 0.5% AEP H++ event, the Baseline and Scheme scenarios predict similar water levels with only negligible differences between them at each comparison point. The impact of the Scheme on water levels is less in the H++ event than it is for the Present Day and Climate Change events. This is because the water levels are much higher for the extreme H++ event than for the Present Day and Climate Change events meaning that the constriction caused by the bridge in channel has less of an impact.

Table 6.13: H++ 0.5% AEP Event Hydraulic Modelling Results

Climate Change	Baseline (mAOD)	Scheme (mAOD)	Difference Scheme – Baseline (m)
Point (Figure 12.4)			
US1	6.54	6.53	-0.01
US2	6.52	6.51	-0.01
US3	6.52	6.51	-0.01

Climate Change	Baseline (mAOD)	Scheme (mAOD)	Difference Scheme – Baseline (m)
US4	6.51	6.50	-0.01
US5	6.51	6.50	-0.01
USW	6.51	6.50	-0.01
USE	6.51	6.50	-0.01
C1	6.51	6.50	-0.01
C2	6.51	6.51	0.00
C3	6.51	6.50	-0.01
DSW	6.51	6.50	-0.01
DSE	6.51	6.50	-0.01
DS5	6.52	6.51	-0.01
DS4	6.54	6.53	-0.01
DS3	6.56	6.56	0.00
DS2	6.60	6.60	0.00
DS1	6.60	6.60	0.00

6.2.51 The impact of the Scheme on water levels on the floodplain within Great Yarmouth has been assessed for the H++ scenario. The impact of the Scheme in the H++ scenario is less than for the Present Day and Climate Change scenarios as the water levels for each event are higher in the H++ scenario and flooding on the floodplain is extensive during the Baseline scenario meaning that the Scheme has less of an impact overall. 12.12 shows a comparison of the predicted water levels for the Baseline and Scheme H++ scenarios for the 0.5% AEP event showing the magnitude of impact with the Scheme in place. The difference in depth and extent of flooding between the Baseline and Scheme scenarios for the 0.5% AEP H++ event is negligible. event is negligible.

6.2.52 In terms of flood risk to the Scheme itself, the bridge deck assumed for this assessment (9.6mAOD) is above the peak water level for even the 0.1% AEP H++ event (7.13mAOD). However, for the 0.5% AEP H++ event, significant flooding is predicted across Great Yarmouth including in the location of the proposed approach roads to the bridge in both the Baseline and Scheme scenarios.

Flood Risk from Rivers and the Sea Conclusion

6.2.53 Tidal flood risk is the most significant flood risk to Great Yarmouth and as a result of the tidal dominance in the River Yare (and across the Norfolk Broads), there is no risk of fluvial flooding to the Principal Application Site. The Scheme is at risk of tidal flooding and has been shown to impact tidal flooding within Great Yarmouth with some areas experiencing a moderate adverse impact with the Scheme in place. Mitigation for tidal flooding is discussed in Section 7.

6.2.54 Given the risk of tidal flooding to the Principal Application Site and the impact of the Scheme on flood risk elsewhere, the Scheme will also be at risk during construction and may have an impact on flood risk elsewhere during this phase too. Therefore, tidal flood risk during construction is discussed in Section 8.

6.3 Flood Risk from Surface Water

6.3.1 The EA web-based Risk of Flooding from Surface Water Map is shown in Plate 6.1 for the Scheme location and this has been used to assess flood risk to the Scheme from surface water.

6.3.2 To the west of the River Yare, there is minimal surface water flood risk and the majority of surface water flooding shown is classified as low risk, which means that in each year there is between a 0.1% and 1% chance of flooding occurring in any given year. Medium (between 1% and 3.33% chance of flooding in any given year) and high (greater than 3.33% flood risk in any given year) flood risk tends to be concentrated along roads and watercourses on the western side of the River Yare. For the Scheme, the approach road on the eastern side of the River Yare and new roundabout are to be built in the area of low and medium surface water flood risk at the junction of Queen Anne's Road with Suffolk Road.

6.3.3 On the eastern side of the River Yare, Plate 6.1 shows low to medium surface water flood risk along South Denes Road and between this road and the river there is a mix of low, medium and high surface water flooding predicted, which would affect port infrastructure. As for the western side of the River Yare, high surface water flood risk is mostly predicted along roads on the eastern side of the river. The approach road on embankment for the Scheme on the eastern side of the River Yare will cross areas of low, medium and high surface water flood risk on the quayside.

6.3.4 Based on the information available, the overall flood risk from surface water runoff to the Scheme is assessed as being moderate. There is only a small area on the eastern quayside of high surface water flood risk that may be displaced by the building of the approach road embankment to the bridge as part of the Scheme. However, the management of surface water on the

Principal Application Site is addressed in the Drainage Strategy (Appendix 12C) and the Scheme design will incorporate embedded mitigation, which will reduce the residual risk of surface water flooding to the Scheme to negligible.

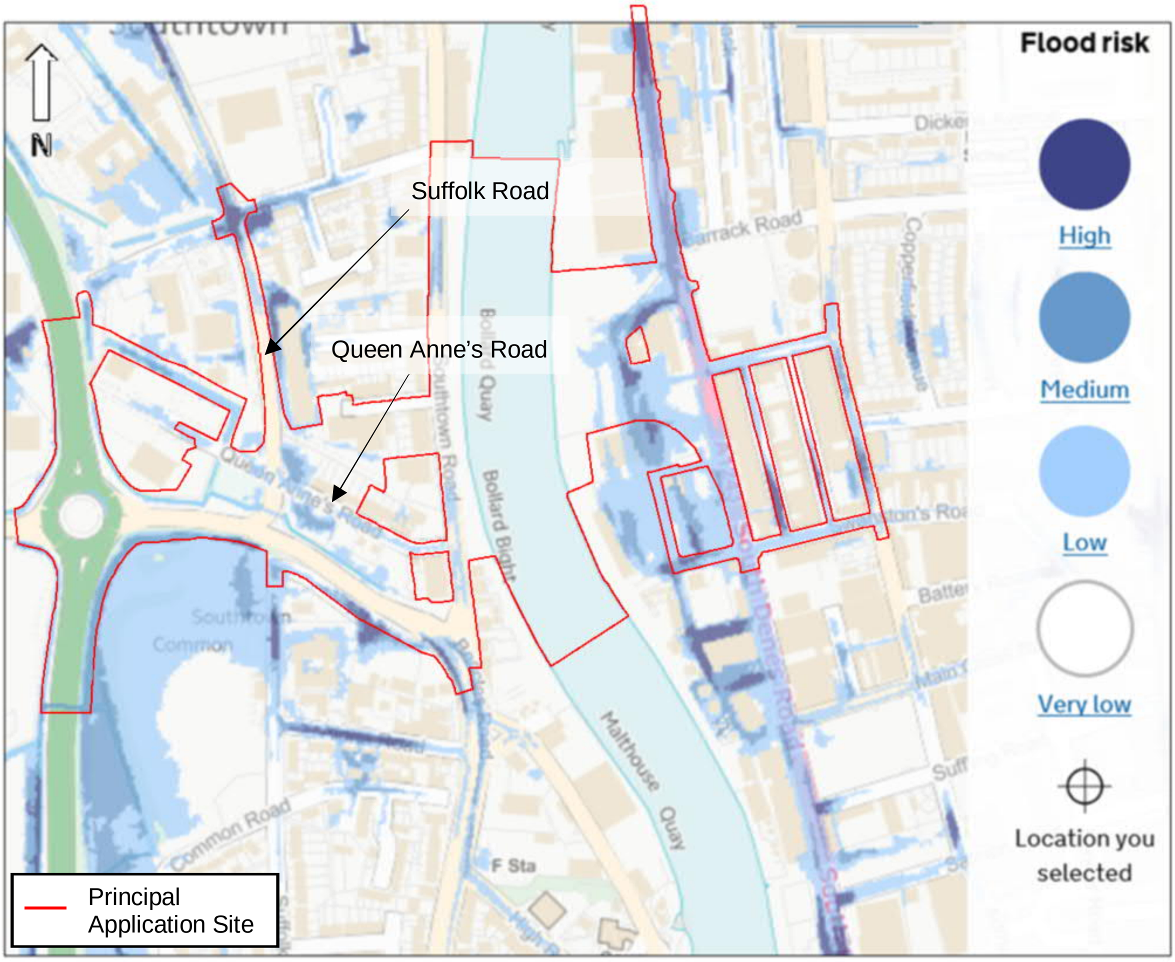

Plate 6.1: Extract from EA Risk of Flooding Surface Water Map

Surface Water Runoff Rates

6.3.5 An initial high-level assessment of the impact of the Scheme on surface water flood risk has been assessed by calculating surface water runoff from the Principal Application Site for both the greenfield and post-scheme scenario. The surface water Drainage Strategy (Appendix 12C) and design will refine these initial runoff and volume values as the assessment here is conservative to understand the worst case in terms of surface water runoff from the Principal Application Site. The Scheme drainage will be as set out in the Drainage Strategy and this will include embedded mitigation to manage surface water runoff from the Principal Application Site and limit runoff to agreed discharge rates. The installation of VMS at the Satellite

Application Sites will not impact on surface water runoff, therefore this assessment is for the Principal Application Site only.

6.3.6 The NPPF (Ref 12B.2) requires that the potential to increase flood risk elsewhere through the addition of hard surfaces and the effect of the development on surface water runoff is incorporated in the FRA. An increase in hard surfaces could increase the surface water runoff from the proposed Scheme, which in turn could increase flood risk elsewhere if this is not properly mitigated for.

Greenfield Scenario

6.3.7 This scenario assumes that the proposed Scheme is wholly greenfield with no impermeable areas identified. In reality, the majority of the Principal Application Site is already covered by hard surfaces and are largely impermeable in nature. The greenfield runoff values from the Principal Application Site in a Qbar (the peak rate of flow from a catchment for the mean annual flood, approximately 43.5% AEP), 3.33% AEP and 1% AEP rainfall event, calculated based on the IH124 method (Ref 12B.21), are summarised in Table 6.14. FEH catchment descriptors for the catchment were used for the IH124 method.

Table 6.14: Greenfield Runoff Rates

Area	Rainfall Event (AEP)	Greenfield Runoff (l/s)
Principal Application Site	Qbar	25.20
	3.33%	64.27
	1%	89.73

Climate Change

6.3.8 Climate change within the UK over the next few decades is likely to result in changes to observed weather patterns, which will be subject to regional variations. This could include milder wetter winters and hotter drier summers. Short duration, high intensity rainfall and more periods of long duration rainfall are expected, in addition to rising sea levels. These factors may lead to an increased risk of flooding to proposed developments and so the consequences of climate change need to be anticipated and mitigated for.

6.3.9 The importance of climate change in regard to flooding and development is highlighted in the EA's 'Flood risk assessments: climate change allowance' guidance. The climate change recommended precautionary sensitivity ranges for rainfall are shown in Plate 6.2. For FRAs, this guidance suggests the assessment of both the central and upper end allowances to understand the range of impact. The design life of the Scheme is 120 years, therefore the 2070 - 2115 peak rainfall intensity increases of both 20% (central) and 40% (upper end) are used.

Applies across all of England	Total potential change anticipated for the '2020s' (2015 to 2039)	Total potential change anticipated for the '2050s' (2040 to 2069)	Total potential change anticipated for the '2080s' (2070 to 2115)
Upper end	10%	20%	40%
Central	5%	10%	20%

Plate 6.2: Extract from EA Peak Rainfall Intensity Climate Change Allowance

6.3.10 The climate change recommended precautionary sensitivity ranges for river flow for the Anglian river basin district are shown in Plate 6.3. Based on a 100 year design life, the 2070 - 2115 peak rainfall intensity increase of both 25% (central) and 65% (upper end) are used.

River basin district	Allowance category	Total potential change anticipated for the '2020s' (2015 to 2039)	Total potential change anticipated for the '2050s' (2040 to 2069)	Total potential change anticipated for the '2080s' (2070 to 2115)
Anglian	Upper end	25%	35%	65%
	Higher central	15%	20%	35%
	Central	10%	15%	25%

Plate 6.3: Extract from EA Peak River Flow Climate Change Allowance

6.3.11 Surface water runoff accounting for climate change was assessed to ensure that an increased risk of flooding and the consequences of climate change are anticipated and mitigated. Accounting for climate change the revised greenfield scenario runoff values are presented in Table 6.15.

Table 6.15: Greenfield Runoff Rates with Central and Upper End Climate Change Allowance

Area	Rainfall Event (AEP)	Greenfield Runoff (l/s)
Principal Application Site	1% + CC Central	112.16
	1% + CC Upper End	148.05
	1% + CC Upper End	3.14

6.3.12 The impacts of climate change need to be taken into account when designing the drainage infrastructure. Surface water needs to be managed in a way that does not increase flood risk offsite, whether through attenuation or infiltration.

Post-Scheme Scenario

6.3.13 The proposed Scheme will increase the area of impermeable surface compared to the greenfield scenario (an artificial scenario in this case as much of the Principal Application Site area is currently impermeable) and also the existing scenario. Table 6.16 provides a comparison of the greenfield surface water runoff rates with the post-scheme runoff rates. The post-scheme runoff rates were derived using the modified rational method (Ref 12B.22).

Table 6.16: Greenfield and Post-Scheme Runoff Rates Comparison

Area	Rainfall Event (AEP)	Greenfield Runoff (l/s)	Post-Scheme Runoff (l/s)	Difference between Greenfield and Post-Scheme Runoff (l/s)
Principal Application Site	3.33%	64.27	329.97	265.70
	1%	89.73	464.53	374.80
	1% + CC Central	112.16	558.74	446.58
	1% + CC Upper End	148.05	656.83	508.78

6.3.14 The EA in general promotes the use of SuDS to manage surface water runoff, maximise water quality improvements and incorporate environmental enhancements where ground conditions are suitable. Should ground investigation establish that infiltration drainage is unviable then attenuation storage and a positive discharge would be required.

6.3.15 An initial estimate of the total post-Scheme runoff for the corresponding rainfall events are set out in Table 6.17; these runoff volumes will require mitigation through appropriate attenuation and/ or infiltration of surface water within the Principal Application Site.

Table 6.17: Initial Estimate of Total Post-Scheme Runoff Volume

Area	Rainfall Event (AEP)	Total Post-Scheme Runoff Volume* (m^3)
	3.33%	4392
	1%	6199

Area	Rainfall Event (AEP)	Total Post-Scheme Runoff Volume* (m^3)
Principal Application Site	1% + CC Central	7367
	1% + CC Upper End	8317

*Based on a six hour storm duration and greenfield discharge allowance

Flood Risk from Surface Water Conclusion

6.3.16 The assessment of surface water flood risk has shown that there is a moderate risk of surface water flooding to the Principal Application Site and there will be an increase in surface water runoff from the area as a result of the Scheme. Therefore, embedded mitigation within the Scheme design will be required in order to prevent surface water flooding to the Scheme itself and to prevent an increase in surface water flooding elsewhere as a result of the Scheme. Surface water flooding mitigation is discussed in Section 7 and more detail is provided in the Drainage Strategy (Appendix 12C). With the embedded mitigation in place, the risk of surface water flooding at the Principal Application Site will be negligible and based on Table 6.4 (with the Scheme considered as less vulnerable) the significance of surface water flooding during the operation phase is neutral.

6.3.17 The risk of surface water flooding to the Scheme during construction is considered to be negligible given the relatively short duration of the construction phase and therefore the significance of surface water flooding during construction is neutral.

6.4 Flood Risk from Sewers

6.4.1 The SFRA (Ref 12B.6) mentioned that approximately 52 sewer flood incidents have been recorded on the Anglian Water's DG5 Register for the Great Yarmouth area, these are summarised in Table 6.18.

Table 6.18: DG5 Register for Great Yarmouth Borough (taken from SFRA)

Area	Postcode	Number of Recorded Flood Incidents
Great Yarmouth	NR30 1	9
Great Yarmouth	NR30 2	1
Great Yarmouth	NR30 3	4
Great Yarmouth	NR30 4	15
Great Yarmouth	NR30 5	9
Great Yarmouth	NR31 6	14
	Total: 52	

6.4.2 All of the areas listed in Table 6.17 are within the north-eastern part of Great Yarmouth and are all at least 800m north of the Principal Application Site, therefore the risk of sewer flooding in the vicinity of the Principal Application Site is negligible and the Scheme itself will not have an impact on sewer flooding. The Drainage Strategy (Appendix 12C) explains how some of the drainage on the Principal Application Site will be connected to Anglian Water sewers. Appropriate discharge rates to sewers have been agreed with Anglian Water to prevent an adverse impact on their network, therefore embedded mitigation will ensure that the Scheme will not increase the risk of sewer flooding in the vicinity of the Principal Application Site. Three of the Satellite Application Sites are situated in the north-eastern part of Great Yarmouth in areas listed in Table 6.17, however as it is only VMS that will be installed at these sites, there will be no impact on sewer flooding at these locations.

Flood Risk from Sewers Conclusion

6.4.3 Given the distance of the reported sewer flooding incidents in Great Yarmouth from the Principal Application Site, flood risk to the Scheme from sewers is considered negligible. The Drainage Strategy (Appendix 12C) provides details on discharges from the Scheme to Anglian Water sewers, discharge rates have been agreed with Anglian Water to ensure there is no increase in sewer flooding as a result of the Scheme. Given the negligible impact of sewer flooding at the Principal Application Site and the negligible impact of the Scheme on sewer flooding, the significance of sewer flooding in this assessment is concluded to be neutral both during the operational and construction phases of the Scheme.

6.5 Flood Risk from Groundwater

6.5.1 The British Geological Survey (BGS) online geology maps show that the underlying geology beneath the scheme is Crag Group bedrock (sand and gravel). This is sedimentary bedrock formed approximately 0 to 5 million years ago in the Quaternary and Neogene periods. The local environment is therefore predominantly dominated by seas.

6.5.2 The superficial geology for the site comprises Breydon formations (clay and silt). Deposits were formed up to 2 million years ago during the Quaternary period. The local environment was previously dominated by shorelines.

6.5.3 According to the BGS Aquifer Maps, the Scheme is located on bedrock geology with ‘Principal Aquifer’ designation. This suggests that the bedrock has high intergranular and/or fracture permeability. This means the bedrock usually provides a high level of water storage and may support water supply and/or river base flow on a strategic scale.

6.5.4 The superficial deposits on the east side of the Scheme have a ‘Secondary A’ designation. This means the permeable layers are capable of supporting water supplies at a local rather than strategic scale. In some cases they form an important source of base flow to rivers.

6.5.5 The Scheme is located entirely in an area which is defined as ‘Major Aquifer High’ as defined by the EA Groundwater Vulnerability Zones mapping.

6.5.6 The SFRA states that there are no groundwater protection zones in the borough. Development proposals are recommended to assess the pollution risk to receiving water bodies and include appropriate treatment steps ahead of any discharge to surface or groundwater.

6.5.7 There are no historical records of groundwater flooding in the SFRA, however, the NCC PRFA identified that 1,000 to 10,000 properties are susceptible to groundwater flooding in Great Yarmouth (see Plate 5.4) suggesting that it could be a significant issue. As part of this assessment, WSP has monitored groundwater levels in Great Yarmouth at various locations in and around the Scheme location.

6.5.8 Figure 12B.3 shows the location of the boreholes where groundwater monitoring has taken place. Groundwater was recorded closest to the surface at Borehole 04A between William Adams Way and Suffolk Road, at this location groundwater was recorded at 1.1m below ground level in November and December 2018. At Borehole 06, close to the location of the western approach road for the Scheme, groundwater was recorded at 1.14m below ground level in June 2018. During November and December 2018, groundwater was recorded at 1.5m below ground level at Borehole 06.

6.5.9 On the eastern side of the Scheme, the closest groundwater to the surface was found at Borehole 15, at 1.26m below ground level.

Flood Risk from Groundwater Conclusion

6.5.10 Although groundwater has been found at the Principal Application Site at only 1.5m below ground level, there are no recorded incidents of ground water flooding at this location. Therefore, the risk of groundwater flooding to the Scheme during the operational phase is considered minor, based on Table 6.4 (considering the Scheme as less vulnerable) the significance of groundwater flooding during the operation phase is slight. The Scheme will not have an impact on groundwater flooding in Great Yarmouth. Therefore, no mitigation is required in terms of groundwater flooding for the operational phase of the Scheme. However, groundwater flooding may be an issue during construction as the groundwater levels are relatively close to the ground surface and construction will involve excavation, this is discussed in Section 8.

6.6 Flood Risk from Artificial Sources

Flood Risk from Reservoirs

6.6.1 The EA web based mapping includes the maximum extent for flooding from reservoirs. Figure 12B.4 shows the nearest reservoirs to Great Yarmouth, the closest of these to the Application Site is Ormesby Reservoir, which is approximately 9km away. The Scheme is not located within the maximum flood extent area of any of the nearby reservoirs. As such the Scheme is assessed to not be at flood risk from reservoirs based on the information available.

Flood Risk from other Artificial Sources

6.6.2 The SFRA stated “in September 2006, heavy rain caused flash flooding to Great Yarmouth borough. The flooding caused pumping stations in Great Yarmouth to fail and over 50 properties were flooded including six schools in Great Yarmouth.” The pumping stations in Great Yarmouth are located away from the town centre (and the Principal Application Ste) in the more rural areas surrounding the town meaning that the Scheme is not at risk of flooding due to pumping station failure.

6.6.3 There are no canals within the vicinity of the scheme, therefore there is no flood risk from canals to the Scheme.

Flood Risk from Artificial Sources Conclusion

6.6.4 As the Principal Application Site is not located near any artificial sources of flood risk (reservoirs, canals or pumping stations), the risk of flooding to the

Scheme from artificial sources can be considered negligible. For the same reason, the Scheme will not have any impact on flooding from artificial sources. Therefore, the significance of flood risk from artificial sources for the Scheme is neutral.

7 Flood Risk Mitigation

7.1 Overview

7.1.1 The assessment detailed in Section 6 concluded that there is risk of flooding to the Scheme during the operational phase from tidal (sea) flooding and surface water flooding. The Scheme was shown to have the potential to increase tidal and surface water flood risk elsewhere as well. Mitigation for flooding from the sea and surface water flooding is discussed in this section.

7.1.2 The assessment has shown that there is negligible flood risk to the Scheme from fluvial, groundwater, sewer and artificial sources of flooding during the operational phase. Similarly, the Scheme was not shown to impact on these sources of flood risk during the operational phase. Therefore, mitigation is not required for fluvial, groundwater, sewer and artificial sources of flooding for the operational phase of the Scheme.

7.1.3 The assessment has shown that the Scheme may be at risk of flooding from the sea and groundwater during construction. There would also be an adverse impact of the Scheme on tidal flood risk during construction. Flood risk during construction and mitigation for this is discussed in Section 8.

7.2 Flood Risk from Sea Mitigation

7.2.1 It has been agreed with the EA that mitigation is not required for the H++ event modelled. This provides a credible maximum scenario against which the Scheme can be assessed. Therefore, mitigation for increases in flood risk during the Present Day and Climate Change tidal flood events have been considered as part of this assessment. Similarly, the 0.1% AEP flood event is an extreme, low probability event and mitigation for this event in the Present Day or Climate Change scenario has not been considered. Therefore, the largest flood event considered in this assessment for mitigation is the 0.5% AEP Climate Change event.

7.2.2 Table 6.10 shows that the largest impact of the Scheme is a moderate adverse impact on residential properties to the south of the Scheme to the west of the River Yare, with increases in water level of up to 0.13m in the Scheme scenario compared to the Baseline scenario for the 0.5% AEP Present Day event. However, this impact is over a very small area and affects two properties. For the 0.5% AEP Climate Change event, the predicted increase is up to 0.07m in the Scheme scenario compared to the Baseline in the same location affecting the same two properties. This is classified as a slight adverse impact. In the 0.5% AEP Climate Change event, all of the adverse impacts to receptors are slight and there is a moderate beneficial impact to the Police Investigation Centre.

7.2.3 Given that there are only two properties within the area where the Scheme was found to have a moderate adverse impact in the Present Day scenario and for other receptors in Great Yarmouth there is only a slight adverse impact in the Present Day and Climate Change scenarios. Using professional judgement it is deemed impractical to provide specific mitigation for the two properties to reduce the level of flooding in these circumstances. The Scheme is essential infrastructure that has to be located in Flood Zone 3 as it has to cross the river, therefore the impact on water levels in Great Yarmouth is unavoidable and the wider sustainability benefits of the Scheme have been shown to outweigh minor increases in flood risk (Appendix A, Case for the Scheme). To the south of the Scheme on the west side of the River Yare, the Baseline flood depths in the Present Day scenario are already up to 0.5m, which would almost certainly be above property threshold levels. The modelled hazard outputs show that the Scheme does not increase flood hazard to any properties. However, mitigation in the form of an emergency preparedness and response plan can be provided to reduce the risk to life and to property, which if implemented appropriately would mean that the significance of flooding to the two properties in question would be reduced from moderate adverse to slight adverse. The use of an emergency preparedness and response plan as mitigation is discussed further below as mitigation for any increases in flood risk across Great Yarmouth as a result of the Scheme.

7.2.4 In terms of the safety and operability of the Scheme, the bridge deck itself is not predicted to flood in any of the scenarios modelled for this assessment (including the H++ events). However, parts of the approach roads on either side of the bridge are predicted to flood. On the western side of the river, the new roundabout that the approach road leads to is predicted to flood to a depth of up to 3m in the 0.5% AEP Climate Change event. However, this is not as a result of the Scheme as the Baseline flood depth in this area is approximately 3m as well (there is actually a slight reduction in flood levels predicted in the Scheme scenario compared to the Baseline in the 0.5% AEP Climate Change event). The eastern approach road to the bridge is predicted to flood up to a depth of approximately 2.5m in the 0.5% AEP Climate Change event but flood levels in this location even in the Baseline scenario are up to 2.5m in this event.

7.2.5 As the impacts of the Scheme on flood risk are negligible in the location of the approach roads on either side of the river, the relative level of flood risk during flood events in these areas remains the same as for the baseline scenario and the figures showing flood hazard for the Present Day and Climate Change scenarios show this (Figures 12.6, 12.7, 12.10 and 12.11). As stated in paragraph 5.109 of the NPS NN (Ref 12B.1) essential infrastructure proposed within Flood Zone 3 should be designed and constructed to remain operational and safe for users in times of flood. The bridge itself remains operational and safe during all flood events modelled but the access roads leading to the bridge do not. Given the Baseline level of flood risk within Great Yarmouth, it is not possible to completely remove the risk of flooding to the access roads during tidal flood events. Ideally, all elements of the Scheme would be raised above the 0.5% AEP Climate Change tidal flood level but this would involve significant raising of the approach roads to the bridge and would likely render the design impractical.

7.2.6 The Scheme does have a safety critical element, being the bridge deck. Although the bridge deck itself is not predicted to flood in any of the scenarios modelled (including the extreme 0.1% H++ scenario), the approach roads to the bridge are predicted to flood and would be impassable in the Baseline 0.5% Present Day event where flood depths up to 0.6m are predicted at the location of the new roundabout on the western side of the river and flood depths of up 1.2m are predicted where the approach road is planned on the eastern side of the river. Due to the negligible changes in water levels predicted at the location of the approach roads during the operational phase of the Scheme, the risk to safety during a flood event is the same as for the Present Day Baseline scenario.

7.2.7 Given the Baseline level of flood risk within Great Yarmouth, it is not possible to completely remove the risk of flooding to the access roads during a tidal flood event. As safe access/egress cannot be achieved, it is proposed that no part of the Scheme is to be opened to the public until an emergency preparedness and response plan has been developed in consultation with GYBC, NCC and the EA and this should be approved in writing by the county planning authority (NCC). Due to the existing significant flood hazard to Great Yarmouth, there are already emergency procedures in place to be implemented during times of flood including the Norfolk Strategic Flood Plan (Ref 12B.23) and the Norfolk Tactical Flood Plan (Ref 12B.24). The response to significant flood events is coordinated by the Norfolk Resilience Forum (made up of the emergency services, local authorities, volunteer organisations and PPGY), any response is based on the predicted severity of the flood event. However, any existing emergency procedures will not address the issues specific to the Scheme and additional mitigation is recommended. It is recommended that the bridge deck of the Scheme is closed for public use during major flooding events in order to prevent vehicles or people becoming stranded. It should be noted that as the major risk of flooding in Great Yarmouth is from tidal sources, which can be predicted 24-48 hours in advance, there would be time for event specific appropriate action to be taken to reduce risk to life and property.

7.2.8 It is noted that the EA is currently designing upgrades to the flood defences through Great Yarmouth to improve the standard of protection in the future but this has not been relied upon in this assessment as the upgraded defences are not currently in place and the proposed levels of these have not been finalised. Construction of the defence upgrades is programmed to begin in December 2019 with completion scheduled for September 2020.

For this assessment, the existing flood defences levels through the town have been assumed in the present day and future scenarios.

7.3 Flood Risk from Surface Water Runoff Mitigation

7.3.1 There is potential for surface water flooding to affect the Principal Application Site and the Scheme will result in an increase in impermeable area compared to the existing site, which would lead to an increase in the surface water runoff at the Principal Application Site post-development (Section 6). The Drainage Strategy (Appendix 12C) explains how surface water on the Principal Application Site will be managed, embedded mitigation will be included in the design for the Scheme to reduce the risk of surface water flooding to the Scheme and prevent an increase in surface water runoff as a result of the Scheme. The surface water runoff calculations in Section 6.2 assume that the Application Site is wholly permeable pre-development to understand the surface water storage required should discharge from the Application Site need to be limited to the greenfield runoff rate. However, the Application Site is not currently wholly greenfield, as 10.44ha of the total 17.33ha Application Site area is currently impermeable.

7.3.2 Where limiting runoff from the Application Site to greenfield runoff rates is not achievable, the post development runoff rates should not exceed the existing runoff rates from the area. The Drainage Strategy (Appendix 12C) explains how the preferred option to manage runoff from the site is to discharge to IDB watercourses and Anglian Water sewers. However, discharging to the River Yare has not been ruled out to allow flexibility in the drainage design for the Scheme. Where it is proposed to discharge into Anglian Water sewers, the runoff rates will be restricted to Anglian Water requirements to ensure the Scheme does not cause any sewer flooding. As the post-development runoff is increased compared to the pre-development scenario, it is necessary to provide storage within the Application Site area to limit runoff. Storage will be included in the design of the Scheme as embedded mitigation as discussed in the Drainage Strategy.

7.3.3 The Great Yarmouth Local Plan (Ref 12B.11) strongly recommends the use of sustainable drainage systems (SuDS) to manage surface water. There are a range of SuDS options available that could be considered and implemented where appropriate including swales and attenuation ponds. The use of any SuDS features within the Scheme is dependent on the site constraints and underlying ground conditions. The Drainage Strategy document considers this in detail and discusses the proposed embedded mitigation for additional surface water runoff. The proposed SuDS features to be used as part of the Scheme are detailed in the Drainage Strategy (Appendix 12C).

8 Flood Risk During Construction

8.1.1 Tidal and groundwater flood risk are considered to have the greatest potential to impact the Scheme during construction.

8.1.2 The construction phase does not have a different footprint in the River Yare channel or on the floodplain to the operational phase of the Scheme as cofferdams are to be constructed the same size as the knuckles in the channel and back filled to create the knuckles. Therefore, it has not been necessary to model a during construction scenario using the hydraulic model developed for this study (described in Section 6). However, as this FRA has found that there is a risk of flooding to the Scheme, there will also be a risk of flooding to the Scheme site during construction. Due to the presence of groundwater at 1.1m below ground level, the potential for groundwater flooding during construction should also be acknowledged.

8.1.3 Due to the relatively short lifespan of the construction phase, a flood management plan should be prepared for the site as part of the full Code of Construction Practice (CoCP). Measures will be put in place for the site to minimise flood damage during large return period events. It is expected that in most instances there will be sufficient warning due to tide level predictions to implement the measures outlined in the full CoCP. This includes time for removal of plant and equipment from the site to higher ground upon receiving a flood warning. This will limit damage and ensure that any hazardous materials with the potential to float will be moved.

8.1.4 As the construction footprint of the Scheme within the River Yare will be the same as the operational phase footprint, the flood risk to the Application Site during construction will be the same as during the operational phase. Given the low likelihood of a significant flood event occurring during the construction phase, the implementation of a flood management plan is sufficient mitigation and the Outline CoCP (para 7.2.1) states that the contractor must prepare a flood management plan to form part of the full CoCP.

9 Conclusions

9.1.1 This FRA has been prepared for the scheme in line with the NPPF, the NPS NN and in consultation with the EA. The Scheme has been designated a NSIP and therefore this FRA has been undertaken in accordance with the requirements of the NPS NN in terms of flood risk. Guidance within the DMRB and the CIRIA SuDS Manual has also informed the FRA.

9.1.2 The following documents have been reviewed to gather information for this study:

- Great Yarmouth Strategic Flood Risk Assessment (SFRA), November 2017 (Ref 12B.6);
- Broadlands Rivers Catchment Flood Management Plan (CFMP), December 2009 (Ref 12B.7);
- Kelling to Lowestoft Ness Shoreline Management Plan 6 (SMP), August 2012 (Ref 12B.8);
- NCC Preliminary Flood Risk Assessment Report (PFRA); July 2011 (Ref 12B.9);
- Norfolk Local Flood Risk Management Strategy (LFRMS), July 2015 (Ref 12B.10);
- Anglian River Basin Flood Risk Management Plan (FRMP), March 2016 (Ref 12B.12); and
- EA data and web based mapping;
- Broads Authority web based mapping.

9.1.3 The Application Site covers 17.33 hectares and includes the Principal Application Site and Satellite Application Sites. The Scheme consists of a bridge approximately 1.6km downstream of the existing Haven Bridge plus approach roads. The Scheme is considered a NSIP and deemed ‘Safety Critical’. Safety critical is defined as any development that is required to remain accessible/functional in an emergency event.

9.1.4 The Scheme is located within Flood Zone 3 (3a), which means there is a 0.5% AEP of flooding from the sea or a 1% AEP chance of flooding from fluvial sources in any given year. The Scheme was initially subject to the Sequential Test, Chapter 3 of the ES (document reference 6.1) explains the reasons for the choice of location for the Scheme, concluding that it is the most appropriate location. The Scheme is classified as essential infrastructure and therefore the Exception Test is required for the Scheme. This FRA has been prepared to address part two of the Exception Test. Part one of the Exception Test is addressed in Appendix A of the CftS, which describes the wider sustainability benefits of the Scheme that outweigh flood risk.

9.1.5 Flood risk from rivers and sea, surface water, sewers, groundwater and artificial sources has been assessed. Flood risk to the Scheme and the impact of the Scheme on flood risk elsewhere during both the operational and construction phases has been assessed. The greatest flood risk in Great Yarmouth is from the sea (tidal flooding), therefore a detailed hydraulic assessment has been undertaken to understand the risk of tidal flooding to the Scheme and the impact of the Scheme on tidal flood risk within great Yarmouth. Due to the tidal dominance in the River Yare, the Application Site is not at risk of fluvial flooding.

9.1.6 A 1D/2D Flood Modeller - TUFLOW model covering the River Yare through Great Yarmouth of floodplain upstream of the town has been developed to assess tidal flooding. A baseline model was developed to represent the existing flood risk within Great Yarmouth. The baseline model was subject to sensitivity testing to ensure the model was robust and could be used to undertake hydraulic assessments as part of the FRA process. The 2013 storm surge event has been modelled and the predicted flooding checked against historic flood extents for Great Yarmouth and photos/anecdotal evidence to calibrate the model. Full details of the modelling undertaken are provided in the Hydraulic Modelling Report (Annex A).

9.1.7 The model has been used to assess the risk of flooding in Great Yarmouth for the present-day scenario and, 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 (based on allowances for the year 2140, 120 years in the future). Due to the designation of the scheme as a NSIP and safety critical infrastructure, the EA has requested that the low probability, high risk flood event (H++) within the UK Climate Projections 2009 (UKCP09) predictions is also modelled to assess a credible maximum scenario. It should be noted that the H++ scenarios were not updated as part of the UKCP18 predictions released in November 2018. It has been agreed with the EA that the scheme does not have to include mitigation for the impacts predicted by the model for the high risk, low probability H++ event.

9.1.8 Once the baseline model had been developed and verified, a version of the model was developed to represent Great Yarmouth post-development of the Scheme to understand the flood risk to the Scheme. The results from the Baseline and Scheme scenarios have been compared in order to also ascertain the impact of the Scheme on flooding elsewhere in Great Yarmouth.

9.1.9 The Scheme bridge deck is above the highest tidal level considered in the assessment (0.1% AEP H++ event) and is therefore not at risk of flooding.

However, the access roads to the bridge were found to be at risk of flooding. This flooding is not as a result of Scheme as the locations where the access roads are proposed are predicted to flood in the Baseline scenario by up to 3m on the western bank of the River Yare and up to 2.5m on the eastern bank of the River Yare.

9.1.10 The results from the hydraulic model show the Scheme has the effect of increasing water levels to the south of the site and decreasing to the north. This is because of the hydraulic constriction caused by the presence of the knuckles in the River Yare channel, which reduce the channel width by 50%. The hydraulic modelling results show that during the 5% AEP Present Day scenario, the Scheme causes a negligible impact on water levels. In larger events, the Scheme has a moderate impact on the peak water level with the largest impact in the 0.5% AEP + CC event. This was found to be a 0.1m increase and situated between the knuckles of the Scheme. The Scheme has beneficial impacts on the water level and the flood extent north of the scheme by moderately reducing the water levels on the floodplain in all overtopping scenarios.

9.1.11 The extreme future H++ scenario has been modelled to understand the full picture of risk in Great Yarmouth. The results of this scenario will not be used to inform the design or mitigation of Scheme. The impact of the Scheme in the 0.5% AEP H++ scenario is negligible as the tidal levels in this scenario are much higher than for the Present Day and Climate Change scenarios meaning that the Scheme has less impact.

9.1.12 The assessment found that the Scheme is at risk of tidal flooding and has been shown to impact tidal flooding within Great Yarmouth with some areas experiencing a moderate adverse impact with the Scheme in place. Given the risk of tidal flooding to the Principal Application Site and the impact of the Scheme on flood risk elsewhere, the Scheme will also be at risk during construction and may have an impact on flood risk elsewhere during this phase too.

9.1.13 The Principal Application Site was found to be at risk of surface water flooding and as the Scheme will result in an increase in impermeable area within the Principal Application Site, the Scheme will increase surface runoff from the area. Embedded mitigation within the Scheme design will be included to manage surface water runoff from the Principal Application Site as discussed in the Drainage Strategy (Appendix 12C). The risk of surface water flooding to the Scheme during construction is considered to be negligible given the relatively short duration of the construction phase

9.1.14 Given the distance of the reported sewer flooding incidents in Great Yarmouth from the Principal Application Site, flood risk to the Scheme from sewers is considered negligible. The Drainage Strategy (Appendix 12C) provides details on discharges from the Scheme to Anglian Water sewers, discharge rates have been agreed with Anglian Water to ensure there is no increase in sewer flooding as a result of the Scheme.

9.1.15 Groundwater monitoring has been undertaken as part of the assessment and although groundwater has been found at the Principal Application Site at only 1.5m below ground level, there are no recorded incidents of ground water flooding at this location. Therefore, the risk of groundwater flooding to the Scheme during the operational phase is considered minor and the Scheme will not have an impact on groundwater flooding in Great Yarmouth. Therefore, no mitigation is required in terms of groundwater flooding for the operational phase of the Scheme. However, groundwater flooding may be an issue during construction as the groundwater levels are relatively close to the ground surface and construction will involve excavation.

9.1.16 As the Principal Application Site is not located near any artificial sources of flood risk (reservoirs, canals or pumping stations), the risk of flooding to the Scheme from artificial sources can be considered negligible. For the same reason, the Scheme will not have any impact on flooding from artificial sources.

9.1.17 The assessment concluded that there is risk of flooding to the Scheme during the operational phase from tidal (sea) flooding and surface water flooding. The Scheme was shown to have the potential to increase tidal and surface water flood risk elsewhere as well. Mitigation for flooding from the sea and surface water flooding is therefore required. The assessment has shown that there is negligible flood risk to the Scheme from fluvial, groundwater, sewer and artificial sources of flooding during the operational phase. Similarly, the Scheme was not shown to impact on these sources of flood risk during the operational phase. Therefore, mitigation is not required for fluvial, groundwater, sewer and artificial sources of flooding for the operational phase of the Scheme. The assessment has shown that the Scheme may be at risk of flooding from the sea and groundwater during construction. There would also be an adverse impact of the Scheme on tidal flood risk during construction.

9.1.18 It has been agreed with the EA that mitigation is not required for the H++ event modelled. Therefore, mitigation for increases in flood risk during the Present Day and Climate Change tidal flood events have been considered as part of this assessment.

9.1.19 In terms of tidal flooding to the Scheme, as the impacts of the Scheme on flood risk are negligible in the location of the approach roads on either side of the river, the relative level of flood risk during flood events in these areas remains the same as for the Baseline scenario. Given the Baseline level of flood risk within Great Yarmouth, it is not possible to completely remove the risk of flooding to the access roads during tidal flood events. Ideally, all elements of the Scheme would be raised above the 0.5% AEP Climate

Change tidal flood level but this would involve significant raising of the approach roads to the bridge and would likely render the design impractical.

9.1.20 Given the Baseline level of flood risk within Great Yarmouth, it is not possible to completely remove the risk of flooding to the access roads during a tidal flood event. As safe access/egress cannot be achieved, it is proposed that no part of the Scheme is to be opened to the public until an emergency preparedness and response plan has been developed in consultation with GYBC, NCC and the EA and this should be approved in writing by the county planning authority (NCC). Due to the existing significant flood hazard to Great Yarmouth, there are already emergency procedures in place to be implemented during times of flood. The response to significant flood events is coordinated by the Norfolk Resilience Forum (made up of the emergency services, local authorities, volunteer organisations and PPGY), any response is based on the predicted severity of the flood event. However, any existing emergency procedures will not address the issues specific to the Scheme and additional mitigation is recommended. It is recommended that the bridge deck of the Scheme is closed for public use during major flooding events in order to prevent vehicles or people becoming stranded. It should be noted that as the major risk of flooding in Great Yarmouth is from tidal sources, which can be predicted 24-48 hours in advance, there would be time for event specific appropriate action to be taken to reduce risk to life and property.

9.1.21 In terms of the impact of the Scheme on flood risk elsewhere, that there are only two properties within the area where the Scheme was found to have a moderate adverse impact in the Present Day scenario and for other receptors in Great Yarmouth there is only a slight adverse impact in the Present Day and Climate Change scenarios. Using professional judgement, it is deemed impractical to provide specific mitigation for the two properties to reduce the level of flooding in these circumstances. The Scheme is essential infrastructure that has to be located in Flood Zone 3 as it has to cross the river, therefore the impact on water levels in Great Yarmouth is unavoidable and the wider sustainability benefits of the Scheme have been shown to outweigh minor increases in flood risk (Appendix A, Case for the Scheme). To the south of the Scheme on the west side of the River Yare, the Baseline flood depths in the Present Day scenario are already up to 0.5m, which would almost certainly be above property threshold levels. The modelled hazard outputs show that the Scheme does not increase flood hazard to any properties. However, mitigation in the form of an emergency preparedness and response plan can be provided to reduce the risk to life and to property, which if implemented appropriately would mean that the significance of flooding to the two properties in question would be reduced from moderate adverse to slight adverse.

9.1.22 Mitigation for surface water flooding to the Scheme and to prevent an increase in surface water runoff from the Principal Application Site during the operational phase will be embedded into the Scheme design. The embedded mitigation measures are discussed in the Drainage Strategy (Appendix 12C). Where limiting runoff from the Application Site to greenfield runoff rates is not achievable, the post development runoff rates should not exceed the existing runoff rates from the area. The Drainage Strategy (Appendix 12C) explains how the preferred option to manage runoff from the site is to discharge to IDB watercourses and Anglian Water sewers. However, discharging to the River Yare has not been ruled out to allow flexibility in the drainage design for the Scheme. Where it is proposed to discharge into Anglian Water sewers, the runoff rates will be restricted to Anglian Water requirements to ensure the Scheme does not cause any sewer flooding.

9.1.23 Tidal and groundwater flood risk are considered to have the greatest potential to impact the Scheme during construction. Due to the relatively short lifespan of the construction phase, a flood management plan should be prepared for the site as part of the full Code of Construction Practice (CoCP). Measures will be put in place for the site to minimise flood damage during large return period events. It is expected that in most instances there will be sufficient warning due to tide level predictions to implement the measures outlined in the full CoCP.

10 References

Ref 12B.1 National Policy Statement for National Networks, Department for Transport, December 2014.

Ref 12B.2 National Planning Policy Framework, Ministry of Housing, Communities & Local Government, July 2018.

Ref 12B.3 Flood Risk and Coastal Change Planning Practice Guidance, Ministry of Housing, Communities & Local Government, March 2014.

Ref 12B.4 Design Manual for Roads and Bridges, Volume 11 Environmental Assessment, Section 3 Environmental Assessment Techniques, Part 10, HD45/09 Road Drainage and the Water Environment, November 2009.Ref 12B.5 The SuDS Manual, CIRIA C753, 2015.

Ref 12B.6 Great Yarmouth Strategic Flood Risk Assessment, JBA Consulting, November 2017.

Ref 12B.7 Broadlands Rivers Catchment Flood Management Plan, Environment Agency, December 2009.

Ref 12B.8 Kelling to Lowestoft Ness Shoreline Management Plan, AECOM, August 2012.

Ref 12B.9 Preliminary Flood Risk Assessment, Norfolk County Council, July 2011.

Ref 12B.10 Norfolk Local Flood Risk Management Strategy, Norfolk County Council, July 2015.

Ref 12B.11 Great Yarmouth Local Plan – Core Strategy 2013 – 2030, Great Yarmouth Borough Council, December 2015.

Ref 12B.12 Anglian River Basin Flood Risk Management Plan 2015-2021, Environment Agency, December 2015.

Ref 12B.131 Investigations Report into Flooding across Great Yarmouth Borough during the Summer of 2014, Norfolk County Council, June 2015.

Ref 12B.14 Flood Estimation Handbook, Centre for Ecology & Hydrology, 1999.

Ref 12B.15 Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities, Environment Agency, 2016.

Ref 12B.16 Flood Risk Assessments – Climate Change Allowances, Environment Agency, February 2017

Ref 12B.17 Volume 11, Section 2, Part 5 of the Design Manual for Roads and Bridges (DMRB) (HA 205/08)

Ref 12B.18 Address Base Products: Classification Scheme, Ordnance Survey, October 2013.

Ref 12B.19 Flood Risks to People Phase 2 FD2321/TR2 Guidance Document, Defra/Environment Agency Flood and Coastal Defence R&D Programme, March 2006.

Ref 12B.20 Supplementary Note on Flood Hazard Ratings and Thresholds for Development Planning and Control Purpose – Clarification of the Table 13.1 of FD2320/TR2 and Figure 3.2 of FD2321/TR1.

Ref 12B.21 Report No. 124 Flood Estimation for Small Catchments, Institute of Hydrology, 1994.

Ref 12B.22 Design and Analysis of Urban Storm Drainage: The Wallingford Procedure Volume 4 The Modified Rational Method, Department of the Environment National Water Council Standing Technical Committee Reports No 31, 2005.

Ref 12B.23 Norfolk Strategic Flood Plan, Norfolk Resilience Forum Severe Weather and Flood Risk Working Group, 2015.

Ref 12B.24 Norfolk Tactical Flood Plan Part One, Norfolk Resilience Forum Severe Weather and Flood Risk Working Group, 2015.

Great Yarmouth Third River Crossing

Application for Development Consent Order

Document 6.2: Environmental Statement Volume II: Technical Appendix 12B, Annex A: Hydraulic Modelling Report

Planning Act 2008

The Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009 (as amended) ("APFP")

APFP regulation Number: 5(2)(a)

Planning Inspectorate Reference Number: TR010043

Author: Norfolk County Council

Document Reference: 6.2 – Technical Appendix 12B, Annex A

Version Number: 0 – Revision for Submission

Date: 30 April 2019

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1 Introduction

1.1 Overview

1.1.1 As part of the Great Yarmouth Third River Crossing (hereafter known as 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 (Appendix 12B). This report is supported by Figures in Volume 3 of the ES (document reference 6.3).

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 (Appendix 12B) itself should be referred to for wider discussion of the model results and the Scheme.

1.2 Study Area

1.2.1 The River Yare is used as a commercial transport hub with a number of large ship berths on either side. Breydon Water is a large lake upstream of Great Yarmouth that forms part of the River Yare and provides a large volume of storage within the catchment. The River Yare is a tidal river approximately 83km in length from its source near Shipdham to its outfall at the North Sea. It is a main arterial route for water in the Norfolk Broads. To the north of Great Yarmouth, the River Bure discharges into the River Yare and is approximately 80km in length.

1.2.2 Great Yarmouth currently has two road bridge crossings, Breydon Bridge and Haven Bridge as shown in Figure 12.1.

1.2.3 As identified in the FRA, the Great Yarmouth Strategic Flood Risk Assessment (SFRA) refers to a number of existing flood defences built to protect Great Yarmouth from tidal surge events. There are several Environment Agency (EA) assets throughout the borough, which consist of a mixture of embankments, quays, bridge abutments, demountable defences, flood gates and walls. The condition of these assets varies. It is noted that at the time of writing the EA are working on improving the defences in Great Yarmouth. The EA has provided WSP with their latest model for Great Yarmouth (JBA, 2018) and as agreed with the EA, the flood defence data from the EA model has been used in this study as it represents the current defence heights through the town. The model used in this assessment includes any completed assets, however upgrades at planning stage are not modelled. It was also identified that much of the borough is heavily dependent on flood defences to protect settlements from flooding, particularly from tidal / coastal sources.

1.3 Previous Studies

1.3.1 At the outset of this study, the EA provided an existing 1D-2D hydraulic model of Great Yarmouth to WSP, which was built by Halcrow on behalf of the EA in 2011 and used to update the flood mapping for the town. WSP have carried out a comprehensive review of this model as part of this assessment to inform the modelling approach for this study (Section 2). The EA are currently carrying out assessments of the tidal defences in Great Yarmouth with a view to improving flood protection in the town. In 2018, JBA created an updated model representing the existing scenario in Great Yarmouth that includes the latest flood defence levels through the town. The EA supplied the JBA model to WSP in November 2018 and the current defence levels within Great Yarmouth have been incorporated into the hydraulic model developed for this study.

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 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 the River Yare built by Halcrow on behalf of EA.

Table 2.1: Summary of Data Collected

Data	Source
1D-2D ISIS TUFLOW River Yare model, 2011	EA / Halcrow
1D-2D Flood Modeller/TUFLOW River Yare model, 2018	EA / JBA
General Arrangement Plans (document reference 2.2) **Engineering Plans, Drawings and Sections (document reference 2.11)**	WSP
OS Mastermap **As built construction drawings for Haven Bridge** **Previous study reports (Ref 12B.22 and 12B.23)**	Norfolk County Council (NCC)
Bathymetric survey of the River Yare through Great Yarmouth taken in 2017	Peel Ports Great Yarmouth (PPGY)
2015, 0.5m LiDAR **2009, 1m LiDAR** **Extreme sea levels** **15 minute gauge data for Haven Bridge, Gorleston, Three Mile House and Burgh Castle**	EA
Current Great Yarmouth flood defence height data from JBA hydraulic model (2018)	EA

2.2 EA/Halcrow 2011 Model Review Summary

2.2.1 Halcrow developed a 1D-2D ISIS TUFLOW model on behalf of the EA as part of the Great Yarmouth Flood Defences Framework for Action (GYFDFFA) project. The model was reviewed to determine whether some or all the model could be used in this assessment. In this section an overview of the major findings of the model review is provided. For the full review, see Supporting Document, Annex A.1. It should be noted that all “must do” actions identified in Annex A.1 have been actioned and this report explains the model updates made.

2.2.2 The Halcrow Great Yarmouth model was originally developed from the Broadlands Environmental Service Limited (BESL) 1D model to assess the existing flood extent in the Great Yarmouth area by creating a 2D domain to simulate the floodplain. An updated version was used in the GYFDFFA project which contains the as-built representation of all the tidal defences in the harbour.

2.2.3 The model has a 2D domain covering Great Yarmouth, Breydon water and the surrounding floodplain. The Halcrow model received for use in this assessment has a large 1D domain representing approximately 135km of river reach. Six of the major watercourses upstream of Great Yarmouth are represented in the 1D domain. These are; the River Yare, River Ant, River Chet, River Bure, River Thurne and River Waveney. The 1D section of the model is the BESL 1D model used by the Broadlands Environmental Service to maintain and improve flood defences on the Norfolk Broads. As this assessment focuses on the section of the River Yare in Great Yarmouth, it is not necessary to model the Broadlands river network as part of this study.

2.2.4 The existing model represents the River Yare in the 1D domain using cross sections through the channel. There is no information regarding the source of the cross sections however it is likely these have been obtained from a survey but their age is unknown. The existing structures in Great Yarmouth such as Haven Bridge are not represented in the Halcrow model.

2.2.5 The model represents the existing defences on the River Yare by increasing the topography locally to the defence height. The defences are along both quays on the River Yare and are quoted to provide a 1% Annual Exceedance Probability (AEP) standard of protection when simulated in the existing model. The defences form the boundary between the 1D and 2D domains in the existing model. Roughness values have been applied in both the 1D and 2D domains using Manning's n values. Across the 2D domain, roughness has been defined for different land uses using OS mastermap. A roughness value of 0.1 has been assigned to buildings, which is low and may not accurately represent the slowing of flow through a building.

2.2.6 The review of the existing model concluded that several updates would be required to ensure the model was suitable for use in this assessment. These include: obtaining accurate structure details for any structures affecting the hydraulics in Great Yarmouth; obtaining updated bathymetry for the River Yare to ensure an accurate representation of the channel in its current form; updating the LiDAR using the latest available data; and cutting down the 1D model to a more manageable size to improve model run times. Given the updates required to ensure the existing model was suitable, 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 Application Site. The Halcrow 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 specifically in Great Yarmouth.

2.3 EA/JBA, 2018 Model Review Summary

2.3.1 The EA provided the 1D-2D JBA model (2018) for Great Yarmouth in November 2018 and it was agreed that the updated defence data from the JBA model should be incorporated into the WSP modelling. The WSP baseline modelling has been updated with all the defence data including the de-facto defences as provided in the JBA model.

2.3.2 It was not necessary to incorporate other elements of the JBA model into the model developed for this study as both have been developed for different, specific purposes.

2.4 Additional Data

2.4.1 Norfolk County Council (NCC) as lead local flood authority provided a number of datasets and documents for use in this assessment. OS mastermap data covering Great Yarmouth was provided, as well as as-built drawings for Haven Bridge.

2.4.2 Peel Ports – Great Yarmouth (PPGY) has provided a detailed bathymetric survey of the River Yare. The dataset contains points measured relative to Chart Datum (CD) taken from a boat that traversed the inner harbour.

2.4.3 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. Great Yarmouth CD is -1.56mAOD and is defined as the approximate level of the lowest astronomical tide at Great Yarmouth. The EA has provided several datasets; the 2015 0.5m resolution LiDAR dataset, the 2009 1m resolution LiDAR dataset, Extreme Sea Levels (ESL) (Ref 12B.22) and daily water level data recorded in the River Yare.

2.4.4 The 0.5m LiDAR was used where available to represent the floodplain in Great Yarmouth. 1m LiDAR has been used to fill in gaps in the 0.5m coverage. There have been no significant changes in the Great Yarmouth 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 (2019) 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.

2.4.5 Plate 2.1 shows a comparison between the recorded data at Gorleston Gauge and Haven Bridge Gauge. Levels are slightly lower at Haven Bridge due to the energy losses occurring as the water travels along the channel from the mouth of the river where the Gorleston Gauge is situated. This is typical in a heavily engineered channel such as the River Yare through Great Yarmouth where the influence of the corrugated sheet pile defences creates form losses along the reach.

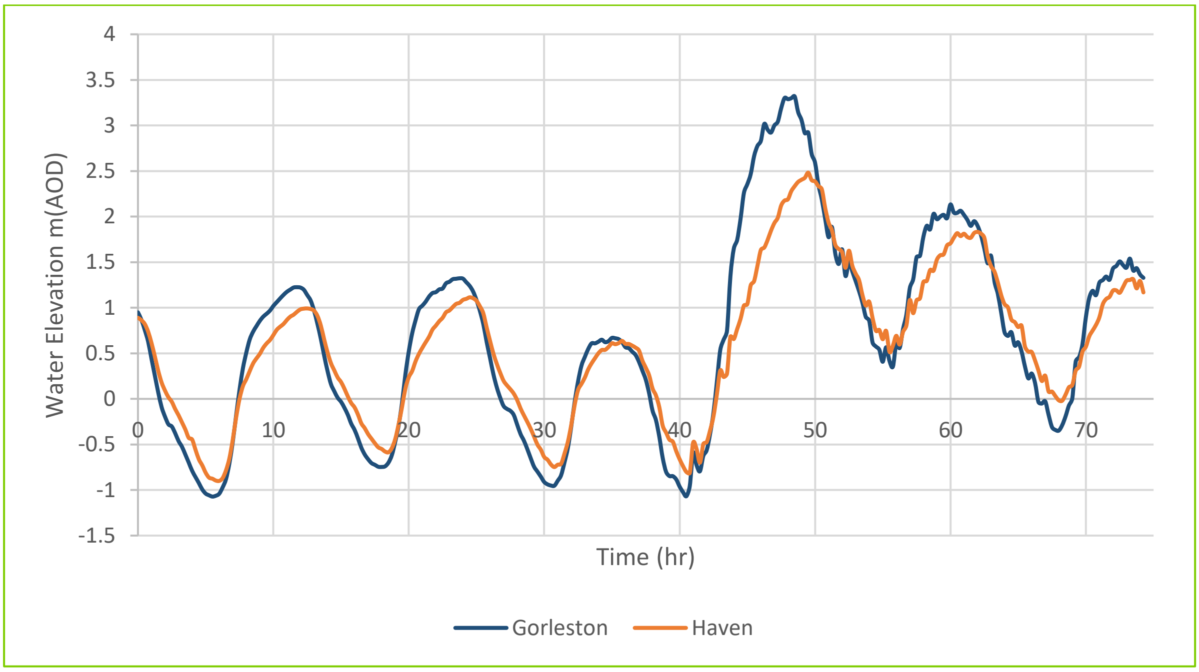


Plate 2.1 - Gauge Flow Comparisons

3 Hydrology

3.1 Overview

3.1.1 The hydrology of the River Yare has been analysed and the EA has 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 Great Yarmouth coast. EA guidance on estimating design sea levels (Ref 12B.22) has been used to derive the tidal boundary used in the model.

3.1.2 Tidal curves for the present day plus two climate change scenarios have been derived for this assessment. The EA stated in their stage 2 consultation response (for details, refer to the Consultation Report (document refence 5.1)) that if the design life of the Scheme is 60 years or greater, the UK Climate Projections 2009 (UKCP09) high emissions scenario against the 2080s projections at the 50% probability level should be applied. The UKCP18, which replace UKCP09, were released in November 2018 and have been considered in this assessment. A realistic climate change scenario has been defined by calculating sea level rise using methods from a number of guidance documents and choosing the maximum increase calculated.

3.1.3 Th EA also stated in their stage 2 consultation response that if the Scheme is considered safety critical, the Scheme should also be assessed against the H++ estimates for sea level rise (high risk, low probability) to assess a credible maximum scenario. However, mitigation is not required for the H++ scenario, it is used to fully understand the risks associated with the Scheme. The H++ estimates have not been updated as part of UKCP18, according to the UKCP18 guidance (Ref 12B.24) the H++ scenario of UKCP09 can still be considered a useful, plausible but unlikely high-end sea level rise estimate.

3.1.4 The EA has requested that three flood return period events are investigated in this assessment; 5% AEP, 0.5% AEP and 0.1% AEP. The three return period events will be assessed for the present day (2019) and two climate change scenarios. In total nine hydrological scenarios have been derived to test in the model, these are:

- 5% AEP present day
- 0.5% AEP present day
- 0.1% AEP present day
- 5% AEP climate change
- 0.5% AEP climate change

- 0.1% AEP climate change
- 5% AEP H++
- 0.5% AEP H++
- 0.1% AEP H++

3.1.5 A summary of the calculations undertaken to define the hydrological boundaries of the model is provided below with more detail provided in Supporting Document, Annex A.2.

3.2 Tidal Curve Derivation

3.2.1 The EA guidance (Ref 12B.22) sets out a 10-step procedure (Table 3.1) to generate a tidal curve.

Table 3.1: EA Procedure to Generate Tidal Curve

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

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

- Estuary boundaries
- Extreme sea levels

- Gauge sites
- Confidence intervals
- Surge shapes

3.2.3 The tidal curve has been derived using the process set out in Table 3.1. As discussed in detail in –the Supporting Documents, Annex A.1 and Annex A.2, 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 EA / Halcrow existing model and scale to the required peaks in Table 4.1 (ESLs). The existing model tidal curve was scaled to the ESLs using the surge shape for Great Yarmouth provided with the guidance. This procedure is explained in detail in Supporting Documents, Annex A.1 and Annex A.2.

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 A range of methods from available guidance for estimating sea level rise have been considered in order to represent climate change and the maximum sea level rise calculated has been used to represent the climate change scenario. This approach ensures that the assessment tests the Scheme and its impacts robustly over the life time of the Scheme.

3.2.7 The methods used to calculate sea level rise were:

- National Planning Policy Framework (NPPF), notably Table 3;
- UKCP18 50% Representative Concentration Pathways (RCP) 8.5;
- UKCP18 95% RCP8.5;
- UKCP18 95% RCP4.5; and
- Upper End, Adapting to Climate Change (2016).

3.2.8 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. The maximum climate change sea level rise was calculated using the UKCP18 95% RCP8.5 scenario, which gave an increase of 1.83m for 2140. 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 flood event modelled.

3.2.9 Due to the safety critical nature of the Scheme, the EA has 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 has 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 (Ref 12B.15). 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 Supporting Documents, Annex A.1 and Annex A.2.

3.2.10 The final ESLs are shown in Table 3.2. 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. Plate 3.1 shows the curves for the Present-day event.

Table 3.2: Peak Sea Level for each Event

Event	5% AEP (m AOD)	0.5% AEP (m AOD)	0.1% AEP (m AOD)
Present day extreme sea level (2019)	2.84	3.50	4.03
Climate change scenario (based on UKCP18 RCP 8.5)	4.67	5.33	5.86
H++ event climate change	5.94	6.60	7.13

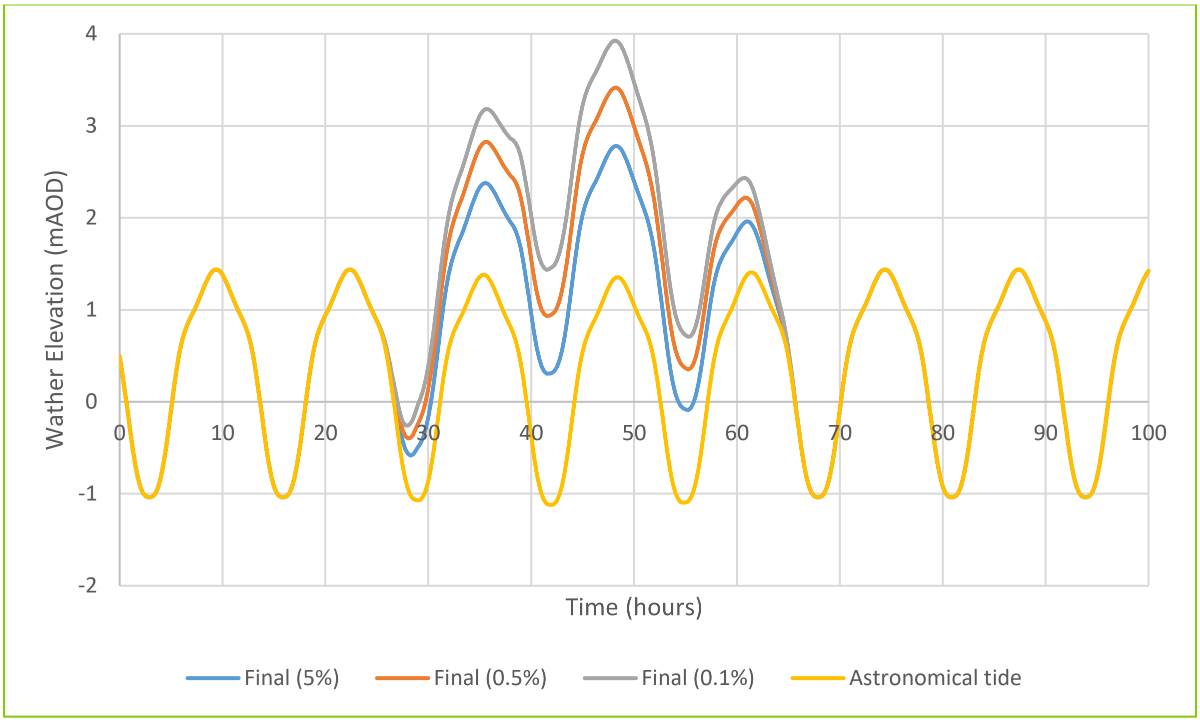


Plate 3.1 - Model Boundary Tidal Curves, Present Day Events

4 Modelling Methodology

4.1 Overview

4.1.1 A 1D/2D Flood Modeller-TUFLOW model of the River Yare through Great Yarmouth 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. Following the model review of the EA / Halcrow model, it was concluded that a new model would be required for this assessment, the new model does make use of the latest available defence level data from the JBA model (2018). The model build for this study is detailed in this section as well as the model verification and calibration undertaken. Section 5 describes the modelling results.

4.2 Model Domain

4.2.1 The model domain extends from the western edge of Breydon Water to the mouth of the River Yare where the river discharges into the sea. The River Yare through Great Yarmouth itself has been included in the 2D model domain (Figure 12B.5) in order to model flow routes through the town. It was not considered necessary to include the upper reaches of the River Yare within the 2D domain but the storage potential of Breydon Water and the northern floodplain has been included in a 1D domain linked to the 2D domain. It should be noted that the 1D domain is not an accurate physical representation of Breydon Water. Using this method, the model represents the function of the storage area without significantly increasing model runtimes as would happen if Breydon Water and the northern floodplain were included in the 2D model domain. The impacts of this are discussed in the Section 4.8.

4.2.2 A 5m cell size has been used within the 2D domain in order to model urban flow paths through Great Yarmouth whilst still maintaining reasonable model run times.

4.3 Floodplain Roughness

4.3.1 Manning's n roughness values have been used to represent different land uses across the 2D domain as shown in

4.3.2 Table 4.1: Domain Roughness Values

4.3.3 . Roughness values have been applied based on the land use classification in the EA model and checked with the OS mastermap data supplied by NCC, 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.

Table 4.1: Domain Roughness Values

Item	Roughness (Manning's *n*)
Buildings and Structures	1
Roads and Paths	0.02
River Channel	0.03
Natural Surfaces	0.05
Trees	0.06
Manmade Surfaces	0.03

4.4 Model Topography

4.4.1 The bathymetric data provided by PPGY, once converted from CD to mAOD has been used to define the bed levels of the River Yare and the outer harbour within the model. The dataset recorded in April 2017 consists of some 250,000 data points taken from a boat traversing the harbour. Towards Haven Bridge, only the eastern side of the River Yare was included in the bathymetric survey as shown on Figure 12B.6. Where this occurs, the model has been set to -7m which is the depth in the channel creating the dredged channel expected on a port.

4.4.2 LiDAR from the 2015 flight at 0.5m resolution has been used for the floodplain elevations. Where 0.5m resolution data is not available, 1m resolution data from the 2009 flight has been used. There is complete coverage of the 2D domain using this combined dataset.

4.5 Boundary Conditions

4.5.1 The North Sea tidal boundary is located to the east of Great Yarmouth as shown on Figure 12B.7. The tidal curves derived for this assessment as summarised in Section 3.2 and have been applied to this boundary in the model. The tidal boundary has been applied close to the river mouth at the gauge representing the worst-case scenario, enabling the highest sea level for a given scenario to be simulated at the harbour entrance.

4.5.2 One HQ boundary was required in the model to allow water to flow out of the 2D domain. Where water would continue to spread across the floodplain, the location of this boundary is shown in brown on Figure 12B.7. At this boundary, the model uses a rating curve based on the topography and roughness of the floodplain to control the release of water from the model.

4.5.3 A 1D boundary has been incorporated into the model, representing the flow of the River Yare and on the Great Yarmouth floodplain into Breydon Water.

4.5.4 A 2D SX line is modelled to allow for transfer of any overland flow in the north of Great Yarmouth between the 1D and 2D domains.

4.6 Initial Water Level

4.6.1 The initial water level in the model is set to -5mAOD across the entire 2D domain and the level in the watercourse is set to the initial water level in the design tidal curves calculated, as described in the Supporting Documents, Annex A.1 and Annex A.2. 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 Plate 3.1).

4.7 Structures

4.7.1 To the north of the River Yare, Haven Bridge has been represented in the model developed for this assessment. Haven Bridge has been represented using TUFLOW Z shapes and flow constriction units to represent energy losses through the structure.

4.7.2 For the 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.

4.7.3 There are no other structures included in the model, as structures further away, such as Breydon Bridge, are too remote from the Application Site to have an impact on the model results in this location.

4.8 Baseline Model

4.8.1 Once the baseline model had been developed as described above, calibration and sensitivity testing were undertaken to ensure the model accurately represented water levels in the River Yare and flood risk to Great Yarmouth.

4.9 Calibration

4.9.1 Following the model build, a calibration of the baseline model was undertaken using gauge data from past flood events, observations and EA flood maps. There are two gauges in the model domain, one at the harbour mouth at Gorleston and one on the southern side of Haven Bridge (Figure 12.1). For the purposes of the calibration, the gauge at Gorleston has been used to define the tidal boundary and the model water level results at Haven Bridge gauge have been compared to recorded data.

4.9.2 The event chosen for the model calibration was the 2013 tidal surge event in Great Yarmouth 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.

4.9.3 The level data provided by the EA for this assessment at the Gorleston gauge has been recorded every 15 minutes and the recorded peak at 3.32mAOD was seen at 22.30 on 5th December 2013. Plate 4.1 shows the gauge data at the time of the 2013 tidal surge event. The graph shows the water elevation in mAOD.

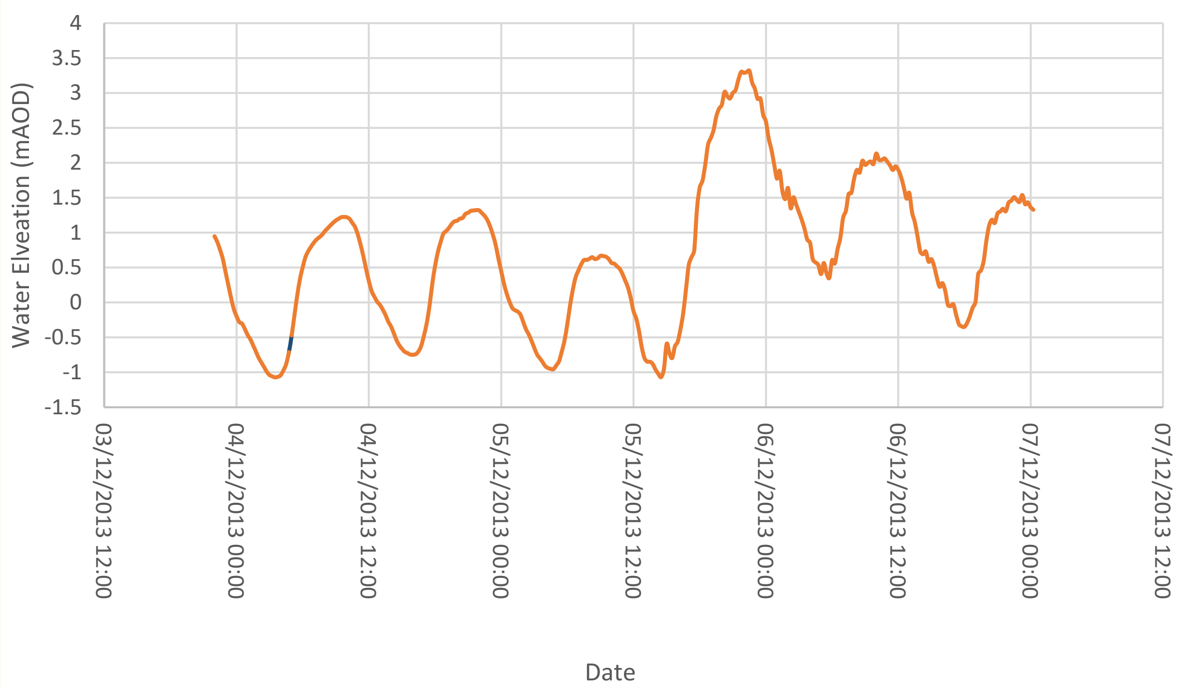


Plate 4.1 – Gorleston Gauge Data

4.9.4 The event data at the gauge shown in Plate 4.1 has been applied at the eastern tidal boundary shown in Figure 12B.7to represent the peak tidal level of 3.32mAOD during the flooding event to achieve the correct water level at the model boundary. The model has then been used to simulate the water levels up the River Yare to the Haven Bridge gauge and the model predicted water levels at this location have been compared to the Haven Bridge gauge data.

4.9.5 Table 4.2 shows the initial peak baseline model water level predicted at the location of Haven Bridge gauge and the peak level recorded at the gauge during the December 2013 event.

Table 4.2: Peak Water Level from the Gauge and Peak Calibration Model Water Level

Haven Gauge - Peak Water Level (mAOD)	2013 Event Calibration - Peak Water Level at Haven Gauge (mAOD)
2.48	3.37

4.9.6 The initial peak modelled water level in the River Yare using the baseline model as described above is 0.89m higher that the recorded level during the event at the Haven Bridge gauge. The flooding through Great Yarmouth predicted for the 2013 event using the initial baseline model was widespread and there is no evidence for the extensive flooding predicted by the model for this event either from anecdotal sources (photographs, eye witnesses etc.) during the 2013 event or on the historic flood maps. Therefore, further work was undertaken to calibrate the model to ensure it accurately represented the flood event in Great Yarmouth.

4.9.7 As the cause of the overestimation of flooding in the model was not immediately apparent, a number of variations of the model, as described in Table 4.3 have been simulated and the results at Haven Bridge gauge for each variation are presented in Table 4.4.

Table 4.3: Variations from the Baseline Comparison Table

Model Name	Variation from Baseline
Upstream Forced Boundary	Applying the data from Burgh Castle and Three Mile House gauges during the event as the upstream boundaries to the model. The gauges are located at the upstream end of Breydon Water and upstream on the River Bure respectively.
Increased Roughness in the River Yare Channel	Increasing the roughness of the river bed through Great Yarmouth to 0.12, representing the combined impact of the corrugated harbour walls and river bed.
Increased Roughness at mouth of River Yare	Increasing the roughness only at the mouth of the River Yare, the 90° turn and a short section of the channel, approximately 1.8km in length.
Downstream boundary further out to sea	Extending the downstream boundary further out to sea using bathymetry from the EA.

Table 4.4: Peak Water Levels shown at Haven Bridge Gauge for the Simulations in Table 4.3

Model Name	Peak Water Level (mAOD)	Difference from Gauge (m)
Baseline	3.37	0.89
Upstream Forced Boundary	3.02	0.54
Increased Roughness in the River Yare Channel	2.45	0.03
Increased Roughness at mouth of River Yare	2.97	0.49
Downstream boundary further out to sea	3.13	0.64

4.9.8 When analysing the results some of the runs have a limited effect on the water level predicted by the model at Haven Bridge gauge. Moving the downstream boundary further away from the harbour decreases the peak water level by 0.24m. This shows that there is limited impact on water levels at Haven Bridge of the flow patterns to the east of the river mouth due to the outer harbour walls. It is therefore appropriate to situate the downstream boundary at the river mouth as shown in Figure 12B.7.

4.9.9 When forcing the upstream boundaries with the event gauge data, the peak water level at Haven Bridge gauge reduces when compared to the initial baseline simulation, however it is still 0.54m above the recorded water level at the gauge. In addition to the effect on the peak water level, forcing the boundaries has increased the amount of oscillations within the model at lower tidal levels. Whilst this is not a major concern in the flood model as high-water level is the driving level, reducing any oscillations in the water flow is preferable. This is an effect of the model resolving significant flow from the two sources.

4.9.10 The increased roughness at the entrance model has shown a reduction in peak water levels at Haven Bridge gauge when compared to the baseline simulation showing a modelled water level of 2.97mAOD (0.49m above recorded level). This is because the model simulates the water losing more energy at the mouth of the harbour which can be attributed to the 90° bend at the mouth. In addition to slightly reducing the water level when compared to the baseline simulation, the area of increased roughness reduces the amount of oscillations at low water which leads to a more realistic simulation.

4.9.11 The increased roughness model has shown a reduction in peak water levels at Haven Bridge gauge when compared to the initial baseline simulation showing a modelled water level of 2.45mAOD (0.03m below recorded level). This is a consequence of energy loss in the channel due to the high roughness values. With the use of higher roughness values, the oscillations seen in the initial baseline simulation are not present meaning the use of high roughness values have stabilised the water level simulation. However, the increased roughness has caused the water to slow down causing the tidal period to increase slightly and the tidal range to reduce slightly.

4.9.12 When comparing all the simulations, it is apparent the best representation of the peak water level is the increased roughness model. As the model has been built for flood risk purposes and the peak water level is the most important factor for this, it has been deemed acceptable to use the high roughness model for the flooding simulations. The high roughness value represents the combined form loss of the bed material and the corrugated harbour walls present along the full extent of the River Yare within the 2D domain, and simulates the energy loss due to the northward turn at the harbour mouth. Figure 12B.8shows the predicted flood extent in the 2D domain for the high roughness model compared to the EA's historic flood map.

4.9.13 Figure 12B.8 shows that the model with the increased roughness provides a reasonable match across the domain with the historic flood map. The flooded area to the south of the River Yare shows the water level is sufficient to breach the tidal defences and water flows across Gorleston Pier; the model predicts flooding in this area well. In the areas on the river banks the modelled flood extent is slightly larger than the historic flood map. This is due to the slightly higher water level in the model and this is considered conservative.

4.9.14 The historic flood map shows an area opposite Haven Bridge gauge that experiences flooding, which the increased roughness model does not predict. Since the water level in the model is 0.06m above the gauge at this location and the area of flooding is relatively small, it is reasonable to assume that there may have been localised damage to the defence wall in this location or flooding from another source.

4.9.15 As well as the model tests, several checks on the gauges themselves have been carried out as part of the due diligence process. These include confirming the datum at the Haven Bridge gauge and confirming the precise location of the Gorleston gauge on the harbour wall.

4.9.16 In the review of the previous study carried out by Halcrow on behalf of the EA, a similar issue was found where the water level at the Haven Bridge gauge was significantly over-estimated without carrying out model updates and it was concluded that the model was acceptable with the difference. However, due to the recent 2013 out of bank flooding event, more information is available that has been used to calibrate the model developed for this assessment and it has been considered acceptable to include some of the variations in order to match the observed flooding.

4.9.17 Following the calibration process, it was considered appropriate to update the model to apply a high roughness coefficient of 0.12 Manning's n to the river bed. Whilst it is acknowledged that this is extremely high in comparison to the recommended value of between 0.025 and 0.045 for a channel, the effect of the change shows a much better prediction of the peak water level in the channel and the flood extent. In this case the roughness value creates a form loss along the reach that more accurately predicts the change in water level between the two gauges. The model predicts approximately a 0.03m higher water level at Haven Bridge gauge. This has been considered an acceptable difference and provides a conservative model for use in the flooding assessment.

4.10 Model Stability

4.10.1 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 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. The cumulative mass balance percentage for the 0.5% AEP climate change event is shown in Plate 4.2. The maximum value found in this model is 0.57% which shows the model is stable especially for a tidal model with very large inflows.

4.10.2 Plate 4.3 shows the total water into and out of the 2D domain. The figure shows there is a significant amount of water retained within the domain particularly during the peak tide. As Great Yarmouth is defended by raised defences, when the tide level is sufficient the defences will overtop. When the tide recedes, there is no immediate route back into the channel for the flood water, therefore water is retained outside of the channel. Taking this flooding mechanism into account, Plate 4.3 shows the expected pattern and gives confidence that the boundary outflows are functioning correctly and removing any excess water preventing unrealistic pooling.

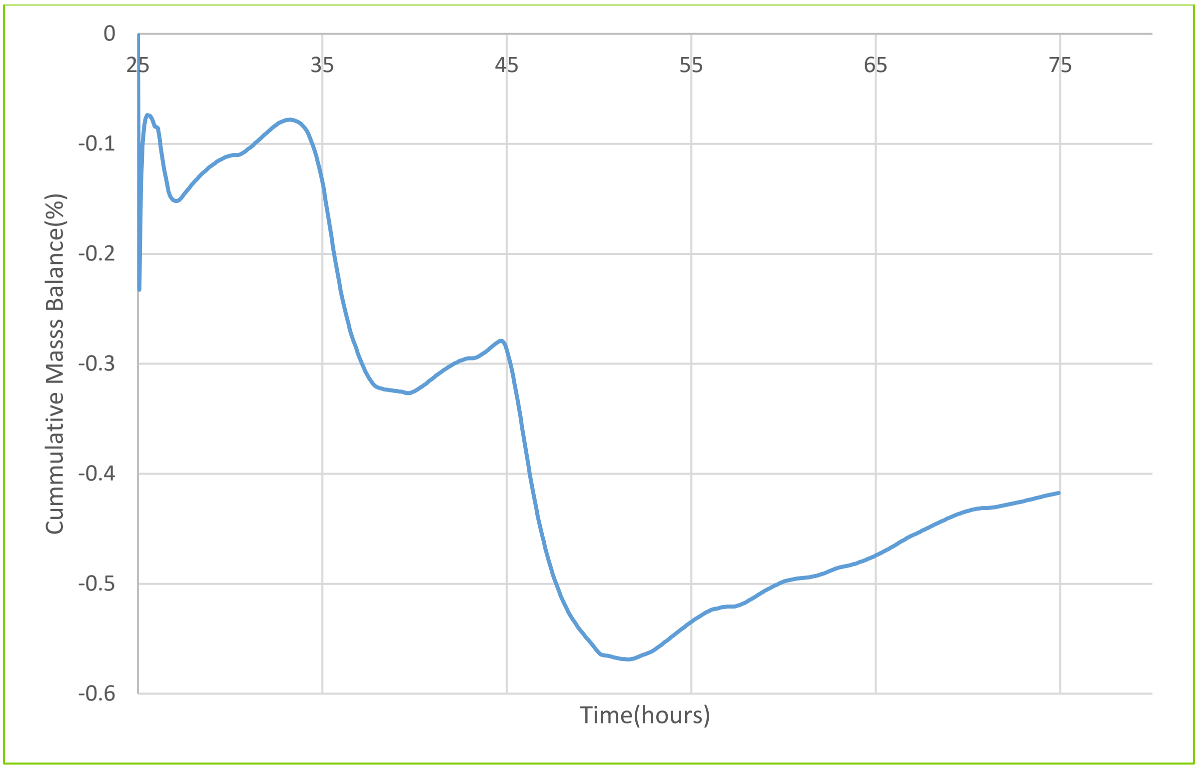


Plate 4.2 – Cumulative Mass Balance for the Baseline 0.5% AEP Climate Change Event

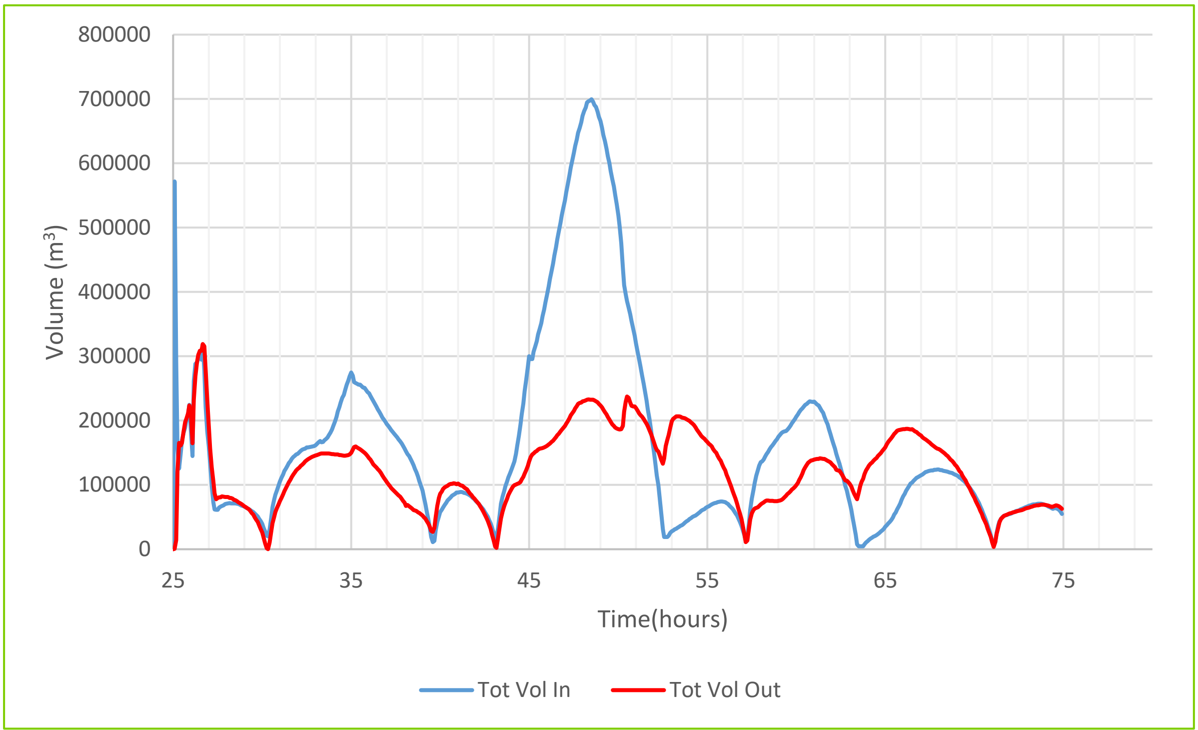


Plate 4.3 - Volume in and out for the 0.5% AEP Climate Change Baseline Simulation

4.10.3 For the 0.5% AEP climate change event, there were no warnings or errors during the model simulation.

4.11 Scheme Representation

4.11.1 Following the development of the baseline model, a version of the model was created to represent the Scheme post-construction scenario by representing the bridge (including the knuckles in the channel) and its approach roads within the model. The flood risk during construction has also been considered as part of this assessment but the footprint during construction within the River Yare channel is no larger than the post-construction footprint. The knuckles in the channel will be created by building a cofferdam on either side of the channel, which will then be back filled. Therefore, it has not been necessary to create a 'during construction' version of the hydraulic model as it would be the same as the Scheme post-construction version.

5 Hydraulic Modelling Results

5.1 Model Runs

5.1.1 The scenarios that have been considered in this assessment are:

- Baseline present day
- Future baseline climate change
- Future baseline H++
- Scheme present day
- Future scheme climate change
- Future scheme H++

5.1.2 Section 3 provides a summary of how the scenarios above have been defined. The impact of fluvial flows on flood risk to the Scheme was considered as part of the hydraulic assessment but these were found to have a negligible impact on flooding. Therefore, only tidal flooding has been modelled as part of this assessment as agreed with the EA. Table 5.1: Modelled Scenarios

5.1.3 provides a summary of each of the model runs undertaken for this assessment.

5.1.4 Flood risk to the Scheme has been identified using the Scheme scenario model and the results of the baseline and Scheme scenarios have been compared to ascertain the impact of the Scheme on flooding elsewhere.

Table 5.1: Modelled Scenarios

Baseline	Scheme
Present Day (2019)	
5% AEP	5% AEP
0.5% AEP	0.5% AEP
0.1% AEP	0.1% AEP
Future Baseline	**Future Scheme**
5% AEP + Climate Change (2140)	5% AEP + Climate Change (2140)
0.5% AEP + Climate Change (2140)	0.5% AEP + Climate Change (2140)
0.1% AEP + Climate Change (2140)	0.1% AEP + Climate Change (2140)
0.5% AEP H++	0.5% AEP H++

5.1.5 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 12.4. Changes in water level across the floodplain have also been investigated by comparing water depths predicted by the model for the baseline and Scheme scenarios.

5.2 Hydraulic Modelling Results – Present Day Scenario

5.2.1 Figure 12.3 shows the flood extents predicted by the model for the Baseline Present Day event. The results show that there is no risk during a 5% AEP Present Day event to Great Yarmouth in the Baseline scenario. The modelling has shown that the urban area of Great Yarmouth floods during the 0.5% AEP and larger events. The 0.5% Baseline Present Day event shows a significant flood extent caused due to water levels overtopping the raised defences through the town. As expected the 0.1% AEP Baseline Present Day event shows extensive flooding throughout the catchment. In addition to the significant flooding in the town centre, the water levels are sufficient to overtop the defences along the southern edge of Breydon Water in the 0.1% AEP Baseline Present Day event.

Table 5.2 shows the Baseline and Scheme water levels predicted by the model in channel for the Present Day scenario for different return periods at each of the comparison points on Figure 12.4 (document reference 6.3).
Table Table 5.2: Present Day Hydraulic Modelling Results

5.2.2 5.2 shows that in the channel during the 5% AEP Present Day event, to the south of the Scheme there is a negligible adverse impact as water levels increase by up to 0.02m. To the north of the Scheme during the same event, there is a minor beneficial impact as water levels in the channel are reduced by up to 0.09m. The negligible increase in water levels in the channel can be attributed to the narrowing of the channel by the bridge knuckles, which reduce the width of the channel under the bridge by approximately 50% compared to its current width.

Table 5.2: Present Day Hydraulic Modelling Results

Climate Change Point (see Figure 12.4 (document reference 6.3))	Baseline (mAOD)			Scheme (mAOD)			Difference (Scheme – Baseline (m))		
	5%	0.5%	0.1%	5%	0.5%	0.1%	5%	0.5%	0.1%
US1	2.38	2.99	3.16	2.33	2.96	3.15	-0.05	-0.04	-0.01

Climate Change Point (see Figure 12.4 (document reference 6.3))	Baseline (mAOD)			Scheme (mAOD)			Difference (Scheme – Baseline (m))		
	5%	0.5%	0.1%	5%	0.5%	0.1%	5%	0.5%	0.1%
US2	2.40	3.01	3.27	2.34	2.97	3.25	-0.06	-0.05	-0.02
US3	2.44	3.04	3.31	2.37	2.99	3.28	-0.07	-0.06	-0.03
US4	2.48	3.07	3.35	2.40	3.01	3.32	-0.08	-0.06	-0.03
US5	2.52	3.12	3.41	2.44	3.05	3.37	-0.08	-0.07	-0.04
USW	2.55	3.15	3.44	2.46	3.07	3.40	-0.09	-0.07	-0.04
USE	2.55	3.14	3.44	2.46	3.07	3.40	-0.09	-0.07	-0.04
C1	2.57	3.17	3.46	2.48	3.08	3.42	-0.09	-0.08	-0.05
C2	2.58	3.18	3.48	2.59	3.20	3.54	0.02	0.02	0.06
C3	2.59	3.20	3.50	2.61	3.22	3.56	0.02	0.02	0.06
DSW	2.61	3.22	3.53	2.63	3.24	3.58	0.02	0.02	0.05
DSE	2.61	3.22	3.53	2.62	3.24	3.58	0.02	0.02	0.05
DS5	2.64	3.26	3.60	2.65	3.28	3.65	0.02	0.02	0.04
DS4	2.67	3.30	3.68	2.69	3.32	3.72	0.01	0.01	0.04
DS3	2.72	3.36	3.79	2.73	3.37	3.82	0.01	0.01	0.02
DS2	2.78	3.43	3.91	2.78	3.43	3.92	0.01	0.00	0.01
DS1	2.82	3.48	4.00	2.83	3.48	4.01	0.00	0.00	0.00

5.2.3 Within the channel, the differences between the Baseline and Scheme scenarios for the 0.5% AEP and 0.1% AEP Present Day events show the same pattern as the 5% AEP event. For the 0.5% AEP Present Day event there is a negligible adverse impact in water levels south of the Scheme of up to 0.02m. However, there is a minor beneficial reduction in water levels north of the Scheme of up to 0.08m. During the 0.1% AEP Present Day event, there is a minor adverse impact south of the Scheme with increases in water level predicted up to 0.06m and to the north of the Scheme there is a minor beneficial impact with reductions in water level of up to 0.05m. These results show that the general effect of the Scheme in the channel is to increase water levels south of the Application Site and decrease them north of the Principal Application Site. This is because of the constriction in the channel caused by the knuckles used to support the Scheme. This reduces the overall capacity of the channel between the supports slowing the flow rate through the area reducing the amount of water that can transit up the channel from the tidal boundary.

5.2.4 It is also necessary to assess the impact of the Scheme on water levels on the floodplain and the different receptors within Great Yarmouth. For the 5% AEP Present Day event, there is no change in flood levels on the floodplain between the Baseline and Scheme scenarios as all the water is retained in the channel for this event and no out of bank flooding occurs.

5.2.5 Figure 12.5 shows a comparison of the predicted water levels for the Baseline and Scheme Present Day scenarios for the 0.5% AEP event showing the magnitude of impact with the Scheme in place. A negligible increase in flood extent on an area of grassland between South Denes Road and Great Yarmouth Power Station is predicted with the Scheme in place because the Scheme water levels are 0.02m higher than the Baseline water levels in this area. There is also a minor increase in flood extent at Southtown Common with the Scheme in place affecting the Common itself and a section of the open channel of the watercourse that flows through the Common. This is due to the minor increase in water levels of up to 0.1m in this area with the Scheme in place compared to the Baseline scenario. To the south of the Scheme, on the eastern bank of the River Yare water levels are increased by up to 0.08m (minor adverse impact) in the Scheme Present Day scenario compared to the Baseline Present Day scenario. On the west bank of the River Yare to the south of the Scheme, water levels are increased by up to 0.1m (minor adverse impact) at Southtown Common.

5.3 Hydraulic Modelling Results – Climate Change Scenario

5.3.1 Figure 12.8 (document reference 6.3) shows the flood extents predicted by the model for the Baseline Climate Change event. The results show that all three climate change events modelled predict flooding to a large part of the study area with a large part of the urban area flooded in each event.

Table 5.3: Climate Change Hydraulic Modelling Results

5.3.2 Table 5.3 shows the Baseline and Scheme water levels predicted by the model in channel for the Climate Change scenario for different return periods at each of the comparison points on Figure 12.4 (document reference 6.3). Table 5.3 shows that in the channel during the 5% AEP Climate Change event, to the south of the Scheme, water levels are raised by up to 0.12m with the largest increase at the location of the bridge (moderate adverse impact). The impact of the Scheme in the Climate Change scenario is actually less during the 0.5% AEP and 0.1% AEP as the peak tidal level for each of these events is above all of the current defence heights through the town. Therefore, the increases seen in the channel are less than for the 5% AEP event, for which some of the defence heights are higher than the peak water level. There is a minor adverse impact in the channel for the 0.5%

AEP event with water levels increased by up to 0.1m in the Scheme scenario compared to the Baseline. The increases in the channel with the Scheme in place for the 0.1% AEP event are negligible (up to 0.02m).

5.3.3 As for the Present-Day scenario, each of the climate change scenarios show a beneficial impact in terms of flood risk to the north of the Scheme with reductions predicted within the channel. For each flood event, the reduction in water levels has a minor beneficial impact.

Table 5.3: Climate Change Hydraulic Modelling Results

Climate Change Point (see Figure 12.4 (document reference 6.3))	Baseline (mAOD)			Scheme (mAOD)			Difference (Scheme – Baseline (m)		
	5%	0.5%	0.1%	5%	0.5%	0.1%	5%	0.5%	0.1%
US1	3.34	4.09	4.93	3.33	4.04	4.87	-0.01	-0.05	-0.05
US2	3.42	4.11	4.93	3.41	4.06	4.87	-0.01	-0.05	-0.06
US3	3.47	4.12	4.93	3.46	4.07	4.87	-0.01	-0.05	-0.06
US4	3.54	4.13	4.92	3.52	4.08	4.87	-0.02	-0.05	-0.06
US5	3.62	4.15	4.92	3.60	4.09	4.88	-0.02	-0.06	-0.04
USW	3.68	4.17	4.95	3.64	4.11	4.90	-0.03	-0.06	-0.04
USE	3.67	4.17	4.94	3.64	4.11	4.90	-0.03	-0.06	-0.04
C1	3.71	4.18	4.96	3.66	4.12	4.91	-0.04	-0.06	-0.05
C2	3.73	4.19	4.97	3.85	4.22	5.00	0.12	0.04	0.02
C3	3.76	4.20	4.99	3.87	4.25	5.01	0.11	0.05	0.02
DSW	3.81	4.23	5.02	3.91	4.30	5.03	0.09	0.07	0.01
DSE	3.81	4.23	5.02	3.91	4.30	5.03	0.09	0.07	0.01
DS5	3.96	4.38	5.14	4.03	4.48	5.16	0.07	0.10	0.02
DS4	4.12	4.63	5.33	4.18	4.70	5.34	0.05	0.07	0.02
DS3	4.31	4.89	5.52	4.35	4.93	5.54	0.04	0.04	0.01
DS2	4.51	5.16	5.74	4.52	5.18	5.75	0.02	0.02	0.01
DS1	4.66	5.36	5.88	4.66	5.36	5.88	0.00	0.00	0.00

5.3.4 The impact of the Scheme on water levels on the floodplain within Great Yarmouth has been investigated for the Climate Change scenario. The impact of the Scheme in the Climate Change scenarios is less than for the

Present Day scenario as the water levels for each event are higher in the Climate Change scenario, and flooding on the floodplain is more extensive during the Baseline scenario meaning that the Scheme has less of an impact overall. Figure 12.9 (document reference 6.3) shows a comparison of the predicted water levels for the Baseline and Scheme Climate Change scenarios for the 0.5% AEP event showing the magnitude of impact with the Scheme in place. The difference in extent of flooding between the Baseline and Scheme scenarios for the 0.5% AEP Climate Change event is negligible. As for the Present Day scenario, there is an increase in water levels to the south of the Scheme and a reduction in water levels to the north. On the floodplain to the south of the Scheme, the maximum increase in water level with the Scheme in place is 0.1m, a moderate adverse impact. Near to the harbour at the end of the River Yare, there is a negligible adverse impact with increases in water level of up to 0.02m with the Scheme in place.

5.4 Hydraulic Modelling Results – H++ Scenario

5.4.1 Figure 12.12 shows the flood extents predicted by the model for the Baseline and Scheme 0.5% AEP H++ events. The results show that for both scenarios a large part of the study area and urban area of Great Yarmouth is predicted to flood.

5.4.2 Table 5.4 shows the Baseline and Scheme water levels predicted by the model in channel for the 0.5% AEP H++ scenario at each of the comparison points on Figure 12.4 (document reference 6.3). Table 5.4 shows that in the channel during the 0.5% AEP H++ event, the Baseline and Scheme scenarios predict similar water levels with only negligible differences between them at each comparison point. The impact of the Scheme on water levels is less in the H++ event than it is for the Present Day and Climate Change events. This is because the water levels are much higher for the extreme H++ event than for the Present Day and Climate Change events meaning that the constriction caused by the bridge in channel has less of an impact.

Table 5.4: H++ 0.5% AEP Event Hydraulic Modelling Results

Climate Change Point (see Figure 12.4 (document reference 6.3))	Baseline (mAOD)	Scheme (mAOD)	Difference Scheme – Baseline (m)
US1	6.54	6.53	-0.01
US2	6.52	6.51	-0.01
US3	6.52	6.51	-0.01
US4	6.51	6.50	-0.01

Climate Change Point (see Figure 12.4 (document reference 6.3))	Baseline (mAOD)	Scheme (mAOD)	Difference Scheme – Baseline (m)
US5	6.51	6.50	-0.01
USW	6.51	6.50	-0.01
USE	6.51	6.50	-0.01
C1	6.51	6.50	-0.01
C2	6.51	6.51	0.00
C3	6.51	6.50	-0.01
DSW	6.51	6.50	-0.01
DSE	6.51	6.50	-0.01
DS5	6.52	6.51	-0.01
DS4	6.54	6.53	-0.01
DS3	6.56	6.56	0.00
DS2	6.60	6.60	0.00
DS1	6.60	6.60	0.00

5.4.3 The impact of the Scheme on water levels on the floodplain within Great Yarmouth has been investigated for the H++ scenario. The impact of the Scheme in the H++ scenario is less than for the Present Day and Climate Change scenarios as the water levels for each event are higher in the H++ scenario, and flooding on the floodplain is extensive during the Baseline scenario meaning that the Scheme has less of an impact overall. Figure 12.12 shows a comparison of the predicted water levels for the Baseline and Scheme H++ scenarios for the 0.5% AEP event showing the magnitude of impact with the Scheme in place. The difference in depth and extent of flooding between the Baseline and Scheme scenarios for the 0.5% AEP H++ event is negligible.

6 Summary

6.1.1 A 1D/2D hydraulic model of the River Yare has been developed to produce an updated model for Great Yarmouth representing the current situation (baseline scenario) and post-development of the Scheme, along with the calibration testing for the 2013 tidal event. This baseline modelling study will form the basis for the next stage of modelling the finalised Scheme and the impact of the Scheme on flood risk elsewhere. It was necessary to develop a model as part of the FRA as the Scheme is 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 EA hydraulic model of Great Yarmouth developed in 2011 and the use of the updated defences data from the 2018 JBA modelling as provided by the EA. 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 proposed Scheme, therefore there is a need to use the most recent and accurate data, particularly close to the Principal Application Site while developing the baseline model. The EA 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 in order to determine the impacts of the Scheme on the hydraulics within the River Yare in the next stage of the modelling.

6.1.3 The hydrology of the River Yare has been analysed and the EA has specified the design events and climate change scenarios to be considered in this assessment. Tidal levels have been derived to define the eastern boundary of the hydraulic model that represents sea levels along the Great Yarmouth coast. EA guidance on estimating design sea levels (Ref 12B.22) has been used to derive the tidal boundary used in the model. Climate change allowances have been calculated using the latest EA guidance.

6.1.4 A 1D/2D model of the River Yare has been developed for this assessment i.e. the baseline and calibration versions of the model have been created. Wave overtopping has been discounted on the basis that the wave overtopping only has an impact prior to tidal defences being overtopped. The site is situated over 0.6km overland from the coastal defences therefore outside of any overtopping effects from the coastal defences. Due to the fetch length in the River Yare, it is unlikely any significant wave heights will be generated within the River Yare.

6.1.5 A calibration process has been carried out for the baseline model by simulating the 2013 tidal event which caused significant flooding in Great Yarmouth. A check against the EA historic flood map showed that the model developed for this study predicts the historic outline reasonable well following an update in the bed roughness parameter to simulate the form loss in channel.

6.1.6 The results from the model have been found to be reasonable. The floodplain extents are in the expected range, which shows the model domain is acting as expected for each return period. The simulated water depths increase as the return period event increases. However, there is more of an impact in lower return periods and between the present-day and climate change scenarios. This is due to the influence of raised defences and water cascading over, meaning a small increase in water level in channel results in a larger volume of water exiting the channel onto the floodplain.

6.1.7 The flow rate over the defences has an exponential relationship to water height therefore small increases in water will exponentially increase the flow rate onto the floodplain increasing the depth of flood water. In the higher return periods, this flow pattern is reduced because in the baseline scenario, the water is sufficient to flood both sides of the defences to a similar level creating a linear relationship.

6.1.8 In conclusion, the model has undergone a comprehensive sensitivity, verification and review process to ensure its suitability for use in assessing flood risk within Great Yarmouth.

6.2 References

Ref 12B.15: Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities, Environment Agency, 2016.

Ref 12B.22: SC060064/TR4: Practical Guidance Design Sea Levels and Open Coast (CFBD) Flood Risk Study JBA for the Environment Agency, 2014.

Ref 12B.23: Great Yarmouth Reporting and Mapping, Great Yarmouth Model Report, Halcrow for the Environment Agency, April 2011.

Ref 12B.24: Fung F and Gawith M (2018) “UKCP18 for UKCP09 users”, UKCP18 Guidance. Met Office, Hadley Centre, Exeter.

6.3 Supporting Documents

Annex A1 Existing Environment Agency Model Review

Annex A2 Design Sea Level Calculations

Great Yarmouth Third River Crossing

Application for Development Consent Order

Document 6.2: Environmental Statement Volume II: Technical Appendix 12B: Annex A1: Design Sea Level Calculations

Planning Act 2008

The Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009 (as amended) (“APFP”)

APFP regulation Number: 5(2)(a)

Planning Inspectorate Reference Number: TR010043

Author: Norfolk County Council

Document Reference: 6.2 – Technical Appendix 12B – Annex A1

Version Number: 0 – Revision for Submission

Date: 30 April 2019

Design Sea Level Calculation Record

CALCULATION CONTROL SHEET
PROJECT: Great Yarmouth, Third River Crossing
PART OF PROJECT: Design Sea Level Calculations
CALCULATION TITLE: Design Sea Level Calculations Record

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 and consultation with the Environment Agency (EA)
Purpose of Calculations To derive design tidal inflow for the sea boundary in the Great Yarmouth hydraulic model.

CHECKING AND REVIEW STATUS					
Rev	**Purpose**	**Author**	**Reviewed**	**Authorised**	**Date**
1	Model Build	DE	JH	SH	December 17

1 Introduction

1.1.1 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

Table 2.1: Overview of Study

Item	Comments
Purpose of Study: Give an overview which includes: • Purpose of study • Approx. no. of tidal boundaries required	As part of the Environmental Statement (document reference 6.1) for the proposed third crossing over the River Yare in Great Yarmouth harbour (‘the Scheme’), it will be necessary to undertake a Flood Risk Assessment (FRA) to ascertain the potential impact of the new bridge on water levels within the River Yare and flood risk to the surrounding area. This document presents the tidal curve calculation for the sea boundary in Great Yarmouth Harbour. 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 (EA, 2011).
Description of Catchment: Brief description of catchment, or reference to section in accompanying report	Great Yarmouth is a seaside town in Norfolk on the east coast of England. The River Yare flows through the centre of the town creating a commercial port with a number of large ship berths. Tidal defences line the river edge, providing protection from coastal flooding to the town. The river flows in a southerly direction, under two existing bridges spanning the harbour to an almost right angle turn to the sea boundary. The River Yare is one of the sea boundaries of the Broadlands rivers catchment and is tidally driven and the flooding mechanism has been shown to be tidal. The tidal boundary is approximately a 12-hour cycle which drives the water levels in the harbour and across the Norfolk Broads.
Flood Estimates Required	Flow hydrographs / peak flow estimates are required for present day (2018) scenario, climate change and H++ as request by the EA: • 20 (5% Annual Exceedance Probability (AEP)), 200 (0.5% AEP), 1000 (0.1% AEP); • 20 plus climate change (5% AEP + CC), 200 plus climate change (0.5% AEP + CC), 1000 plus climate change (0.1% AEP + CC); • 20 plus H++ Scenario (5% AEP + H++), 200 plus H++ Scenario (0.5% AEP + H++), 1000 plus H++ Scenario (0.1% AEP + H++).

Table 2.2: Source of Sea Level Data

What is the source of the sea level data? • Admiralty Tidal Time Charts • Gauge Data	There are two gauges within the proposed modelled area, Gorleston (NGR TG534943822) at the harbour entrance and Haven Bridge (NGR TG521987513)

Table 2.3: Site Information

Watercourse	Station Name	Gauging Authority Number	Grid Reference	Period of Available Data	Type of Data
River Yare	Great Yarmouth	T341504	TG534943822	14 years	Tidal (Level)
River Yare	Haven Bridge	T341506	TG521987513	14 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’. Additional information has been reviewed from the National Tidal and Sea Level Facility[1] at the main gauge in Lowestoft, approximately 12km south.				

Table 2.4: Other Data Available

Item	Comments
Other Flow / levels gauging sites	Two other gauges outside of proposed study area, Three Mile House and Burgh Castle
Historic flood data	New reports of a significant flooding event on the 5th/6th December 2013 which saw tidal inundation as the peak water levels exceeded the tidal defences.
Flow data for events	No flow data is available.
Results from previous studies / models	-
Other data (e.g. Groundwater, tidal	-

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

Table 2.5: Sea Level Derivation Method

Item	Comments
Outline the method	The conceptual method chosen here follows the guidance; *SC060064/TR4: Practical Guidance design sea levels.* In April 2008, the Environmental Agency (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[2]*)*, with the aim to update and consolidate the outdated methods for producing tidal curves suitable for FRAs. 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 FRAs. A recent update carried out by JBA[3] has provided updated extreme sea levels that will be used in this assessment.

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

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

3 Tidal Curve Calculations

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

Table 3.1: Guidance

Ten Step Procedure
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
10. Apply allowance for climate change

3.1.2 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:

Table 3.2: Additional Data Sets

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

3.1.3 Following the guidance, the event tidal curves are generated.

3.2 Check Study Location is Outside of Estuary Boundaries

3.2.1 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, Plate 3.1 shows a comparison between the River Yare estuary boundary and the Great Yarmouth model tidal boundary.

Plate 3.1: Estuary Boundary Check

3.2.2 Plate 3.1 shows the estuary boundary of The River Yare in red and the proposed tidal boundary of the Great Yarmouth tidal model in blue. The tidal boundary is outside of the estuary, this shows the guidance is suitable for use in this application.

3.3 Select the Appropriate Chainage Point for Extreme Sea Levels

3.3.1 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 Great Yarmouth tidal boundary passes closest to 4150 chainage node as shown on Plate 3. 2.

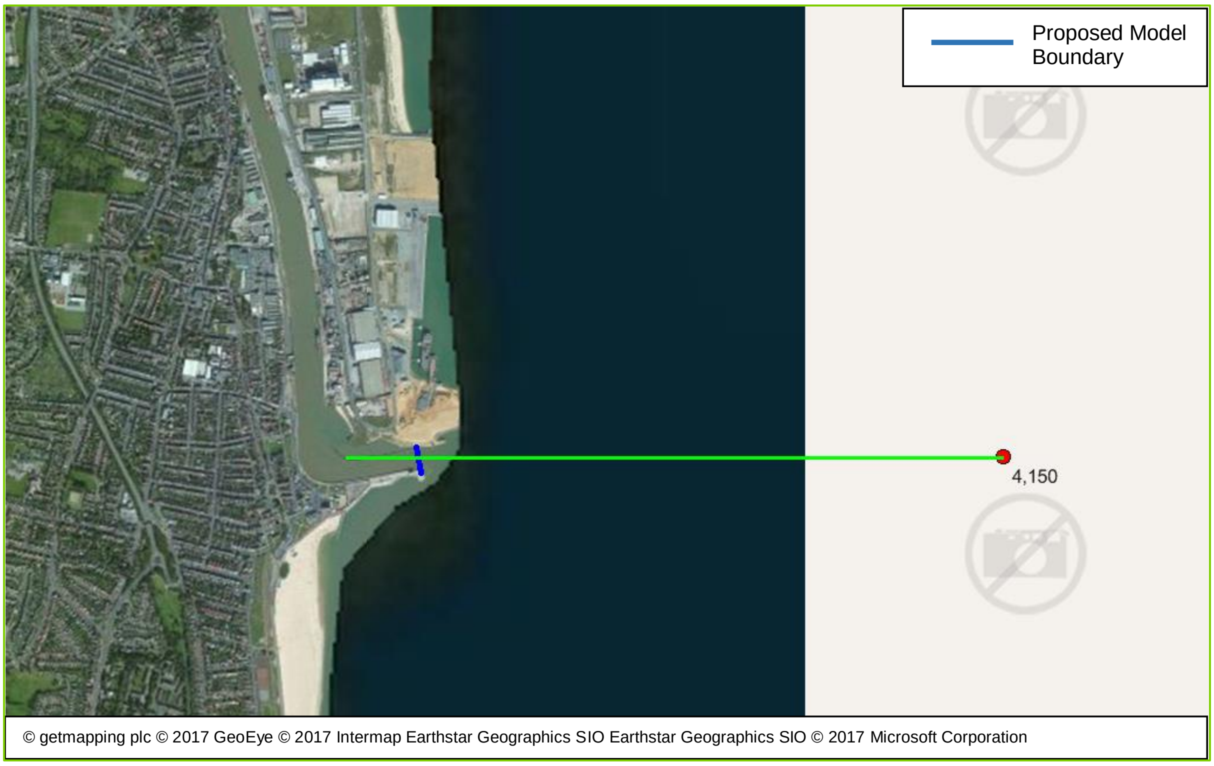


Plate 3.2: Chainage

3.4 Select an Annual Exceedance Probability Peak Sea Level

3.4.1 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 modelled by JBA on behalf of the EA at node 4150 are provided in Table 3.3 for the events considered in this study.

Table 3.3: Extreme Sea Levels

AEP	Extreme Sea Levels (m AOD)
5%	2.84
0.5%	3.5
0.1%	4.03

3.5 Consider Allowance for Uncertainty

3.5.1 As part of the SC060064/TR4 project, confidence in the extreme sea levels are provided as shown in Table 3.4 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.

Table 3.4: Uncertainty Levels (node 4150)

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

3.6 Identify Base Astronomical Tide

3.6.1 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 3.5 shows the HAT and MHWS values for Lowestoft from the National Tidal and Sea Level Facility[4] (NTSLF). This has been used as the HAT and MHWS were not available at the Gorleston gauge and the guidance recommends using the nearest gauge on the national network which in this case is Lowestoft. The tidal levels are provided in chart datum in Great Yarmouth harbour. Conversion to ordnance datum is to add -1.5m, this is carried out in part 3.7 This is because the gauge at Lowestoft is used to derive the astronomical tide.

Table 3.5: HAT and MHWS for Lowestoft

HAT (mCD)	MHWS (mCD)
2.98	2.58

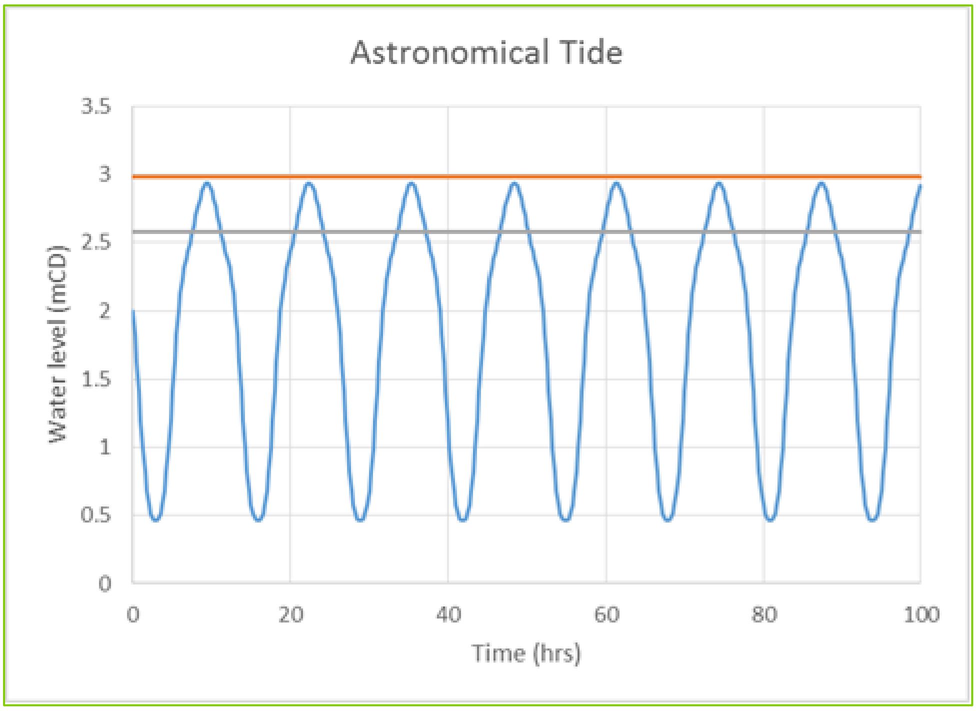
3.6.2 The SC060064/TR4 guidance states that the Admiralty tidal tables should be used to estimate the astronomical tide. This step is unnecessary because Great Yarmouth has a tidal gauge in the harbour meaning that an astronomical tide can be obtained from recorded data.

3.6.3 Browsing the gauge data, a tidal profile with a peak tide of 2.85mCD was found at the Lowestoft gauge, it is deemed appropriate to use the HAT and MHWS as the guidance recommends the nearest suitable primary gauge. A check of the astronomical tide shows that the peak is within the HAT and

[4] National Tidal & Sea Level Facility (online). Lowestoft Tidal Gauge.

MHWS range as recommended by the guidance. Plate 3.3 shows the astronomical tidal profile comparison to the HAT and MHWS.

Plate 3.3: Astronomical Tidal Profile Comparison



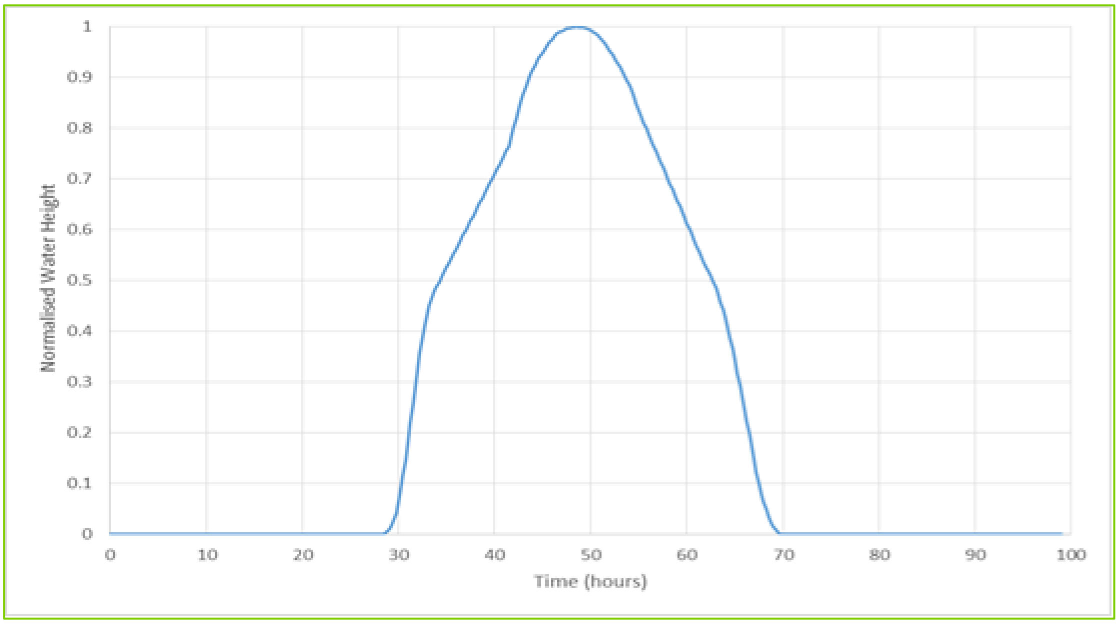
3.7 Convert Levels to Ordnance Datum

3.7.1 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. In this case, the 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.

3.8 Identify Surge Shape

3.8.1 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.

Plate 3.4: Shape 9 – Lowestoft Surge



3.8.2 Plate 3.4 shows the normalised surge shape at Lowestoft which is combined with the astronomical tidal profile to derive the design tide curve.

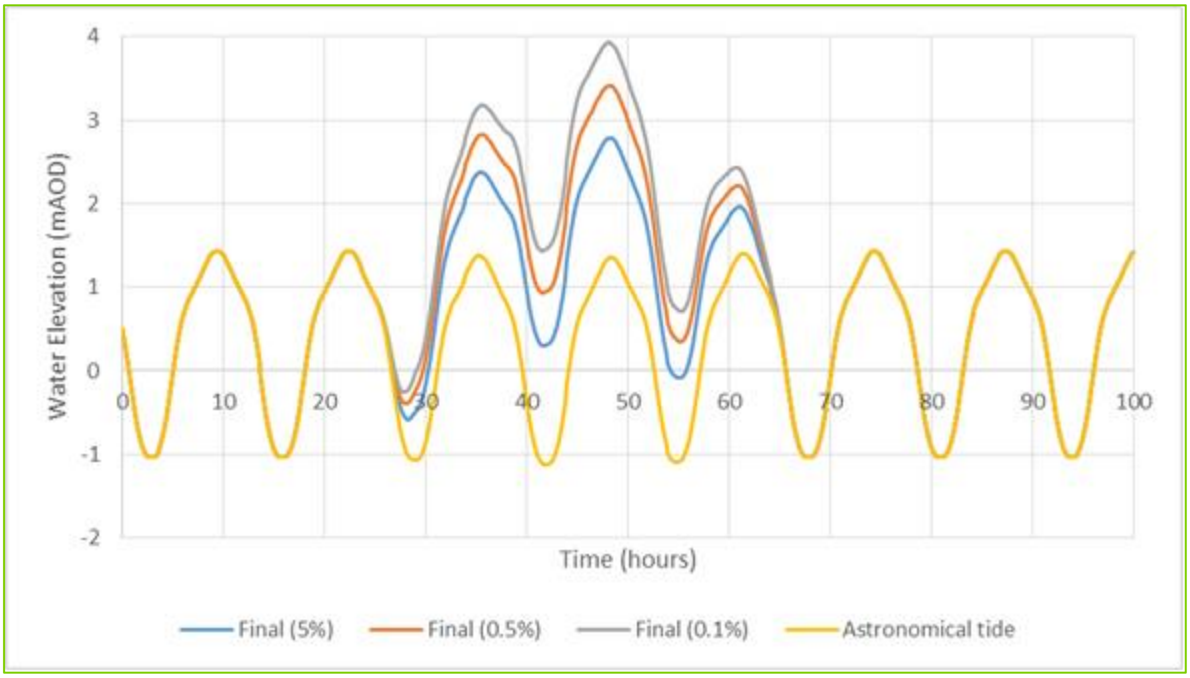
3.9 Produce the Resultant Design Tide Curve

3.9.1 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 48.25 hours in line with the astronomical tidal curve.

3.9.2 Once the Astronomical 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 (3.5m AOD) and the astronomical peak (1.48m AOD) is calculated which in this example is 2.02m. As the surge shape is aligned with the peak water level time in the astronomical 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 2.02/1.0 = 2.02 m AOD, thus creating a surge height which can be added to the astronomical tidal curve resulting in the required peak water level for the event.

3.9.3 This procedure is carried out of each return period, scaling to the extreme sea level for a given design event (Table 3.3).

Plate 3.5: Final Design Event Tidal Curves



3.9.4 Plate 3.5 shows the final tidal curves for the 5% AEP, 0.5% AEP and 0.1% AEP events used in the model simulations.

3.10 Sensitivity Test

3.10.1 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.

3.11 Climate Change Calculations

3.11.1 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[5] 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. Five different datasets shown in Table

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

3.6 have been assessed to ensure the worst-case scenario for climate change for the available information is applied to the tidal curve.

Table 3.6: Climate Change

Method	Climate Increase
NPPF - Table 3	1.539m
UKCP18 50% RCP8.5	1.21m
UKCP18 95% RCP8.5	1.83m
UKCP18 95% RCP4.5	1.25m
Upper End (EA guidance[6])	1.529m

3.11.2 The maximum climate change sea level rise was calculated using the UKCP18 95% RCP8.5 scenario, which gave an increase of 1.83m for 2140.

3.11.3 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. The H++ estimates have not been updated as part of UKCP18, according to the UKCP18 guidance[7] the H++ scenario of UKCP09 can still be considered a useful plausible but unlikely high-end sea level rise estimate. 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. Table 3.7 shows the sea level rise applied for each period using the guidance for the H++ event.

Table 3.7: Sea Level Rise H++ Scenario

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

3.11.4 Using Table 3.7, the total sea level rise for the H++ scenario is 3.1m based on 120 years from 2020-2140.

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

[7] Fung F and Gawith M (2018) "UKCP18 for UKCP09 users", UKCP18 Guidance. Met Office, Hadley Centre, Exeter

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

4 Conclusions

4.1.1 The extreme tidal levels in Table 4.1 have been derived following the guidance, SC060064/TR4 and discussed in the previous section.

Table 4.1: Sea Level Rise H++ Scenario

Event	5% AEP (m AOD)	0.5% AEP (m AOD)	0.1% AEP (m AOD)
Present day extreme sea level (2019)	2.84	3.5	4.03
Climate change Scenario (based on UKCP18 95% RCP8.5)	4.67	5.33	5.86
H++ event climate change	5.94	6.6	7.13

4.1.2 The final tidal curves generated will be used as the inflow boundary to the hydraulic model developed for the Great Yarmouth Third River Crossing FRA. For the tidal curves for all events see Appendix 1.

4.2 Limitations

4.2.1 There are a number of limitations highlighted in the guidance documents. These are presented in Table 4.2.

Table 4.2: Limitations of the Tidal Curve Derivation Method

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.

4.2.2 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 Great Yarmouth due to the Scheme. The UK climate change prediction dataset is being updated and is due for release in November 2018, the impact of this release will be considered if more information becomes available.

Appendix 1: Final Tidal Curves

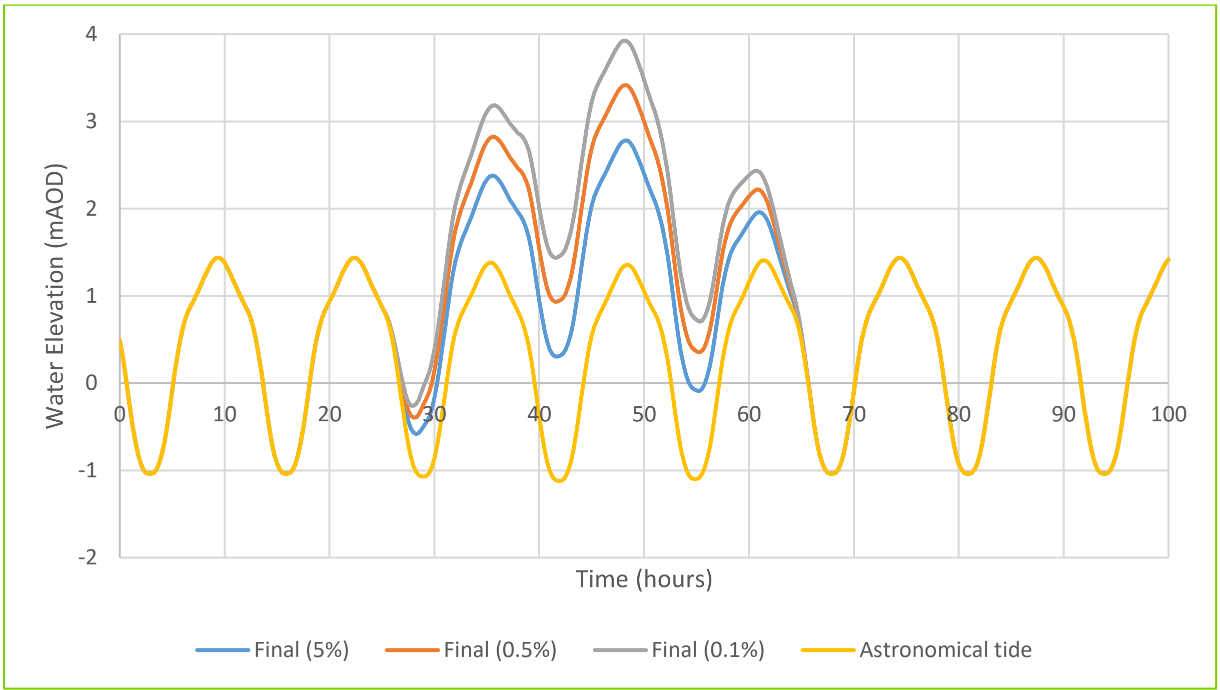


Figure A1: Final design event tidal curves

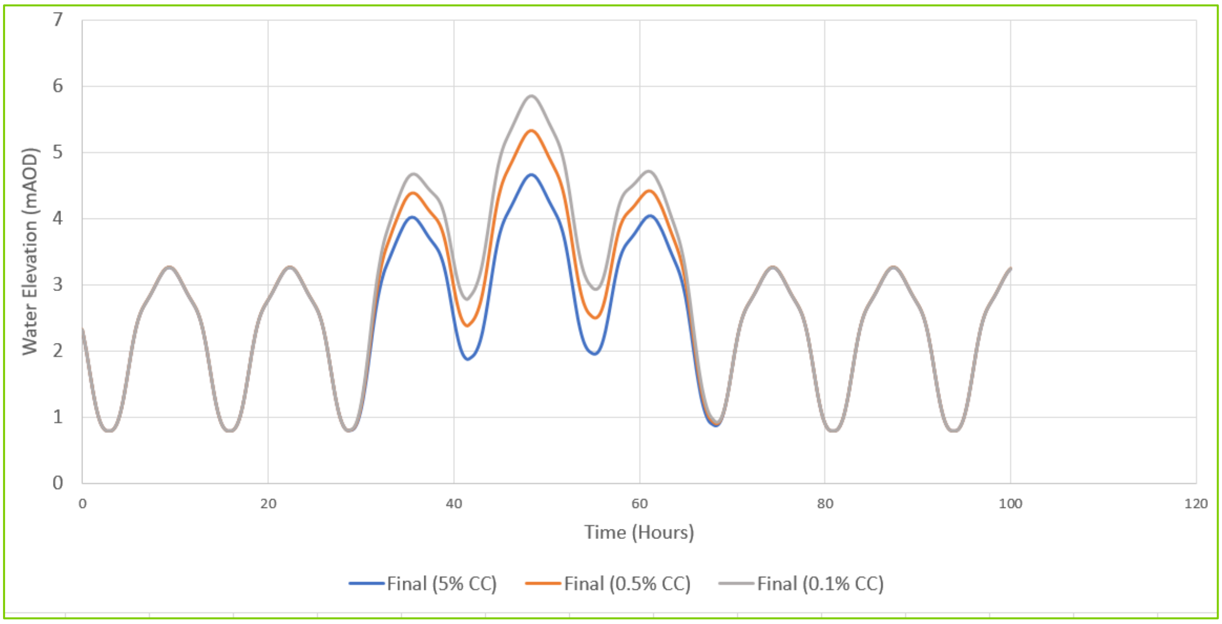


Figure A2: Final present-day climate change scenario tidal curves (based on UKCP18 95% RCP8.5 sea level increase scenario)

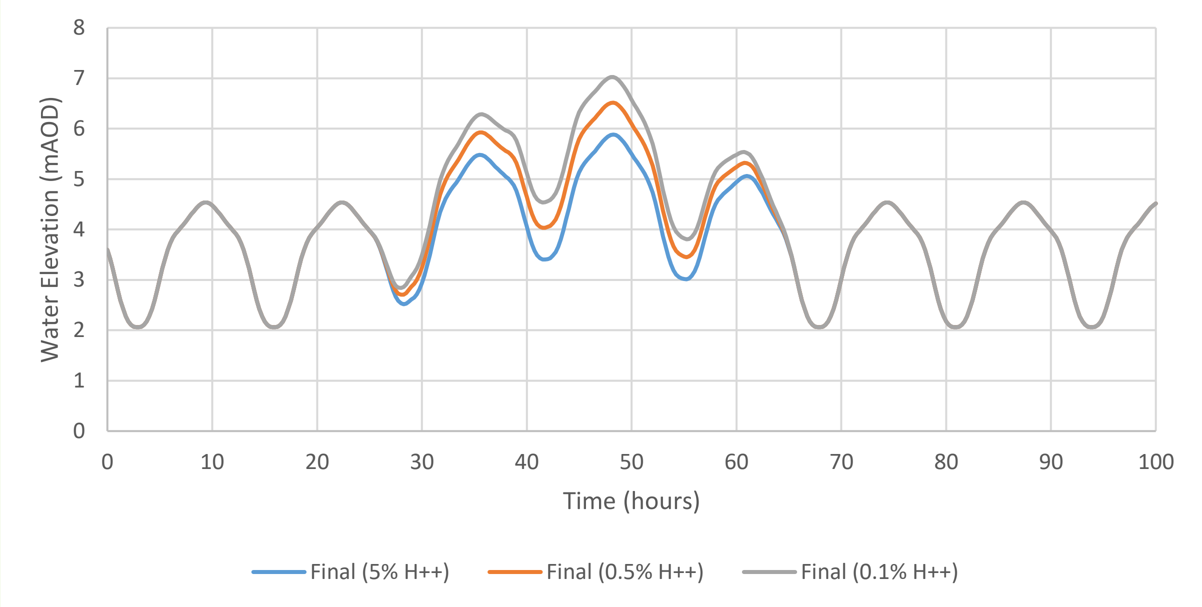


Figure A3: Final H++ scenario tidal curves

Great Yarmouth Third River Crossing

Application for Development Consent Order

Document 6.2: Environmental Statement Volume II: Technical Appendix 12B: Annex A2: Supporting Document: Model Review Form

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Planning Act 2008

The Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009 (as amended) (“APFP”)

APFP regulation Number: 5(2)(a)

Planning Inspectorate Reference Number: TR010043

Author: Norfolk County Council

Document Reference: 6.2 – Technical Appendix 12B – Annex A2

Version Number: 0 – Revision for Submission

Date: 30 April 2019

Great Yarmouth, Third River Crossing

Technical Note (Model Review Form)

Aug 2017

Produced for

Norfolk County Council

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Document Control Sheet

Project Title	Great Yarmouth Third Crossing
Report Title	Environment Agency (EA) model review.
Revision	1
Status	Final

Record of Issue

Issue	Status	Author	Date	Check	Date	Authorised	Date
1	Final	D Eddon	August 17	J Hunt	August 17	J Hunt	August 17

Distribution

Organisation	Contact	Copies
Norfolk County Council		Electronic

1 Background to this review

Item:	Comment:
1.1 Review title:	Great Yarmouth 1d/2d ISIS-TUFLOW model
1.2 Review purpose:	**Context:** The review of the Environment Agency (EA) Great Yarmouth model provided to WSP in July '17 has been carried out to assess whether the model can be used to investigate the impacts of the proposed Great Yarmouth Third River Crossing bridge on the water levels in the River Yare, Great Yarmouth. The Great Yarmouth model was originally developed from the Broadlands Environmental Service Limited (BESL) 1D model to assess the existing flood extent in the Great Yarmouth area by creating a 2D domain to simulate the flood plain. An updated version was used in the Great Yarmouth Flood Defences Framework for Action (GYFDFFA) project which contains the as-built representation of all the tidal defences in the harbour. The model provided by the EA to WSP is a 1D/2D ISIS-TUFLOW model which uses the as-built defence elevation data and the tidal curve calculated in 2009, for this reason the 'present date scenario' was set in 2009. Along with the above mentioned hydraulic models, the following documents were also received by WSP: • Great Yarmouth Modelling Report, 2011 • GYRM_ISIS-TUFLOW_log_v6.xls – Model log. The model reviewed here is the most recent model for Great Yarmouth in the files received by WSP. The report states that the defences are set at design level and have not taken into account any deterioration in the intervening years. There are a number of return periods modelled (5yr,20yr,75yr,100yr,200yr,1000yr) therefore WSP has chosen to focus this review on the most recent 1 in 100 year present day model, noting that a later model with increased roughness has been included to simulate larger return periods (1000yr). The model is reviewed with the Great Yarmouth Third River Crossing hydraulic assessment in mind. As a result, the majority of the 1D network of the Norfolk Broads is not reviewed in detail however comments are made where appropriate.
1.3 Reviewed	Model hydraulics and hydrology.
1.4 Review undertaken for:	Norfolk County Council
1.5 Review undertaken by:	Dan Eddon, WSP
1.6 Date of review:	August 2017

1.7 Review version (s):	GYMR_20100826_GM01.dat and all associated files.
1.8 Model produced by:	Halcrow Group Limited
1.9 Action levels	Recommendations are made with three priority levels as described below: [red] Must be addressed as part of the current study [amber] Please follow recommendation if time allows [green] Not strictly necessary in this case but good practice to consider for future studies n/a No action required
1.10 Study aims & objectives:	The aim of the current study is to assess the existing level of flood risk within Great Yarmouth and determine the impact of the proposed third crossing on flood risk within the town.
1.11 Area of interest:	The model simulated the Norfolk Broads in 1D representing the large storage areas using spill units and reservoirs. The Great Yarmouth area is represented using 1D channel units to simulate the harbour and 2D domain to simulate the surrounding flood plain. The specific area of interest in this review is the River Yare through Great Yarmouth and the surrounding floodplain.

2 Background to this review

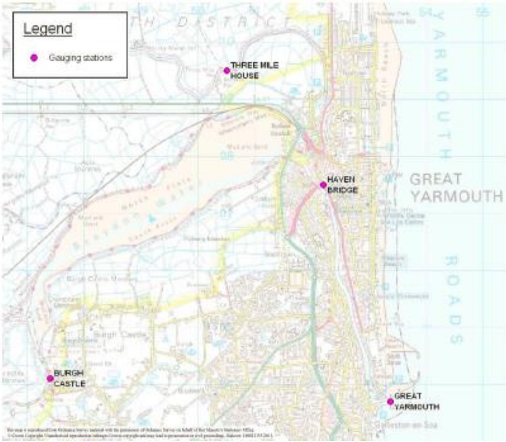
Subject document / file	Description	Version/Date	Filename	Reviewer's comments
2.1 Hydraulic model Guide	Modelling report provided with the model.	Final report issued in April 2011	GreatYarmouth_Report_2011-04-18_GM.doc	Note provides sufficient detail on the Great Yarmouth model development.
2.2 Flood estimation calculation record	N/A	N/A	N/A	The report references the tidal curve calculations stating that the derivation was carried out in 2009. It states that the process used gauge data to produce an astronomical tide and used the peak water levels from the Royal Haskoning 2007 Extreme Tide Level Report.
2.3 Model log Document	A model log is provided listing all the model files, both 1D and 2D for the simulations.	Last entry : 20/9/2010	GYRM_ISIS-TUFLOW_log_v6.xls	The model log document is provided for the model and the roughness patch model. However, in the model files there is a model; GYMR_20110617_GM03.DAT which is not included. It would be

				useful to obtain a description of this model. The model log does not appear to be up to date. It appears that additional models for the 2011 tidal curve update have also been supplied. Limited information is provided in the appendix of the report regarding this model. A comprehensive model log is recommended.

3 Model summary

Issue		Summary	Reviewer comments	Action
3.1	Software used, including versions	The model results have been included in the data and have been simulated on: - ISIS Version 3.4 with a numerical engine core version 6.4.0.52 - TUFLOW build 2009-07-DA-iSP Current software available to WSP: Flood Modeller VER= 4.2 TUFLOW = 2016-03-AD (License limited to 1000 1D nodes)	The model runs are simulated on outdated software versions which have been significantly updated. This review recommends using the most up to date modelling software versions in the Great Yarmouth Third River Crossing assessment.	**Must do**
3.2	Return periods provided for review	A full range of return period models have been provided. - 5yr, 20yr, 75yr, 100yr, 200yr, 1000yr – 2009 - 5yr, 20yr, 75yr, 100yr, 200yr, 1000yr – 2109	n/a	n/a
3.3	Scenarios provided for review	The EA provided a number of scenarios - GYMR_20100826_GM01.DAT – standard model - GYMR_20100902_GM01.DAT – increased roughness	n/a	n/a
3.4	All model files provided for review?	Yes	n/a	n/a
3.5	Does the model run as provided?	Yes – according to the model log.	WSP cannot run the model as supplied due to the node limit on the software license. However, the model log states that the model runs and 1D and 2D results have been provided by the EA.	n/a

4 Hydrology

4.1 Hydrology – Methodology	The report discusses the procedure used to derive the tidal curve. It states that the Royal Haskoning, 2007 Extreme Sea level Report is used for the extreme water levels. Regional Net Sea Level Rise Allowances, Defra 2006 is used to provide the climate change increases. The report states that the river flow is insignificant in a flood event as the flood mechanism is predominately tidal. Therefore nominal base flows are provided for the fluvial sources.	A review of the tidal curve is recommended using the most up to date guidance. At the time of writing this review, it is recommended that the '*Coastal flood boundary conditions for UK mainland and islands, EA 2011'* is used for the extreme sea levels and surge shape. The climate change allowance should be obtained following the guidance in '*Adapting to Climate Change, EA 2016'*. It is also recommended that the EA be consulted during this procedure. The EA Extreme Sea Levels have recently been updated and these should be used in the third crossing study. Nominal fluvial base flows are considered appropriate for this application.	**Must do**
4.2 Gauging stations	There are four level gauges in Great Yarmouth as shown in Plate 1 taken from the model report.  **Plate 1 – Gauge Locations (Halcrow, 2011)**	The model uses the Great Yarmouth tidal gauge to obtain the astronomical tide and compares the model simulation results to the three inland level gauges as validation.	N/A

4.3 Catchment delineation and catchment characteristics	River catchments are not critical in this model as the system is tidally driven. Catchment descriptors are used within FEH boundary units within the model but the flows are scaled by 0.001 to provide a nominal inflow.	N/A	n/a
4.4 River inflow peaks	River inflows are set at a nominal base flow.	N/A	n/a
4.5 Pooling Group	Statistical analysis was not undertaken.	N/A	n/a
4.6 Model inflows	The model uses a HT boundary at the coastal boundary in Great Yarmouth calculated using the procedure in the Royal Haskoning 2007 Extreme Sea Levels report. This method uses an astronomical tide profile which has been derived from the Great Yarmouth gauge at the harbour entrance. The astronomical tide is then scaled by the tidal surge profile which is provided in the Extreme Sea level report to the required water level. A number of FEH boundary units are used to simulate the fluvial sources in the 1D network. They use catchment descriptors to produce a hydrograph and then scaled by 0.001 to input a nominal flow.	The tidal boundary procedure is appropriate for use in this study however the tidal peaks should be updated (see 4.1). The method of using nominal fluvial base flows is appropriate in this case.	n/a

5 1D Domain - General

Issue	Summary	Reviewer comments	Action
5.1 Length of 1D domain(s)	The 1D model covers the Norfolk broads; a complex network of navigable rivers, lakes and low-lying wetlands. The River Yare and the major tributaries (Rivers Ant, Bure, Chet, Thurne and Waveney) are simulated in 1D totalling approximately 135.5km of modelled reach. - River Yare : 42km - River Ant: 7.5km - River Chet: 6km - River Bure: 36km - River Thurne: 11km - River Waveney: 33km -	n/a	n/a
5.2 Node summary and model extent	4165 nodes in total. Each of the watercourses has an upstream inflow unit which has been calculated using FEH and scaled by 0.001 to produce a nominal inflow. Similarly, lateral boundaries are scaled in the same way.	n/a	n/a

	The model has one downstream boundary at Great Yarmouth. At this location, a tidal curve (see 4.1) is applied and routed though the 1D channel. The sea boundary at Lowestoft has not been included because it is assumed that the lock separating the Broads and the Harbour stops all water and Oulton Broad is sufficiently large to store flood water.		
5.3 Naming convention	Naming convention based on section and chainage, for example GY198 is 198 metres from the north sea in Great Yarmouth.	Suitable naming convention	n/a
5.4 Topographic/ Bathymetric survey	No survey was made available for use in this review.	It has not been possible to check the model geometry against survey data. This review recommends survey data for the bridge area should be obtained and will be required to assess the suitability of the LiDAR in the critical area. A bathymetric survey of the harbour should also be provided to create an accurate representation of the harbour channel.	**Must Do**

6 Hydraulics

<table>
<tr><th>Issue</th><th>Summary</th><th>Reviewer comments</th><th>Action</th></tr>
<tr><td>6.1 Downstream boundary</td><td>Downstream boundary is the tidal curve.</td><td>This is appropriate.</td><td>n/a</td></tr>
<tr><td>6.2 Channel width</td><td>The 1D cross section width in the ISIS model has been compared to the inactive code layer width throughout the 1D-2D linked reach, the 1D channel widths in ISIS are the same as the 1D channel width represented in 2D. WLL lines are used to show the 1D water levels in the 2D domain.</td><td>This is considered best practice.</td><td>n/a</td></tr>
<tr><td rowspan="2">6.3 Manning's N</td><td rowspan="2">At the stage of this review WSP does not have any information from the site regarding channel and floodplain materials. In the model, the roughness in the harbour channel in Great Yarmouth is set to 0.025, equivalent to a gravel bed. The roughness on the Broads is set between 0.05 and 0.03.

A short section (400m) of the harbour near the tidal boundary has been increased to 0.035 in all model runs for stability in higher return periods (5yr,20yr,75yr,100yr,200yr,1000yr)

The 2D roughness values are presented in Table 1.

Table 1 – Roughness Values in 2D domain
<table>
<tr><th>Material</th><th>Roughness</th></tr>
<tr><td>Buildings</td><td>0.1</td></tr>
<tr><td>Manmade</td><td>0.04</td></tr>
<tr><td>Natural</td><td>0.06</td></tr>
<tr><td>Trees</td><td>0.08</td></tr>
</table></td><td>The roughness values in the 1D channel are appropriate in this situation. However, it is best practice to not use roughness patches if possible. It is therefore a recommendation of this review that the roughness patch at the harbour entrance is removed if possible.</td><td>Useful</td></tr>
<tr><td>The roughness values in the 2D domain are predominately appropriate, however, the building representation should be increased to 1 and used in the conjunction with the stubby building method.</td><td>Must Do</td></tr>
</table>

6.4 Structures	There are no structures represented in the 1D domain or in the 2D domain in Great Yarmouth. There are a large number of spill units to represent the flow out of the channel onto the flood plains in the 1D only sections of the network.	It is recommended that sensitivity testing is carried out on Haven Bridge in Great Yarmouth and if necessary it should be included in the final model. It is recommended to represent the energy loss through the bridge.	**Must Do**

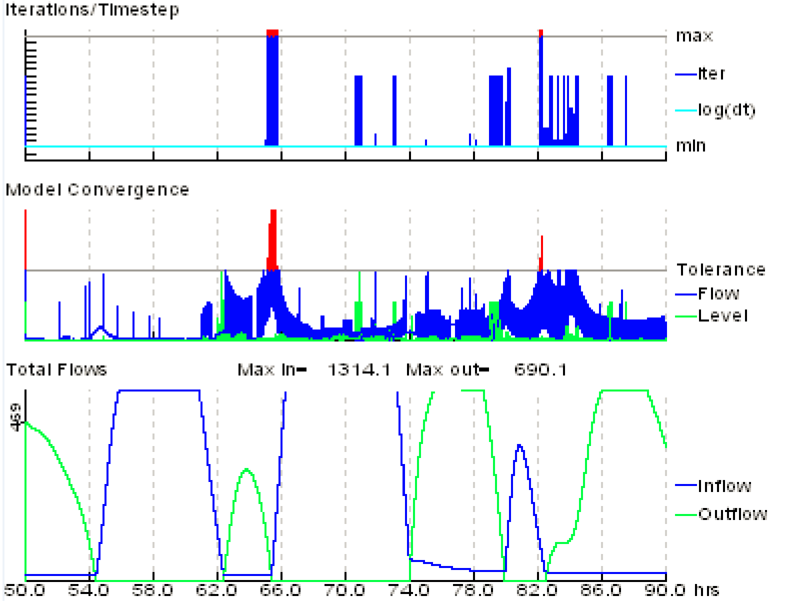
7 2D Domain - General

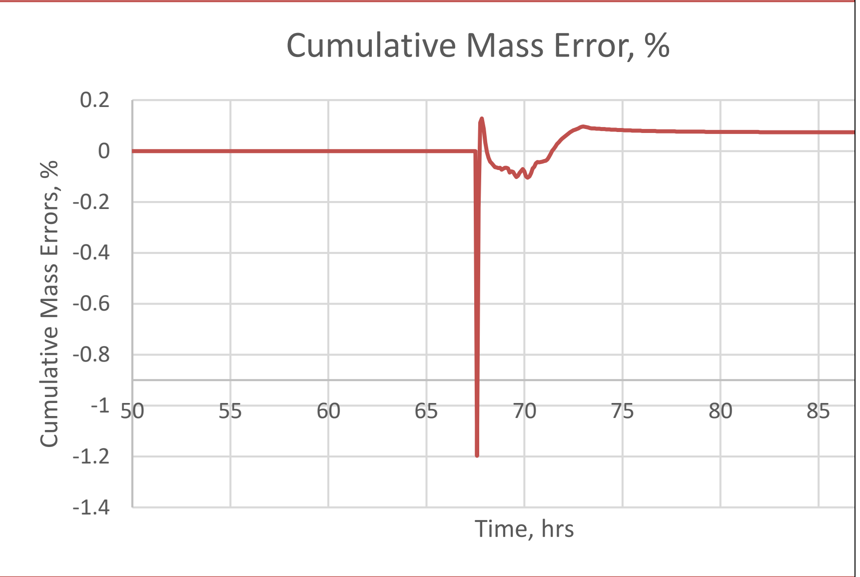
Issue	Summary	Reviewer comments	Action
7.1 General, Cell size(s), Suitable for study objectives?	10m grid size. The 2D grid simulates all Great Yarmouth, the River Yare and the land mass between the River Yare and the River Bure.	Cell size should be reduced if possible.	**Useful**
7.2 Base topography	The Grid is initially set up using 'Read MID Zpts': - 2d_zpt_SAR_GYMR_20100825_GM01.mid The zpts are based on Synthetic-Aperture Radar (SAR) data from EA.2002, which has now been partially superseded by LiDAR. LiDAR is read into the model where available. - 2d_zpt_LiDAR_GYMR_20100825_GM01.mid The LiDAR used 0.25, 0.50, 1 and 2 m LiDAR flown in August and October 2009 and covers the area near the coast.	It is recommended that the most up to date LiDAR dataset is used to create the surface. There is full LiDAR coverage 2D domain, there is no need to use SAR data within the model.	**Must Do**

7.3 Topographical Adjustment	The following adjustments were made to the topography: - 2d_zsh_bank_level_GYMR_20100826_GM01.MIF: remove rivers to avoid low zpts. - 2d_zsh_roads_GYMR_20100826_GM01.mif: ensure roads are raised sufficiently. - 2d_zsh_flow_path_GYMR_20100827_GM01.MIF: subways only below Gapton Hall Road. - 2d_zpt_corr_GYMR_20100826_GM01.MID: correct occasional zpt at SX and river banks. - 2d_za_buildings_GYMR_20100825_GM01.MIF: raise building by 0.3m. - 2d_zsh_defences_GYMR_20100828_GM01.MIF: raise defences along river bank - 2d_zsh_additional_defences_GYMR_20100827_GM01.MIF: additional defences at Yarmouth, Abberton Farm and Gapton Hall Retail Park	Sensitivity testing on the Rivers zpts file is recommended. Updates in software since model inception may increase stability allowing modelling of smaller watercourses in the region within the 2D domain.		**Useful**
		Comparing the defence elevations to existing site information is recommended to ensure the most up to date defence elevations are used.		**Must Do**
7.4 Buildings representation	Buildings are represented by Manning's n roughness value of 0.1 in conjunction with a 0.3m threshold level using the stubby building method.	The stubby building method is best practice however it is recommended that the roughness value is set at 1 to represent the slowing of flows through buildings.		**Useful**
7.5 1D-2D linking	There are several links between the 1D and 2D domains; - 2d_bc_sx_GYMR_20100826_GM01.MIF: boundary between reservoirs in ISIS and 2D TUFLOW domain - 2d_bc_hx_GYMR_20100827_GM01.MIF: Boundary between river and land (spill between 1D and 2D domains) There are two small Estry networks to simulate the flow under an overpass: - GYMR_20100830_GM01_100yr_2009.ecf	Boundaries appear to be stable and show no local significant mass balance errors.		n/a
7.6 Abstraction units	The report states a number of pumps are used in Great Yarmouth in low lying areas which have been represented using abstraction units in the 2D domain.	This review recommends a review of current pumps in Great Yarmouth and if required update the operation of the abstraction units.		**Must Do**

8 Model Run Parameters and Model Performance

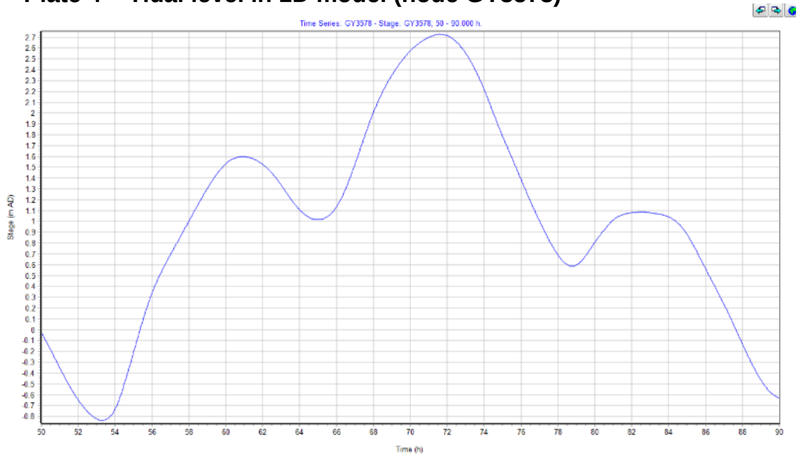
Issue	Summary	Reviewer comments	Action
8.1 Computational Time-step and run time	1s in 1D and 2s in 2D. (runtime 8:53:24)	This is considered suitable for model configuration. This can be decreased if the large events cause stability issues. Reducing the runtime would be preferable if possible.	**Good Practice**
8.2 Run parameters (amended from default)	Automated Priessmann slots applied to river sections Qtol is set at 0.03 Theta is set at 0.55 Other parameters are as default The model is run from restart files, GYMR_20100828_GM01_1000yr_2009.trf simulating 50hr to 90hrs.	Automated Priessmann slots are applied within 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.	**Good Practice**
		The Qtol value should be reduced to default 0.01 if possible. Similarly Theta should be set to the default value of 0.7.	**Useful**

8.3	Convergence	ISIS model runs show that there are some instances of poor model convergence (Plate 2). **Plate 2 – Model Convergence**  Datafile: ...\ISIS\2010-08-26\GYMR_20100826_GM01.DAT Results: ...\2010-08-30\GYMR_20100830_GM01_100YR_2009.zzl Ran at 16:24:14 on 04/09/2010 Ended at 01:17:39 on 05/09/2010 Start Time: 50.000 hrs End Time: 90.000 hrs Timestep: 1.0 secs Current Model Time: 90.00 hrs Percent Complete: 100 %	The poor convergence is at the high water point. In a tidal model of this size, this is acceptable however it should be reduced if possible.	**Useful**

8.4	Mass errors (target ± 1% for fluvial models)	The cumulative mass error is less than ± 1% for the majority of the simulation, except a point during the high tide where the error reaches -1.2% (Plate 3). **Plate 3 – Cumulative Mass Balance Errors** 	This is acceptable when considering tidal models in TUFLOW due to the influx of large volumes of water. However, it is recommended that the Cumulative Mass Error is reduced if possible. Additional checks should be made in larger events	**Useful**
8.5	Error Messages	58 Warnings prior to simulation; - XY: WARNING 2117 - Inactive 2D cell made active by 2D SX link.	na	

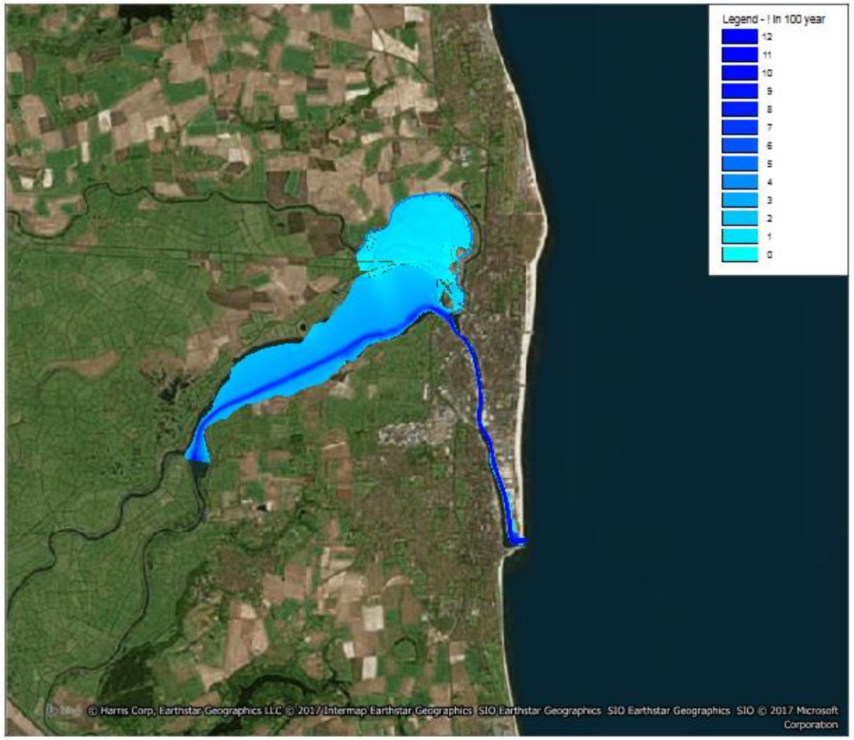
9 Model Results

For the purpose of this review, the results in the area surrounding Great Yarmouth will be considered. It is assumed that the rest of the 1D domain is providing a nominal flow only.

Issue	Summary	Reviewer comments	Action
9.1 1D water surface profile	The 1D water surface profile looks reasonable. The animation plot of the long section along the Great Yarmouth channel shows expected cyclical behaviour. Plate 4 shows a typical tidal curve in the harbour channel from the 1 in 100 year model results. **Plate 4 – Tidal level in 1D model (node GY3578)** 	n/a	n/a
9.2 2D results	A validation procedure has been carried out and described in the model report. The conclusion showed that the model predicted the water level at the three in land gauge sites well, with slight variation at peak water level. A number of sensitivity tests have been carried out in an attempt to better represent the peak water levels at the gauges. Nothing tried had a realistic impact on the water levels, therefore it was decided that, despite the overestimation of the water level, the model would continue to be used in the assessment. The flood map shows that the tidal defences in Great Yarmouth can protect the town in events up to the 1 in 100 year. The storage provided by the large lake to the north of the town is sufficient to store any additional water from the peak tide (Plate 5). Significant flood inundation is seen in the landmass between the Rivers Yare and Bure.	An investigation to assess the reasons for the mismatch in peak water levels is recommended and if possible create a better fix to actual data. A reduction in model output file sizes is recommended. For this size of model output every 15 minutes is reasonable.	**Must Do**

The data output files are very large. One simulation approximately outputs 3.4GB of data for the 2D results maps. WLL lines are used to interpolate the 1D water levels in the 2D domain and are saved every 300 seconds (5 mins).

Plate 5 – 1 in 100 peak water levels flood map



10 Audit Trials

Issue		Summary	Reviewer comments	Action
10.1 Logbook provided?		Log book listing most of the files used in the models up to the models run in 2008.	A log book has been provided for this model although it does not appear to be up to date. There is no information on a model produced in 2011. From an assessment of this model it appears to have a different tidal inflow. This review recommends that a comprehensive model log file should be produced as part of the ongoing assessment.	**Useful**
10.2 Suitable file naming, structure & management?		No	The model files are not saved in the recommended format. Each model is saved in a folder named after the date of the modification/simulation. This creates confusion when trying to find files for each model. This review recommends a project folder is set up in the standard TUFLOW file structure and the results and any bespoke model files are saved in folders with appropriate names, not referencing the date the work was carried out.	**Must do**
10.3 Check files provided		Yes	n/a	n/a
10.4 Comments provided within model?		Some comments are in the model file.	The model has a limited number of comments that refer to the 1D BESL model. There is limited commenting on the updates carried out since.	na

11 Conclusions

Conclusions

This review note presents comments noted during the review and recommendations for required actions. Recommendations are made with three priority levels:

Must do Must be addressed as part of the current study **(to be discussed and agreed)**

- Update the tidal curve inflow using mode up-to-date peak levels;
- Request gauge data from level gauges in study area;
- Request/obtain survey data at the proposed bridge location;
- Obtain existing bridge data and perform a sensitivity;
- Update LiDAR to most recent;
- Carry out an updated calibration procedure;
- Reduce model output file sizes by reducing the output time;
- Create standard folder structure and model log;
- Review water pumping stations and update abstraction units if necessary;
- Perform a roughness update and calibration;
- Review and compare the existing defence levels.

Useful

- Remove roughness patches near the harbour entrance;
- Reduce cell size;
- Add rivers into the 2D domain and perform tests;
- Reduce QTol to default (0.01) and Theta should be set to the default value of 0.7;
- Reduce model convergence in 1D and Mass balance errors in 2D.

Good Practice

- Reduce overall runtime run time and output file size;
- Remove Preissmann Slots.