Norwich Western Link

Environmental Statement

Chapter 12: Road Drainage and the Water Environment

Appendix 12.2: Flood Risk Assessment

Sub Appendix B: River Wensum Hydraulic Modelling Report

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Glossary of Abbreviations and Defined Terms

The definition of key terms used in this report are provided below. These definitions have been developed by reference to the definitions used in EU and UK legislation and guidance relevant to the water environment as well as professional judgement based on knowledge and experience of similar schemes in the context of the Proposed Scheme.

Term	Definition
1D model	A hydraulic model used for watercourses that calculates flow in the direction of the channel only. It does not calculate movement vertically or horizontally in the channel.
2D model	A hydraulic model used for watercourses and floodplains that calculates flow along a plane in two directions, often at 90 degrees to each other. It does not calculate movement in the vertical direction.
Climate Change Allowance	An uplift applied to peak flow or rainfall estimates, which are based on data available today, to account for predicted increases in rainfall in the future.
Culvert	Arched, enclosed or piped structure constructed to carry water under roads, railways and buildings
Digital Terrain Model	A surface produced from LIDAR data where surface features such as buildings and vegetation have been removed so that is represents ground level.
Drainage Strategy	Demonstrates how surface water will be managed within a scheme so it does not increase flood risk elsewhere, how the scheme is compliant with the relevant legislation and manages risks to water quality.

Term	Definition
Flood Estimation Handbook	A manual consisting of 5 volumes that sets out the techniques to be used within the UK to derive flood flows, which are used to support Flood Risk Assessments.
Flood Map for Surface Water	A nationally available dataset showing areas that are susceptible to surface water (or pluvial i.e. from rainfall) flooding produced by the Environment Agency.
Flood Modeller Pro	A hydraulic modelling software package
Flood Risk Assessment	As assessment that identifies and assesses the risk of flooding to and from a proposed development for all sources. It is a requirement under the national planning policy framework for all new developments that are in flood zone 2 or 3 and are more than 1 hectare.
Flood Zone	The classification of an area based on its risk of flooding from fluvial or tidal sources.
Floodplain	Valley floor adjacent to a river that is (or was historically) inundated periodically by flood waters and is formed of sediments deposited by the river
Fluvial Flood Risk	Flooding resulting from a flows within a watercourse exceeding the capacity of that watercourse.
Hydraulic Model	A software tool used to estimate water levels during a flood event based on topographical data of watercourse channels and the floodplain and flood event flows or rainfall data.
Hydrology	The study of the properties, distribution, and effects of water on the earth's surface, in the soil and underlying rocks.

Term	Definition
Left Bank	Left bank is defined by the direction of flow of the watercourse, looking downstream in the direction of flow. For the purposes of this FRA both the River Wensum and Foxburrow Stream run in a south-easterly direction in the vicinity of the Proposed Scheme. The left bank is therefore on the north-east side of these watercourses.
LIDAR	Light Detection and Ranging, a method used to collect ground level data from an aircraft allowing large areas to be collected. The data in its unfiltered form will pick up vegetation and properties. A filtered form is generated to represent the ground surface and is used in assessments.
Manning's Roughness Value or Coefficient	A coefficient to represent different surface roughness and used in the Manning equation to understand the relationship between flow and water depth.
Model cell size	The resolution that LIDAR data is sampled at for use in the model. Smaller cell sizes increase the length of time it takes for a model to run.
NMU (non-motorised users)	A specific group of road users including walkers, cyclists or horse riders.
Norwich Western Link Highway	The highway section of Proposed Scheme which encompasses 6 Kilometre (Km) of long dual-carriageway road connecting the A1067 Fakenham Road and the A47 and a dualled section of the A1067 to the existing A1270 roundabout
Pre-Earthwork Ditch	An earth ditch that will run along the outer edge on the Norwich Western Link Highway to collect and convey surface water runoff
Proposed Scheme	The proposed Norwich Western Link scheme.

Term	Definition
QMED	The median flow extracted from an AMAX series. This is considered to represent the 1 in 2 annual probability event flood.
ReFH	The Revitalised Flood Hydrograph rainfall runoff method. One of the Flood Estimation Handbook methods for determining peak flows and hydrographs.
Right Bank	Right bank is defined by the direction of flow of the watercourse, looking downstream in the direction of flow. For the purposes of this FRA both the River Wensum and Foxburrow Stream run in a south-easterly direction in the vicinity of the Proposed Scheme. The right bank is therefore on the south-west side of these watercourses
River Gauge	A location within a watercourse where the flow and depth relationship is understood so that accurate data on river flows can be collected.
River Wensum Viaduct	(BR1). Drawing Structure Reference. Viaduct crossing the River Wensum Special Area of Conservation and floodplain (approximately 490m long). The ten-span bridge design includes piled piers within the floodplain.
Surface Water Drainage Strategy	Demonstrates how surface water will be managed within a scheme so it does not increase flood risk elsewhere, how the scheme is compliant with the relevant legislation and manages risks to water quality.
Temporary Works Platform	The term to refers to the temporary platform across the floodplain use to construct the viaduct. It will cross the River Wensum by means of a temporary bailey bridge.
TUFLOW	A hydraulic modelling software package

Term	Definition
WC5	An ordinary watercourse situated to the south of the River Wensum. It runs parallel to the River Wensum and is situated within its floodplain and so is hydraulically connected during flood flows. It outfalls to the River Wensum at Ringland.

1 Introduction

1.1.1 Some users may not be able to access all technical details of this document. If you require this document in a more accessible format please contact norwichwesternlink@norfolk.gov.uk

1.2 Project requirements

1.2.1 This modelling report forms an Appendix of the **Flood Risk Assessment** (Document Reference: 3.12.02) and should be read in conjunction with the **River Wensum Technical Modelling Log** (Document Reference: 3.12.02c) and **River Wensum Hydrology Verification** (Document Reference: 3.12.02d).

1.3 Site overview

1.3.1 A hydraulic model of the River Wensum has been developed to determine the baseline fluvial flood risk and the potential impacts of the proposed road scheme to both the road itself and to third parties during construction and operation of the development.

1.3.2 There are a number of features within the area that are expected to influence flood extents and flows, including numerous field drains and hydraulic structures. The extent of the hydraulic model, shown in **Figure 1-1**, incorporates these features so that their hydraulic influence can be properly accounted for.

1.3.3 Note that throughout this report the terms right bank and left bank are used. These are defined by the direction of flow of the watercourse, looking downstream in the direction of flow. For the purposes of this report the River Wensum runs in a south easterly direction in the vicinity of the Proposed Scheme. The left bank is therefore on the north-east side of the River Wensum and the right bank of the south west side of the River Wensum.;

1.4 Background data

Hydraulic Modelling Studies

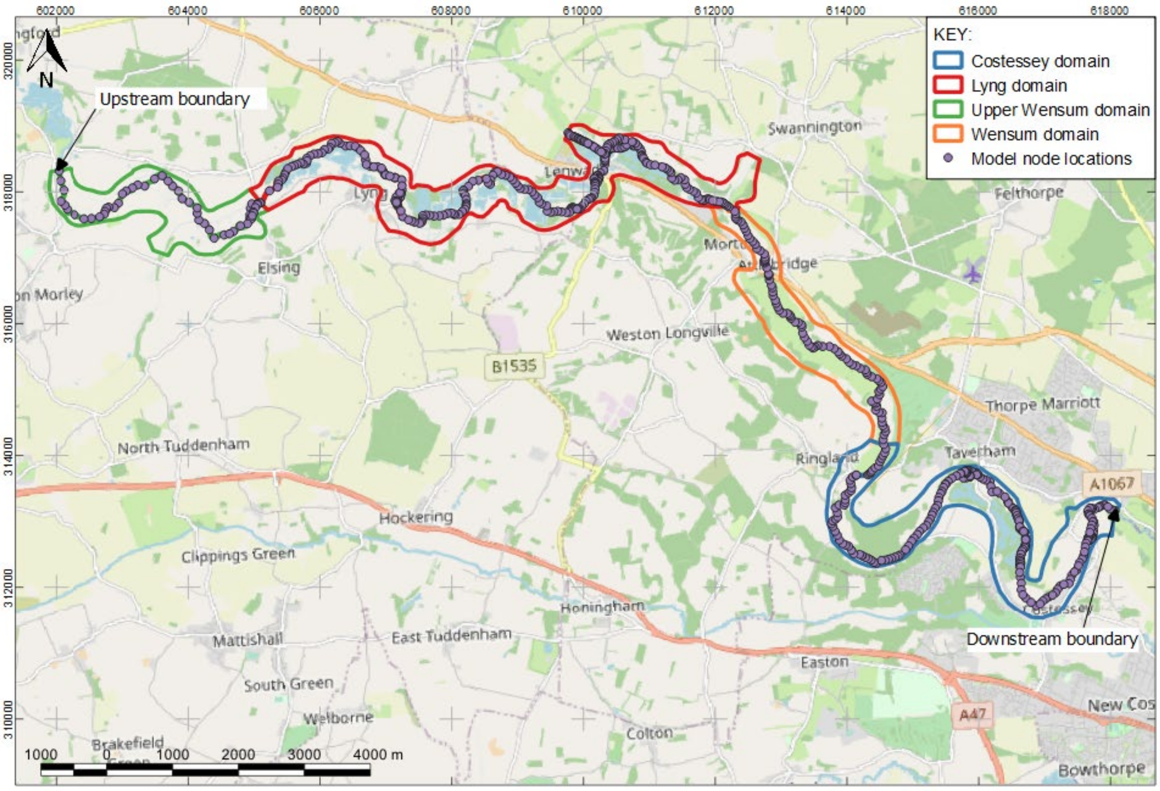
1.4.1 A number of previous hydraulic modelling studies of the River Wensum and its tributaries have been undertaken. The summary below details the most recent studies with greatest relevance to this study.

1.4.2 In September 2017, JacksonHyder were commissioned by the Environment Agency to undertake a flood modelling study along the River Wensum. The purpose of the study was to determine if the proposed restoration features being placed in the channel and on the floodplain at Costessey, Lenwade and Lyng in Norfolk, would have an impact on the flood levels and extents.

1.4.3 The work undertaken included the conversion of the Environment Agency's existing 1D only FMP flood model to a linked 1D-2D FMP-TUFLOW model and the incorporation of the proposed restoration features. The work is detailed in a Technical Memorandum produced by JacksonHyder with reference UA009719-ARC-XX-XX-RP-CW-0001-P1.1. The updated model of the River Wensum was provided to WSP by the Environment Agency in November 2020.

1.4.4 The updated model extent covers the section of the River Wensum between Swanton Morley at National Grid Reference (NGR) TG 02034 18450 to downstream of Drayton at NGR TG 18151 13098. The model is large and complex, comprising four 2D domains and a total of 931 1D model units. A schematic of the incoming hydraulic model is shown in **Figure 1-1**.

Figure 1-1 Schematic of JacksonHyder 2017 model showing domains and node locations

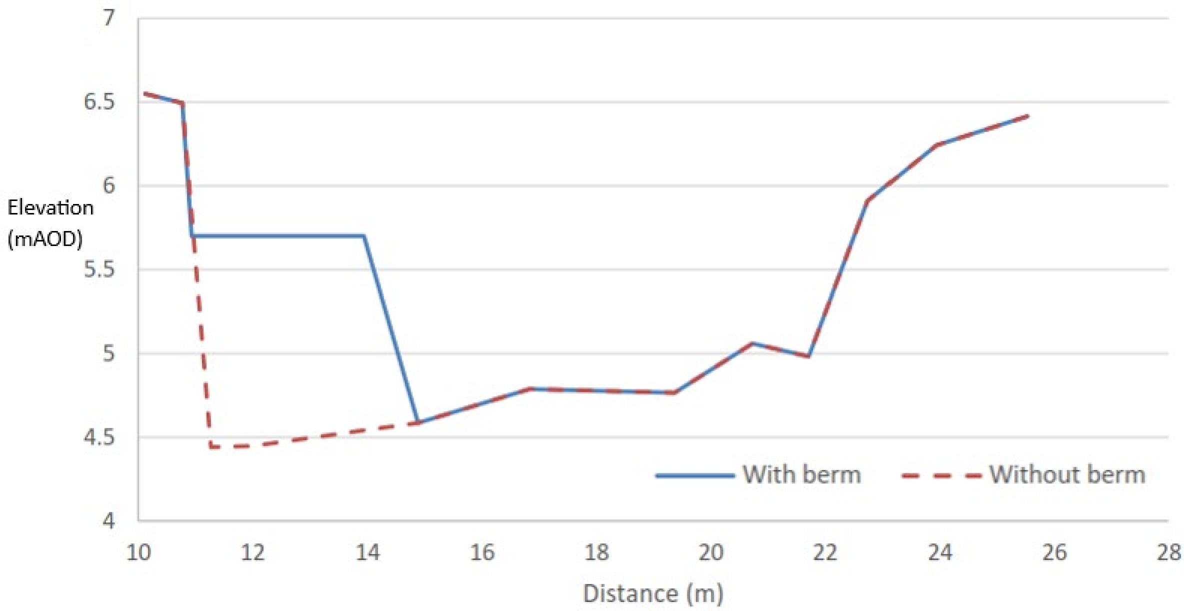


1.4.5 Both the baseline and restoration versions of the updated model of the River Wensum have been provided by the Environment Agency. It is understood that the proposed restoration features have been approved and are to be incorporated into the channel and floodplain of the River Wensum.

1.4.6 To ensure that the Proposed Scheme does not impact on the restoration features, an analysis of the modifications made to the baseline model has been undertaken. A summary of the modifications made to the baseline model to incorporate the restoration features, and the impact of these changes on the flood levels and extents is given below.

1.4.7 Modifications to represent the restoration features have been made within both the 1D channel and 2D floodplain domains. In-channel features, such as berms, woody material, glides, pools, hinged willows, woody deflectors, pinned wooden stakes, sections of nicospan and riffles, have been represented via the addition of modified river cross sections at the location of each restoration feature. Both the geometry and Manning's roughness values for the cross sections have been varied to represent each feature. The in-channel modifications have been applied at select locations in the Costessey, Lenwade and Lyng areas of interest. An example of the modifications that have been made is shown in **Figure 1-2**.

Figure 1-2 Adjustment of cross section WENS01_1830 made by JacksonHyder to represent a brushwood berm at this location



1.4.8 In the 2D floodplain, modifications have included areas of high roughness to represent tree enclosures at Costessey, the use of a series of zlines and zpoints to carve field drains into the floodplain at Costessey and Lyng, and low points in the bank of the River Wensum to encourage spills to reconnect the floodplain and channel.

1.4.9 A comparison between the modelled flood extents in the baseline and restoration model scenarios indicates that the introduction of the restoration features has caused a localised increase in water levels on the floodplain at both Costessey and Lenwade. At Lyng, the introduction of the restoration features has caused a reduction in the water level on the floodplain. The variation in water levels has been shown to occur only within the areas of interest, and there is no impact further upstream and downstream due to the restoration features. As the proposed viaduct location is not local to any of the areas of interest in the JacksonHyder study, it is not predicted that the Norwich Link Road will infringe on any of the restoration features.

1.4.10 The restoration model has been taken forward for use within the Norwich Western Link study, as it is considered to most closely represent the restoration features which will be in place when the Norwich Link Road is constructed.

Historical data

1.4.11 The Environment Agency does not hold any historical flood outlines in the study area.

Gauge data

1.4.12 The Costessey Mill river gauge is approximately 6.4 kilometres downstream of the area of interest. In the absence of historical flood outlines, flows in the model will be evaluated against the design flows that have been produced in the Hydrology study undertaken in 2017 by CH2M. This is further discussed in the Hydrology section of this report.

1.5 Approach to the study

Incoming model review

1.5.1 The restoration model has been reviewed to assess its suitability for use in this study. A number of issues have been identified with the current schematisation and stability of the model. These issues include:

- Inconsistencies in the chainage length between cross sections in the 1D domain and the distance between cross sections in the 2D domain. There is an example of this between WENF2_22750 and WENF2_22473d, where the 1D chainage length is 62.5 metres but the 2D distance between nodes is 39 metres.
- The bridge over the River Wensum at Ringland Road (model node WENF2_17740Br) has been represented using a USBPR type bridge unit with a single pier with a width of 1.5 metres. Available online

mapping indicates that the bridge has 5 piers, which have not been represented. Similarly, the USBPR bridge at node WENF2_15976Br does not have the pier shown in the survey included within the structure.

- The embankments adjacent to the bridges at WENF2_22445u, WENF2_17740Br and WENF2_15976Br and WENF2_8695u, at the locations shown in **Figure 1-3**, have not been formally included within the floodplain, although they may act as significant barriers to flow.
- Floodplain flow beneath or through the road embankment at Fakenham Road, the embankment adjacent to the campsite on Costessey Lane (WENF2_15976Br), and the embankment beneath the Marriott's Way near Drayton have been represented by "stamping" into the 2D domain DTM, rather than using a 1D floodplain structure. This could be overestimating the flows which are passed forward, particularly as Fakenham Road does not overtop.
- There are discrepancies in the width of the 1D channel and the width of the de-activated area in the 2D domain, for example at node WENF2_23500 the 1D channel width is 13.5 metres but the distance between the HX lines is 26.4 metres.
- Model run parameters, including dflood and maxitr, have been set at significantly larger values than default. This suggests that these values have been altered to allow the model to run regardless of instabilities or fluctuations in water level.

1.5.2 There are significant oscillations in water level throughout the model as the hydrograph approaches the peak flow value at approximately 54 hours. **Figure 1-3** shows a long section of the water level in the model during the 1 in 100 annual probability event.

Figure 1-3 Location of floodplain embankments through the modelled area

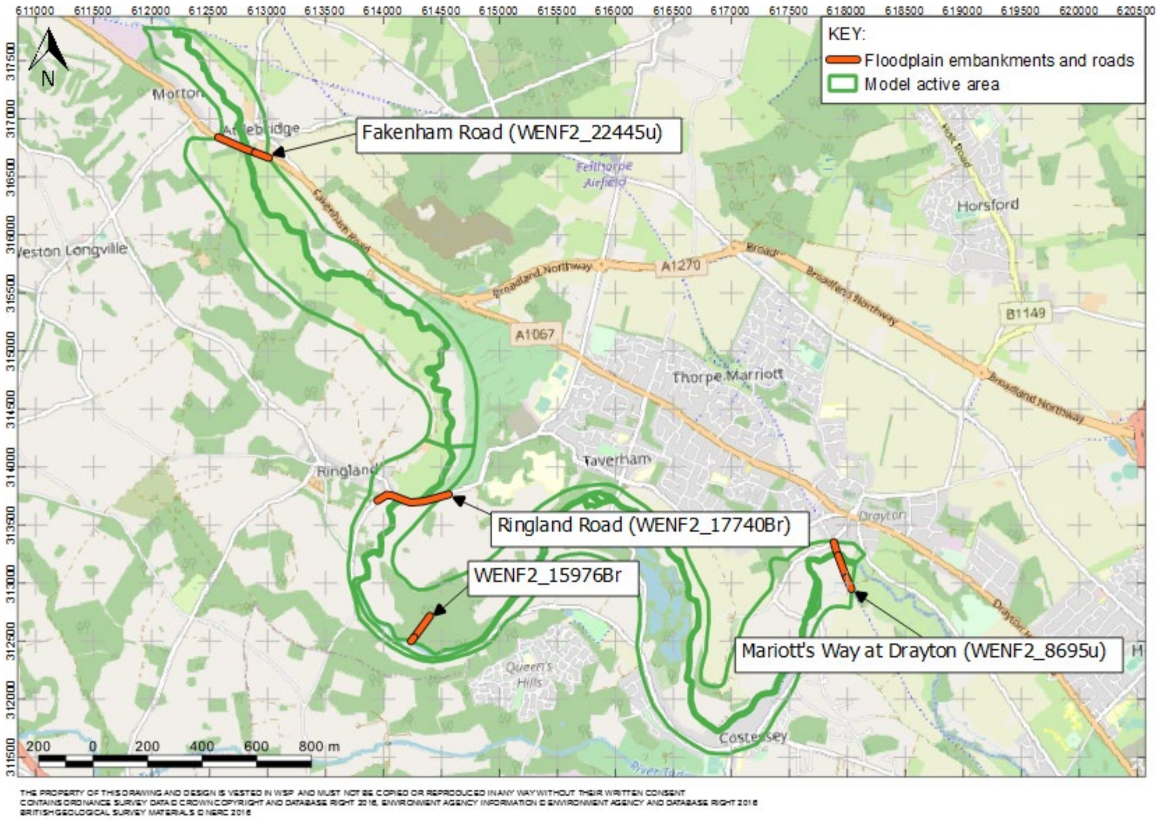
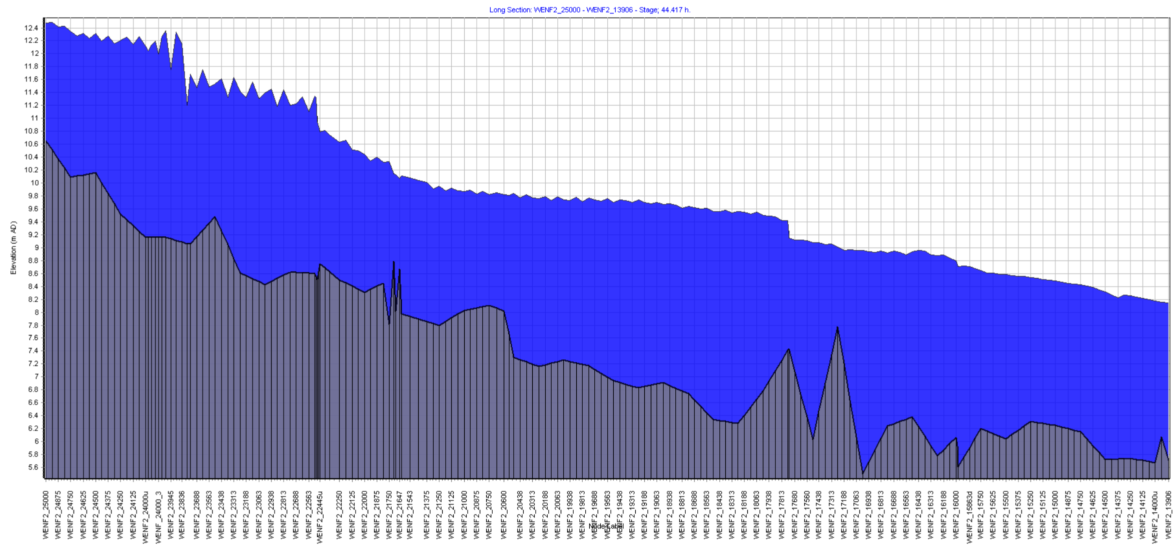


Figure 1-4 Water level in the incoming restoration model in the 1 in 100 annual probability event at approximately 44 hours into the simulation



1.5.3 As the oscillations in water level are relatively severe, it was considered that the use of the incoming restoration model as provided was not appropriate in its received form to assess the flood risk in the baseline and post-development scenarios. Therefore, as part of the study the incoming model has been modified to improve its schematisation and stability.

1.6 Model updates

Model extent

1.6.1 The incoming model has been trimmed significantly so that it comprises only the Wensum and Costessey domains. This was done to reduce run times and prevent upstream instabilities in the model from propagating downstream to the area of interest surrounding the proposed viaduct location.

1.6.2 The model was cut at node WENF2_23782u, which is the most upstream node in the Wensum domain and where the River Wensum passes beneath a railway embankment. This embankment represents a major hydraulic control and all water is in bank at this location. This location also represents the start point at which the inflows for the lower Wensum are distributed along the reach.

1.6.3 The inflow in question is W9int and it is distributed between Trout Steam, a tributary of the Wensum which joins immediately upstream of the railway embankment, and Costessey Pits. For the purposes of the study it was deemed appropriate to apply the inflows associated with Trout Stream downstream of the railway embankment so the updated model contained all contributing flows from W9int. The lateral inflow was not applied immediately downstream of the railway embankment to prevent stability issues with the application of the upstream QTBDY.

Model stability

1.6.4 In order to improve the stability of the model, a number of updates have been made. The modifications include:

- Adding a zshape to enforce the railway embankment at the upstream extent of the model to a set level of 15mAOD;
- Removing interpolates between WENF2_23782u and WENF2_14000u to provide additional volume in each 1D river section and so improve model stability;
- Using zshapes to smooth over topographic low points and ditches which interact with the model HX lines;
- Widening the first section WENF2_23782u by extending the section using the full cross section found in the 2019 CH2M 1D model and altered HX lines and inactive area accordingly;
- Widening the sections between WENF2_16750 and WENF2_15250 using the full cross section data found in the 2019 CH2M 1D model to prevent water from “sitting” on the right bank and re-circulating into the 1D channel;
- Removing initial curve in HX lines on the left bank downstream of WENF2_23782u as water appears to be re-circulating into the 1D channel here;

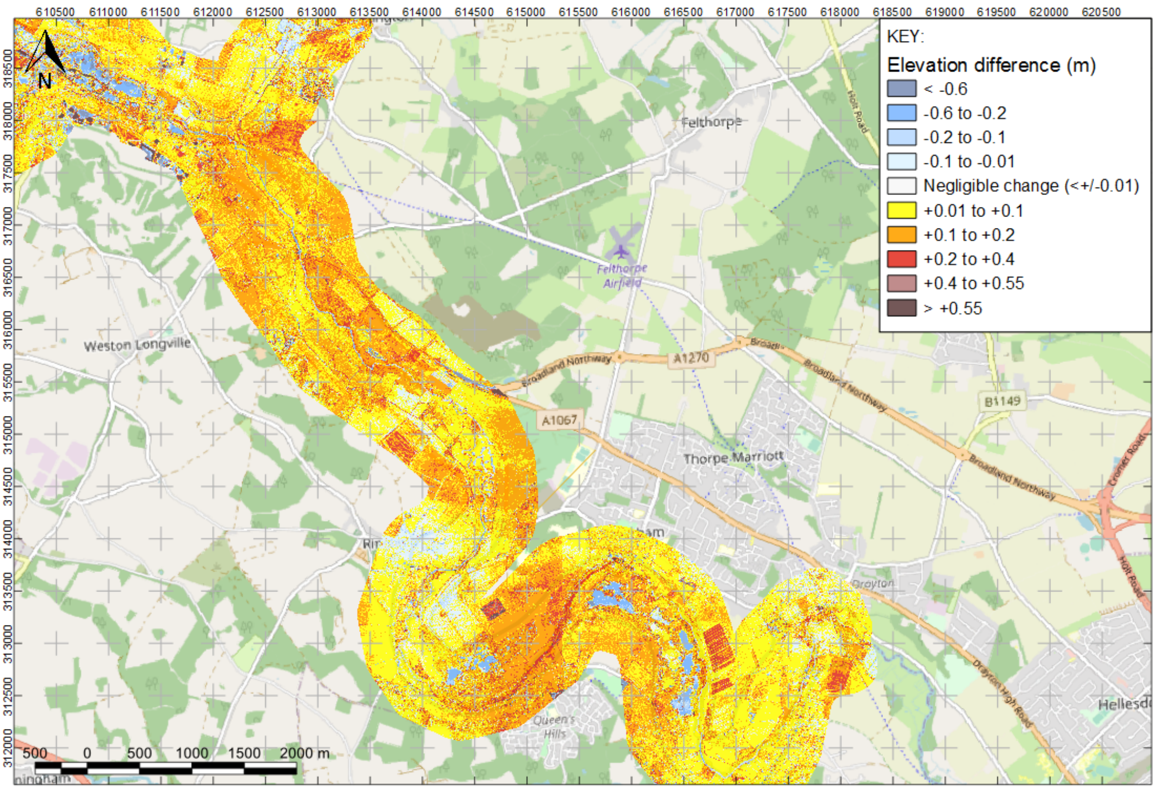
- Modifying the material file to remove small features such as drainage ditches that are generally smaller than the cell size and therefore causing fluctuations in material values over a small area;
- Removing the HX line on the left bank of watercourse adjacent to node WENF2_19750 to prevent water seesawing between the 1D and 2D domains in this narrow section of floodplain flow. An interpolate unit has been added up and downstream of WENF2_19750 so the length of the river channel without a HX connection is constrained;
- Adding additional piers at bridges WENF2_17740Br and WENF2_15976Br in line with available information;
- Fixing the chainage lengths in the 1D domain where they are not consistent with the distance between model nodes in the 2D domain;
- Fixing the width of the channel in the 2D domain where it does not match the cross section width in the 1D domain;
- Widening cross sections WENF2_18000, WENF2_20750 and WENF2_20600 on the left bank using the full cross section data found in the 2019 CH2M 1D model; and
- Returning run parameters in the .ief file to default.

Topographic data

1.6.5 The LIDAR data used in the incoming model was flown in 2014. The Environment Agency has since released the 2019 composite dataset, which includes LIDAR flown in 2018. The more recent dataset has been obtained for use within the trimmed model, as it provides a more recent representation of ground elevations.

1.6.6 A comparison has been made between the previous LIDAR data and the more recent LIDAR data. **Figure 1-5** shows an elevation difference map centred on the area of interest, which indicates that the difference in elevation between the datasets is less than 0.2 metres in the floodplain. On average, the new dataset is approximately 0.08 metres higher than the previous dataset.

Figure 1-5 Map showing the difference in elevation between the 2019 composite LIDAR dataset and the 2014 LIDAR dataset



1.6.7 Comparison of the levels in the survey data and the 2014 LIDAR data indicated that there was generally good concordance between the two datasets. In order to maintain the same relation between the surveyed data and the LIDAR data as was in the incoming model, the 2019 composite LIDAR dataset has been adjusted by -0.08 metres. This adjustment was applied by reading in an additional .asc grid with a value of -0.08 metres after the updated LIDAR in the model run files.

1.6.8 The bankpoints in the incoming restoration model have been populated with elevation data from the surveyed model cross sections where available. At interpolate units elevations from the 2014 LIDAR dataset have been applied instead. For the updated model new bank points at interpolate units have been extracted from the adjusted LIDAR data for continuity with the previous approach.

Further updates

1.6.9 In addition to the improvements to the model stability, the following updates were made as identified in the initial model review:

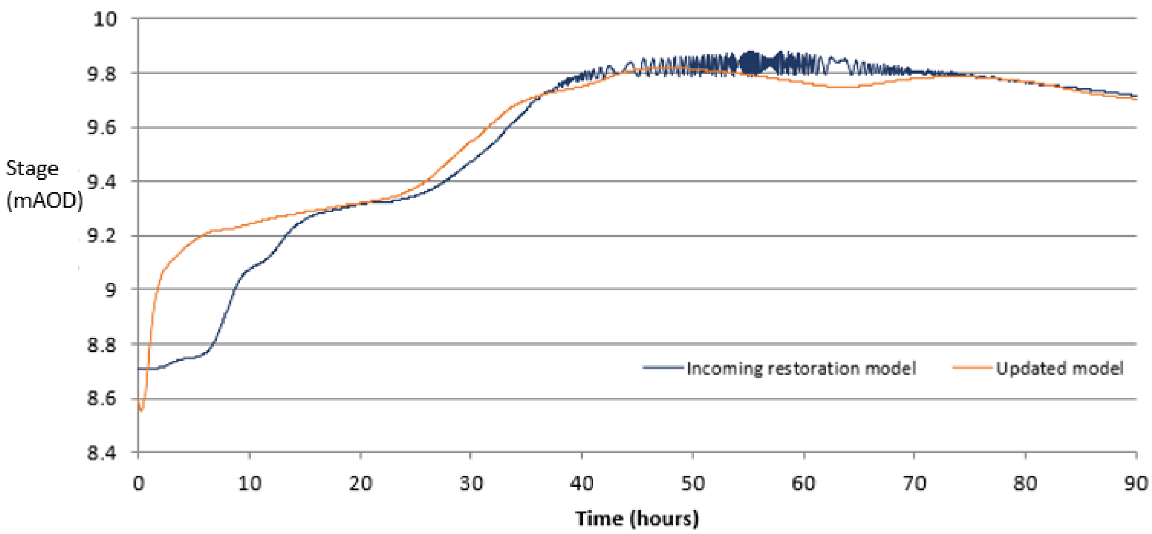
- Update of the bridge over the River Wensum at Ringland Road (model node WENF2_17740Br) to include 5 piers.
- Update of the footbridge bridge adjacent to Three Corner Plantation (WENF2_15976Br) to include its pier.
- Update to include the embankments adjacent to the bridges at WENF2_17740Br and WENF2_15976Br in the floodplain using crest levels extracted from the LIDAR.
- The latest composite LIDAR dataset (2019) has been read into the model to populate the model DTM – the LIDAR data has been adjusted to be consistent with the relationship between the previous model DTM and the survey data as described above.
- Incorporation of the culvert beneath Ringland Road, and improved schematisation of the bypass structure at Fakenham Road based on asset data received from Norwich County Council.

1.6.10 Finally, to decrease the run time of the model, the grid cell size in the Costessey domain has been increased from 4 metres to 5 metres. The 2d timestep for the domain has been adjusted accordingly, from 2s to 2.5s. As the Costessey domain is sufficiently far from the area of interest, it is unlikely that this modification would have an impact on the flood levels and extents in the area surrounding the proposed Norwich Link Road.

1.7 Summary

1.7.1 **Figure 1-6** shows the water level throughout the 1 in 100 annual probability event in both the incoming restoration model and the updated trimmed model at node WENF2_20500, which is situated in the approximate location of the Proposed Scheme where it crosses the River Wensum. This shows a significant improvement in stability, and a reduction in the oscillations in water level in the model.

Figure 1-6 Comparison of water level during the 1 in 100 annual probability event at model node WENF2_20500



2 Hydrological Assessment

2.1 Overview

2.1.1 In the JacksonHyder study, model inflows were derived by re-running the existing CH2M 1D model of the River Wensum and tributaries and extracting flows from the appropriate upstream node. Inflow hydrographs for the updated model have been extracted from the existing 2017 CH2M model results at the updated model trim location, WENF2_23782u.

2.1.2 The modelling and hydrology report for the CH2M 2017 flood model indicates that inflows have been derived using ReFH rainfall boundaries with a 43 hour critical storm duration that have been scaled to match statistical peaks (From Appendix A of Wensum_Model_Report_2017-05-30_CH2M, report reference Upper_Wensum_HydrologyReport_2017-04-19). The statistical peaks have been derived at three gauge locations, Swanton Morley, Fakenham and Costessey Mill. To match these peaks consistent scaling factors have been applied to the rainfall run-off ReFH boundaries, which are shown in **Table 2-1** below.

Table 2-1 Scaling factors applied to ReFH inflows

Gauging Station	Inflow Label	Scaling Factor
Fakenham	W0	2.6
Fakenham	W1int	2.6
Swanton Morley	W3int	1
Swanton Morley	W5int	1
Costessey Mill	W6int	1 – 50% and 0.1% AEP 1.3 – 20% AEP 1.6 – 10% AEP 1.8 – AEPs between 5% and 0.5%
Costessey Mill	W8	1.8
Costessey Mill	W7int	1.8

Gauging Station	Inflow Label	Scaling Factor
Costessey Mill	W9int	1.8
Wendling	W13	1
Wendling	W14int	1

2.1.3 The inflow hydrograph at the upstream model node (WENF2_23782u) has been applied as a QT boundary within the trimmed model. The Trout Stream tributary is located immediately upstream of the railway embankment, therefore the flows extracted from the 2017 flood model to apply at the railway embankment have been taken immediately upstream of Trout Stream. The inflows from Trout Stream are applied within W9int and incorporated downstream of the railway embankment.

2.1.4 Climate change allowances for the Broadland Rivers management catchment are shown in **Table 2-2**. Central, Higher and Upper allowances for the 2080s epoch have been considered suitable to assess the impact of future climate change at the Proposed Scheme location.

Table 2-2 Climate change allowances for the Broadland Rivers management catchment

Year	Central (%)	Higher (%)	Upper (%)
2020s	8	14	27
2050s	3	10	27
2080s	11	20	44

2.1.5 As the incoming hydrology does not include hydrographs for the 11%, 20% and 44% climate change allowances, these have been generated by increasing the scaling factors in the CH2M 1D model hydrology by the appropriate climate change factor. Inflows for this study have then been derived by re-running the original 2017 flood model of the River Wensum, and then extracting flow hydrographs at WENF2_23782u. A comparison between the climate change flows and the FEH statistical flows with the climate change uplift applied is provided in **Section 3.2**.

2.2 Hydrology verification

2.2.1 A number of checks have been undertaken to determine whether the existing hydrological study, undertaken in 2017 by CH2M consulting, is considered suitable to inform fluvial inflow hydrographs for the River Wensum modelling study.

2.2.2 The CH2M study uses flow data from 1999-2014, and therefore it was considered that subsequent years of data may change the derivation of both QMED and growth curves for the study site.

2.2.3 The checks that have been undertaken include:

- Derivation of an up to date AMAX series using the 2012 JBA rating to confirm QMED using all available gauge data;
- Comparison of the updated QMED value with that used previously in the CH2M study;
- An ungauged pooling group assessment, noting the pooling group review completed in the CH2M study for consistency, using HiFlows v10 data and WINFAP Version 5; and
- Comparison of updated peak flows, using the latest QMED and growth factors, to the peak flows used within the CH2M study.

2.2.4 The original QMED value derived in the CH2M study is 22.7m^3/s. The updated QMED value using the additional years of data is 21.7m^3/s. This is a decrease in QMED value of 4.4% in comparison to the previous estimate. As this value is relatively small, it indicates that incorporation of the most recent AMAX series data into the QMED estimate does not have a significant impact on the QMED value.

2.2.5 To maintain the same method as used previously, an enhanced single site analysis for the Yare@Colney was used to derive an updated growth curve using all available data. It was flagged that the use of enhanced single site analysis at a nearby gauge station is non-standard. The updated growth curve is very similar to the one produced by CH2M previously. Updated peak flows have been derived using the latest QMED and growth curve, which produces peak flows that are very similar to those derived previously by CH2M. The average reduction in peak flow value is 5.98%. This is mainly attributed to the difference in QMED value due to the similarity in the growth curve.

2.2.6 The checks have shown that incorporation of the latest available data into estimates of QMED and the growth curve does not result in significant changes to peak flow values. Therefore, the original flows and hydrology have been retained for further use within the Proposed Scheme.

2.2.7 Additional information regarding the hydrological analysis that has been undertaken is provided in the **River Wensum Hydrology Verification** (Document Reference: 3.12.02d).

3 Baseline Strategic Case

3.1 Overview

3.1.1 A hydraulic model of the River Wensum between Fakenham Road, Attlebridge and Costessey Mill, Drayton has been produced from a previous linked 1D-2D study of the River Wensum, which includes numerous restoration features. A number of updates have been undertaken to improve stability and better represent available topographic and structural information.

3.1.2 The updated model will be used to establish the existing flood risk in the area, and then determine the impact to flood risk of installation of the Proposed Scheme.

3.1.3 A technical modelling log is provided in the **River Wensum Technical Modelling Log** (Document Reference: 3.12.02c).

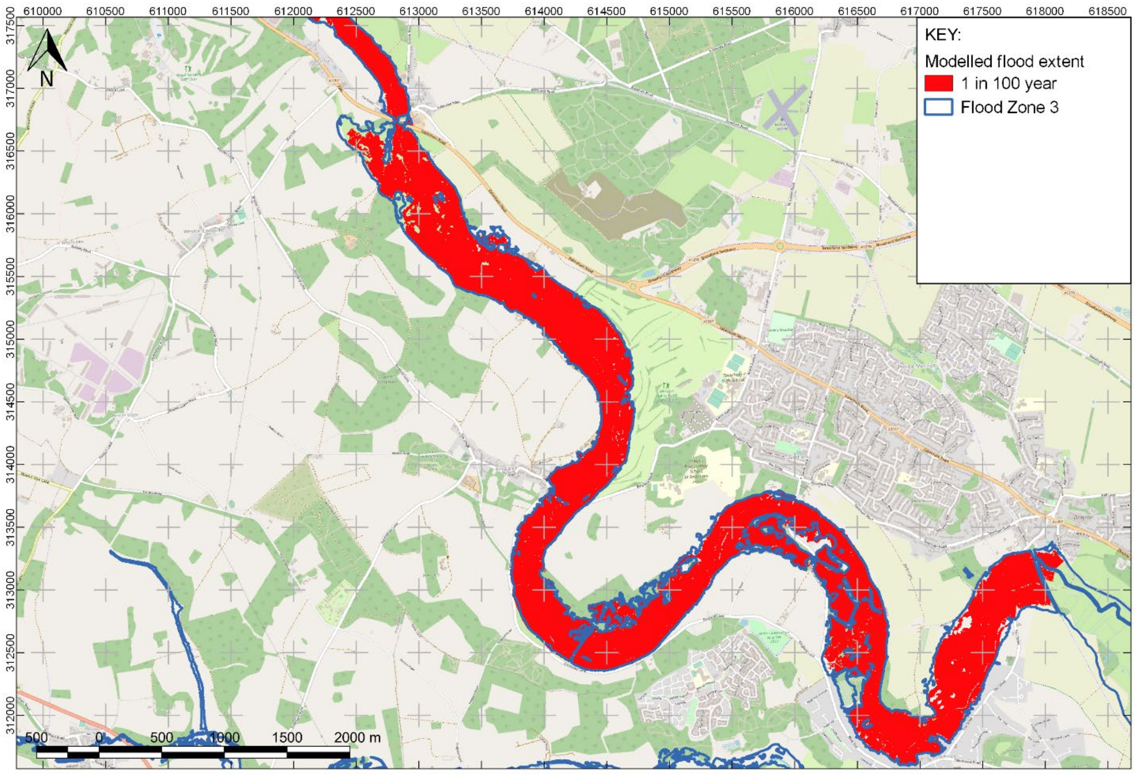
3.2 Model calibration

Flood zone comparison

3.2.1 Data for calibration is limited in this area, however a comparison has been made between the updated model results and the existing Flood Zones.

3.2.2 A comparison of the 1 in 100 annual probability event modelled flood outline and Flood Zone 3 outline shows generally good concordance, with the two datasets showing approximately the same area flooding. There are some areas of discrepancy, primarily near Attlebridge to the southwest of Fakenham Road, where the modelled flood extent is smaller than Flood Zone 3. **Figure 3-1** shows a comparison of the two flood outlines.

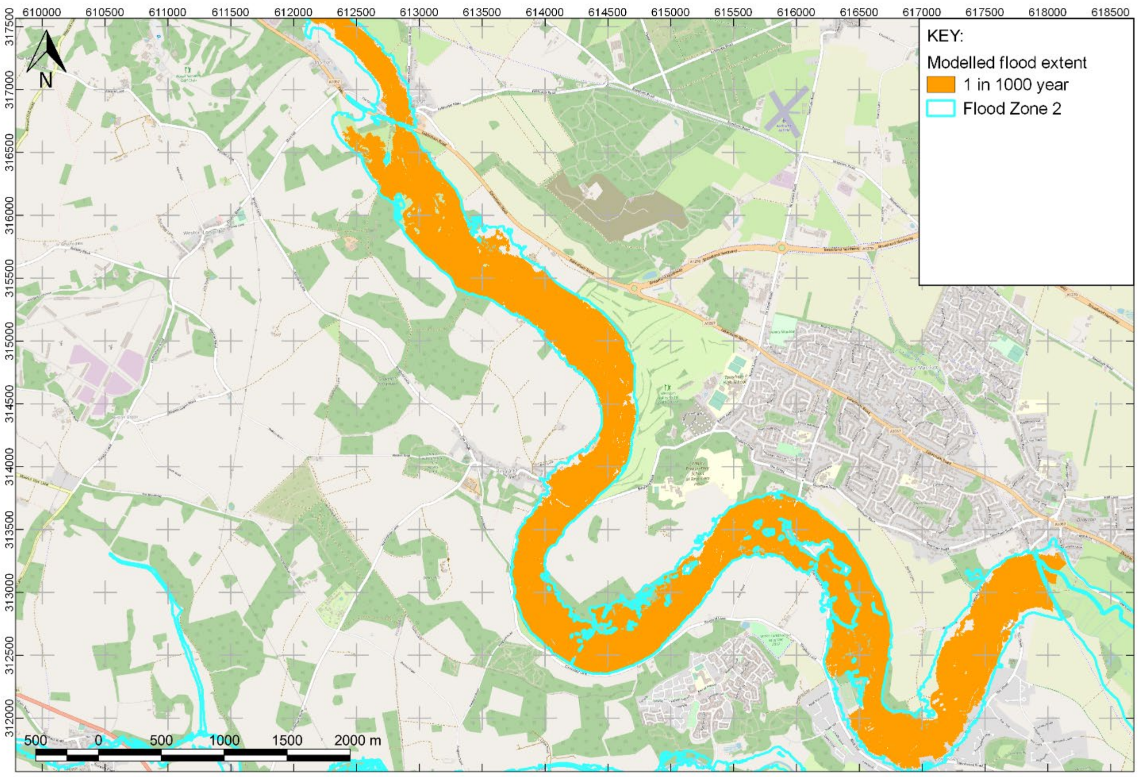
Figure 3-1 Comparison of modelled 1 in 100 annual probability event and Flood Zone 3



3.2.3 A comparison of the 1 in 1000 annual probability event modelled flood outline and Flood Zone 2 shows a similar concordance, with the most notable exception being adjacent to Fakenham Road as in the 1 in 100 annual probability event comparison.

3.2.4 **Figure 3-2** shows a comparison of the two flood outlines.

Figure 3-2 Comparison of modelled 1 in 1000 annual probability event flood extent and Flood Zone 2



3.2.5 It is understood that the flood zones have been derived from the 2017 1D only model results, by extrapolating water levels across the floodplain. This method of producing flood outlines is unlikely to take into consideration smaller barriers to flow paths in the floodplain that are more likely to be picked up in a linked 1D-2D flood model.

3.2.6 The general agreement between the two datasets indicates the floodplain in this location is relatively constrained and not overly sensitive to changes in the modelling approach.

Costessey mill flow comparison

3.2.7 The Costessey Mill river gauge is approximately 6.4 kilometres downstream of the area of interest. Flows in the model have been evaluated against the design flows that have been produced in the Hydrology study undertaken in 2017 by CH2M. The maximum flows derived at Costessey Mill for a range of return periods are given in **Table 3-1**.

Table 3-1 Peak flows at Costessey Mill from CH2M hydrology study

Annual Probability Event	Costessey Mill Peak Flows (m^3/s)
1 in 20	33.3
1 in 5	47.6
1 in 100	66.2
1 in 1000	99.7
1 in 100 plus 20%	79.4
1 in 100 plus 44%	95.3

3.2.8 In-channel flows have been extracted from the model at node location WENF2_9457u, the crump weir at Costessey Mill, and out of bank flows have been extracted from the floodplain adjacent. The modelled peak flows at this location, taken from both the updated WSP model and the incoming EA restoration model are given in **Table 3-2**.

Table 3-2 Peak flows at Costessey Mill extracted from the incoming EA model and updated model

Annual Probability Event	Incoming EA RST Model (m^3/s)	Updated WSP RST Model (m^3/s)
1 in 20	28.3	28.8
1 in 5	48.2	44.8
1 in 100	54.56	64.8
1 in 1000	Not applicable	83.29
1 in 100 plus 20%	Not applicable	84.31
1 in 100 plus 44%	Not applicable	103.32

3.2.9 At low return periods, both models provide a similar flow value at Costessey Mill. The flow is comparable to that produced in the CH2M hydrology study, potentially reflecting the smaller amount of floodplain storage in the lower return period events.

3.2.10 In the 1 in 20 annual probability event, the updated WSP model flow at Costessey Mill is lower than that in the hydrology and in the incoming EA model. In the larger return period events, the updated model matches the peak flows from the hydrology assessment fairly well. There is a larger discrepancy between the incoming model and the peak flows.

3.2.11 The assessment indicates that the updated WSP RST model produces flows at Costessey Mill that are generally in agreement with those produced using the Statistical method. The Environment Agency model produces generally similar flows, but appears to diverge from the peak flows derived in the hydrological assessment at larger return periods.

3.3 Baseline flood risk and extents

3.3.1 The updated model has been run for the 1 in 2, 5, 20, 50, 100, 100 + 11%, 100 + 20%, 100 + 44% and 1 in 1000 annual probability events. Baseline flood depth and extent maps for a range of modelled return periods are provided in the **Flood Risk Assessment Figures** (Document Reference: 3.12.02a).

Flood mechanism

3.3.2 The general flood mechanism represented in the model is presented below. It is important to recognise that the modelled design events are based on a single peak event, representative of FEH approaches. The River Wensum drains a chalk catchment and is heavily influenced by groundwater flows. Water levels are observed to remain elevated for months in the vicinity of the proposed scheme given these groundwater influences. There is therefore a difference between the design event response and the actual watercourse response. The details presented below represent the hydraulics of the area and the progression of inundation during the design flood.

3.3.3 For all modelled return periods, water is shown to exit the channel and flow onto the floodplain. This occurs early in the simulation time, at approximately 1 hour. The floodplain is relatively flat, allowing water to spread out across the fields adjacent to the channel.

3.3.4 A description of the 1 in 100 annual probability event flood mechanism is given below.

3.3.5 Water initially comes out of the Wensum channel approximately 1 hour into the model simulation at the upstream extent of the model, downstream of the railway embankment. The water then proceeds to flow across the floodplain to the south-east, approximately parallel to the River Wensum. After 5 hours, water from the River Wensum starts to spill out of the right bank onto the floodplain in the vicinity of the Proposed viaduct. Water rapidly spread across the floodplain due to the flat elevation of the topography in this area. Flood waters reach the full width of the floodplain within 15 hours of the simulation but it is around 30 hours into the simulation that the floodplain can be described as full. The floodplain continues to fill, with water lying against the numerous road and rail embankments through the floodplain. Flow is conveyed through these embankments via a series of bypass culverts and structures.

3.3.6 Both the Fakenham Road embankment and the embankment next to the camp site on Costessey Lane are not shown to overtop during the course of the simulation, and therefore the bypass structures are the primary control on flow conveyance between different parts of the floodplain. The Ringland Road embankment is overtopped on the left bank and right bank approximately 26 hours and 31 hours into the simulation respectively. The floodplain continues to fill, with the extent of the floodplain being constrained by the topography as it rises away from the flat, low lying areas. The residential area surrounding Costessey begins to be inundated by water approximately 33 hours into the simulation, with the rear gardens of properties along West End and The Street shown within the flood extent. Water levels in the floodplain peak at approximately 45-52 hours into the simulation. Water is relatively slow to recede, with water remaining on the floodplain until the end of the model simulation at 90 hours.

3.3.7 The majority of the floodplain consists of open fields, with sparse farm buildings and associated access tracks. Toward the downstream of the model, the floodplain becomes more urbanised as the River Wensum flows through Costessey. There are a number of properties at risk in this area in the larger flood events.

3.3.8 In the area of interest, no properties are currently shown to flood. Two properties, Low Farm on the right bank of the River Wensum and Old Hall Farm on the left bank, are located on the perimeter of the existing maximum flood extent and are not affected in events up to and including the 1 in 1000 annual probability event.

Comparison to previous modelling

3.3.9 The hydraulic modelling undertaken as part of this study is considered to provide an improved estimation of flood depth, extent and flow mechanisms in comparison to previous modelling that has been undertaken.

3.3.10 As detailed previously, the updates made to the model have significantly improved the model stability as evidenced by extracted flow and water level time series which show a significantly smoother profile with fewer instability fluctuations. The improvement to stability has allowed run parameters in the 1D model to be returned to default values, giving greater confidence in the model output as model tolerances are no longer inflated above typical values. Similarly, the model has been improved by altering the model schematisation according to typical model best practice such as ensuring that chainage lengths and cross section widths in the 1D domain are consistent with the distance between model nodes and the width of the channel in the 2D domain. This has made the model more consistent with the available survey data and therefore the schematisation is more representative of how the channel might behave in reality.

3.3.11 Structure data has been used to improve the representation of hydraulic structures throughout the model. This has included the addition of piers that were missing from numerous bridge structures, the incorporation of the culvert beneath Ringland Road, and improved schematisation of the bypass structure at Fakenham Road. The representation of afflux at bridges has been improved by the incorporation of piers, and similarly improving the representation of the bypass structures through the road embankments that cross the Wensum floodplain has allowed a better understanding of how these embankments impact the conveyance of flow in the floodplain.

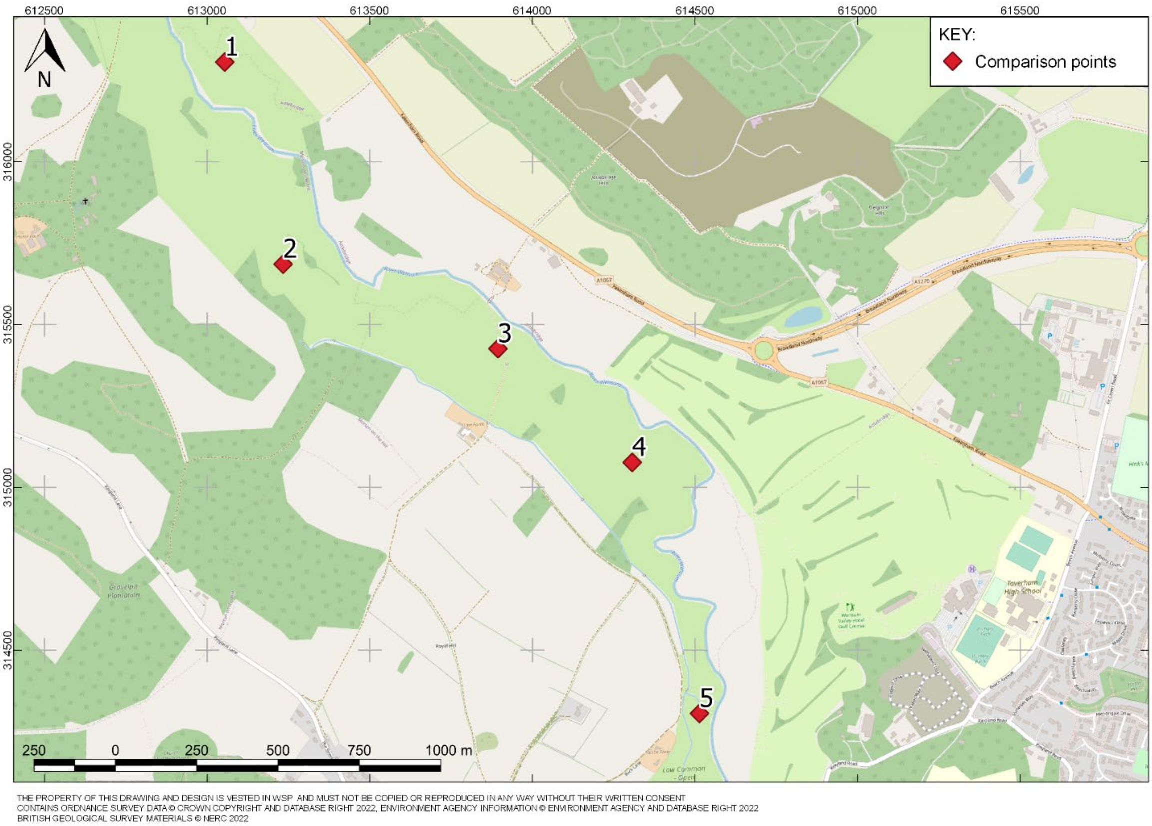
3.3.12 The latest available LIDAR data has been used to populate the model DTM. This data is likely to be the best representation of the elevation and geometry of both the floodplain and floodplain features, such as field drains and embankments. Further, the latest LIDAR data has been used to update the elevations of bank points at interpolate units. The bank points control the elevation at which water spills from the 1D channel representation to the 2D floodplain elevation, and therefore using the latest available data has improved the representation of this spill mechanism.

3.4 Sensitivity testing

3.4.1 Sensitivity testing has been undertaken to determine the variability in model output when model parameters, including roughness, inflow, structure coefficients and the downstream boundary are changed.

3.4.2 Various model sensitivity scenarios have been run for the 1 in 100 annual probability event. In order to quantify the sensitivity of the model, water levels at various locations, shown in **Figure 3-3**, have been extracted for comparison with the baseline model. These locations reflect a reasonable spread of locations in the floodplain at the location of the Proposed Scheme and upstream and downstream.

Figure 3-3 Point comparison locations



Roughness

3.4.3 Roughness values in the model have been retained from the existing model. Values have been verified against available photographs and satellite imagery and appear sensible. Roughness values in both the 1D and 2D models have been increased and decreased by 20% to determine the impact of changes in roughness to flood outlines and depths.

3.4.4 **Table 3-3** shows a comparison of water levels at various locations in the model when roughness values are varied.

Table 3-3 Roughness sensitivity water depth comparison

Point location	Baseline water depth (m)	Roughness +20% water depth (m)	Roughness -20% water depth (m)
1	0.37	0.42	0.31
2	0.76	0.84	0.66

Point location	Baseline water depth (m)	Roughness +20% water depth (m)	Roughness -20% water depth (m)
3	0.61	0.69	0.53
4	0.85	0.92	0.77
5	0.89	0.95	0.82

3.4.5 Increasing the roughness values causes an increase in water levels throughout the model domain. The increase in water level is generally 0.07 metres. There is an associated increase in flood extent throughout the model domain, however this is generally minor and no new major flow routes are observed. Adjacent to the scheme location, a similar increase in flood depth and extent is observed.

3.4.6 Decreasing the roughness values causes a decrease in water levels throughout the model domain. The decrease in water level is generally 0.07 metres. There is an associated decrease in flood extent. Adjacent to the scheme location, water levels and flood extents are marginally decreased.

3.4.7 The sensitivity tests indicate that the model is not unreasonably sensitive to variation in roughness values and the model behaves as expected when these parameters are altered. Variation of the roughness values does not result in a change to the assessment of flood risk at the scheme location.

Inflow

3.4.8 Typically in order to assess model sensitivity to increases in flow, inflow values are increased by 10% or 20%. As these values are similar to the climate change allowances for this area, the climate change model results have been used as a proxy for inflow sensitivity testing.

3.4.9 **Table 3-4** shows a comparison of water levels at various locations in the model when inflow values are varied.

Table 3-4 Flow sensitivity water depth comparison

Point location	Baseline water depth (m)	Inflow +11%	Inflow + 20%
1	0.37	0.42	0.44
2	0.76	0.85	0.88
3	0.61	0.69	0.73
4	0.85	0.93	0.96
5	0.89	0.96	0.99

3.4.10 The model responds sensibly to increases in inflow values, with a stepped increase in both flood levels and extents. The model remains stable as inflow values are increased, and mass balance error values remain below the +/- 1% threshold. Therefore, the model is not considered unduly sensitive to increases in inflow.

Structure coefficients

3.4.11 Spill structure coefficients in the 1D domain have been retained at a value of 1, as set in the original model. This value is considered appropriate to represent a bridge deck, which will have higher flow impedance than a man-made weir structure. The coefficient has been increased and decreased by 20% to test the sensitivity of the model to this parameter.

3.4.12 **Table 3-5** shows a comparison of water levels at various locations in the model when spill structure coefficient values are varied.

Table 3-5 Structure coefficient sensitivity water depth comparison

Point location	Baseline water depth (m)	Structure coefficients +20% water depth (m)	Structure coefficients -20% water depth (m)
1	0.37	0.37	0.37
2	0.76	0.76	0.76
3	0.61	0.61	0.61

Point location	Baseline water depth (m)	Structure coefficients +20% water depth (m)	Structure coefficients -20% water depth (m)
4	0.85	0.85	0.85
5	0.89	0.89	0.89

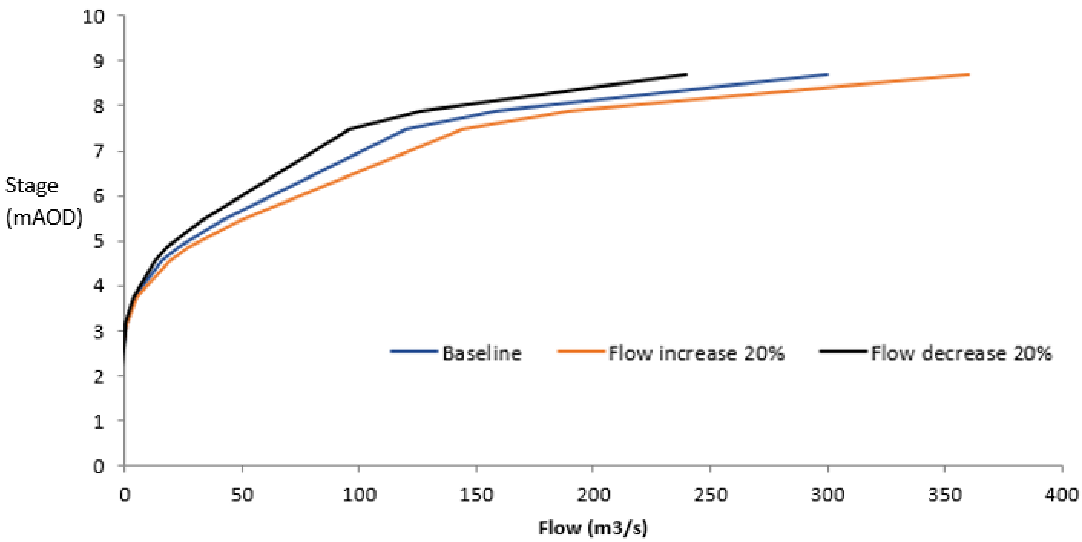
3.4.13 Variation of the spill structure coefficient does not have a significant impact on water levels and extents, and therefore the model is not considered sensitive to this parameter. This reflects the significant level of bypass of these structures in the floodplain.

Downstream boundary

3.4.14 The downstream boundary in the 1D model comprises a rating curve based on modelling results extracted from the updated 2016 Norwich model. This boundary has been retained from the previous modelling study undertaken by JacksonHyder and has not been altered. In the 2D domain, the downstream boundary comprises a series of HQ boundaries perpendicular to the channel with a ‘b’ gradient value of 0.001.

3.4.15 Flow values in the rating curve have been increased and decreased by 20% in order to undertake a sensitivity test. The ‘b’ gradient value in the 2D HQ boundaries have also been increased and decreased by 20%. **Figure 3-4** shows a comparison of the original rating curve and the ratings curves used within the sensitivity tests.

Figure 3-4 Comparison of rating curves used in downstream model boundary sensitivity test



3.4.16 **Table 3-6** shows a comparison of water levels at various locations in the model when the downstream boundary flow values are altered.

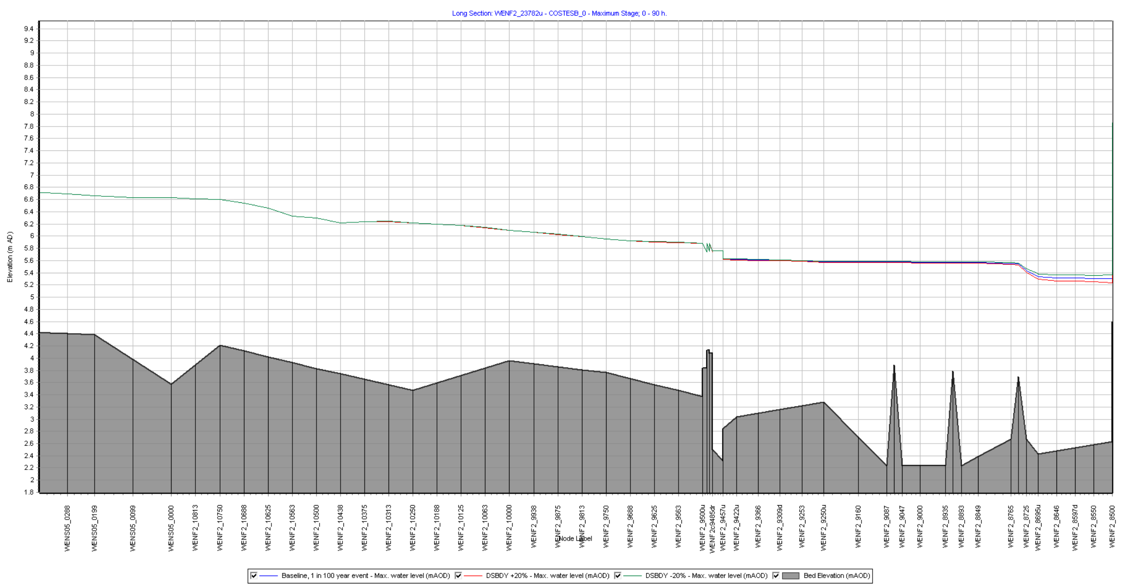
Table 3-6 Downstream boundary sensitivity water depth comparison

Point location	Baseline water depth (m)	Downstream boundary flow +20% water depth (m)	Downstream boundary flow -20% water depth (m)
1	0.37	0.37	0.37
2	0.76	0.76	0.76
3	0.61	0.61	0.61
4	0.85	0.85	0.85
5	0.89	0.89	0.89

3.4.17 The model results in the floodplain indicate that in the area of interest, changes to the downstream boundary do not impact water levels.

3.4.18 **Figure 3-5** shows a long section of maximum water levels in the 1D domain for both baseline and downstream sensitivity scenarios. The long section shows that variation in the downstream boundary results in water level fluctuations local to the boundary only. Approximately 1 kilometre upstream of the downstream boundary, the water levels are comparable to the baseline water level.

Figure 3-5 Long section for comparison of downstream boundary sensitivity results



3.4.19 Increasing the rating curve flow value results in a localised decrease in water levels, with a maximum decrease of 0.07 metres at the downstream boundary. The flood extent remains largely similar to the baseline extent, however there is a slight decrease in extent local to the downstream boundary.

3.4.20 Decreasing the rating curve flow value results in an increase in water levels upstream of the boundary. The maximum increase in water level of 0.07 metres occurs at the downstream boundary. The flood extent remains largely similar to the baseline extent, however there is a slight increase in extent local to the downstream boundary.

3.4.21 In both sensitivity tests, the changes in water level do not propagate upstream to the area of interest. Therefore, variation in the downstream boundary is unlikely to impact the assessment of flood risk at the scheme location. The model behaves as expected when the downstream boundary is altered, and therefore the model is not considered unduly sensitive to changes in this parameter.

Taverham mill restoration

3.4.22 It is understood that restoration works are being considered in order to improve the ecological condition of the River Wensum. One of the potential units for restoration, Unit 53, comprises the section of the watercourse and surrounds between Lenwade Mill and Taverham Mill.

3.4.23 The Feasibility and Environmental Scoping Assessment for River Unit 53 has been produced in January 2010 by Atkins. The report states, "*The reach is particularly affected by the Taverham Mill structures and the channel widening and deepening that accompanied mill development and subsequent flood defence maintenance. Large sections are straightened, dredged, with embankments, and ponded backwater conditions affect the whole reach.*" (Implementation River Unit 53 Lenwade Mill to Taverham Mill, Feasibility & Environmental Scoping Assessment", January 2020, Atkins)

3.4.24 From discussion with the Environment Agency, it appears likely that the restoration works will focus on addressing the impoundment of water at the mill structure, which in turn is likely to impact water levels on the River Wensum. Due to the location of the planned Norwich Western Link road scheme, a change in water level downstream may impact the assessment of flood risk at the location of interest.

3.4.25 The main hydraulic control within the mill complex is the weir structure on the main Wensum channel, and therefore any works at Taverham Mill are likely to address this structure specifically. A sensitivity test model has been run with an additional channel connecting the main Wensum channel to the central mill channel, downstream of the triple sluice structure. This channel allows water to bypass the weir structure. Due to the lack of available concrete information, the sensitivity test is extremely high level and has been designed to provide a conservative estimate of how the Taverham Mill works are likely to impact water levels and velocities at the area of interest.

3.4.26 The model results indicate that immediately upstream of Taverham Mill, at node WENF2_14250, there is a 12mm reduction in maximum water level in the sensitivity test model when compared to the updated restoration model. This change in water level does not propagate far upstream, and by the scheme location at node WENF2_20500 there is no difference in water levels between the two model scenarios. Similarly, the velocities at the scheme location remain the same between the two scenarios.

3.4.27 Based on the results of the sensitivity test, it is considered that the proposed works at Taverham Mill will have a minimal impact on water levels and velocities at the area of interest. Therefore, the updated restoration model will be used to inform both the baseline and scheme flood risk and further consideration of the "*future baseline*" scenario will not be undertaken at this stage.

4 Proposed Scheme Hydraulic Modelling

4.1 Overview

4.1.1 Full details of the Proposed Scheme are provided in the **Flood Risk Assessment** (Document Reference: 3.12.02). The hydraulic modelling has assessed the impact of both the Proposed Scheme and the Proposed Temporary Works.

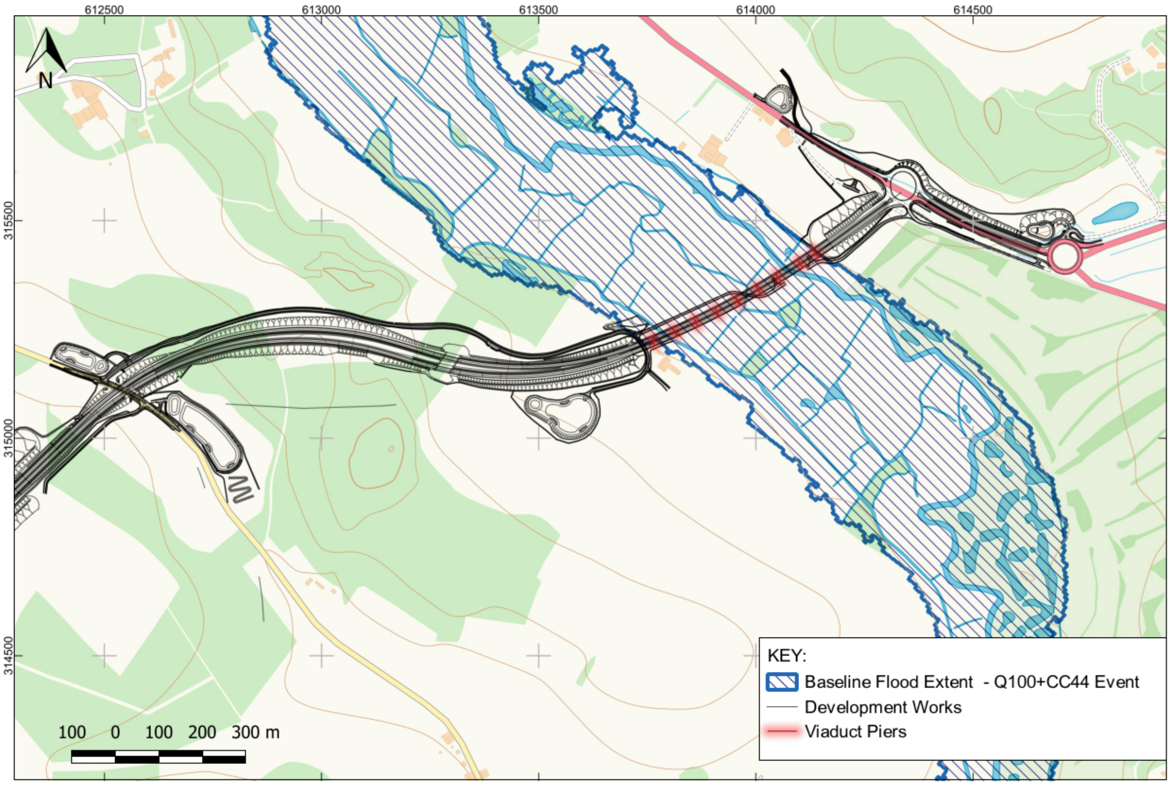
4.2 Permanent works

4.2.1 Within the vicinity of the River Wensum floodplain the Proposed Scheme Design consists of the following:

- Piers carrying the viaduct across the Wensum will sit in the floodplain. The Proposed Scheme includes for 9 sets of 3 circular piers 2.7 metres in diameter.
- Left and right bank viaduct abutments. These are located outside of the 100yr + 44% flood event extent.
- A maintenance track runs along the upstream face of the viaduct from the right bank crossing to the downstream face midway across the floodplain and continuing to a turning head 40 metres from the right bank of the River Wensum. This will also become Non-motorised User (NMU) Route 10a.
- A second maintenance track runs along the downstream face of the viaduct from the left bank to the left bank of the River Wensum

4.2.2 **Figure 4-1** provides an overview of the piers, abutments and maintenance track.

Figure 4-1 Details of the Proposed Scheme in the vicinity of the River Wensum



4.2.3 The abutments and access tracks have been incorporated into the model as ASCII grids developed from the 3D model of the Proposed Scheme.

4.2.4 Piers have been represented as thin break lines despite the fact that the Proposed Scheme consists of 3 circular piers. This approach has been preferred over using flow constriction losses within each model cell containing the piers which reflects the methodology outlined in Modelling Bridge Piers in 2D using TUFLOW (Modelling Bridge Piers in TUFLOW pdf). The angle of approach for floodplain flow means that the pier losses need to be treated individually rather than as a connected column and as such a structure wide loss approach is not appropriate. The representation using break lines is perhaps conservative but allows flows to be diverted through the openings between the piers and can be considered to allow for the risk of debris build up on the piers.

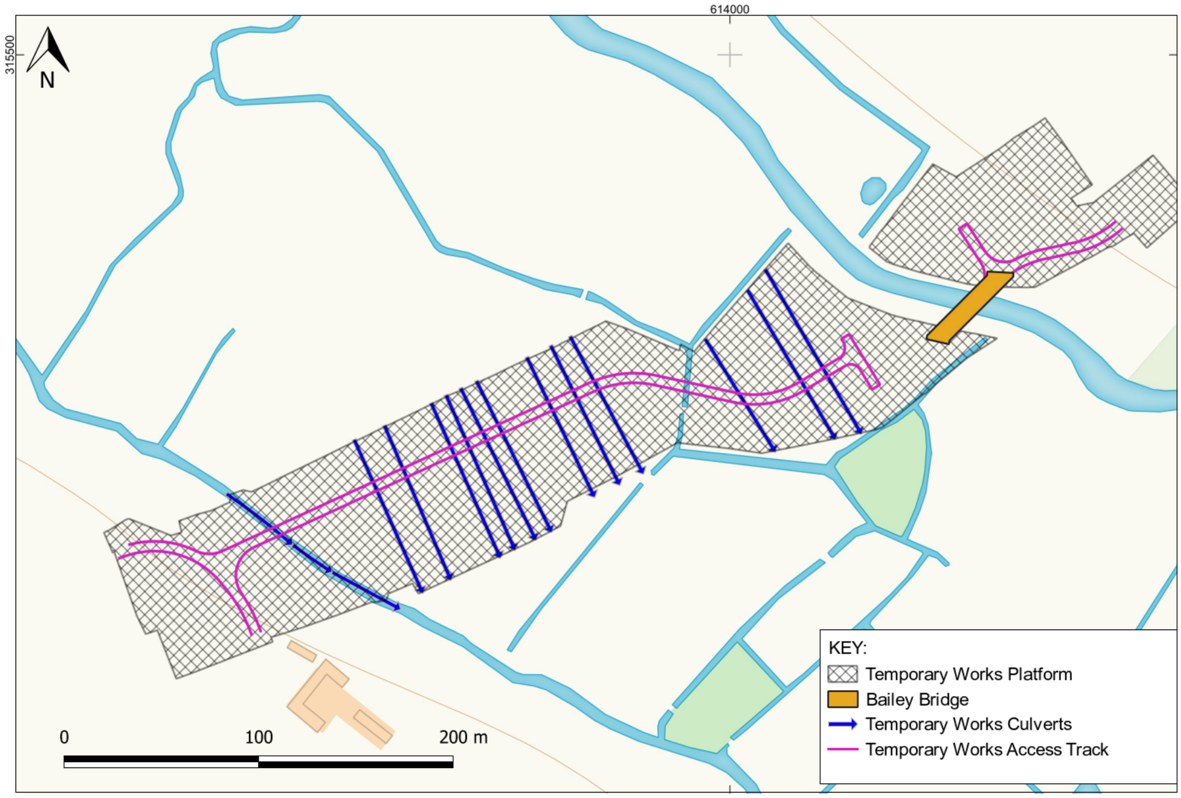
4.2.5 Floodplain compensation requirements are limited, associated with access tracks only. A conservative approach has been adopted for the hydraulic modelling and floodplain compensation areas are excluded from the model.

4.2.6 In addition to the permanent works described above, the temporary works consists of the following within the vicinity of the River Wensum:

- A raised working platform extending across the full width of the River Wensum floodplain constructed to a height sufficiently high to avoid overtopping in all flood events.
- A culvert to provide continued connectivity for WC5.
- Flood relief culverts within the River Wensum floodplain beneath the Temporary Works Platform to reduce the risk of flooding upstream.
- A bailey bridge to provide connectivity between the Temporary Works Platform on either side of the River Wensum.

4.2.7 **Figure 4-8** provides an overview of the Temporary Works Platform, conveyance and floodplain culverts and the bailey bridge.

Figure 4-2 Details of the temporary works in the vicinity of the River Wensum



4.3 Proposed scheme results

4.3.1 Details of the Proposed Scheme and the impacts during construction and operation are presented in the **Flood Risk Assessment** (Document Reference: 3.12.02) and are not duplicated here. The relevant sections of the FRA are as follows:

- **Section 4.2** presents the fluvial flood risk impacts from the River Wensum during construction.
- **Section 4.3** presents the reservoir flood risk impacts in the Wensum Valley during construction.
- **Section 5.2** presents the fluvial flood risk impacts from the River Wensum during operation.

- **Section 5.4** presents the reservoir flood risk impacts in the Wensum Valley during operation.
- **Flood Risk Assessment Figures** (Document Reference: 3.12.02a) presents the flood maps relevant to the assessment within the Wensum Valley.

Flooding mechanism

4.3.2 A description of the 1 in 100 annual probability event flood mechanism for the Temporary Works Proposals and the Proposed Scheme are given below.

Temporary Works Proposals

4.3.3 As for the baseline scenario water initially comes out of the Wensum channel approximately 1 hour into the model simulation at the upstream extent of the model, downstream of the railway embankment. The Temporary Works Proposals prevent water spilling onto the floodplain beneath the footprint of the viaduct after 5 hours. By 15 hours there is a clear change in the flooding mechanism as more water spills out upstream of the Temporary Works Platform and is conveyed towards the downstream via the culverts beneath the Temporary Works Platform. In the vicinity of the Proposed Scheme there is a reduced flood extent downstream of the Temporary Works Platform. Around 30 hours into the simulation the floodplain is consistently full upstream and downstream of the Temporary Works Platform and more comparable to the baseline scenario. Around the peak of the event water levels are sufficiently higher upstream of the Temporary Works Platform for there to be an observable difference in flood extent. Downstream of the Temporary Works Platform the flood extents are much more consistent with the baseline. Difference maps are presented in the **Flood Risk Assessment Figures** (Document Reference: 3.12.02a).

Proposed Scheme

4.3.4 The flooding mechanism for the Proposed Scheme is equivalent to the baseline scenario. There are very minor observable differences in the flood extents between 5 hours and 15 hours into the simulation as flood waters work their way across the floodplain and around the piers. By 35 hours the differences are essentially limited to velocity profiles around the locations of the piers. At the peak of the event the difference between the baseline and the proposed flood extents are minimal. Difference maps are presented in the **Flood Risk Assessment Figures** (Document Reference: 3.12.02a).

4.4 Sensitivity testing

4.4.1 The sensitivity testing methodology outlined in **Section 3.4** has been undertaken on the Proposed Scheme and Temporary Works models to understand the potential variability in model outputs when the model parameters roughness, inflow and structure coefficients.

4.4.2 The sensitivity testing on structure coefficients has focussed on the new structures associated with the Proposed Scheme and Temporary Works rather than existing structures given that these are typically located some distance from the Proposed Scheme.

4.4.3 In addition tests have been included to understand the implication of shading beneath the River Wensum viaduct and proposals for environmental enhancements in the floodplain upstream of the Proposed Scheme.

4.4.4 The downstream boundary has not been reassessed as the findings from the baseline sensitivity tests indicate no impact at the location of the Proposed Scheme.

Roughness

4.4.5 Roughness values in both the 1D and 2D models have been increased and decreased by 20% to determine the impact of changes in roughness to flood outlines and depths.

4.4.6 **Table 4-1** and **Table 4-2** show a comparison of water levels at various locations in the model when roughness values are varied for the Proposed Scheme and Temporary Works model scenarios respectively.

Table 4-1 Roughness sensitivity water depth comparison for Proposed Scheme

Point location	Proposed Scheme water depth (m)	Roughness +20% water depth (m)	Roughness -20% water depth (m)
1	0.37	0.42	0.31
2	0.76	0.84	0.67
3	0.61	0.69	0.53
4	0.85	0.92	0.77
5	0.89	0.95	0.82

Table 4-2 Roughness sensitivity water depth comparison for Temporary Works

Point location	Temporary Works water depth (m)	Roughness +20% water depth (m)	Roughness -20% water depth (m)
1	0.39	0.46	0.32
2	1.08	1.16	1.00
3	1.00	1.08	0.94
4	0.84	0.91	0.76
5	0.89	0.94	0.82

4.4.7 Increasing the roughness values causes an increase in water levels throughout the model domain. The increase in water level ranges from 0.06 to 0.09 metres. There is an associated increase in flood extent throughout the model domain, however this is generally minor and no new major flow routes are observed. Adjacent to the scheme location, a similar increase in flood depth and extent is observed.

4.4.8 Decreasing the roughness values causes a decrease in water levels throughout the model domain. The decrease in water level ranges from 0.04 to 0.09 metres. There is an associated decrease in flood extent. Adjacent to the scheme location, water levels and flood extents are marginally decreased.

4.4.9 The sensitivity tests indicate that the model is not unreasonably sensitive to variation in roughness values and the model behaves as expected when these parameters are altered. Variation of the roughness values does not result in a change to the assessment of flood risk at the scheme location.

Inflow

4.4.10 Typically in order to assess model sensitivity to increases in flow, inflow values are increased by 10% or 20%. As these values are similar to the climate change allowances for this area, the climate change model results have been used as a proxy for inflow sensitivity testing.

4.4.11 **Table 4-3** and **Table 4-4** show a comparison of water levels at various locations in the model when inflow values are varied for the Proposed Scheme and Temporary Works model scenarios respectively.

Table 4-3 Flow sensitivity water depth comparison for Proposed Scheme

Point location	Proposed Scheme water depth (m)	Inflow +11%	Inflow + 20%
1	0.37	0.42	0.44
2	0.76	0.85	0.88
3	0.61	0.70	0.73
4	0.85	0.93	0.96
5	0.89	0.96	0.99

Table 4-4 Flow sensitivity water depth comparison for Temporary Works

Point location	Temporary Works water depth (m)	Inflow +11%	Inflow + 20%
1	0.39	0.47	0.50
2	1.08	1.19	1.24
3	1.00	1.08	1.13

Point location	Temporary Works water depth (m)	Inflow +11%	Inflow + 20%
4	0.84	0.92	0.96
5	0.89	0.96	0.99

4.4.12 The model responds sensibly to increases in inflow values, with a stepped increase in both flood levels and extents. The model remains stable as inflow values are increased, and mass balance error values remain below the +/- 1% threshold. Therefore, the model is not considered unduly sensitive to increases in inflow.

Structure coefficients

4.4.13 Sensitivity testing of structure coefficients has been approached differently for the Proposed Scheme and Temporary Works models than the approach presented for the baseline. The tests described reflect the new structures installed as a result of the Proposed Scheme.

4.4.14 For the Proposed Scheme the representation of the piers is considered to be reasonably conservative, as it does not allow flow between the piers. Sensitivity to this approach has been assessed by modelling each of the piers as flow constrictions as a proportion of the cell size within the cell that each sits. As noted previously, the angle of approach of flows means that the methods indicated in Modelling Bridge Piers in 2D using TUFLOW do not translate well to this location. This sensitivity test reflects a reduction in the losses associated with the piers.

4.4.15 For the Temporary Works sensitivity testing has focussed on the parameters associated with the various culverts beneath the Temporary Works Platform. A review of the operation of these structures during the 1 in 100 annual probability event indicates all are downstream controlled at the event peak. The impact of the hydraulic efficiency of these structures has been assessed by increasing and decreasing the pipe roughness Manning's value by 0.005

from 0.02 and increasing and decreasing the entry loss coefficient by 0.2 from 0.5.

4.4.16 **Table 4-5** and **Table 4-6** show a comparison of water levels at various locations in the model when structure coefficients are varied for the Proposed Scheme and Temporary Works model scenarios respectively.

Table 4-5 Structure coefficient sensitivity water depth comparison for Proposed Scheme

Point location	Proposed Scheme water depth (m)	Pier losses as flow constrictions water depth(m)
1	0.37	0.37
2	0.76	0.76
3	0.61	0.61
4	0.85	0.85
5	0.89	0.89

Table 4-6 Structure coefficient sensitivity water depth comparison for Temporary Works

Point location	Temporary Works water depth (m)	Increase in culvert roughness and entry losses water depth (m)	Decrease in culvert roughness and entry losses water depth (m)
1	0.39	0.40	0.39
2	1.08	1.11	1.09
3	1.00	1.01	1.01
4	0.84	0.84	0.84
5	0.89	0.89	0.89

4.4.17 There is no variation in depths at the points assessed when changing the representations of piers in the model. This is attributed to the very localised nature of the change in water levels associated with the piers compared to the locations of the sensitivity assessment location points. It does however confirm that the impact of the piers remains localised irrespective of the approach adopted.

4.4.18 Variation of the structure coefficients does not have a significant impact on water levels and extents, and therefore the model is not considered sensitive to this parameter. Flows through the culverts do increase and decrease with the changes however these changes are balanced by a similar opposite change in flows at the bailey bridge. The changes then rebalance the distribution of flows between the structures but generally have little impact on the overall flows crossing the Temporary Works Platform.

Shading

4.4.19 Sensitivity testing of the impact of shading resulting from the construction of the viaduct has been assessed by applying a localised roughness patch that reflects the area of impact within the **Solar Exposure Analysis** (Document Reference: 3.10.37). The test has decreased the roughness within this area to a Manning's value of 0.035 from a typical value of 0.04.

4.4.20 **Table 4-7** show a comparison of water levels at various locations in the model when a reduction in vegetation cover beneath the viaduct is assumed.

Table 4-7 Shading sensitivity water depth comparison for Proposed Scheme

Point location	Proposed Scheme water depth (m)	Shading sensitivity water depth(m)
1	0.37	0.37
2	0.76	0.75
3	0.61	0.60
4	0.85	0.85
5	0.89	0.89

4.4.21 The results show there are minor localised impacts only. These are constrained to approximately 1 kilometre in distance upstream of the Proposed Scheme and 200 metres in distance downstream of the Proposed Scheme.

Environmental Mitigation

4.4.22 Sensitivity testing of the impacts of the environmental mitigation measures has been assessed by applying a localised roughness patch that reflects the footprint of grassland creation within the floodplain upstream of the Proposed Scheme. A Manning's value of 0.055, increased from a typical value of 0.04, has been applied in this area. In addition, roughness along the banks of the channel covering the reach between WENF2_22000 and WENF2_21627 has been increased to reflect the riparian planning along this reach. A Manning's value of 0.06, increased from 0.05, has been applied. Finally the length of the channel at WENF2_22000 has been increased by 60 metres to reflect the reduced gradient associated with a new meander in this location.

4.4.23 In this instance an additional comparison in water levels has been completed upstream of the A1067 Fakenham Road Bridge. This is the location of the commercial and residential receptors. Furthermore, given the importance of this assessment for the FRA, the sensitivity test has also been completed for the 1 in 100 plus 44% and 1 in 1000 annual probability events.

4.4.24 **Table 4-8** show a comparison of water levels at various locations in the model when the environmental mitigation proposals are assumed to be in place.

Table 4-8 Environmental mitigation sensitivity water depth comparison for Proposed Scheme in the 1 in 100 annual probability event

Point location	Proposed Scheme water depth (m)	Environmental enhancements sensitivity water depth(m)
1	0.37	0.40
2	0.76	0.76
3	0.61	0.61
4	0.85	0.85
5	0.89	0.89
Upstream A1067 Fakenham Road	1.13	1.13

Table 4-9 Environmental mitigation sensitivity water depth comparison for Proposed Scheme in the 1 in 1000 annual probability event

Point location	Proposed Scheme water depth (m)	Environmental enhancements sensitivity water depth(m)
1	0.47	0.49
2	0.93	0.93
3	0.77	0.77
4	1.00	1.00
5	1.02	1.02
Upstream A1067 Fakenham Road	1.46	1.46

Table 4-10 Environmental mitigation sensitivity water depth comparison for Proposed Scheme in the 1 in 100 plus 44% annual probability event

Point location	Proposed Scheme water depth (m)	Environmental enhancements sensitivity water depth(m)
1	0.49	0.53
2	0.97	0.97
3	0.82	0.82
4	1.05	1.05
5	1.07	1.07
Upstream A1067 Fakenham Road	1.53	1.53

4.4.25 The results show that with changes to the River Wensum and channel consistent with the changes presented in this sensitivity test the proposed environmental enhancements will not have an impact upstream of the A1067 Fakenham Road Bridge. Initial assessments indicated significant changes within the Wensum channel, equivalent to an increase in roughness to 0.06 for long stretches, could potentially have an impact. The proposals do not currently reflect such a change and these should continue to be avoided.

5 Model Limitations

5.1.1 The following presents outstanding limitations noted with the hydraulic model:

- The cross section spacings downstream of Taverham Mill remain small in comparison to the updated reaches upstream of Taverham Mill. In particular there are section spacings as small as 5 metre through the restoration reach. These small reaches cause local instabilities in the model through this reach. The presence of Taverham Mill means these instabilities do not propagate upstream to the area of interest. Given the whole point of using the restoration model was to make sure the proposed restoration changes were considered as part of this assessment, it has been deemed appropriate to leave this section of the model unchanged and accept the restoration design modelling as a limitation.

- There are undulations in bed levels through the Ringland Road Bridge and for a reach of approximately 1 kilometres downstream of this structure. There are no obvious structures through this reach. The bed levels have been reviewed against surveys and these reflect the data available and as such have been left unchanged in the model.

- Buildings within the model have been represented using changes in roughness only. This approach may not deflect flows around buildings to the same degree as alternative approaches to building representation. The River Wensum floodplain is predominantly rural with very few buildings present and as such buildings within the floodplain are not a dominant factor in predicting floodplain flow routes. For this reason the approach is noted as a limitation only.