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NORTH HYKEHAM RELIEF ROAD
NHRR HYDRAULIC MODELLING REPORT

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NHRR HYDRAULIC MODELLING REPORT

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1. INTRODUCTION

1.1 Overview

1.1.1 Lincolnshire County Council, as Highway Authority, is seeking to obtain planning permission for the North Hykeham Relief Road (NHRR), which will complete the last section of the ring road around Lincoln, linking the A15, Lincoln Eastern Bypass (LEB), with the A46, Western Bypass. The NHRR (the 'Proposed Scheme') will also form part of the Lincolnshire Coastal Highway.

1.1.2 A key constraint to the NHRR is the crossing of the river Witham and floodplain, designated as being within Flood Zones 2 and 3 in accordance with the National Planning Policy Framework (NPPF)[1]. All development within Flood Zones 2 or 3 requires a Flood Risk Assessment (FRA). Ramboll were commissioned by Balfour Beatty Construction to undertake an FRA for the NHRR. To support the FRA, hydraulic modelling of the River Witham was necessary to determine potential risks from and to the Proposed Scheme.

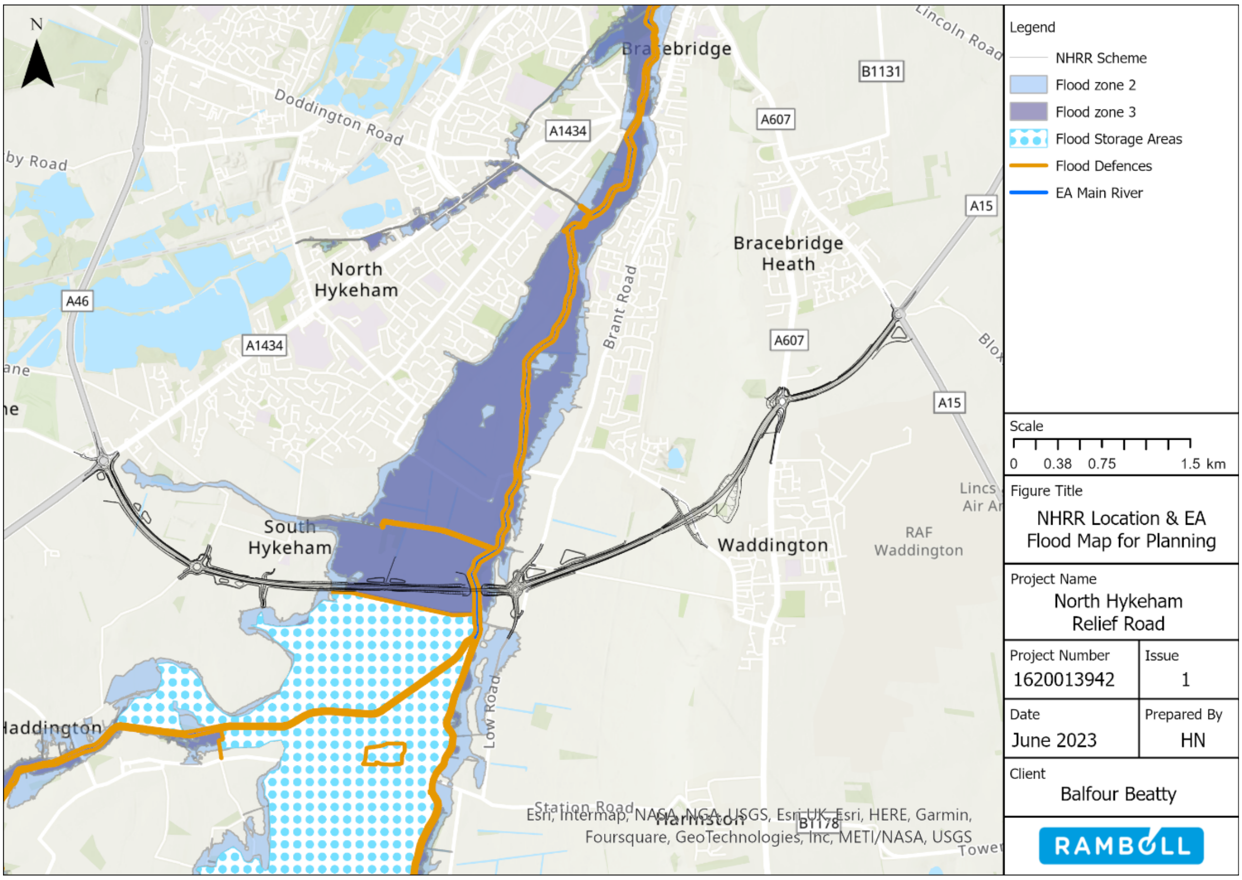

Figure 1-1: NHRR Location and EA Flood Map for Planning

1.1.3 An existing Environment Agency (EA) hydraulic model to determine Flood Zones for the area was developed using a 1D-2D Infoworks RS model, last updated in 2015 by Mott Macdonald[2]. The EA are in the process of building a new model using 1D-2D Flood Modeller Pro-TUFLOW. Unfortunately, the updated model would not be available over the timescales required for NHRR so it was agreed with the EA that Ramboll would complete their own model conversion of the existing Infoworks RS model to assess the impacts of the NHRR scheme. The details of Ramboll's consultation with the EA including this agreement are presented in the Hydraulic Modelling Design Input Plan (October 2022).

[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005759/NPPF_July_2021.pdf
[2] Upper Witham Model Improvements Study, Hydraulic Modelling Report, July 2015, Mott Macdonald (Environment Agency)

1.1.4 Consultation with the EA identified that the key concern relating to flood risk is how the NHRR scheme could impact existing flood risk management arrangements. Specifically, assessing the potential impact to/from the proposed NHRR structure should existing flood defences fail or be overtopped in an exceedance event.

1.2 Aims

1.2.1 There are two aims for this study:

- Assess the impact to/from the proposed NHRR structure should the existing flood storage embankment and flood levees fail or be overtopped in an exceedance event; and
- Assess the impact of the NHRR on existing flood risk in the River Witham floodplain.

1.3 Objectives

1.3.1 To satisfy the study aims, the objectives of this study are to:

- Convert the existing EA Infoworks RS 1D hydraulic model for the area to a 1D-2D ESTRY-TUFLOW model.
- Utilise existing EA hydrology for the hydraulic modelling study.
- Use the converted 1D-2D ESTRY-TUFLOW hydraulic model to:
  - Assess the impact of the NHRR on the existing flood risk at the river Witham floodplain; and
  - Assess the impact of flood defence breach and overtopping to the NHRR and existing flood storage embankments.
- Develop a technical report describing the hydraulic modelling methodology, modelling results and an assessment of the flood risk impacts of the NHRR.

2. KEY STAKEHOLDERS

2.1 Environment Agency

2.1.1 The EA highlighted several items that should be considered with the NHRR scheme and how it could impact existing flood risk management arrangements. The key concern is any potential impact to/from the proposed NHRR structure should the existing flood storage embankment fail or be overtopped in an exceedance event. The EA posed the following questions:

- Does flood water get trapped behind the proposed NHRR?
- Might the various embankments on the floodplain (existing and proposed) be eroded thus affecting their integrity?
- Can the exceedance and breach flow be conveyed under the NHRR without risk to road users and exacerbating erosion of floodwater-retaining embankments?
- How many/what size of flood conveyance culverts will be required through the NHRR embankment?

2.1.2 Table 2-1 outlines EA consultation items raised during the meeting of the 20th May 2022[3].

Table 2-1: EA items for consideration of flood risk for the NHRR

Item	Comments
Residential property	Residential estates in North Hykeham are slightly raised and the EA are confident that these are not currently at risk of fluvial flooding.
Commercial property	There is only one property in the 0.1% AEP flood zone downstream of the storage area (the Internal Drainage Board (IDB) depot).
NHRR level	The road would not need to be too high above existing ground level for flood resilience but could be higher if required for other reasons.
Flood compensation storage	The flat topography of the area means the floodplains are passive and are only in play during a major incident. The NHRR scheme is therefore not anticipated to make a material difference to flood storage. There would therefore be no requirement to provide compensatory storage, noting that compensatory storage was not required for the Lincoln Eastern Bypass (LEB) scheme.
New Witham bridge	The recently completed LEB included a bridge over the river Witham further downstream. The EA envisage a similar design for the proposed NHRR bridge. While the impacts of the NHRR bridge do need to be considered, they are not likely to be the main focus with regard to flood risk impacts.

2.2 Lincolnshire County Council

2.2.1 Lincolnshire County Council (LCC) stated[3] that farmland severed by the NHRR may need to be reconnected and underpasses may be an option. The underpasses could also have a dual purpose of conveying flood flows.

[3] 2022-05-20 NHRR Water Environment Meeting Minutes - EA-BB-Ramboll.pdf

2.3 Internal Drainage Board

2.3.1 The IDB are key stakeholders in the NHRR scheme. The IDB provided specific information to the EA on their requirements, conveyed to Ramboll during early consultation with the meeting with the EA on the 20th May 2022[3], stating that the IDB ditches should be continued under/through the NHRR embankment to convey the IDB channels on either side of the River Witham embankment parallel to the river. Figure 2-1 shows the key IDB drains along the proposed NHRR route.

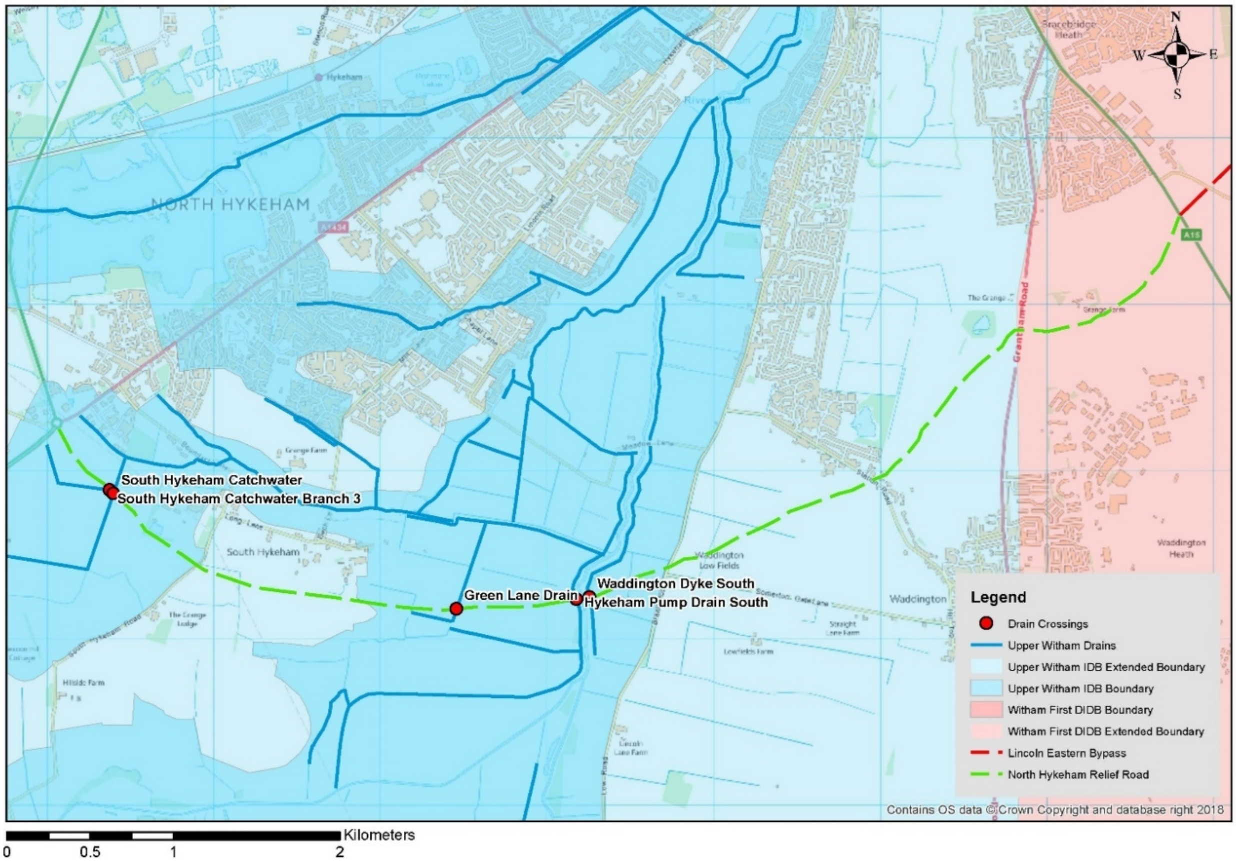

Figure 2-1: Key IDB Drains along the NHRR rooute

2.3.2 During a subsequent meeting between Ramboll, the EA and IDB (on the 17th August 2022), the IDB outlined the drainage network surrounding the scheme. From this, it was agreed that two separate models would be used to assess the impact of the NHRR scheme:

- A model to assess the overall flood risk relating to the main River Witham. This model will assess the possible impact to the integrity of the Main River flood defences and the impact following a flood defence breach. The approach for this modelling will be outlined in this report.
- A model to assess the impact of the NHRR scheme to the IDB drainage network. This will be completed by the team working on drainage design and is not included in this reporting.

3. PROJECT BACKGROUND

3.1 Existing EA Hydraulic Model

3.1.1 The current EA hydraulic model for the area is the Upper Witham 1D/2D Infoworks model (2015) and covers a very large catchment area, encompassing most of the Upper Witham to near Grantham. The downstream boundary is in the centre of Lincoln at the confluence with the River Till. The EA has stated that the current model's downstream boundary contains a notable ±0.5 m error.

3.1.2 The EA are in the process of updating of the Upper Witham model. It is understood that the EA model update will:

- Create the model using Flood Modeller Pro (FMP)-TUFLOW;
- Automate the control structures;
- Incorporate some survey that has already been undertaken from the storage area to the downstream boundary; and
- Revisit the flows in the model but not necessarily update them.

3.1.3 The EA is hopeful that the update can be completed in 2023. However, it was clear the update would not be available over the timescales required for the NHRR project. To expedite the NHRR hydraulic modelling process, the EA has shared details of the main errors in the existing model so that Ramboll could use the existing hydraulic model to assess the impact of the NHRR, completing updates and following best practice.

3.2 Existing EA Hydrological Approach

3.2.1 The EA's 2015 model included the calculation of new hydrological model inflows, documented in a hydrology report[4]. The hydrology report describes the derivation of design hydrology for fluvial inflows, which formed the boundary conditions for the hydraulic model for assessing flood risk within the Upper Witham Catchment, summarised in this section.

3.2.2 Design flow estimates were calculated using the FEH Statistical Method, with the Hybrid ReFH approached used for the 1 in 500 year (0.2%) and 1 in 1,000 year (0.1%) Annual Exceedance Probability (AEP) events. These design flow estimates were used as target flows for the Upper Witham – Lincoln model, with ReFH inflows scaled accordingly.

3.2.3 Downstream of the target flow locations, no flood frequency analysis for the purpose of target flow estimation was possible because of the influence of the Witham, Brant and Till Washlands on attenuating floods through Lincoln. For these catchments, no scaling of the ReFH inflow hydrographs was carried out and inflows from the tributaries were phased to ensure coincident peaks along the main River Witham.

3.2.4 At the upstream limit of the Upper Witham – Lincoln model, a standardised hydrograph profile, taken from an historical flow event from November 2000 was scaled to the derived target flow for Claypole and used as the design inflow for the catchment upstream of Claypole.

3.2.5 ReFH model parameters: Time to Peak, Baseflow Lag and Baseflow Recharge were optimised at each of the gauge locations for the four calibration and verification events. These optimised parameters were used to enhance the ReFH model at the ungauged catchments for design and calibration events.

3.3 Existing Flood Storage Arrangements

3.3.1 The EA outlined the current flood storage arrangements operating in the vicinity of the scheme during the previously-described meeting of 20th May 2022. Figure 3-1 shows the existing flood risk management arrangement in the vicinity of the NHRR.

[4] Upper Witham Model Improvements Study, Hydrology Report, July 2015, Mott Macdonald (Environment Agency)

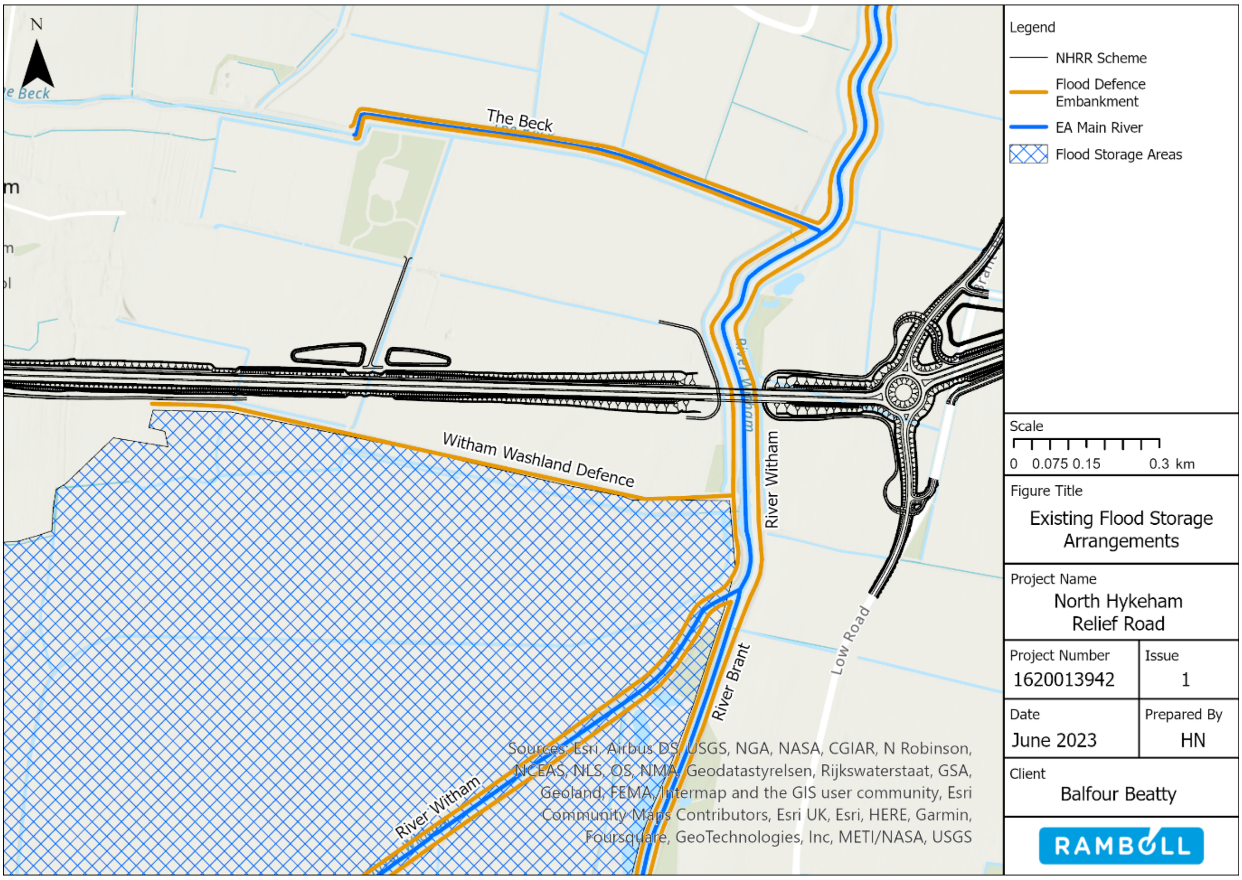

Figure 3-1: Existing flood risk management arrangements around the NHRR scheme

3.3.2 In addition to the River Witham, there are several tributaries within the floodplain close to the proposed NHRR crossing including The Beck and the River Brant. There are raised flood defences along the riverbanks and a raised defence perpendicular to the River Witham on the western floodplain. The perpendicular embankment creates a Flood Storage Area (FSA) to the south, designed to provide protection for events up to and including the 1% AEP fluvial flood. This embankment is designed to withstand overtopping and includes a concrete capping beam. The storage area has sufficient volume for it to be classified under the Reservoirs Act and has a maximum water depth (when full) of approximately 1.5 m.

3.3.3 There is a control structure on the Witham adjacent to the perpendicular defence. If Lincoln is expected to flood, the side gates are opened to allow water to flood into the storage area. If the river keeps rising, then the control structure can be raised, preventing water in the storage area from returning to the river.

3.3.4 According to the EA, the river embankments were raised in the early 1990s and are subject to vegetation growth and burrowing animals which may have reduced their ability to withstand a breach/erosion.

3.4 The NHRR Scheme

3.4.1 The proposed NHRR crosses the floodplain perpendicular to the dominant direction of flow of the River Witham. The proposed layout could impact flood flow conveyance and floodplain storage, increasing flood risk elsewhere. The potential for the NHRR to increase flood risk elsewhere must be assessed.

4. MODEL APPROACH AND JUSTIFICATION

4.1 Hydrological Approach

4.1.1 The hydrological approach used for the EA's existing modelling study has been applied for consistency in Ramboll's work. This is summarised in Section 3.2. The aim of this study is to understand the impact of and to the NHRR, should a breach of existing flood defences occur during extreme return period events. The impact on flood risk caused by the NHRR has been assessed, but it is not the focus of this model. With this understanding, it was considered that the hydrological analysis did not need to be amended and no updates were completed. The hydrological approach and methods were applied directly from the hydrological report[4] to minimise and avoid possible errors arising from the model conversion process.

4.1.2 The design events simulated were the 1% and 0.1% present day events and 1% and 0.1% Climate Change for the Witham Management Catchment peak river flow allowances, Higher 2080s (34%), following the latest Government Guidance.

4.1.3 The owners of the various reservoirs upstream are required to assess against a 10,000 year/Probable Maximum Flood (PMF) event. The NHRR does not interact with the reservoirs upstream and allows flow to pass the NHRR structure under bridges and through culverts therefore, the NHRR does not fall under the Reservoir Safety Act. This has been agreed by the EA after confirmation with the reservoir engineer during a meeting with the EA held on the 4th May 2023[5]. The 10,000-year event and PMF have therefore not been simulated.

4.2 Hydraulic Modelling approach

4.2.1 Utilising the existing EA 1D-2D Infoworks RS hydraulic model for the area was not considered to be an effective or proportionate approach considering its very large, catchment-scale size and the comparatively small design-scale required for the NHRR scheme. To assess the potential impacts of the scheme on flood risk and to answer the questions the EA has raised, Ramboll therefore constructed a purpose-built 1D-2D ESTRY-TUFLOW model to assess the NHRR scheme.

4.2.2 The NHRR hydraulic model area encompasses the floodplain upstream and downstream of the NHRR proposed development, incorporating the existing flood storage area, with the upstream boundaries set as per the existing EA Upper Witham – Lincoln Model, and the downstream extent set to A1434 road bridge in the Bracebridge area of Lincoln, set far enough downstream to incorporate any backwater effects in accordance with best modelling practice. The Bracebridge road bridge was identified by the EA as the main flow restriction point associated with the NHRR scheme.

4.2.3 The new NHRR 1D-2D ESTRY-TUFLOW Hydraulic model sourced most of the model data from the existing EA Infoworks RS Hydraulic model, specifically the Upper Witham Lincoln Model, accounting for errors identified by the EA, to encourage consistency and comparability in final model outputs. ESTRY and TUFLOW are industry-standard hydraulic modelling software packages for flood risk modelling and are well understood by the EA.

4.2.4 New channel survey data for the River Witham were provided for this study by the EA. These were used in preference to the Infoworks RS model data where coverage aligns for consistency and comparability with future EA hydraulic modelling results.

4.2.5 The hydraulic modelling approach was chosen with consideration of the trade-off between computational demands, the required spatial extent, and the accuracy of results. A 1D-2D model was selected for the following reasons:

- A 1D model linked to a 2D domain allows flow interactions between individual watercourses and structures to be accurately modelled, effectively representing the complex flow routes expected along the watercourses and within the floodplain of the study area.

[5] 2023-05-04 NHRR Meeting Minutes - EA-BB-Ramboll.pdf

- The 1D-2D linked model allows for an accurate simulation of in-channel hydraulics, coupled with detailed out-of-bank representation of flood routes, depths, flows and velocities. This provides a robust simulation of the effect of key hydraulic features both in and out of bank.
- A combined 1D-2D approach enables robust estimation of hazard in the floodplain, including the combined impact of coincident velocities and depths.

4.3 Model conceptualisation

4.3.1 The aim of this study is to use hydraulic modelling to understand the impact on flood risk from the NHRR scheme. The following scenarios have been considered:

1. Baseline Scenario (BAS)
   - Representing the current setup of the river Witham.
2. NHRR Scheme Scenario (NHRR)
   - Simulates the NHRR road scheme, including road embankment with wide span bridge and culverts conveying IDB rivers and drains.
3. NHRR Scheme Scenario (NHRR_Breach_RWUS)
   - Simulates the NHRR road scheme with a breach in the River Witham embankment between the NHRR crossing and the FSA embankment.
4. NHRR Scheme Scenario (NHRR_Breach_FSA)
   - Simulates the NHRR road scheme with a breach in the FSA embankment.

5. HYDROLOGICAL INFLOWS APPLICATION

5.1 Coverage

5.1.1 The ESTRY-TUFLOW model is a truncated version of the Infoworks RS model and therefore did not require all the inflows from the previous study. Five different design flows were carried forward into the ESTRY-TUFLOW model as presented below:

Table 5-1: Coverage of design flows carried forward from Infoworks RS model to ESTRY-TUFLOW model

Model Inflow	River	Coverage	Washland Influence
Witham_US_Brant (Witham_U_5)	Witham	Applied to the reach between the upstream model extent and the confluence with the river Brant	Witham
Witham_US_BC (Witham_U_2)	Witham	Applied to the reach between the confluence with the River Brant and the downstream model extent.	Witham and Brant
Brant_GS_US	Brant	Applied to the reach between the upstream model extent to upstream of Brant Broughton	Brant
Brant_GS_DS	Brant	Applied to the reach between Brant Broughton and the confluence with the River Witham.	Brant
Claypole	Witham	Applied to upstream extent of the River Witham. Upstream of Claypole, downstream of Doddington Ln.	None

5.2 Washland Influenced Catchments

5.2.1 Due to the presence of the Witham and Brant Washlands attenuating floods through Lincoln, the 2015 hydrological study identified that scaling hydrographs to target flow estimates for the river reaches passing through the Washland areas was not appropriate. For the four catchments influenced by the Washlands (Table 5-1), model inflows were derived using ReFH inflow hydrographs.

5.2.2 The FEH Catchment Descriptors applied to create the ReFH hydrographs were sourced from the previous 2015 hydrology report[6]. The FEH Catchment Descriptors used to create the model inflows are shown in Table 5-2.

Table 5-2: FEH Catchment Descriptors sourced from the 2015 Hydrology Report

	Catchment ID			
Parameter	**Witham_US_Brant**	**Witham_US_BC**	**Brant_GS_US**	**Brant_GS_DS**
AREA	89.01	45.14	65.68	81.14
URBEXT1990	0.016	0.016	0.005	0.004
SAAR	564	596	574	579
C	-0.021	-0.020	-0.019	-0.019
D1	0.331	0.325	0.313	0.310
D2	0.336	0.332	0.358	0.336
D3	0.217	0.215	0.198	0.209
E	0.303	0.303	0.301	0.302
F	2.472	2.485	2.492	2.510
PROPWET	0.27	0.14	0.27	0.25
BFIHOST	0.411	0.436	0.369	0.364
DPLBAR	11.682	8.062	8.54	11.104
DPSBAR	7.208	21.146	18.4	13.876

[6] Upper Witham Model Improvements Study, Hydrology Report, July 2015, Mott Macdonald (Environment Agency)

5.2.3 The ReFH hydrographs were then phased to ensure coincident peaks along the River Witham (Table 5-3). This was consistent with the methodology used during the original design of the washlands flood management scheme.

Table 5-3: Summary of Phasing Adjustments for model inflows sourced from the 2015 Hydrological Report

Inflow	Time delay applied to ReFH Hydrograph (hours)
Witham_US_Brant	5.5
Witham_US_BC	17
Brant_GS_US	9.5
Brant_GS_DS	9.5

5.2.4 The previous hydrological study optimised key ReFH model parameters (Time to Peak, Baseflow Lag and Baseflow Recharge) at gauge locations for four calibration and verification events. These optimised parameters were used to enhance the ReFH model at the ungauged catchments. Table 5-4 shows the donor corrections factors for the ReFH inflow hydrographs.

Table 5-4: Summary of Donor Correction Factors for ReFH Inflow Hydrographs sourced from the 2015 Hydrological Report

Catchment ID	Time to Peak (TP)	Baseflow Lag (BL)	Baseflow Recharge (BR)	Cini	Donor Catchment
Witham_US_Brant	0.74	1.1	1.1	0.8	Brant Broughton Gauging Station
Witham_US_BC					
Brant_GS_US					
Brant_GS_DS					

5.2.5 The 2015 hydrological study completed storm duration analysis using 10-hour, 40-hour and 60-hour storm durations. The 40-hour storm duration was found to be critical for the majority of the sections, while a 10-hour storm duration was critical only for the Boultham Catchwater. As the Boultham Catchwater is outside the ESTRY-TUFLOW model area, only the 40-hour storm duration events have been simulated for the ESTRY-TUFLOW model.

5.3 Claypole

5.3.1 The design inflows for Claypole, providing inflows to the upstream limit of the Witham, use a standardised hydrograph profile taken from the November 2000 event which is scaled to the derived target flow for Claypole (Table 5-5).

Table 5-5: Target Peak Flows for Claypole, sourced from the 2015 Hydrological Report

AEP	Claypole flows (m^3/s)
1%	42.9
0.10%	77.55

5.3.2 Table 5-6 shows the Dimensionless hydrograph Ordinates for Claypole, sourced from Appendix F of the 2015 Hydrological Report.

Table 5-6: Claypole Dimensionless Hydrograph Ordinates for the 40 storm duration (Appendix F of 2015 Hydrological Report)

Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow
0	0.11	13.72	0.73	27.45	1	41.18	0.67	54.9	0.46	68.63	0.38
0.22	0.11	13.95	0.74	27.67	1	41.4	0.66	55.13	0.46	68.85	0.38
0.45	0.11	14.17	0.75	27.9	1	41.63	0.65	55.35	0.47	69.08	0.38
0.67	0.11	14.4	0.77	28.13	1	41.85	0.65	55.58	0.47	69.3	0.38
0.9	0.11	14.62	0.78	28.35	1	42.08	0.64	55.8	0.47	69.53	0.37
1.12	0.11	14.85	0.78	28.58	1	42.3	0.63	56.03	0.47	69.75	0.37
1.35	0.11	15.07	0.79	28.8	1	42.53	0.63	56.25	0.47	69.98	0.37

Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow	Time (hrs)	Non-dimen-sional flow
1.57	0.11	15.3	0.8	29.03	1	42.75	0.62	56.48	0.47	70.2	0.37
1.8	0.11	15.52	0.8	29.25	1	42.98	0.61	56.7	0.47	70.43	0.37
2.02	0.11	15.75	0.8	29.48	0.99	43.2	0.61	56.93	0.47	70.65	0.37
2.25	0.11	15.97	0.81	29.7	0.99	43.43	0.6	57.15	0.47	70.88	0.37
2.47	0.11	16.2	0.81	29.93	0.99	43.65	0.59	57.38	0.46	71.1	0.37
2.7	0.11	16.42	0.81	30.15	0.98	43.88	0.59	57.6	0.46	71.33	0.36
2.92	0.11	16.65	0.81	30.38	0.98	44.1	0.58	57.83	0.46	71.55	0.36
3.15	0.11	16.87	0.81	30.6	0.97	44.33	0.57	58.05	0.46	71.78	0.36
3.37	0.11	17.1	0.81	30.83	0.97	44.55	0.57	58.28	0.46	72	0.36
3.6	0.11	17.32	0.82	31.05	0.97	44.78	0.56	58.5	0.46	72.23	0.36
3.82	0.11	17.55	0.82	31.28	0.96	45	0.56	58.73	0.46	72.45	0.36
4.05	0.11	17.77	0.82	31.5	0.96	45.23	0.55	58.95	0.46	72.68	0.36
4.27	0.11	18	0.83	31.73	0.96	45.45	0.55	59.18	0.46	72.9	0.36
4.5	0.11	18.22	0.84	31.95	0.95	45.68	0.54	59.4	0.46	73.13	0.36
4.72	0.11	18.45	0.84	32.18	0.92	45.9	0.54	59.63	0.45	73.35	0.35
4.95	0.11	18.67	0.85	32.4	0.92	46.13	0.54	59.85	0.45	73.58	0.35
5.17	0.11	18.9	0.86	32.63	0.91	46.35	0.53	60.08	0.45	73.8	0.35
5.4	0.11	19.12	0.86	32.85	0.91	46.58	0.53	60.3	0.45	74.03	0.35
5.62	0.11	19.35	0.86	33.08	0.91	46.8	0.52	60.53	0.45	74.25	0.35
5.85	0.11	19.57	0.87	33.3	0.9	47.03	0.52	60.75	0.44	74.48	0.35
6.07	0.12	19.8	0.87	33.53	0.9	47.25	0.51	60.98	0.44	74.7	0.34
6.3	0.12	20.02	0.88	33.75	0.9	47.48	0.51	61.2	0.44	74.93	0.34
6.52	0.13	20.25	0.88	33.98	0.89	47.7	0.51	61.43	0.44	75.15	0.34
6.75	0.14	20.47	0.89	34.2	0.89	47.93	0.5	61.65	0.44	75.38	0.34
6.97	0.14	20.7	0.89	34.43	0.88	48.15	0.5	61.88	0.43	75.6	0.34
7.2	0.15	20.92	0.89	34.65	0.88	48.38	0.49	62.1	0.43	75.83	0.33
7.42	0.16	21.15	0.9	34.88	0.88	48.6	0.49	62.33	0.43	76.05	0.33
7.65	0.17	21.37	0.9	35.1	0.87	48.83	0.49	62.55	0.43	76.28	0.33
7.87	0.18	21.6	0.91	35.33	0.86	49.05	0.49	62.78	0.43	76.5	0.33
8.1	0.19	21.82	0.91	35.55	0.86	49.28	0.48	63	0.42	76.73	0.33
8.32	0.21	22.05	0.92	35.78	0.85	49.5	0.48	63.23	0.42	76.95	0.33
8.55	0.23	22.27	0.94	36	0.85	49.73	0.48	63.45	0.42	77.18	0.32
8.77	0.25	22.5	0.95	36.23	0.84	49.95	0.47	63.68	0.42	77.4	0.32
9	0.28	22.72	0.96	36.45	0.83	50.18	0.47	63.9	0.41	77.63	0.32
9.22	0.3	22.95	0.96	36.68	0.82	50.4	0.47	64.13	0.41	77.85	0.32
9.45	0.33	23.17	0.97	36.9	0.82	50.63	0.47	64.35	0.41	78.08	0.32
9.67	0.36	23.4	0.98	37.13	0.81	50.85	0.47	64.58	0.41	78.3	0.31
9.9	0.39	23.62	0.98	37.35	0.8	51.08	0.47	64.8	0.41	78.53	0.31
10.12	0.42	23.85	0.98	37.58	0.8	51.3	0.47	65.03	0.41	78.75	0.31
10.35	0.45	24.07	0.99	37.8	0.8	51.53	0.46	65.25	0.4	78.98	0.31
10.57	0.47	24.3	0.98	38.03	0.78	51.75	0.46	65.48	0.4	79.2	0.31
10.8	0.5	24.52	0.98	38.25	0.77	51.98	0.46	65.7	0.4	79.43	0.3
11.02	0.52	24.75	0.98	38.48	0.76	52.2	0.46	65.93	0.4	79.65	0.3
11.25	0.54	24.97	0.98	38.7	0.75	52.43	0.46	66.15	0.39	79.88	0.3
11.47	0.56	25.2	0.98	38.93	0.74	52.65	0.46	66.38	0.39	80.1	0.3
11.7	0.58	25.42	0.98	39.15	0.74	52.88	0.46	66.6	0.39	80.33	0.3
11.92	0.61	25.65	0.99	39.38	0.73	53.1	0.46	66.83	0.39	80.55	0.3
12.15	0.63	25.87	0.99	39.6	0.72	53.33	0.46	67.05	0.39	80.78	0.29
12.37	0.64	26.1	0.99	39.83	0.71	53.55	0.46	67.28	0.39	81	0.29
12.6	0.66	26.32	0.99	40.05	0.71	53.78	0.46	67.5	0.39		
12.82	0.68	26.55	0.99	40.28	0.7	54	0.46	67.73	0.38		
13.05	0.69	26.77	1	40.5	0.69	54.23	0.46	67.95	0.38		
13.27	0.71	27	1	40.73	0.68	54.45	0.46	68.18	0.38		
13.5	0.72	27.23	1	40.95	0.67	54.68	0.46	68.4	0.38		

5.4 Minimum Flows

5.4.1 The Infoworks RS model included several uses of "minimum flows", where low flows were set at locations throughout the model to prevent channels from going "dry" which can cause instabilities. It is unlikely that the inclusion of these flows would make a significant difference as the model is testing extreme fluvial events: the 100-year, 1,000-year and 100-year plus climate change event. To be consistent with the previous modelling, these "minimum flows" were retained in the ESTRY-TUFLOW model.

6. HYDRAULIC MODELLING METHODOLOGY

6.1 Modelling Software

6.1.1 Hydraulic modelling has been undertaken using the ESTRY 1D - TUFLOW 2D (version 2023-03-AA-iSP-w64) software.

6.2 Model Extent

6.2.1 A truncated area was proposed that centred on the area affected by the NHRR scheme, specifically the areas to the south of Lincoln, covering the River Witham and River Brant. The extents were set with consideration to the backwater effect from key structures and to include the various Washland storage areas protecting Lincoln from flood risk. Figure 6-1 shows the NHRR ESTRY-TUFLOW model extent.

6.2.2 The downstream boundary is set at the A1434 road bridge in the Bracebridge area of Lincoln, identified by the EA as the main flow restriction point associated with the NHRR scheme. The upstream boundaries were located at the upstream extent of the River Witham and the River Brant, in line with the Infoworks RS model.

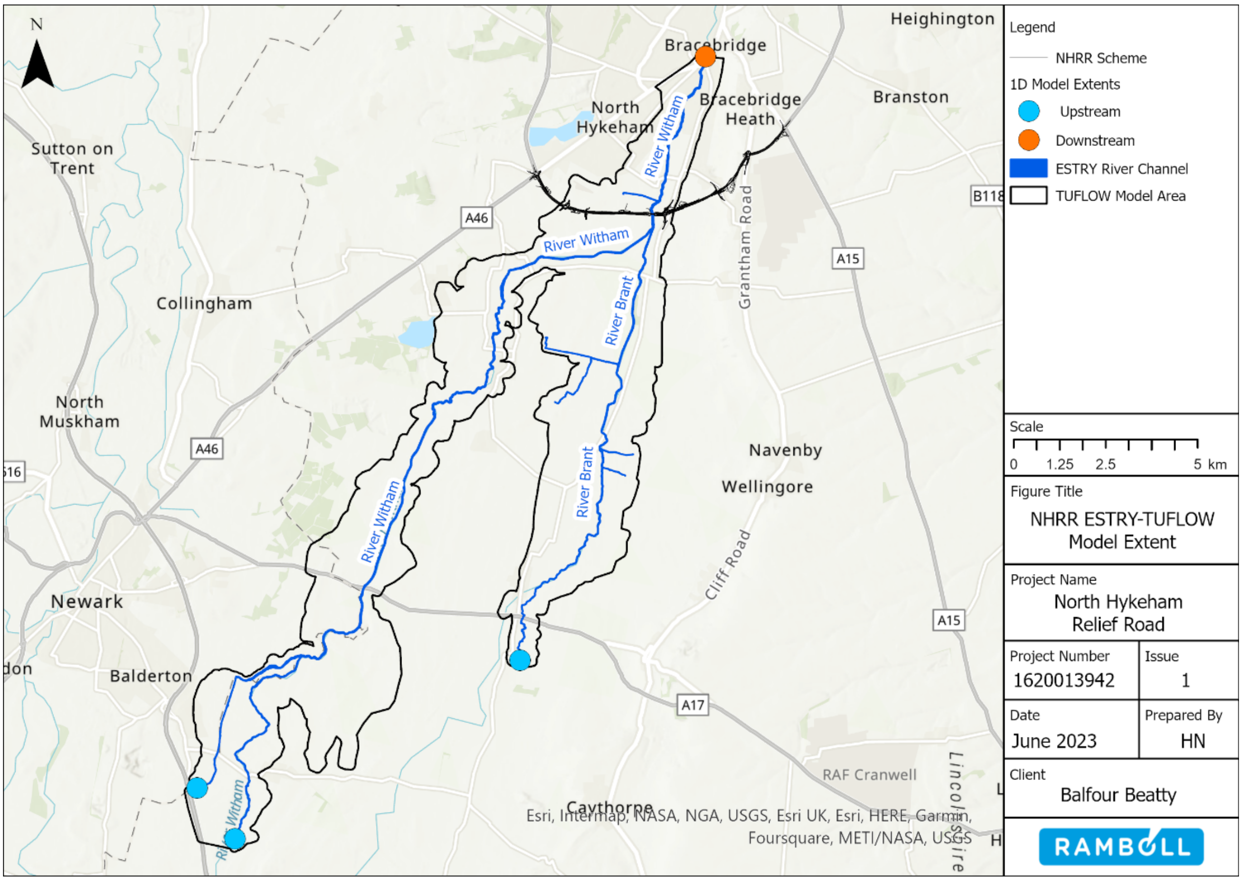

Figure 6-1: NHRR ESTRY-TUFLOW Model Extent

6.3 1D Channel

Channel cross sections

6.3.1 The survey data for the NHRR ESTRY-TUFLOW model in-bank 1D channel was sourced mostly from the Infoworks RS model. Several different sources of topographic data were used to create the Infoworks RS model, the original data of which was not available for the NHRR study.

6.3.2 The EA provided new survey data for the River Witham which has been incorporated into the model. This survey data was used in preference of the Infoworks RS data covering the same area. Table 6-1 outlines the EA Witham Survey data details.

Table 6-1: EA Witham Survey Data details

Parameter	Details
River Surveyed	River Witham
Surveyor	Environment Agency
Survey Date	November 2018
Datum	ODN
Number of Cross-Sections	122
Upstream Extent (NGR)	491250, 362542
Downstream Extent (NGR)	496571, 368205

6.3.3 Figure 6-2 Shows the extent of the new EA survey and the existing Infoworks RS model.

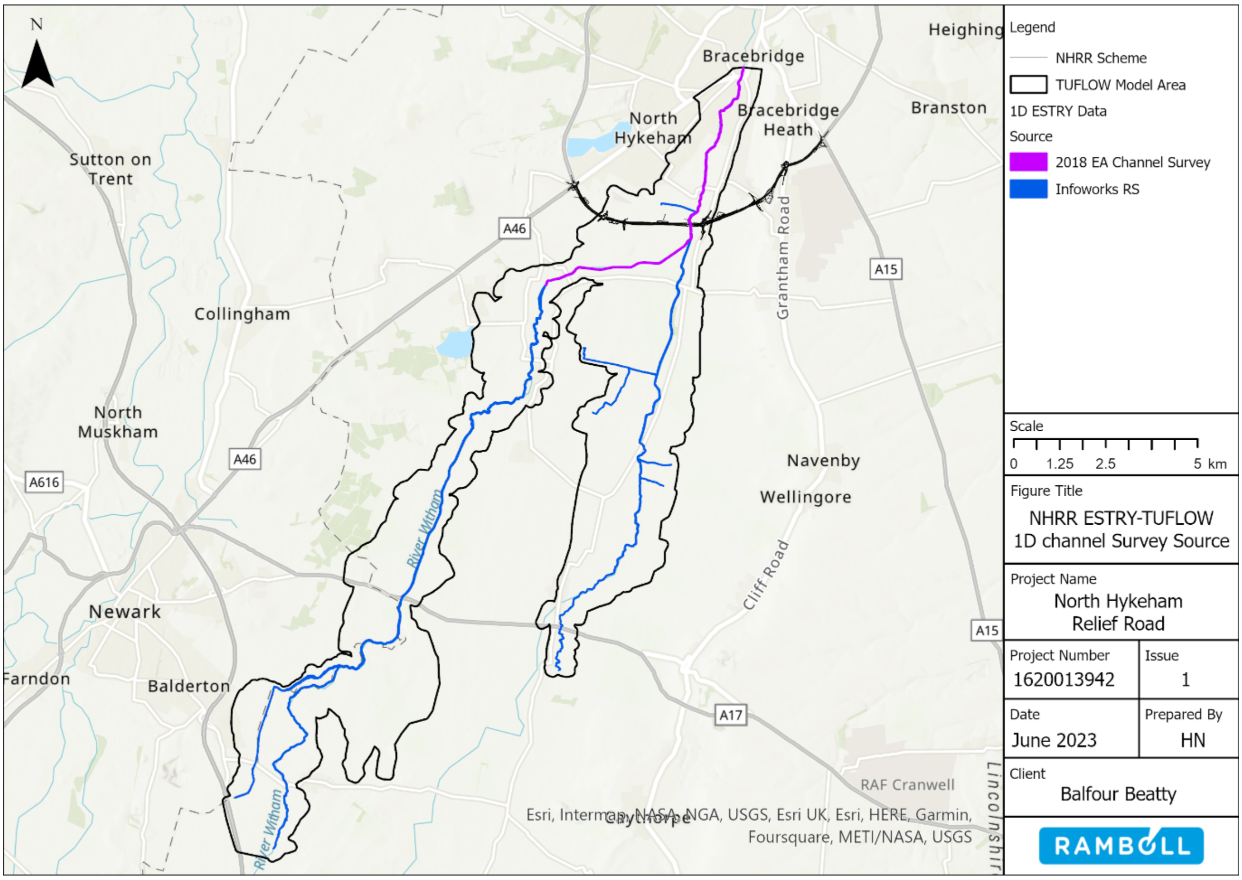

Figure 6-2: Extent and source of the channel survey data used in the 1D ESTRY channel of the NHRR ESTRY-TUFLOW model

1D Roughness Coefficients

6.3.4 In channel roughness values used in the NHRR ESTRY-TUFLOW model were sourced from the Infoworks RS model for consistency and comparability. The Infoworks RS hydraulic model report set the 1D roughness values through model calibration and performance testing.

Table 6-2: In-channel Roughness Values carried forward from the Infoworks RS hydraulic model

Reach	Assigned Manning's 'n' Value
• River Witham upstream of Aubourn Weir • River Brant upstream of Brant Broughton	0.045
• River Witham Aubourn Weir to Washlands • River Brant downstream of Brant Broughton	0.040
• River Witham downstream of Washlands	0.030

Structures

6.3.5 The 1D ESTRY Channel models several hydraulic structures including bridges, culverts, weirs, sluice gates and pumps. The structural information for these was sourced from the 2018 EA Survey data of the River Witham and the Infoworks RS model. In cases where the data were sourced from the Infoworks RS model, the original survey data were not available for the NHRR study and limited information was provided in the modelling report. The structure setup was reviewed during the conversion process from the Infoworks Model to the NHRR ESTRY-TUFLOW model, however the suitability of the adopted setup was difficult to assess with the limited information available.

6.3.6 An assumption has been made that the structures were suitable and properly represented in the Infoworks Model. This approach is deemed appropriate considering the purpose of the model is not to assess the overall flood risk from the River Witham and River Brant, but to understand the impact to and from the NHRR in the occurrence of a breach of the Washland Reservoir Embankment or the Witham Bank levels during an extreme flood event.

Table 6-3: Structures included in the NHRR ESTRY-TUFLOW model

Structure	Count
Flat Deck Bridge	30
Arch Bridge	9
Circular Culvert	3
Rectangular Culvert	6
Flapped Rectangular Culvert	3
Weirs and Spills	54
Operational Pump	3
Operational Sluice Gate	4

Operational structures

6.3.7 Figure 6-3 shows the location of the operational structures included in the NHRR ESTRY-TUFLOW model.

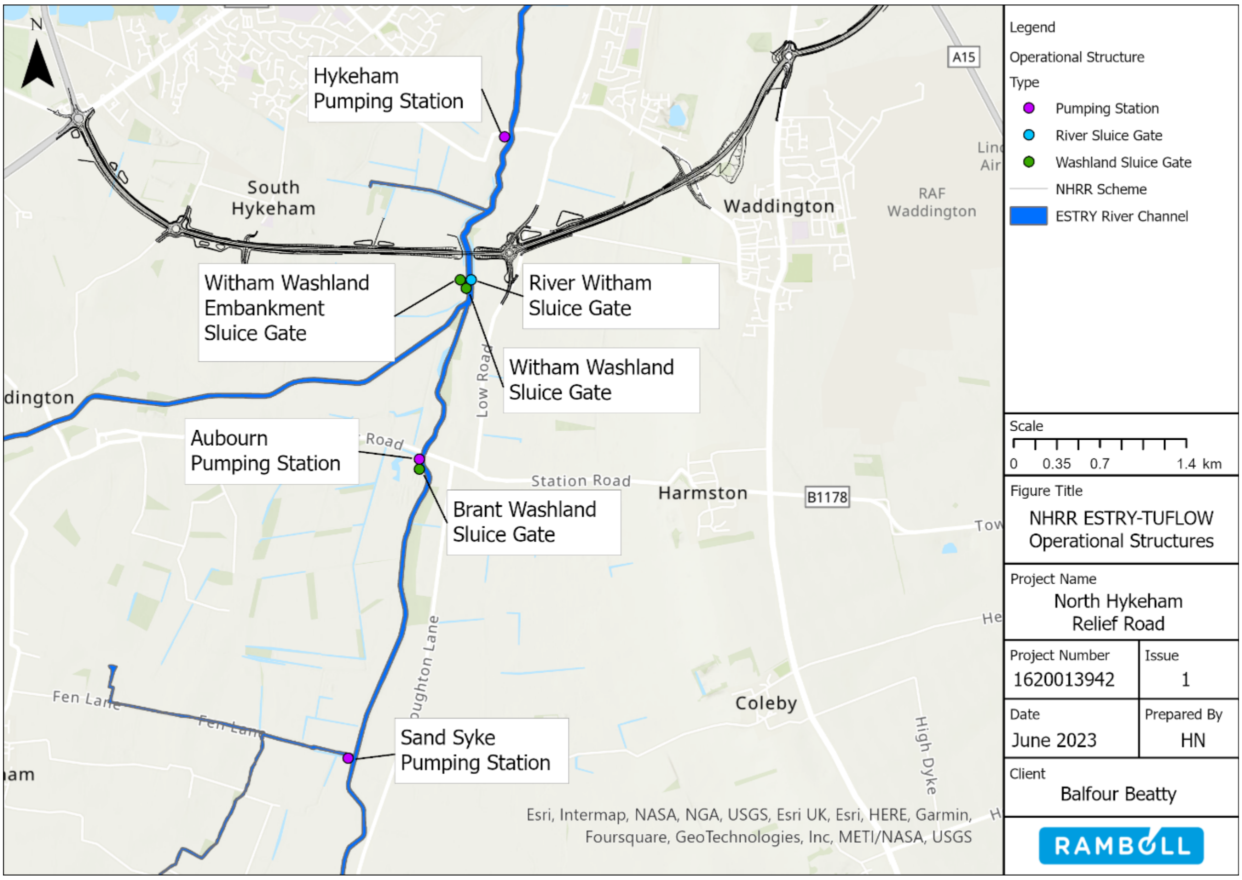

Figure 6-3: Location of the operational structures included in the NHRR ESTRY-TUFLOW Model

6.3.8 The Witham and Brant Washland sluice gates operate under the Lincoln Washlands Operating Procedures (November 2011). The structure setup follows the same method as the Infoworks RS model for consistency. Table 6-4 summarises the operating procedures and how they have been implemented within the NHRR ESTRY-TUFLOW model.

Table 6-4: Summary of control rules applied at the Witham and Brant Washland Sluice Gates, sourced from the Infoworks RS Hydraulic Modelling Report

Trigger Location	Operational Procedures (November 2011)	Representation in the Model
Immediately downstream of the Witham Control Sluice (WCS)	Maintain a level of 6.80 – 6.90 m AOD	Gates begin to open if Level at WCS > 6.8,
Hykeham Bridge (HB)	Maintain a level of 6.60 – 6.70 m AOD	OR Level at HB > 6.6 OR Level at B > 6.1
Bracebridge (B)	Maintain a level of 6.10 – 6.20 m AOD	Gates begin to close if Level at WCS < 6.7, OR Level at HB < 6.55 OR Level at B < 6.05 Otherwise maintain position

6.3.9 In addition to the Washland sluice gates, there are rules applied to the River Witham control sluice gates. The control rules applied were taken directly from the Infoworks RS model. After testing, the Infoworks RS model slightly amended the control rules away from the operational guidance to reflect the overall objective of the Washlands, to maintain safe water levels through Lincoln. This was to overcome model instabilities. The NHRR ESTRY-TUFLOW model carried forward these amendments for consistency and comparability. The rules that have been used at the River Witham control sluice gates are summarised in Table 6-5, sourced from the Infoworks RS Hydraulic Modelling Report.

Table 6-5: Summary of control rules applied at the river Witham control sluice gate, sourced from the Infoworks RS Hydraulic Modelling Report.

Location	Representation in Model
River Witham control sluice gate	Gates begin to rise if: Flow through the washland sluices is > 0.1 m³/s, AND Level at WCS > 6.9, OR Level at HB > 6.7 OR Level at B > 6.2 Gates begin to lower if Flow through the washland sluices is < 0.1 m³/s, AND Level at WCS < 6.9, OR Level at HB < 6.7 OR Level at B < 6.2 Otherwise maintain position

6.3.10 An additional Washland control sluice was included in the Infoworks RS model, although it was not referenced in the accompanying Hydraulic Modelling Report. The control sluice allows flows from the Witham Washlands through the Witham Washland Embankment as a drainage feature after a flood event. The NHRR ESTRY-TUFLOW model has replicated the operational setup applied in the Infoworks RS model however, it is unclear as to the origins of the data used to setup the structure.

Table 6-6: Summary of control rules applied at the Witham Washland Embankment control sluice gate, sourced from the Infoworks RS model.

Location	Representation in Model
Witham Washland Embankment control sluice	Gate begins to close if: Witham Washland Sluice Gate is Open Gate begins to close if: Witham Washland Sluice Gate is Closed, AND Level at Witham Washland > 4.0, Gate begins to open if: Witham Washland Sluice Gate is Open, AND Level at Witham Washland < 4.0,

6.3.11 The representation of pumping stations within the NHRR ESTRY-TUFLOW model have been set up to reflect that used in the Infoworks RS model. The Infoworks RS model set up the pumping station operational rules using information provided by the IDB (Table 6-7). In some cases, the Infoworks RS model pumping station setup differed slightly from the IDB information to allow for model stability and hydraulic modelling sensibility. The ESTRY-TUFLOW model has carried this forward for modelling consistency and comparability.

Table 6-7: Summary of Pump Operation in Upper Witham IDB provided for the Infoworks RS model construction

Location	Pump	Capacity	Start Level	Stop Level
Sand Syke	1	0.5	4.9	4.3
	2	0.5	5.1	4.7
Aubourn	1	0.5	3.7	3.3
	2	0.5	4.1	3.6
Hykeham	1	0.79	3.14	2.53

Initial water levels

6.3.12 Initial water level values for the 1D ESTRY river channel were sourced from the Infoworks RS model. In cases where the 2018 EA River Survey was available, the initial water levels were set as the water level on the date of survey.

6.4 2D Floodplain

6.4.1 The majority of the Infoworks RS model area that was converted for the NHRR ESTRY-TUFLOW model was modelled in 1D. The NHRR ESTRY-TUFLOW model is a 1D-2D linked model to allow for a better representation of the impact of the breach through existing flood defences close to the NHRR scheme. This section outlines how the 2D TUFLOW floodplain has been represented.

Model Resolution

6.4.2 A 10 m grid size has been applied to represent the 2D TUFLOW floodplain. This grid size was chosen with consideration to the scale of the model alongside the aim of the modelling. A detailed understanding of the flood risk for the area is not required, therefore a detailed refined grid is not necessary. A 10 m grid is considered refined enough to assess the impact of a breach through existing flood defences close to the NHRR scheme, considering the very large floodplain areas simulated.

Lidar

6.4.3 A Digital Terrain Map (DTM) was used to inform the ground levels of the 2D domain within the model, representing the "bare earth" ground surface. The dataset used was the EA 1m filtered composite LiDAR 2020 (Figure 6-4). Spot checks between the bank levels surveyed in the EA cross-sections survey data from 2018 found reasonable comparability with EA Composite LiDAR data.

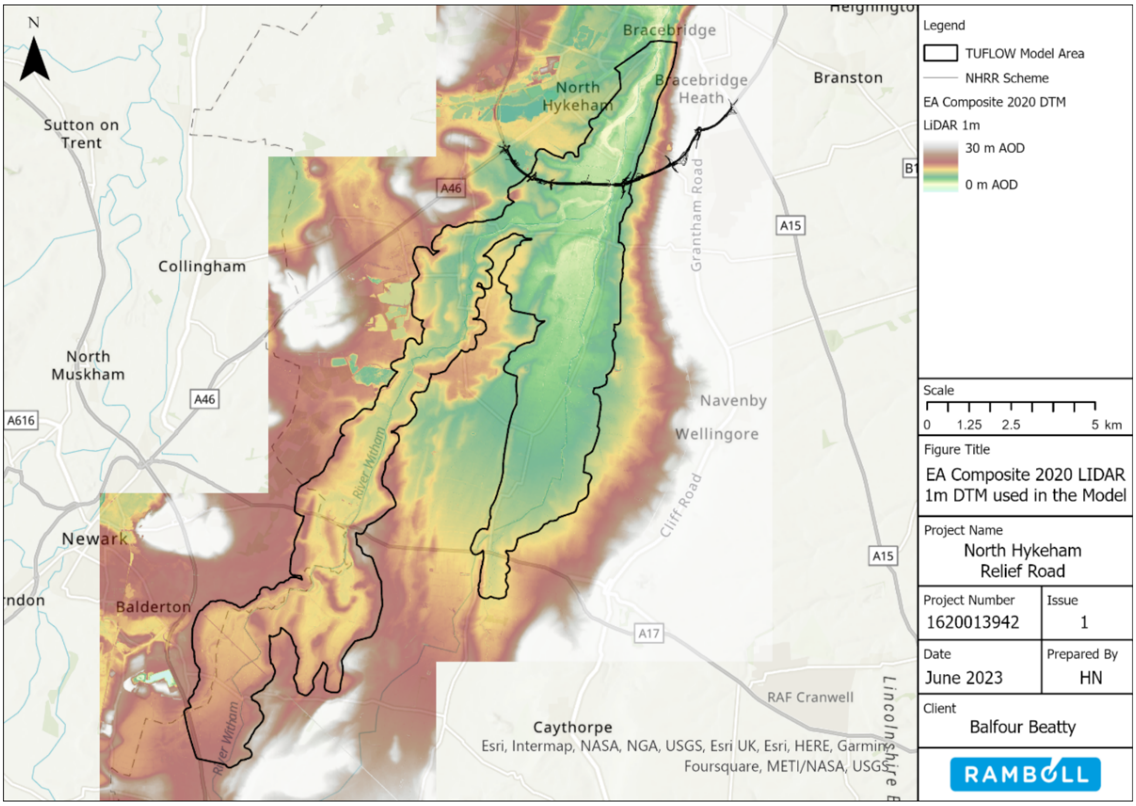

Figure 6-4: EA 1m Composite DTM LIDAR (2020)

6.4.4 Although the EA composite LIDAR was created in 2020, the survey date of the LIDAR used to create the composite LIDAR was found to be mostly made up of data from 2009 (Figure 6-5).

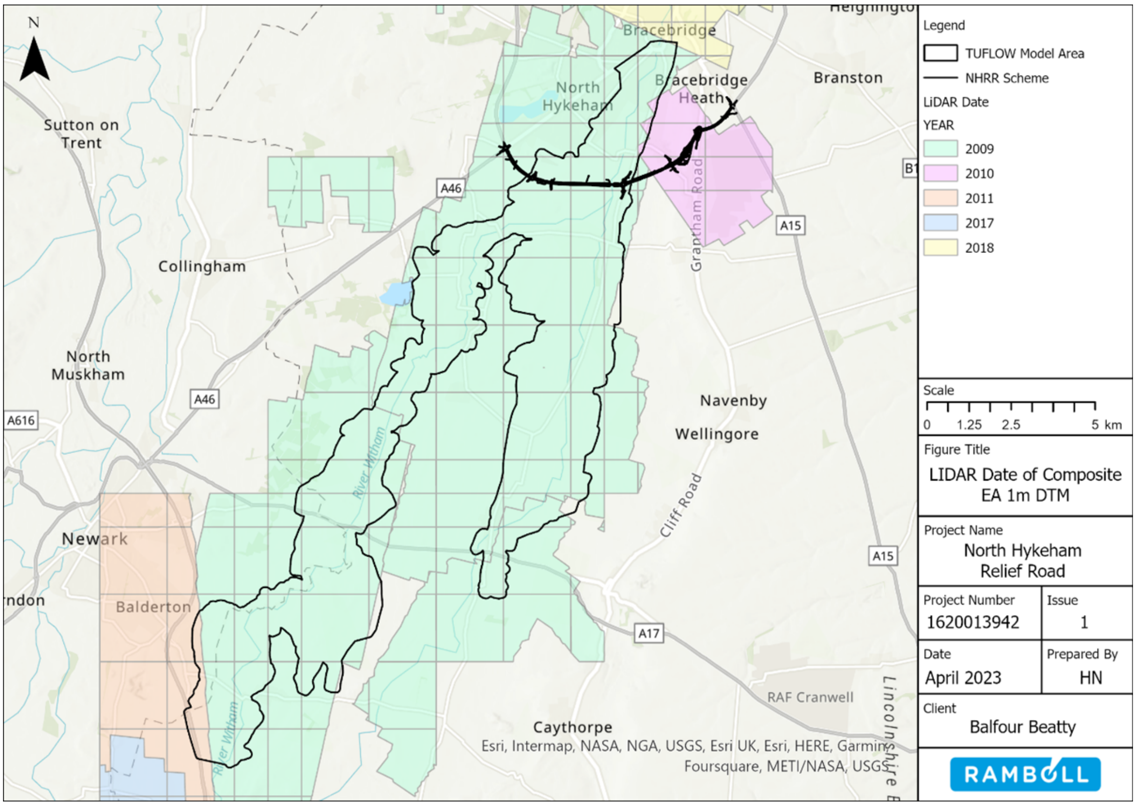

Figure 6-5: Survey date of the LIDAR used to create the EA 1m DTM Composite Lidar 2020 used to create to inform the ground levels of the 2D domain of the NHRR ESTRY-TUFLOW model

Bank lines

6.4.5 Riverbank lines have been stamped into the model so that the flood defence levees lining the watercourses are not filtered out of the 2D domain of the model by the 10 m model grid size. The bank levels were defined using the EA 1m composite LiDAR data at the crest of the levees and the surveyed level from the river cross section in the 1D ESTRY domain, sourced from the Infoworks RS model or the EA 2018 River Witham Survey.

6.4.6 The representation of the NHRR ESTRY-TUFLOW bank levels was compared against Asset Information and Maintenance (AIMs) data where available. The defence levels created from EA 1m composite LiDAR data were used in preference to the AIMS data as these provided a better representation of the variation in levels across the length of each defence.

Witham Washland defence crest

6.4.7 The Witham Washland defence is located immediately upstream (south) of the proposed NHRR scheme (Figure 6-6). It is understood that the standard of protection provided by the Witham Washland Defence is up to the 100-year event. The Witham Washland Defence would directly affect flood risk at the NHRR scheme.

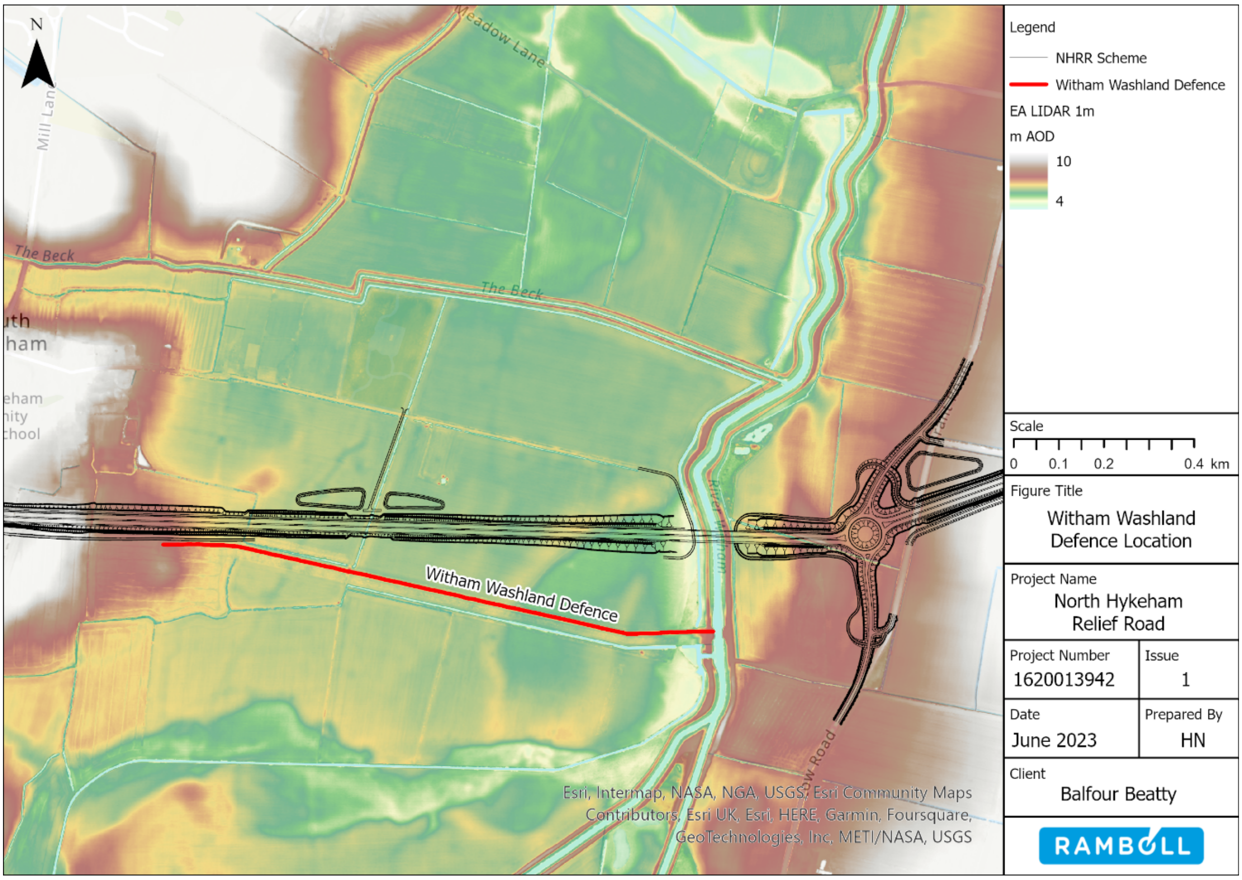

Figure 6-6: Witham Washland Defence location

6.4.8 The Witham Washland defence crest was set to 7.54 m Above Ordnance Datum (mAOD) in the Infoworks RS model. The EA AIMS Defence dataset records the effective crest level for the Witham Washland Defence in three sections, West at 7.28 m AOD, middle at 7.30 m AOD and East at 7.25 m AOD. A recent survey completed by the EA measured the Witham Washland defence crest at 7.4 m AOD. Following consultation with the EA, the NHRR hydraulic model has set the defence crest using the most recent survey measurement of 7.4 m AOD, to be comparable with future modelling results.

Floodplain channels

6.4.9 To represent the numerous watercourses and land drains crossing the floodplain in the 2D domain, the model topography has been lowered by 1 m using OS MasterMap data delineating rivers and streams.

Culverts

6.4.10 Two culverts have been included in the 2D floodplain domain of the NHRR ESTRY-TUFLOW model (Figure 6-7). The details of these culverts were extracted from the Infoworks RS hydraulic model.

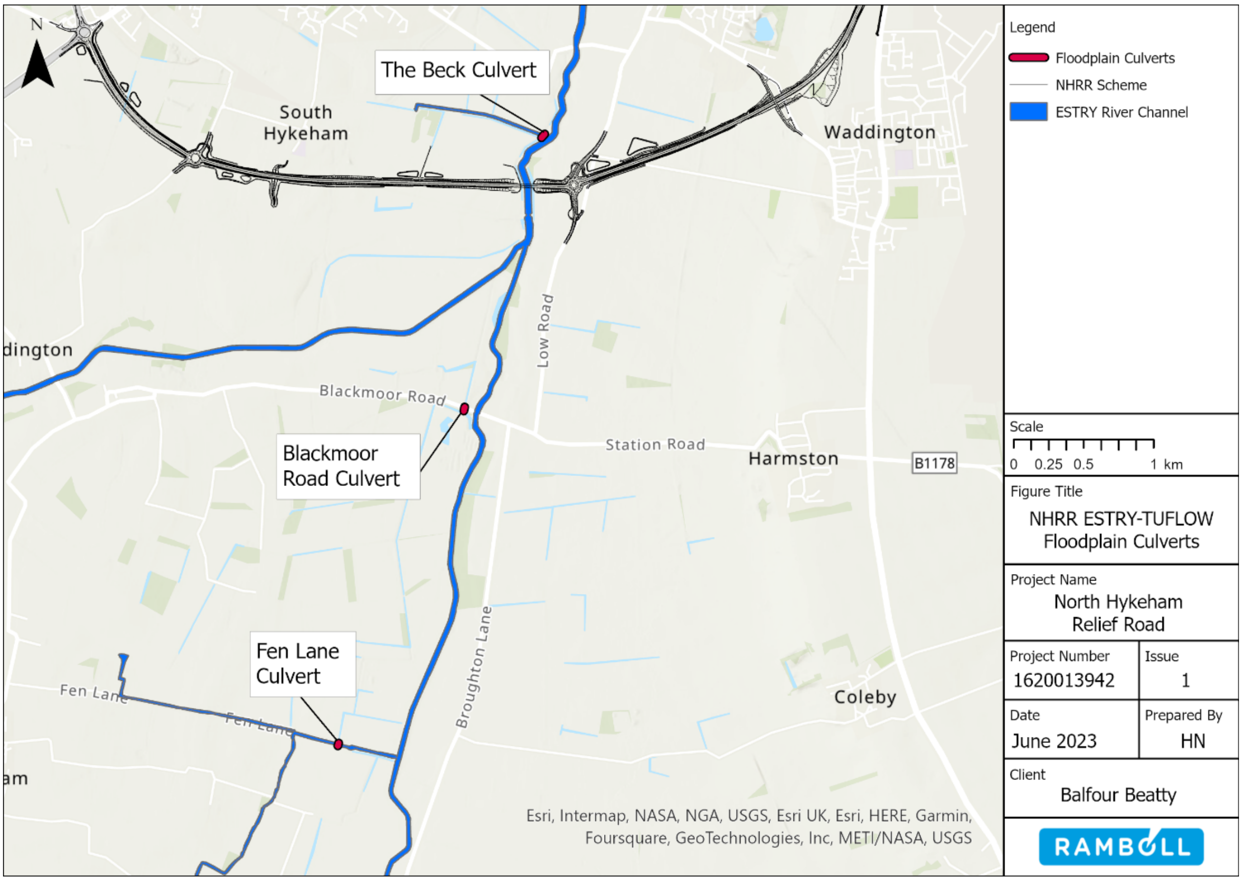

Figure 6-7: Floodplain Culverts represented in the 2D Floodplain

Roughness

6.4.11 The NHRR ESTRY-TUFLOW model has utilised OS MasterMap[7] to specify the roughness factors in the 2D domain. The specific roughness factors were set using roughness guidance Chow, 1959 (Table 6-8).

Table 6-8: Manning's 'n' roughness values used specify the roughness in the 2D TUFLOW domain

Land coverage type	Manning's 'n' value
Building	0.300
General Surface Multi Surface	0.020
General Surface Step	0.020
General Surface Agricultural Land	0.035
General Surface manmade	0.020
Glasshouse	0.200
Inland Water	0.035
Landform Slope	0.035
Landform Cliff	0.040
Natural Environment Shingle	0.030

[7] Ordnance Survey data © Crown copyright and database right 2022

Land coverage type	Manning's 'n' value
Natural Environment Scrub	0.050
Natural Environment Rough Grassland	0.035
Natural Environment Trees	0.080
Natural Environment Trees (Scattered)	0.060
Path Step	0.030
Path	0.030
Rail	0.025
Road or Track	0.015
Roadside	0.025
Structure	0.030
Pylon	0.030
Natural Environment; Tidal	0.030
Tidal Water	0.035
Unclassified	0.030

6.5 Model Boundaries

Inflow Boundaries

6.5.1 The model boundary setup applied in the previous Infoworks RS model was applied in the converted truncated ESTRY-TUFLOW model. This includes two 1D inflows, 4 sets of 1D lateral inflows, 1 2D point inflow and 4 storage area inflows.

6.5.2 The Infoworks RS model included 4 inflows to 1D storage areas which were intended to represent IDB pumped catchments. To represent these inflows in the 2D TUFLOW floodplain, SA (Flow versus Time (m^3s) over an area) polygons were applied. These were setup to apply flow directly onto the 2D floodplain cells within the polygon area representing the pumped IDB catchment, with flow distributed over the wet cells, starting from the lowest cell based on the floodplain elevations.

6.5.3 Table 6-9 shows the model inflow boundaries setup applied in the TUFLOW model.

Table 6-9: Model inflow boundaries setup applied in the TUFLOW model

Infoworks Setup						TUFLOW Setup				
Catchment ID	Boundary Node Name	Proportion of Inflow	Inflow Type	Additional Comments		TUFLOW Name	bc_dbase Source File	Inflow Type	Domain	Proportion of Inflow
Claypole	Claypole	1	1D Point inflow			UWC_7019	UWC_7019_40hr.csv		1D	1
Witham_US_Brant (Witham_U_5)	Witham_US_Brant	1	1D Lateral Inflow	Split between 4 locations:						
				Location	Proportion					
				SR_2054	11%	Witham_U_5A	Witham_U_5_FEH_40hr.csv	QT	1D	0.11
				SR_2054_int3376	11%	Witham_U_5B	Witham_U_5_FEH_40hr.csv	QT	1D	0.11
				UWB_16223!	51%	Witham_U_5C	Witham_U_5_FEH_40hr.csv	QT	1D	0.51
				UWB_4927	27%	Witham_U_5D	Witham_U_5_FEH_40hr.csv	QT	1D	0.27
Witham_US_BC (Witham_U_2)	Witham_US_BC1	0.21	1D Point inflow	Applied to upper limit of South Hykeham Drain		SH_1036	Witham_U_2_FEH_40hr.csv	QT	1D	0.21
	Witham_US_BC2	0.29	1D Lateral Inflow	Split between 2 locations:						
				Location	Proportion					
				UWA_5340	50%	Witham_U_2B	Witham_U_2_FEH_40hr.csv	QT	1D	0.145
				UWA_7345	50%	Witham_U_2A	Witham_U_2_FEH_40hr.csv	QT	1D	0.145
	Witham_US_BC3	0.25	2D Point inflow	Applied along Pike Drain		Pike_Drain	Witham_U_2_FEH_40hr.csv	QT	2D	0.25
	Witham_US_BC4	0.25	2D Point inflow	Applied along Pike Drain		Watercourse not connected to modelled River Witham				
Brant_GS_US	Brant_GS_US	1	1D Lateral Inflow	Split between 2 locations:						
				Location	Proportion					
				RB_12359	71%	Brant_GS_US1	Brant_GS_US_FEH_40hr.csv	QT	1D	0.71
				RB_14384	29%	Brant_GS_US2	Brant_GS_US_FEH_40hr.csv	QT	1D	0.29

Infoworks Setup						TUFLOW Setup				
Catchment ID	**Boundary Node Name**	**Proportion of Inflow**	**Inflow Type**	**Additional Comments**		**TUFLOW Name**	**bc_dbase Source File**	**Inflow Type**	**Domain**	**Proportion of Inflow**
Brant_GS_DS	Brant_GS_DS	0.905	1D Lateral Inflow	Split between 9 locations						
				Location	Proportion					
				BF_1601	3%	Brant_GS_DS9	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.02715
				CR_688	3%	Brant_GS_DS6	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.02715
				RB_2305	15%	Brant_GS_DS5	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.13575
				RB_5128	9%	Brant_GS_DS4	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.08145
				RB_6920	9%	Brant_GS_DS3	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.08145
				RB_8751	21%	Brant_GS_DS1	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.19005
				SK_977	8%	Brant_GS_DS8	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.0724
				WB-462	3%	Brant_GS_DS7	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.02715
				WB_2636	29%	Brant_GS_DS2	Brant_GS_DS_FEH_40hr.csv	QT	1D	0.26245
	Brant_GS_DS_1	0.016	1D Point inflow	Applied to storage area AUBOURN		Brant_GS_1	Brant_GS_DS_FEH_40hr.csv	SA	2D	0.016
	Brant_GS_DS_2	0.026	1D Point inflow	Applied to storage area Brant Washland North		Brant_GS_2	Brant_GS_DS_FEH_40hr.csv	SA	2D	0.026
	Brant_GS_DS_3	0.014	1D Point inflow	Applied to storage area Brant Washland South		Brant_GS_3	Brant_GS_DS_FEH_40hr.csv	SA	2D	0.014
	Brant_GS_DS_4	0.039	1D Point inflow	Applied to storage area Sand_Syke		Brant_GS_4	Brant_GS_DS_FEH_40hr.csv	SA	2D	0.039

6.6.1 Figure 6-7 shows the NHRR ESTRY-TUFLOW model boundary types and locations.

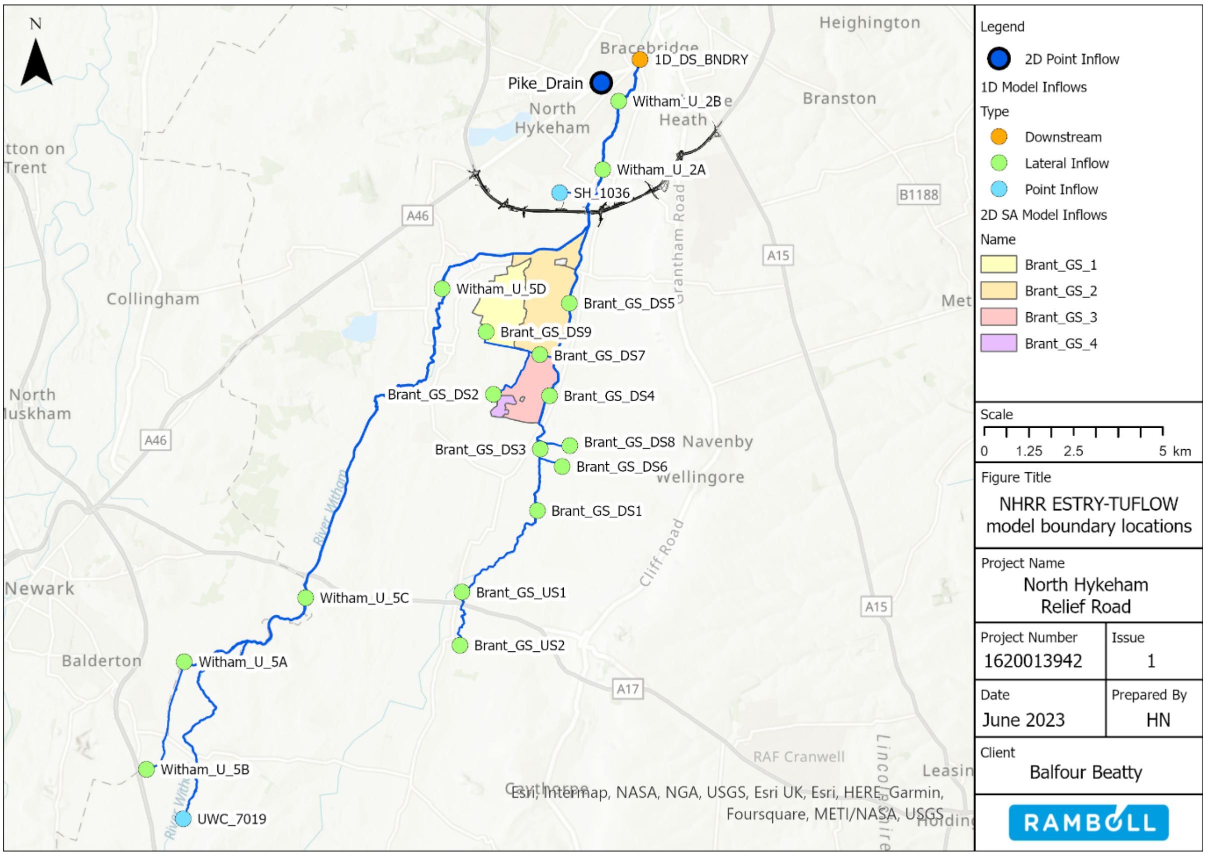

Figure 6-8: NHRR ESTRY-TUFLOW Model Boundary Locations

Downstream Boundaries

6.6.2 The downstream boundary has been placed just downstream of Bracebridge road bridge (Figure 6-8). The location of the downstream boundary is in accordance with the EA, who advised that this location, a significant constriction point situated far enough downstream to not influence the flood risk at the NHRR crossing point.

6.6.3 A 1D stage-discharge (HQ) boundary was used to allow flows to leave the model at the downstream extent of the 1D ESTRY channel. The 1D HQ boundary was developed using the Manning's Equation. A 2D HQ boundary was used to allow flows to leave the model at the downstream extent of the 2D TUFLOW floodplain. The 2D HQ boundaries applied a 0.001 m/m water surface slope for the automatic calculation of the stage-discharge relationship.

6.7 NHRR

6.7.1 The Proposed NHRR design as it crosses the river Witham floodplain consists of the following:

- The NHRR would cross the river Witham floodplain, perpendicular to the direction of flow, on an earth embankment.
- A wide-span bridge is proposed for the NHRR to cross the River Witham. Approximately 109 m from the left to right embankment and 30 m wide, from upstream to downstream face.
- Two sets of four 2.25 m diameter circular piers. The two sets of piers would sit on either side of the river Witham positioned on the existing flood levees.
- A culvert allowing the continued passage of flows of IDB channel Green Lane Drain through the earth embankment.
- The IDB channels Hykeham Pump Drain South and Waddington Dyke South will not require a culvert as the two IDB channels will pass under the wide span bridge crossing the river Witham.

6.7.2 The NHRR design has been represented in the 2D domain:

- The NHRR earth embankment has been incorporated using an ascii terrain dataset.
- The culvert under the embankment has been incorporated using a 1D circular culvert, with CN-SX boundary connecting the 1D-2D domains.
- The wide span bridge deck will be over 1 m above the maximum flood level simulated for this event and so has not been included.
- The bridge piers are proposed to be less than a quarter of the model grid size of 10 m at 2.25 m and therefore have not been included in the hydraulic modelling.

6.8 Breach Guidance

6.8.1 Breach widths vary depending on the nature of the defence. The flood defences in place at the NHRR site are earth embankments protecting from a fluvial event, thus a breach width of 40 m would be appropriate. The length of time a breach occurs varies depending on its location. The general guidance from the EA is that a breach occurring in an urban setting would be simulated for 30 hours while a breach in a rural setting would be simulated for 56 hours. Following this guidance, a breach of 56 hours would be appropriate. It was agreed with the EA that a 40 m wide breach occurring for 56 hours was appropriate for the NHRR assessment. An instantaneous breach and restore was applied to provide a conservative approach.

6.8.2 The method generally used to model a defence breach is to start a breach when water levels reach the defence crest. Unfortunately, this was not possible for all breach scenarios as water levels did not already reach defence crests. Following discussion with the EA, Table 6-10 shows the agreed approach for each scenario.

6.8.3 The agreed location for the breach of the River Witham Levee is downstream of the River Witham flood gate. The location of the breach poses several difficulties in setting an appropriate time/water level to initiate the breach, the key issues being the impact of flood gate closures on water levels and the impact of flood waters spilling from the floodplain over the defence into the Witham channel during the extremely high return period events. The breach has therefore been set to occur when the peak water level is reached upstream of the river Witham flood gates. This approach should capture the worst-case impact of a breach as it occurs when the flood peak reaches the NHRR area.

Table 6-10: Method applied to specify the start of the two NHRR Breach Scenarios

Event	Breach of Witham Washland Defence (Trigger set at Witham Washland)	Breach of River Witham Levee (Trigger set upstream of River Witham Flood Gate)
100-year	Maximum Water Level (6.8 m AOD)	Maximum Water Level (7.14 m AOD)
100-year Climate Change (2080 Higher)	Defence Level (7.4 m AOD)	Maximum Water Level (7.45 m AOD)
1,000-year	Defence Level (7.4 m AOD)	Maximum Water Level (7.62 m AOD)
1,000-year Climate Change (2080 Higher)	Defence Level (7.4 m AOD)	Maximum Water Level (7.76 m AOD)

6.9 Assumptions

6.9.1 The underlying data and parameterisation in the original EA Infoworks 2015 model are assumed to be acceptable for use and forms the basis of the NHRR ESTRY-TUFLOW model used in this study.

6.9.2 For smaller tributaries, the watercourse bed profile is reasonably represented by the LiDAR to the extent that it would not considered to significantly affect model performance in the areas of primary interest for this study.

7. MODEL SCENARIOS

7.1 Model scenarios

7.1.1 The 1D-2D ESTY-TUFLOW hydraulic model has been used to simulate four different scenarios outlined in Table 7-1. The model results were interrogated to understand the difference in flood depth, velocity, and hazard to determine the impact on flood risk.

Table 7-1: Proposed scenarios for the NHRR hydraulic model

Type	Reference	Reason
Baseline	BAS	Provide an understanding of the existing flood risk without the NHRR Scheme for comparison.
Development	NHRR	Simulates the NHRR road scheme. Road embankment with wide span bridge and culverts conveying IDB rivers and drains. The 1 in 1,000-year AEP event will simulate overtopping of the FSA Embankment.
Breach	NHRR_Breach_RWUS	Simulates the NHRR road scheme with a breach in the River Witham embankment between the NHRR crossing and the FSA embankment. • Instant Breach • 40m Width (earth embankment) • 56 hours (rural area)
Breach	NHRR_Breach_FSA	Simulates the NHRR road scheme with a breach in the FSA embankment. • Instant Breach • 40m Width (earth embankment) • 56 hours (rural area)

7.2 Model Events

7.2.1 Through consultation, the EA has identified that the flat topography of the area means the floodplains are passive and are only in play during a major incident. The key area of concern for the EA is how the NHRR would impact the flooding mechanisms should the flood storage embankment or the river embankments fail or overtop during an exceedance event. Therefore, the NHRR hydraulic model assessed the following extreme return period fluvial events:

- 1 in 100-year event (1% AEP event)
- 1 in 1,000-year event (0.1% AEP event)
- 1 in 100-year event plus climate change Higher 2080 (32%)
- 1 in 1,000-year event plus climate change Higher 2080 (32%)

8. MODEL PROVING

8.1 Run Performance

8.1.1 Figure 8-1 and Figure 8-2 shows the mass balance error for the baseline scenario for the 1D ESTRY and 2D TUFLOW model domains respectively. The accepted tolerance range recommended by the software manual is +/-1%[8]. The overall 2D mass balance error is between -1% to +1% for all simulations. The 1D mass balance for the 100-year and 100-year plus climate change (2080 Higher) event is between -1% and 1%. The 1D mass balance for the 1,000-year and 1,000-year plus climate change (2080 Higher) event exceed the 1% value. Investigation shows that the 1D mass balance issues focused on the downstream extent of the model, as the water leaves the 1D domain. For the purposes of this study, the higher 1D mass balance for the extreme return period event is acceptable. Figure 8-3 and Figure 8-4 shows the change in total volume of water since the previous time step within the 1D ESTRY and 2D TUFLOW model domains respectively. The dVol shows a relatively smooth profile with minor fluctuations which indicates the model is generally stable.

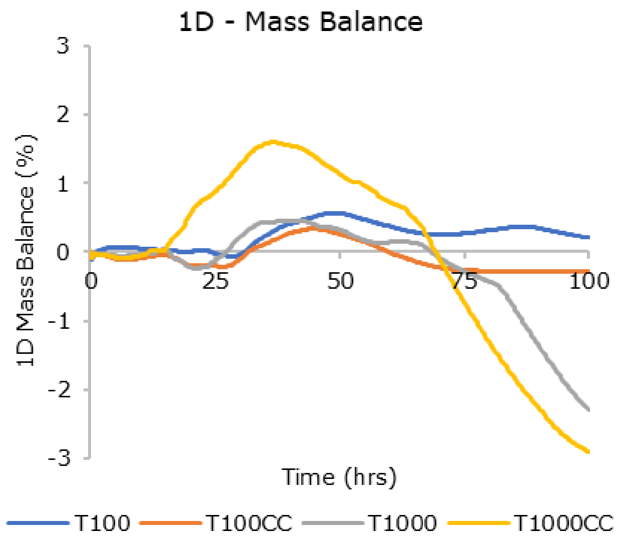

Figure 8-1: 1D Mass Balance Error for the NHRR Scenario

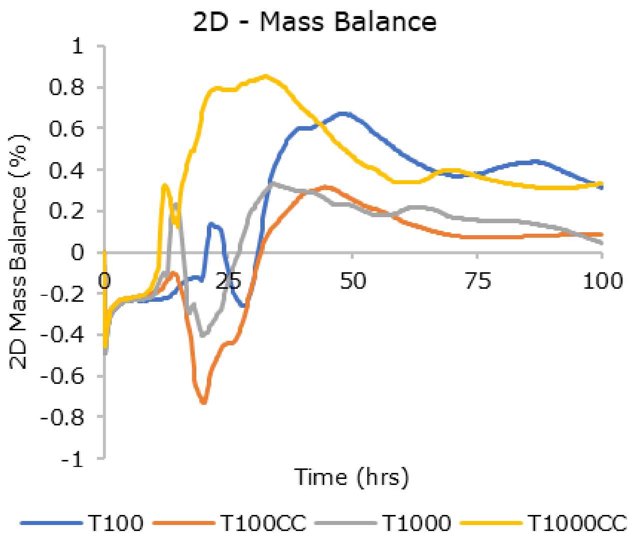

Figure 8-2: 2D Mass Balance Error for the NHRR Scenario

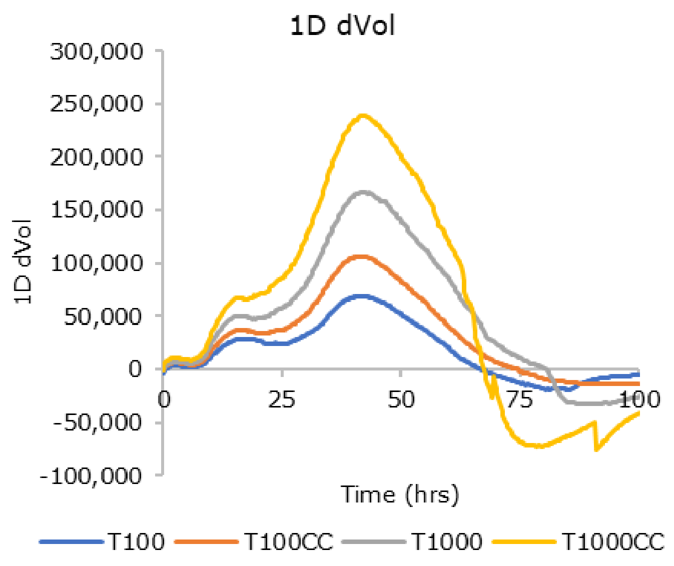

Figure 8-3: 1D dVol for the NHRR Scenario

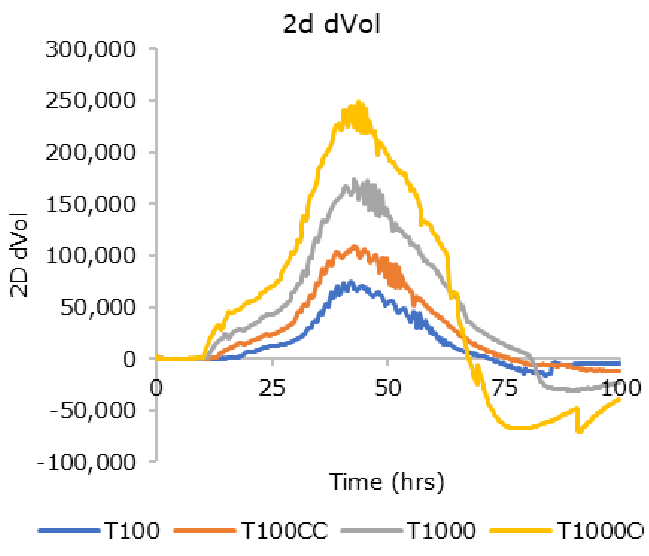

Figure 8-4: 2D dVol for the NHRR Scenario

[8] BMT TUFLOW 1D/2D Fixed Grid Hydraulic Modelling – TUFLOW Classic/HPC User Manual Build 2018-03-AD

8.2 Sensitivity Analysis

8.2.1 Sensitivity analysis was carried out to understand the hydraulic model's uncertainty and result reliability. Sensitivity testing was carried out under the 100-year plus climate change (2080 Higher) event using the Baseline setup for the following parameters:

- Downstream boundary water surface slope +/-20%; and
- 1D-2D Channel and Floodplain Manning's n Roughness +/-20%.

Downstream Boundary

8.2.2 An HQ boundary has been applied to represent the downstream boundary of the 1D and 2D domain of the model. The 2D HQ boundary applied a 0.001 m/m water surface slope for the automatic calculation of the stage-discharge relationship. Sensitivity testing of the 2D HQ boundary was applied by increase and decreasing the water surface slope by +/- 20%. The 1D HQ boundary stage discharge relationship was developed using the Manning's Equation. Sensitivity testing of the 1D HQ boundary was applied by increasing and decreasing the discharge value of the HQ boundary by +/-20%.

8.2.3 Figure 8-5 and Figure 8-6 shows the flood depth difference of the downstream boundary sensitivity results compared to the baseline results, increasing (D20P), and decreasing (D20M) the boundary by 20% respectively. Table 8-1 shows the downstream sensitivity results at eight points around the NHRR crossing. Figure 8-5 shows that increasing the water slope boundary by 20% has negligible (< +/- 10 mm) impact at the NHRR crossing location. Figure 8-6 shows that decreasing the water slope boundary by 20% causes an increase in flood depths at the NHRR crossing location. Considering the distance between the downstream model extent and the NHRR crossing location, combined with the calculated backwater effect of the Witham, the simulated impact to flood risk at the NHRR crossing location of changing the downstream boundary is unusual. The reason for the impact is because one the trigger points for the operation of the Witham and Washland floodgates is located just upstream of the downstream boundary, at Bracebridge. Therefore, any changes to the downstream boundary that may result in an increase in water levels at the downstream extent of the model, could impact the flood risk upstream beyond the calculated backwater effect distance, because it may trigger the operation of the floodgates.

8.2.4 The downstream sensitivity results would suggest that the model results at the site location are sensitive to changes to the downstream boundary, to the scale of -6 mm to +137 mm. It is noted that the D20M sensitivity scenario at the cumulative error of -2.65%, which is greater than the acceptable error of +/- 1% for modelling.

Table 8-1: Downstream Sensitivity Results at eight points around the NHRR crossing

ID	Baseline Depth (m)	D20P		D20M	
		Depth (m)	Depth Difference (mm)	Depth (m)	Depth Difference (mm)
1	1.319	1.321	2	1.326	8
2	1.644	1.645	1	1.653	9
3	0.055	0.055	1	0.111	56
4	0.538	0.531	-6	0.675	137
5	0.796	0.790	-6	0.933	137
6	0.268	0.269	1	0.324	56
7	0.267	0.267	1	0.321	54
8	0.183	0.182	-1	0.273	90

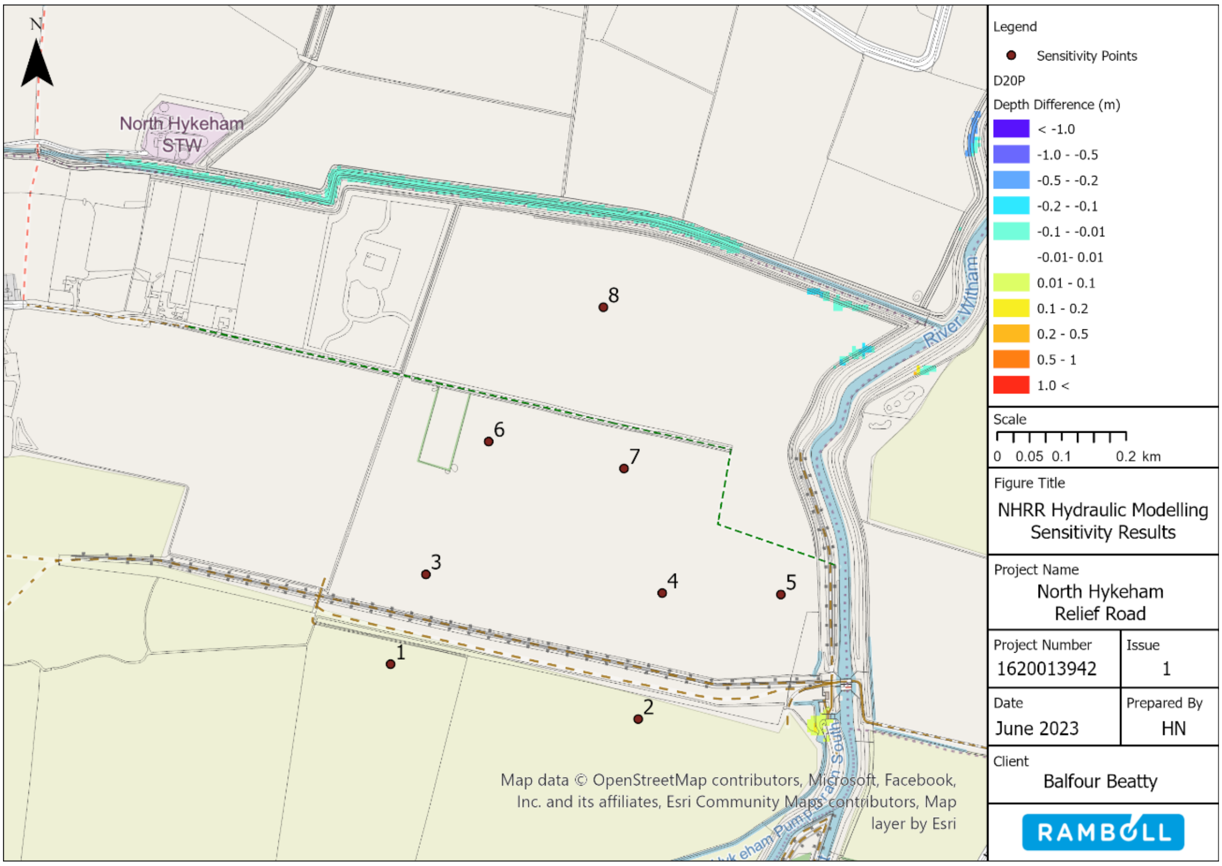

Figure 8-5: Downstream boundary sensitivity difference increased by 20%

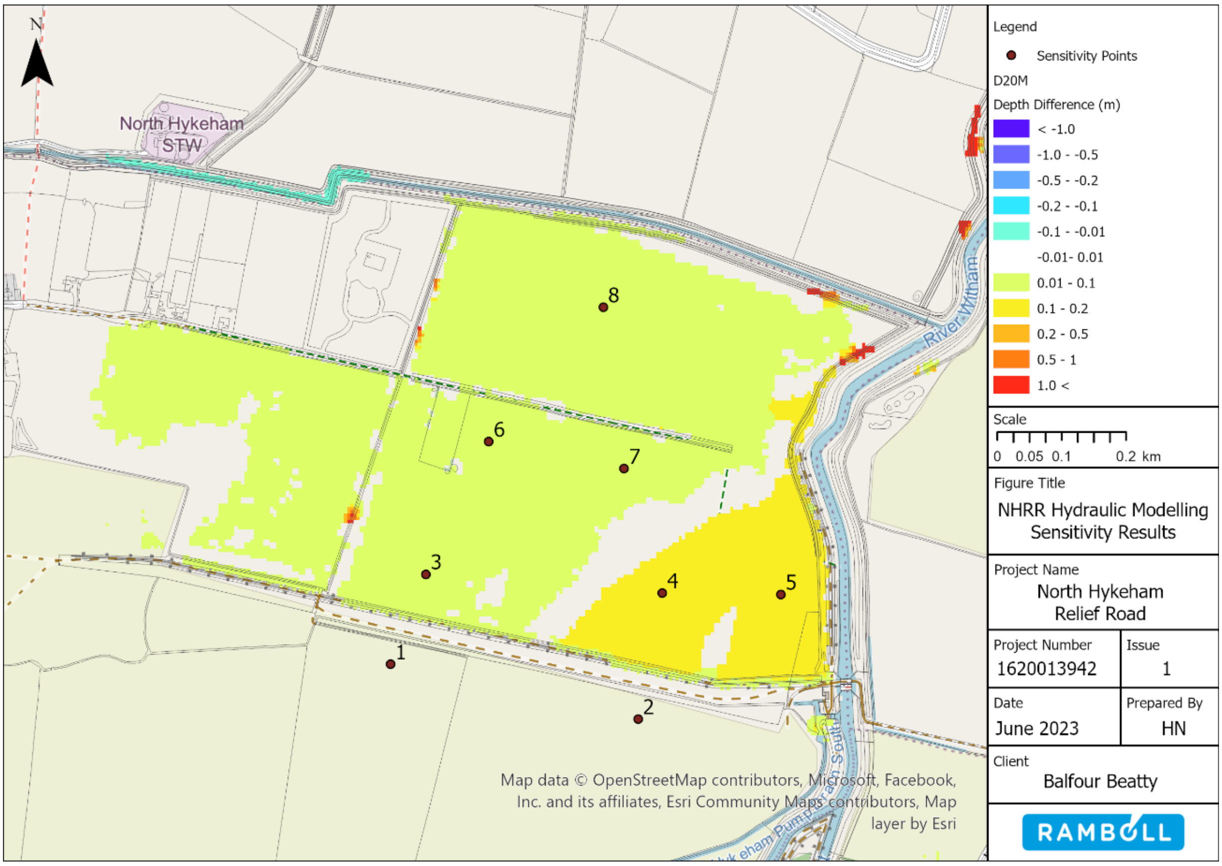

Figure 8-6: Downstream boundary sensitivity difference decreased by 20%

Model Roughness

8.2.5 To assess the model sensitivity to channel and floodplain roughness, the manning's n values applied in the 1D and 2D model domains were increased and decreased by 20%.

8.2.6 Figure 8-7 and Figure 8-8 shows the flood depth difference of the roughness sensitivity results compared to the baseline results, increasing and decreasing the model roughness by 20% respectively. Table 8-2 shows the roughness sensitivity results at eight points around the NHRR crossing. Increasing the model roughness by 20% increases the water levels around the NHRR crossing location by as much as 830 mm. Decreasing the model roughness by 20% decreases the water levels in the Witham Washland by 87 mm, such that the modelled water levels no longer overtop the Witham Washland defence to flood the area proposed for the NHRR crossing.

8.2.7 The roughness sensitivity results would suggest that the model results at the site location are sensitive to changes to model roughness, to the scale of -796 mm to +830 mm. The lower value of -796 mm is taken from the maximum depth of the Baseline scenario extracted from the sensitivity points, as reducing the roughness by 20% results in no flooding at the crossing site during the 100-year plus climate change (2080 Higher) event. It is noted that the R20M sensitivity scenario at the cumulative error of -2.50%, which is greater than the acceptable error of +/- 1% for modelling.

Table 8-2: Roughness Sensitivity Results at eight points around the NHRR crossing

ID	Baseline Water Level (m AOD)	R20P		R20M	
		Water Level (m AOD)	Water Level Difference (mm)	Water Level (m AOD)	Water Level Difference (mm)
1	7.440	7.472	33	7.353	-87
2	7.440	7.473	33	7.357	-83
3	6.139	6.815	676		
4	5.984	6.814	830		
5	5.984	6.814	830		
6	6.138	6.814	676		
7	6.137	6.814	677		
8	6.034	6.814	780		

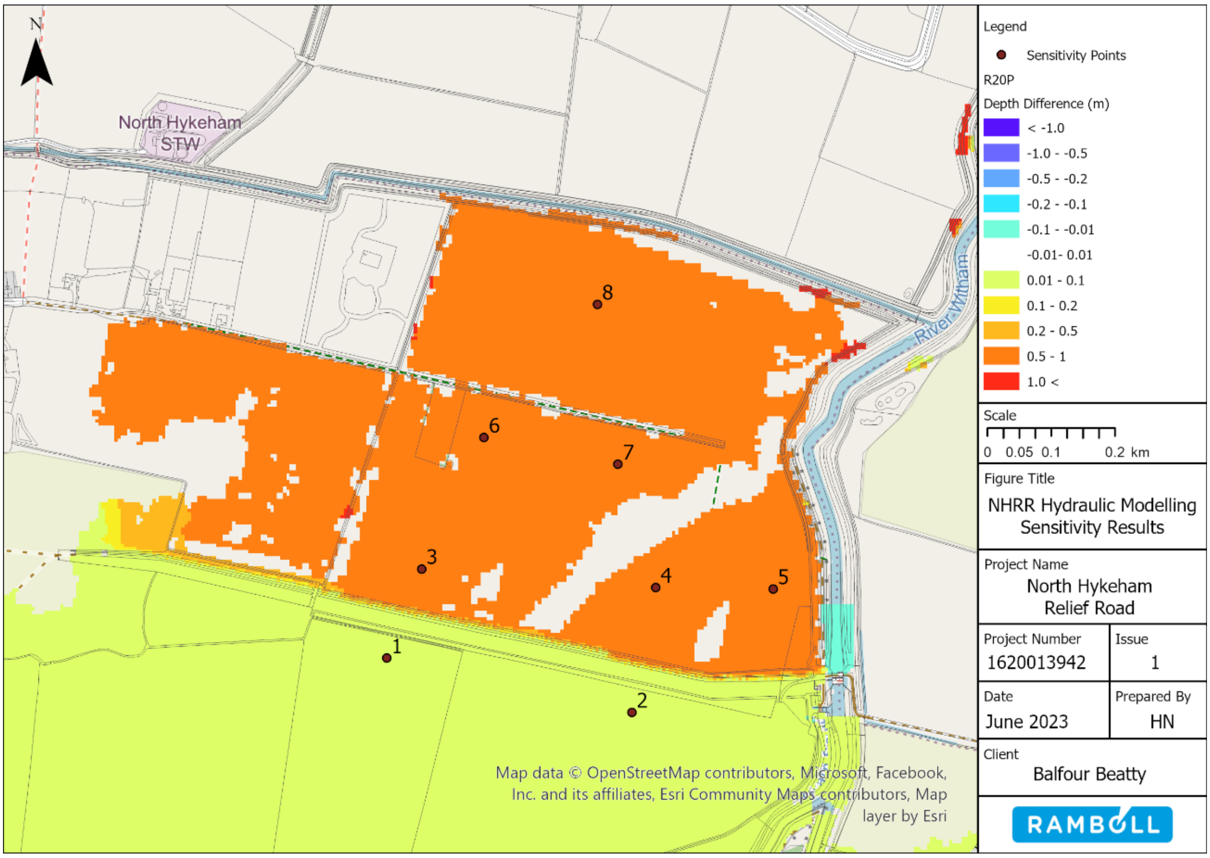

Figure 8-7: Model roughness sensitivity difference increased by 20%

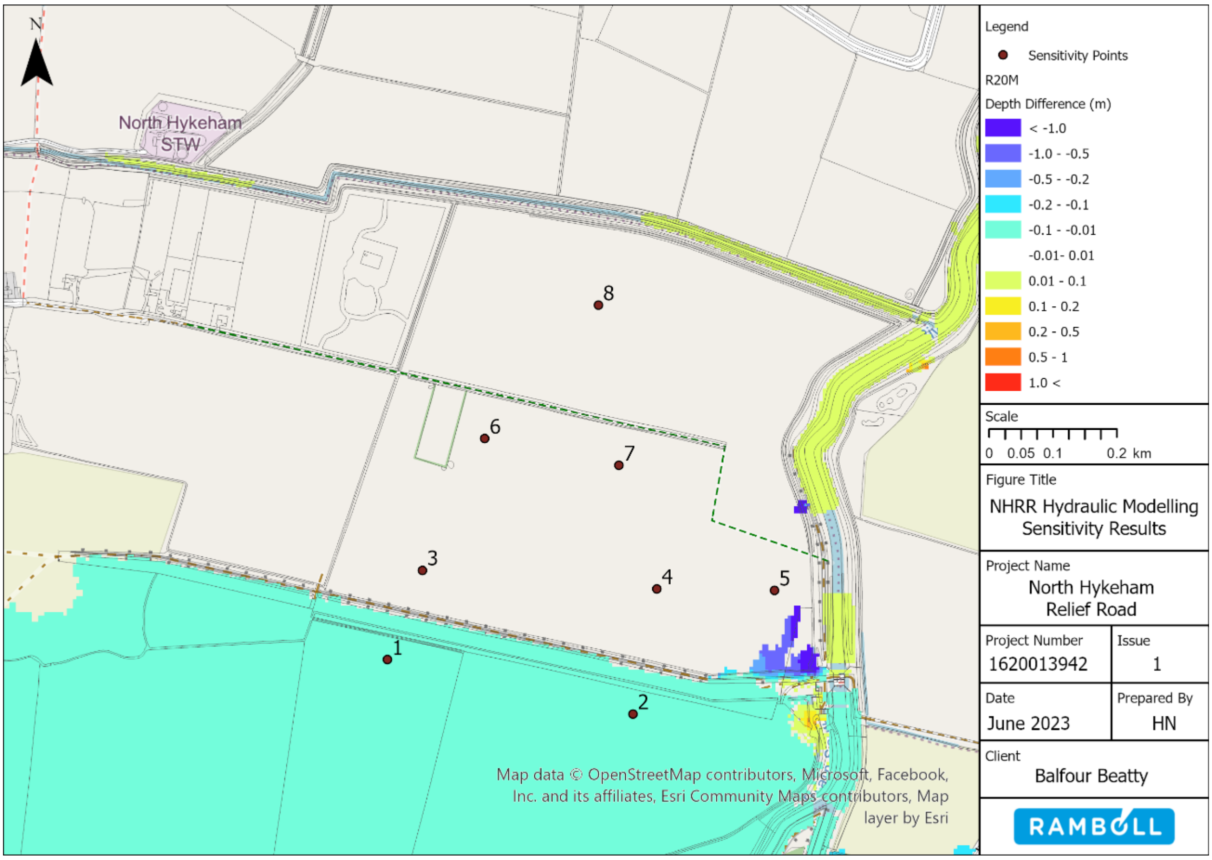

Figure 8-8: Model roughness sensitivity difference decreased by 20%

8.2.8 The sensitivity testing showed that the model is sensitive to changes in the downstream boundary and model roughness at the boundary location, both in terms of flood risk and cumulative model error. The sensitivity results show that at the NHRR crossing location,

- Model Roughness sensitivity is between -796 mm to +830 mm
- Model Downstream boundary sensitivity is between -6 mm to + 137 mm

8.3 Resolving 1D Oscillations

8.3.1 During model development, the 1D water levels around the washland and Witham floodgates showed significant oscillations. The cause of the oscillations is a direct result of the operation of the flood gates, set to operate when water levels at key locations along the 1D channel exceed a set value. The result is that significant volumes of water are suddenly released from the 1D to 2D domain and/or the main 1D channel is suddenly blocked when water levels and flows exceed a specifical water level, which is generally near the peak of an extreme event.

8.3.2 To improve the oscillations in the 1D water levels and following consultation with TUFLOW Support, several methods have been tested (Table 8-3). Figure 8-9 and Figure 8-10 show the 1D water levels at cross sections around the Witham flood gates, comparing the base 1D water level and the various methods tested to improve 1D oscillations. Figure 8-11 shows a comparison between the base [033] flood extent and the various methods tested to improve 1D oscillations.

Table 8-3: Methods tested in the 1D domain to improve 1D water level stability at the flood gates in the NHRR hydraulic model

Test	Code	Reasoning	Outcome	Utilised
Original	033	Base model where 1D oscillations affect the 1D river channels around the flood gates		
Set river channel type to "SN"	042-SN	For a non-inertial channel, the inertial terms are ignored which might help stabilise problematic S channels.	Magnitude of oscillations in the 1D river channel around the flood gates increases	✗
Include "Period of no Change < 15 mins" in the structure TUFLOW Operation Control file	043-TOC	Test to reduce the feedback loop of opening and closing the operational structures triggered by water levels. Theory being that the water levels respond to the opening and closures causing further opening and closing of structures, causing further fluctuating water levels. By adding a pause after a structure has been triggered, that may allow water levels to stabilise, reducing oscillations.	Magnitude of oscillations in the 1D river channel around the flood gates increases, the frequency of oscillations decreases.	✗
Extend the 1D-2D SX boundary for the flood gates to 3 model cells.	044-3SX	Although against best practice, this method was tested to address the significant volumes of water flowing from the 1D to 2D domain. The length of the line is similar to the width of the 1D river section.	Severity of oscillations slightly reduced but with spurious points of increased magnitude.	✗
Increase the number of cross sections around the Witham Flood Gates	045-XS	Test to see if more cross section detail in the 1D domain around the flood gates would provide more stability.	Magnitude of oscillations in the 1D river channel around the flood gates increases	✗
Reduce flood gate speed to 0.005 m/s	048 - Gate Speed	Slowing the gate speed may improve stability.	Slight reduction in the severity of the oscillations in the 1D river channel	✗
Set Opening / Closing period to 10 minutes	049 - Period closing	Slowing the opening and closing period of the structures may improve stability.	Significant reduction in the severity of the oscillations in the 1D river channel	✓

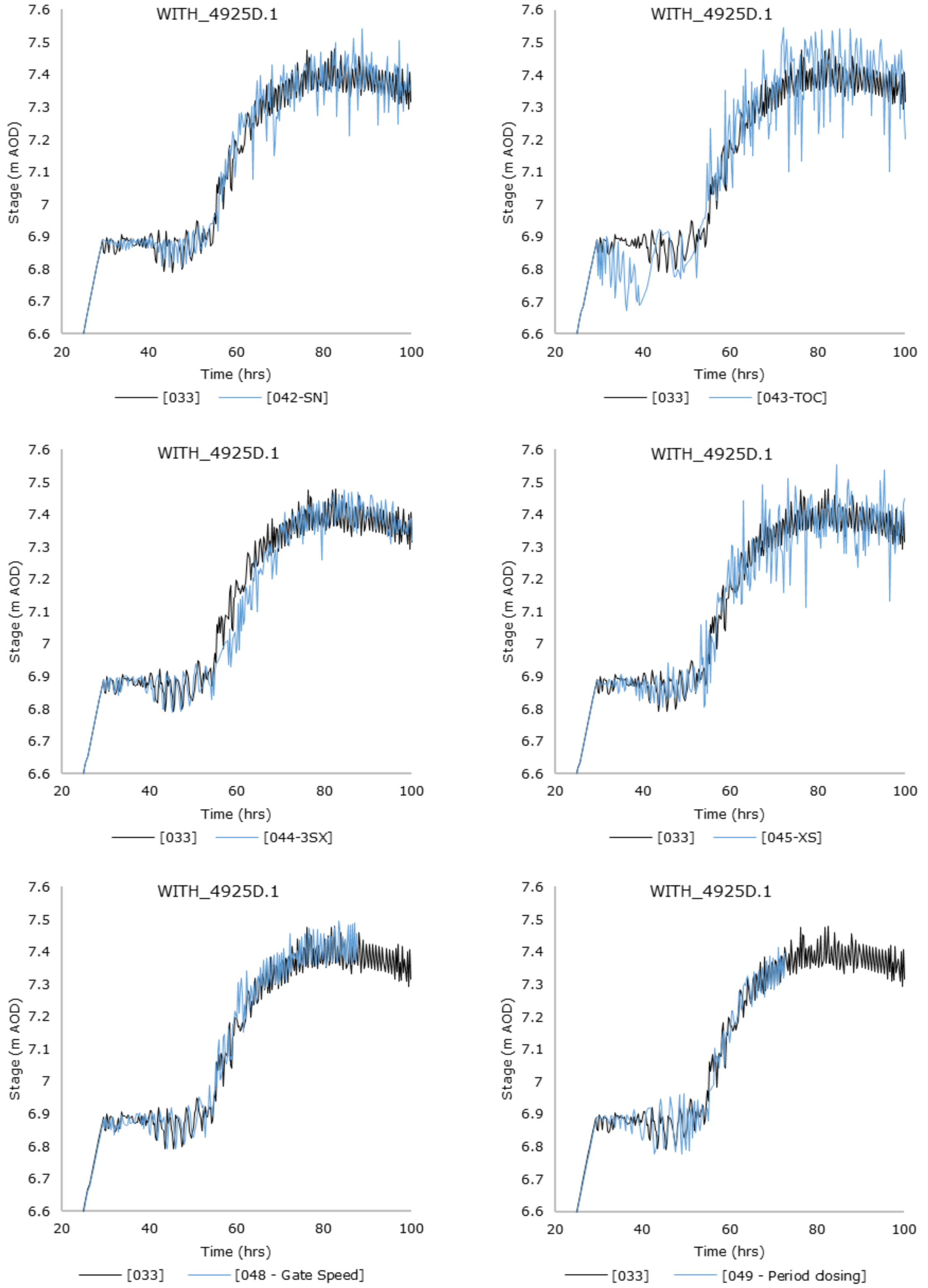

Figure 8-9: 1D water levels at WITH_4925D cross section, (located upstream of the river Witham flood gate and next to the Witham Washland flood gate). Comparison between the base 1D water level and the various methods tested to improve 1D oscillations.

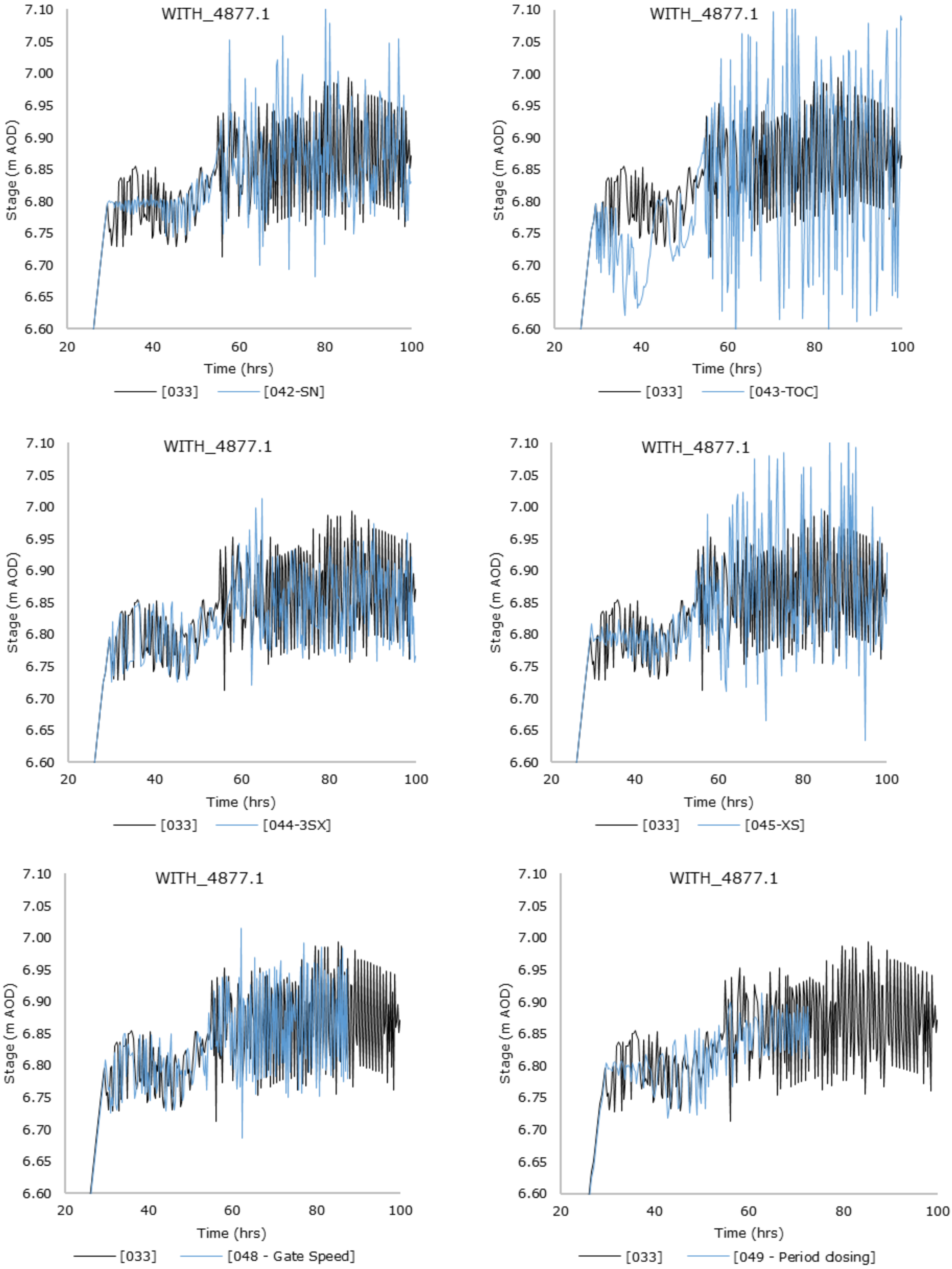

Figure 8-10: 1D water levels at WITH_4877 cross section, (located downstream of the river Witham flood gate). Comparison between the base 1D water level and the various methods tested to improve 1D oscillations.

Figure 8-11: Comparison between the base [033] flood extent and the various methods tested to improve 1D oscillations

8.3.3 The severity of the oscillations in the 1D water levels have a significant impact on the flood extents in the 2D domain around the NHRR crossing. The greater the magnitude and severity of the 1D oscillations, the greater the flood extent in the 2D domain. This indicates that the 1D oscillations were resulting in unrealistic flood extents.

8.3.4 None of the test runs simulated flooding of the NHRR, the lowest point set to be above the maximum flood level.

8.3.5 Following the stability testing, the most appropriate measure was to apply test 049, and set the opening / closing period to 10 minutes, slowing down the opening and closing period of the structures to allow more time for the 1D water levels to adjust. Oscillation are still present, but at a much small magnitude and considered acceptable for the purposes of this modelling.

8.3.6 In addition to the 1D stability measures, Table 8-4 summarises the stability measures applied in the 2D domain.

Table 8-4: Modelling methods applied in the 2D domain to improve 1D water level stability at the flood gates in the NHRR hydraulic model

Method	Reasoning	Outcome	Utilised
Reduce the variation in model roughness at the 1D-2D boundary of Flood Gates	Sharp changes in manning’s n roughness over a small area can cause instabilities	• Slightly reduced fluctuations in maximum water level at the 1D-2D boundary • Slightly reduced fluctuation in water levels in the 1D channel	✓
Smooth 2D terrain elevation at the 1D-2d boundary of Flood Gates	Rapid changes in elevation immediately adjacent to the boundary should be avoided, the terrain should be reasonably smooth	• Significantly reduced fluctuation in water levels in the 1D channel	✓
Raise the 2D terrain elevation to equal the flood gate outlet invert.	Important for stable 1D-2D transfer of flows	• Slightly reduced fluctuations in maximum water level at the 1D-2D boundary • Significantly reduced fluctuation in water levels in the 1D channel	✓

9. RESULTS – FLOOD RISK

9.1 Flood Extent

9.1.1 Based on the modelling completed, the NHRR is not predicted to flood under any of the scenarios modelled. All flows were simulated to be conveyed under the NHRR, either under the proposed wide-span bridge connecting the west and east NHRR embankments or through the culvert allowing the continued conveyance of the IDB Green Lane Drain. The main impact to flood extents of the NHRR scheme is to the floodplain around the NHRR crossing. Upstream and downstream of the NHRR crossing, the changes in flood extents are very small, limited to the slight variations at the edges of the flood extents.

9.1.2 The 100-year event flood extent is not affected by the NHRR scheme. The existing flood defences operating in the vicinity of the NHRR crossing retain the 100-year event within the river Witham and the various flood storage areas therefore, the 100-year flood waters do not interact with the NHRR scheme.

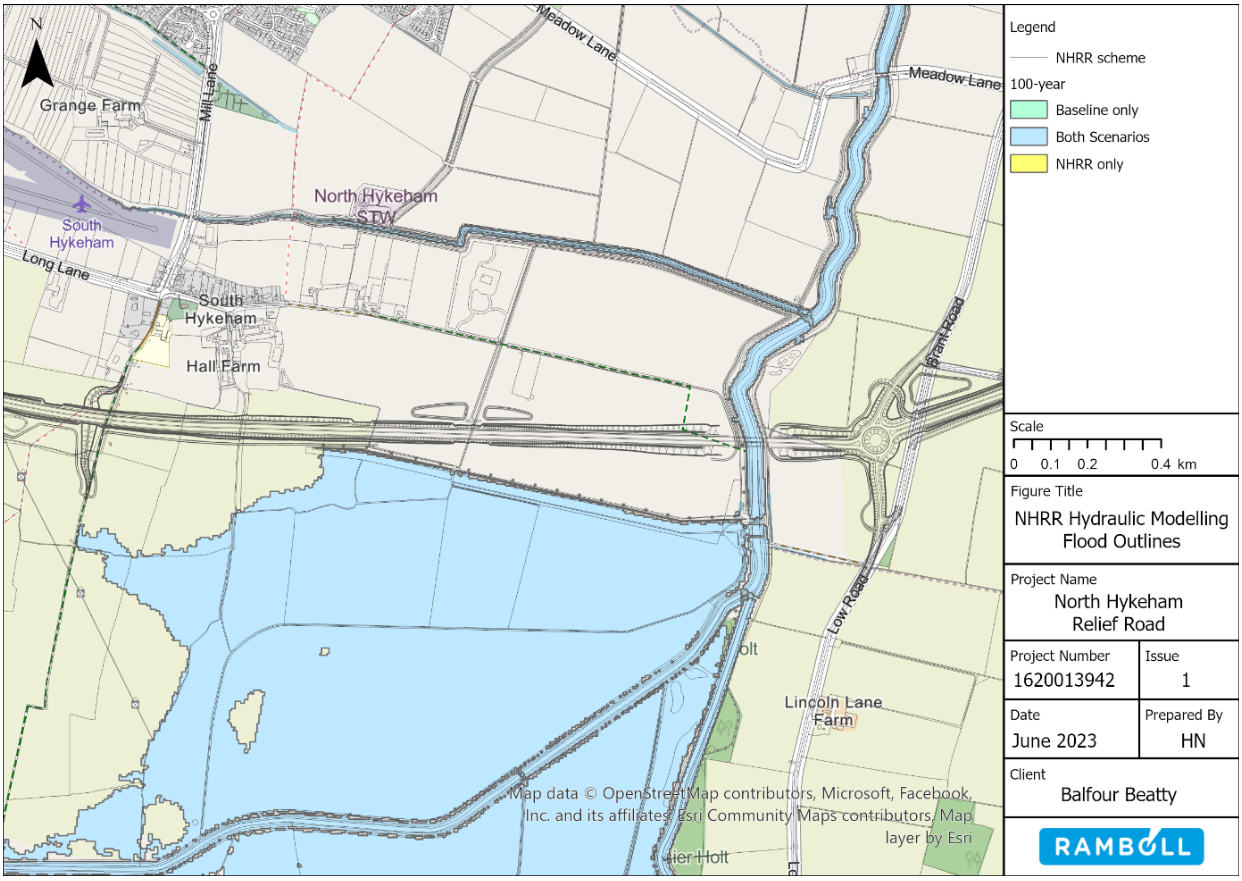

Figure 9-1: 100-year flood extents showing the Baseline (green), NHRR (yellow) and where there is no change/Both (Blue) scenario at the NHRR crossing

9.1.3 The impact of the NHRR scheme on the flood extent of the 100-year plus climate change (2080 Higher) event is limited to the floodplain upstream and downstream of the NHRR crossing (Figure 9-2). The NHRR scheme acts to prevent the spread of flood water overtopping the Witham Washland defence. This results in a reduction to the flood extents north of the NHRR crossing and an increase to the flood extent to the south in the area between the NHRR crossing and the Witham Washland defence.

9.1.4 The water accumulating between the NHRR crossing and the Witham Washland defence during the 100-year plus climate change (2080 Higher) event passes north between the NHRR embankment and the existing river Witham defence under the proposed wide span bridge. The water then spreads to the floodplain north of the NHRR crossing and into the IDB drain Hykeham Pump Drain South running parallel to the river Witham. Due to the position of the wide span bridge, more flood water is directed to the IDB channel compared to the baseline scenario. The result is that during the NHRR scenario, there is an increase in the flood extent at the IDB drain Hykeham Pump Drain South, with flooding extending north to Meadow Lane, and a decrease in the flood extent to the floodplain north of the NHRR crossing.

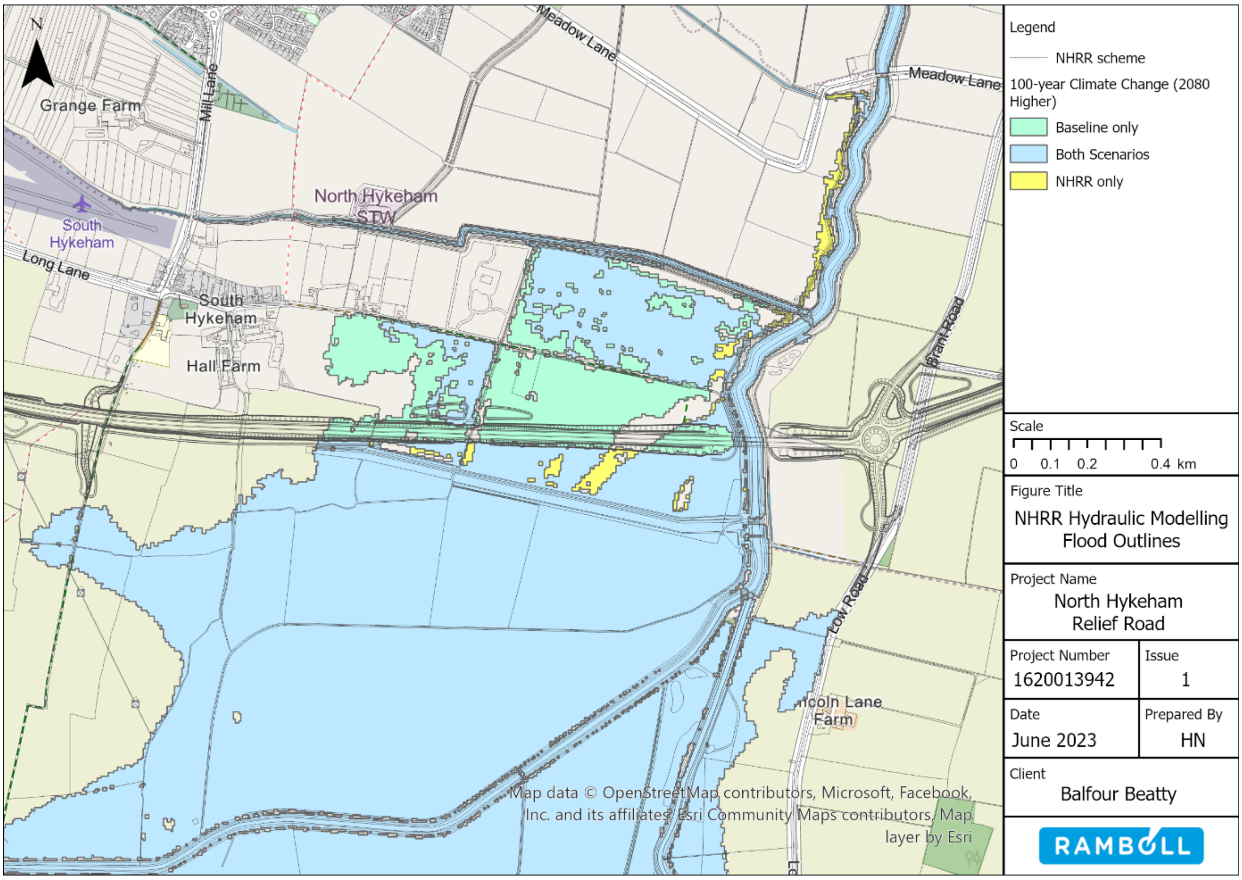

Figure 9-2: 100-year plus climate change (2080 Higher) flood extents showing the Baseline (green), NHRR (yellow) and where there is no change/Both (Blue) scenario at the NHRR crossing

9.1.5 The impact of the NHRR scheme on the flood extent of the 1,000-year event and the 1,000-year event plus climate change (2080 Higher) is limited to the area around the NHRR crossing (Figure 9-3 and Figure 9-4). The NHRR scheme acts to prevent the spread of water across the floodplain, resulting in a reduction in NHRR flood extent. Upstream and downstream of the NHRR crossing, the changes in flood extents are very small, limited to the slight variations at the edges of the flood extents.

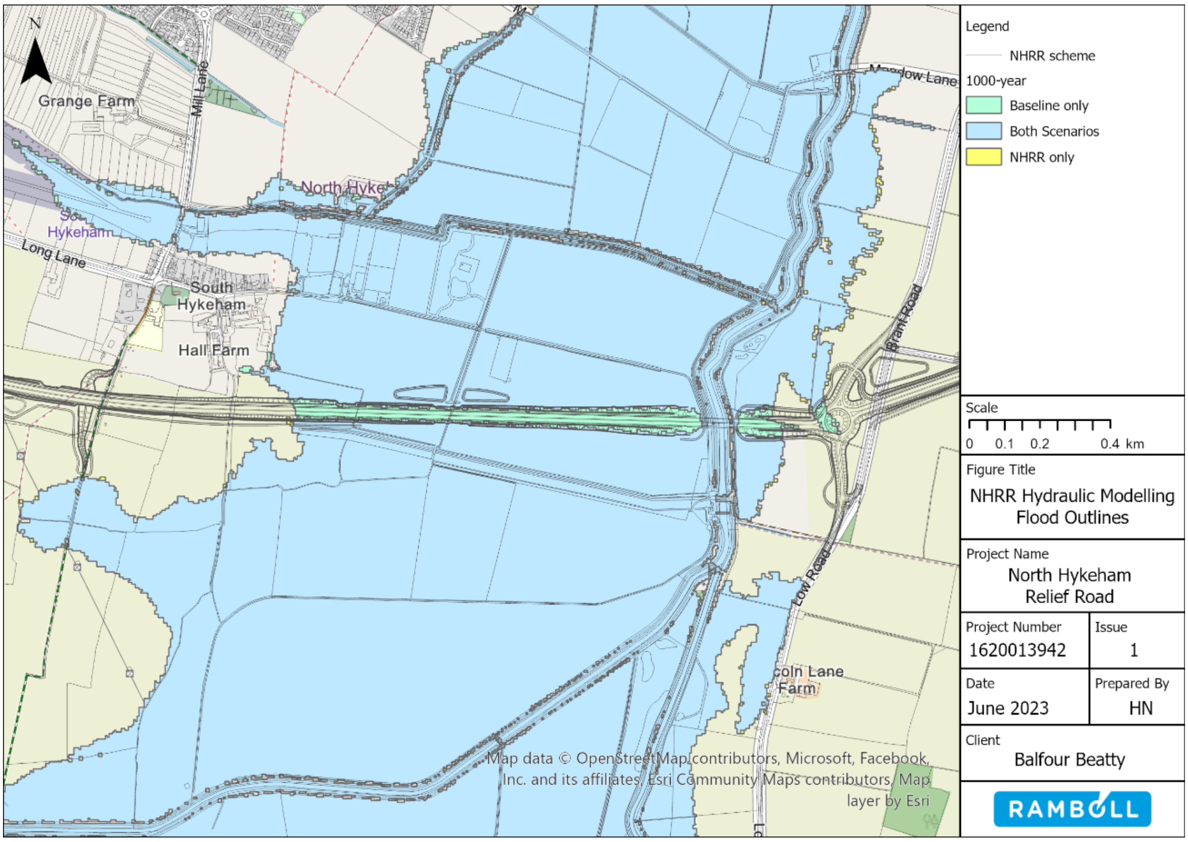

Figure 9-3: 1,000-year flood extents showing the Baseline (green), NHRR (yellow) and where there is no change/Both (Blue) scenario at the NHRR crossing

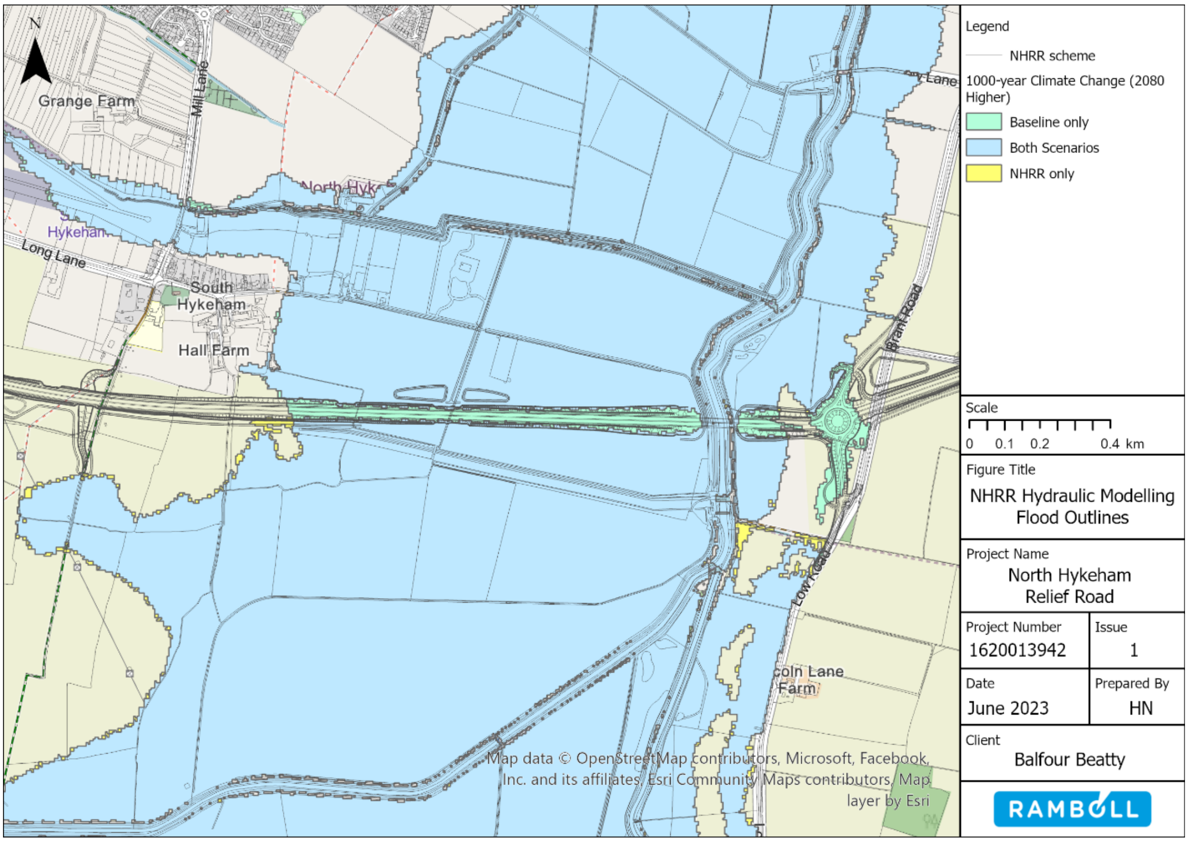

Figure 9-4: 1,000-year plus climate change (2080 Higher) flood extents showing the Baseline (green), NHRR (yellow) and where there is no change/Both (Blue) scenario at the NHRR crossing

9.2 Flood Depths

9.2.1 Figure 9-5 shows the flood depth difference between the NHRR scenario and the Baseline scenario during the 100-year plus climate change (2080 Higher) event. Figure 9-6 and Figure 9-7 show the flood depths for the Baseline and NHRR scenarios during the 100-year plus climate change (2080 Higher) event.

9.2.2 During the 100-year plus climate change (2080 Higher) event, the impact on flood depths is limited to the area upstream and downstream of the NHRR crossing. The NHRR scheme acts to prevent the spread of flood water overtopping the Witham Washland defence north. This results in a reduction to the flood depths north of the NHRR crossing of between 50 mm to 100 mm, and an increase to the flood depths to the south in the area between the NHRR crossing and the Witham Washland defence by between 20 mm to 200 mm

9.2.3 The water accumulating between the NHRR crossing and the Witham Washland defence during the 100-year plus climate change (2080 Higher) event passes north between the NHRR embankment and the existing river Witham defence under the proposed wide-span bridge. The water then spreads to the floodplain north of the NHRR crossing and into the IDB drain Hykeham Pump Drain South running parallel to the river Witham. The additional water fills the IDB Hykeham Pump Drain South up to Meadow Lane during the NHRR scenario compared to the baseline scenario, where flood waters filled the Hykeham Pump Drain South up to the Beck.

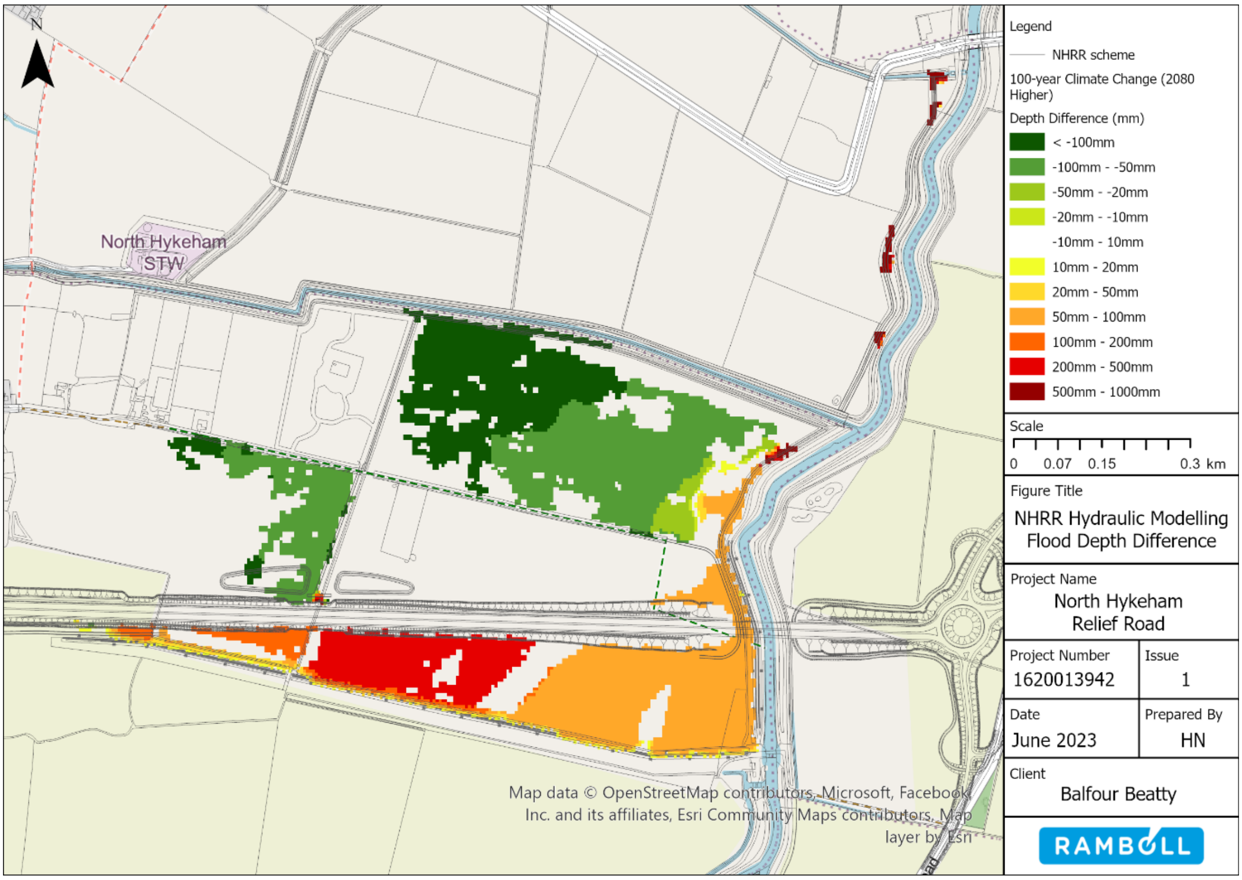

Figure 9-5: 100-year plus climate change (2080 Higher) flood depth difference between the Baseline and NHRR Scenario

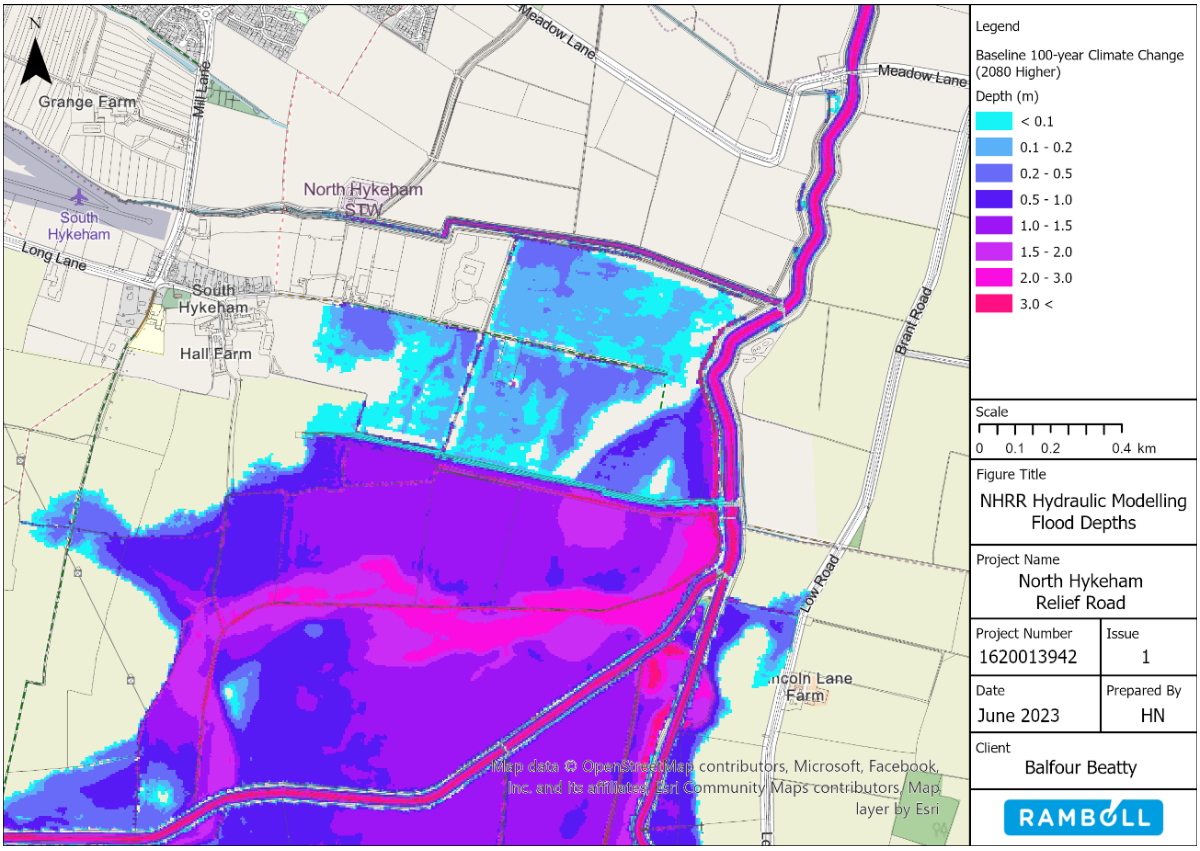

Figure 9-6: 100-year plus climate change (2080 Higher) flood depths for the Baseline Scenario

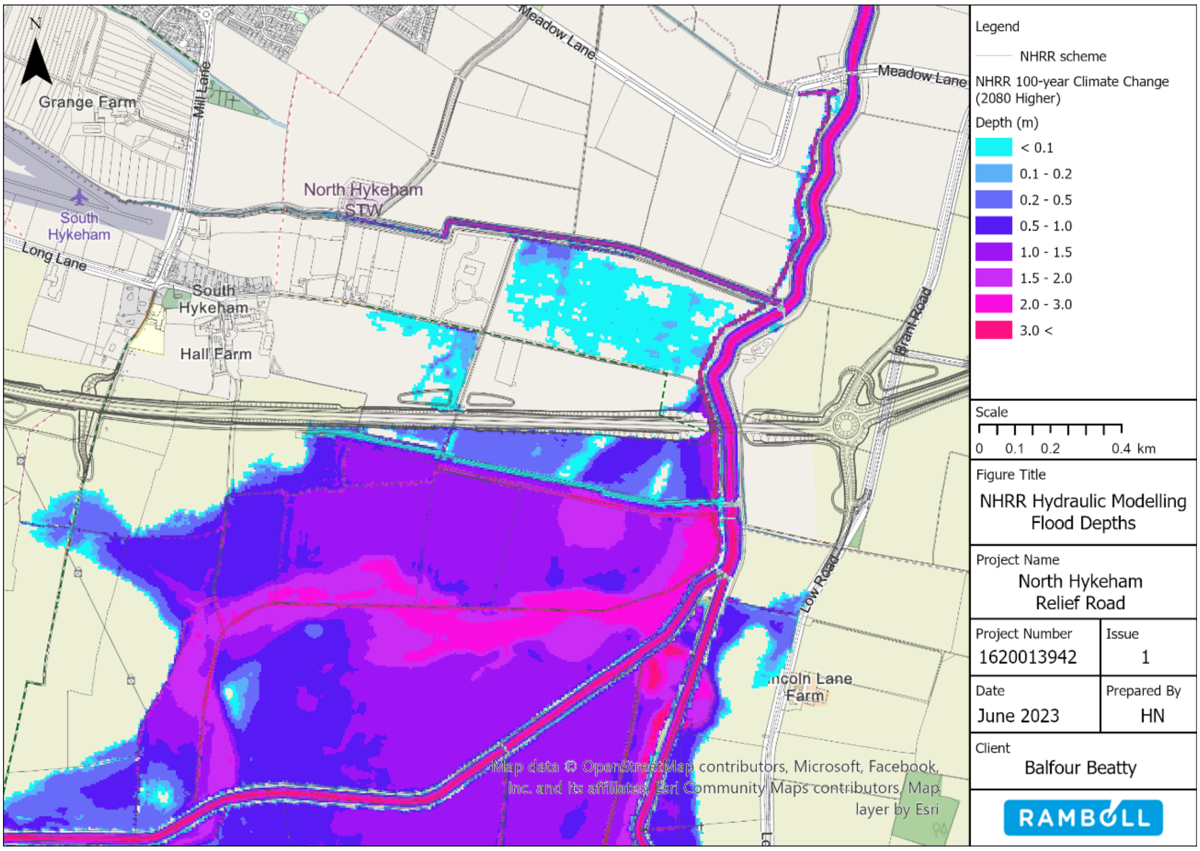

Figure 9-7: 100-year plus climate change (2080 Higher) flood depths for the NHRR Scenario

9.2.4 Figure 9-9 shows the flood depth difference between the NHRR scenario and the Baseline scenario during the 1,000-year event. Figure 9-10 and Figure 9-11 show the flood depths for the Baseline and NHRR scenarios during the 1,000-year event.

9.2.5 During the 1,000-year event, as the Witham Washland flood gates open and the River Witham flood gates close to protect Lincoln, flood waters first fill the Witham Washland. As the flood levels increase, flood waters overtop the Witham Washland Defence to fill the floodplain to the north. As the flood levels increase further, the flood waters from the floodplain overtop the levees lining the River Witham downstream of the River Witham flood gates, spilling into the main river. Figure 9-8 shows the River Witham water levels downstream of the River Witham flood gates during the 1,000-year event. There is a clear increase in water levels marking where the floodwaters from the floodplain start to overtop the River Witham levees into the main river channel, where water levels were formerly controlled by the operation of the River Witham flood gates.

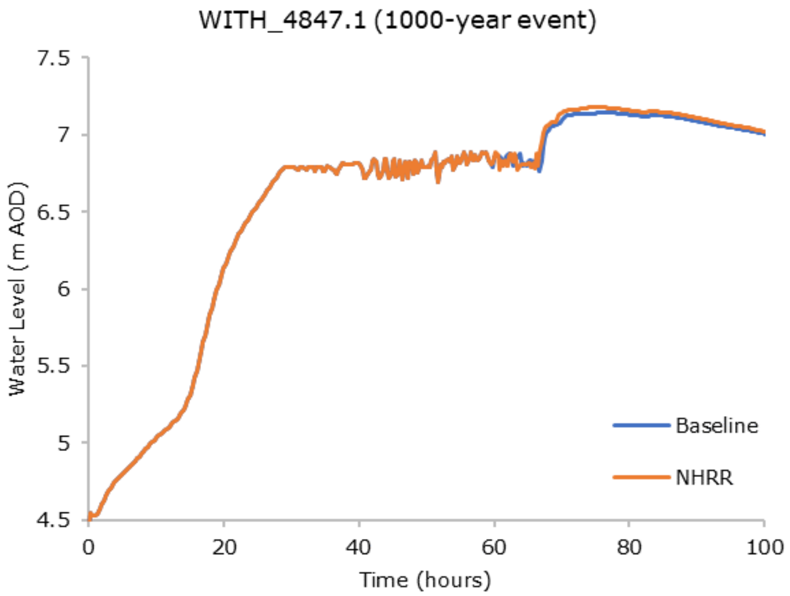

Figure 9-8: 1,000-year event Water levels in the River Witham downstream of the River Witham flood gates

9.2.6 The NHRR scheme acts to prevent the spread of flood water overtopping the Witham Washland defence. This results in a reduction to the flood depths north of the NHRR crossing of between 20 mm to 50 mm. An increase in flood depths is simulated to the south in the area between the NHRR crossing and the Witham Washland defence by between 50 mm to 100 mm near the river Witham to between 100 mm to 200 mm further west. An increase in flood risk of between 20 mm to 50 mm is simulated on the eastern river Witham floodplain.

9.2.7 The increase in flood depth during the NHRR scenario compared to the baseline scenario in the area between the Witham Washland Defence and the NHRR crossing is the cause of the very minor increase in water levels, (< 30 mm) shown in the River Witham downstream of the River Witham flood gates during the 1,000-year event (Figure 9-8). The higher water levels simulated between the Witham Washland Defence and the NHRR crossing overtop the River Witham levees slightly earlier and for a slightly longer period than during the Baseline scenario. The increase is very minor because it is offset by the reduction in flood levels at the floodplain north of the NHRR embankment during the NHRR scenario compared the baseline scenario. In this area, water levels overtop the River Witham levees slightly later and for a slightly shorter period than during the Baseline scenario.

9.2.8 The impact of the minor increase in water levels in the River Witham channel during the NHRR 1,000-year event compared to the Baseline scenario is a slight increase in floodplain flood depths downstream of the NHRR at Bracebridge. An increase of between 20 mm to 50 mm is simulated at Bracebridge Low Fields on the eastern floodplain of the River Witham, and an increase of 10 mm to 20 mm at South Witham Marsh on the western floodplain of the River Witham.

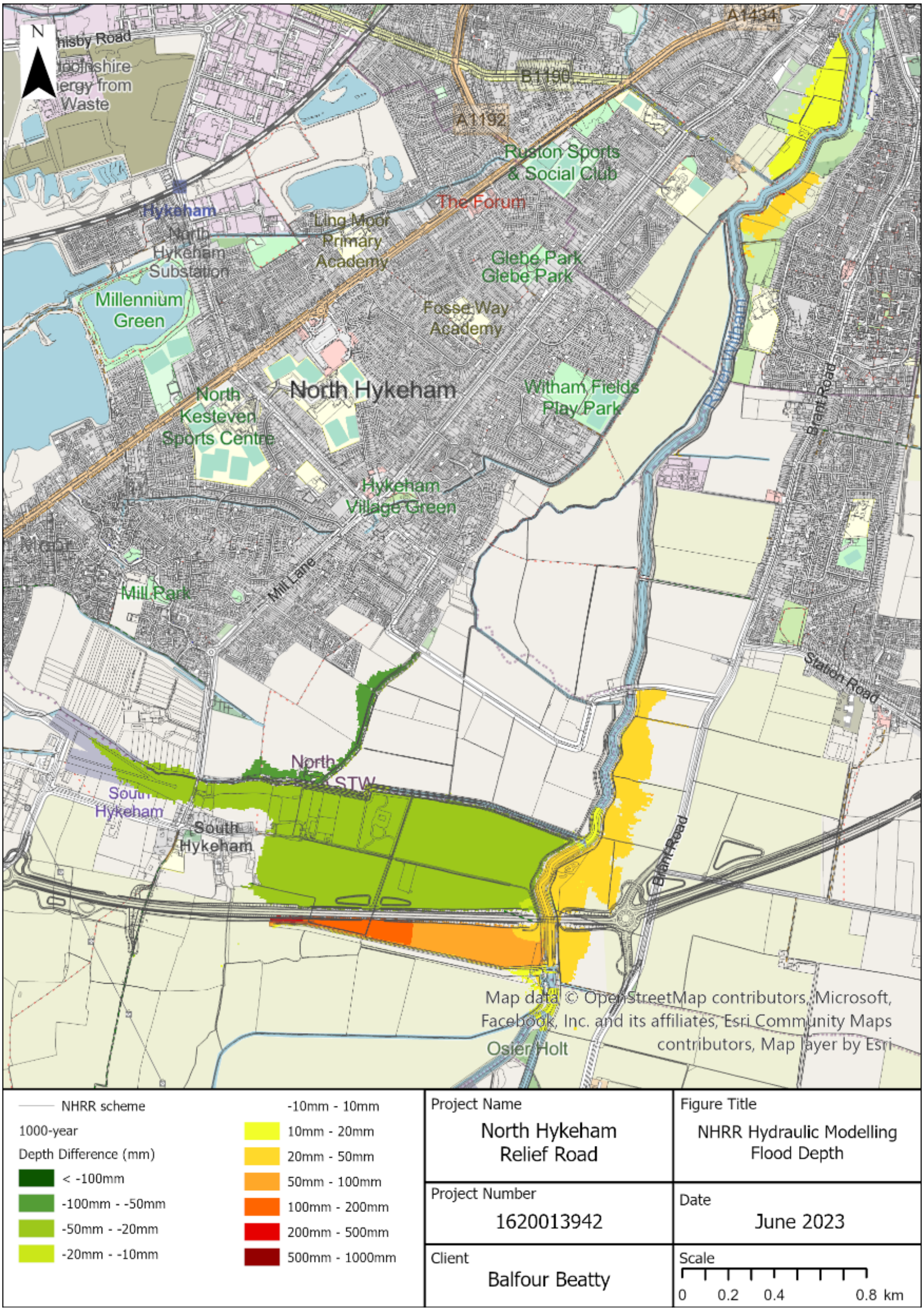

Figure 9-9: 1,000-year flood depth difference between the Baseline and NHRR Scenario

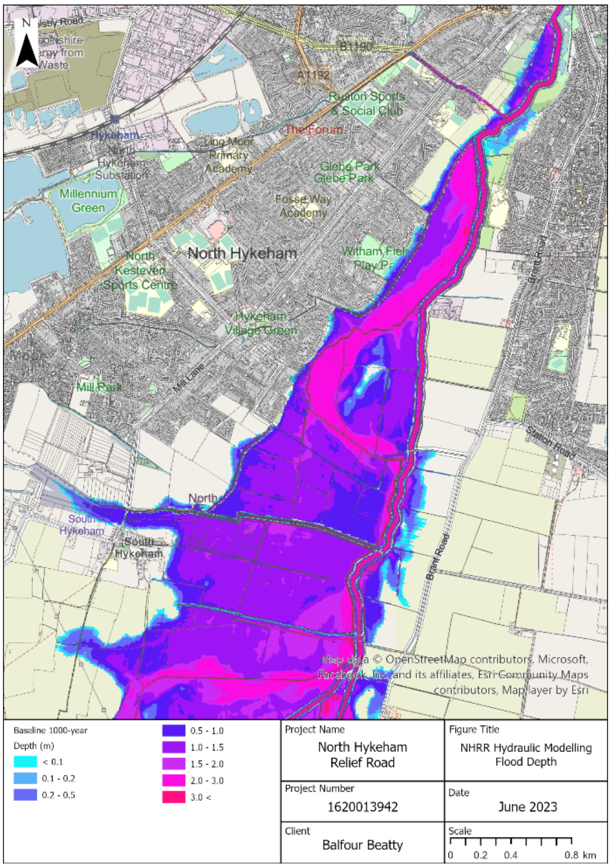

Figure 9-10: 1,000-year flood depths for the Baseline Scenario

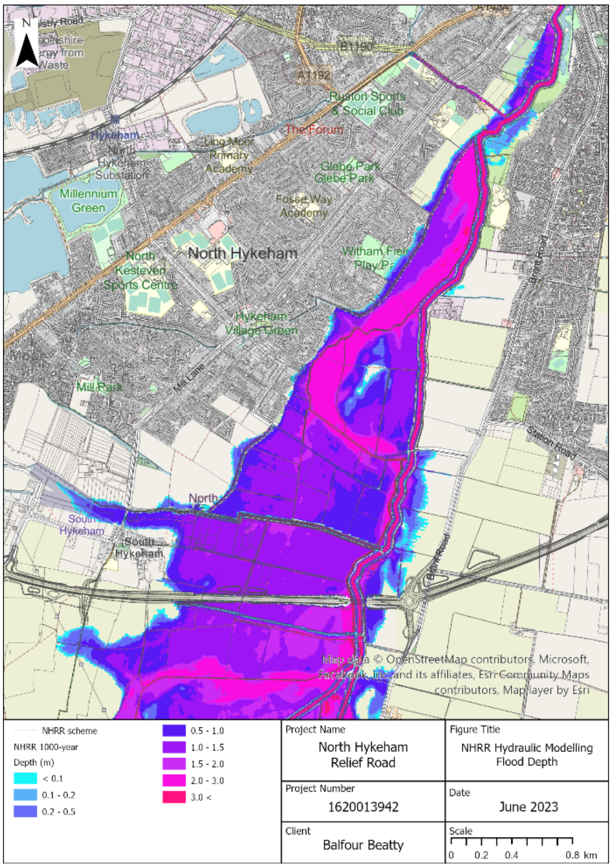

Figure 9-11: 1,000-year flood depths for the NHRR Scenario

9.2.9 Figure 9-12 shows the flood depth difference between the NHRR scenario and the Baseline scenario during the 1,000-year plus climate change (2080 Higher) event. Figure 9-13 and Figure 9-14 show the flood depths for the Baseline and NHRR scenarios during the 1,000-year plus climate change (2080 Higher) event.

9.2.10 For the 1,000-year event plus climate change (2080 Higher) event, the NHRR scheme acts to prevent the spread of flood water overtopping the Witham Washland defence north. This results in a reduction to the flood depths north of the NHRR crossing of between 10 mm to 50 mm and an increase to the flood depths to the south in the area between the NHRR crossing and the Witham Washland defence by between 100 mm to 200 mm near the river Witham to between 200 mm to 500 mm further west. The 1,000-year plus climate change (2080 Higher) event does not simulate an increase in flood depth downstream (North) of the Beck during the NHRR scenario compared to the Baseline scenario.

9.2.11 The 1,000-year event plus climate change (2080 Higher) event simulates an increase in flood depth of between 50 mm to 100 mm in the Witham Washland storage area, which is less than a 5% increase compared to the baseline flood depth. An increase of between 20 mm to 50 mm in flood depth is simulated to the Brant Washland storage areas which, for much of this area, equates to an increase of less than 2% compared to the baseline flood depth.

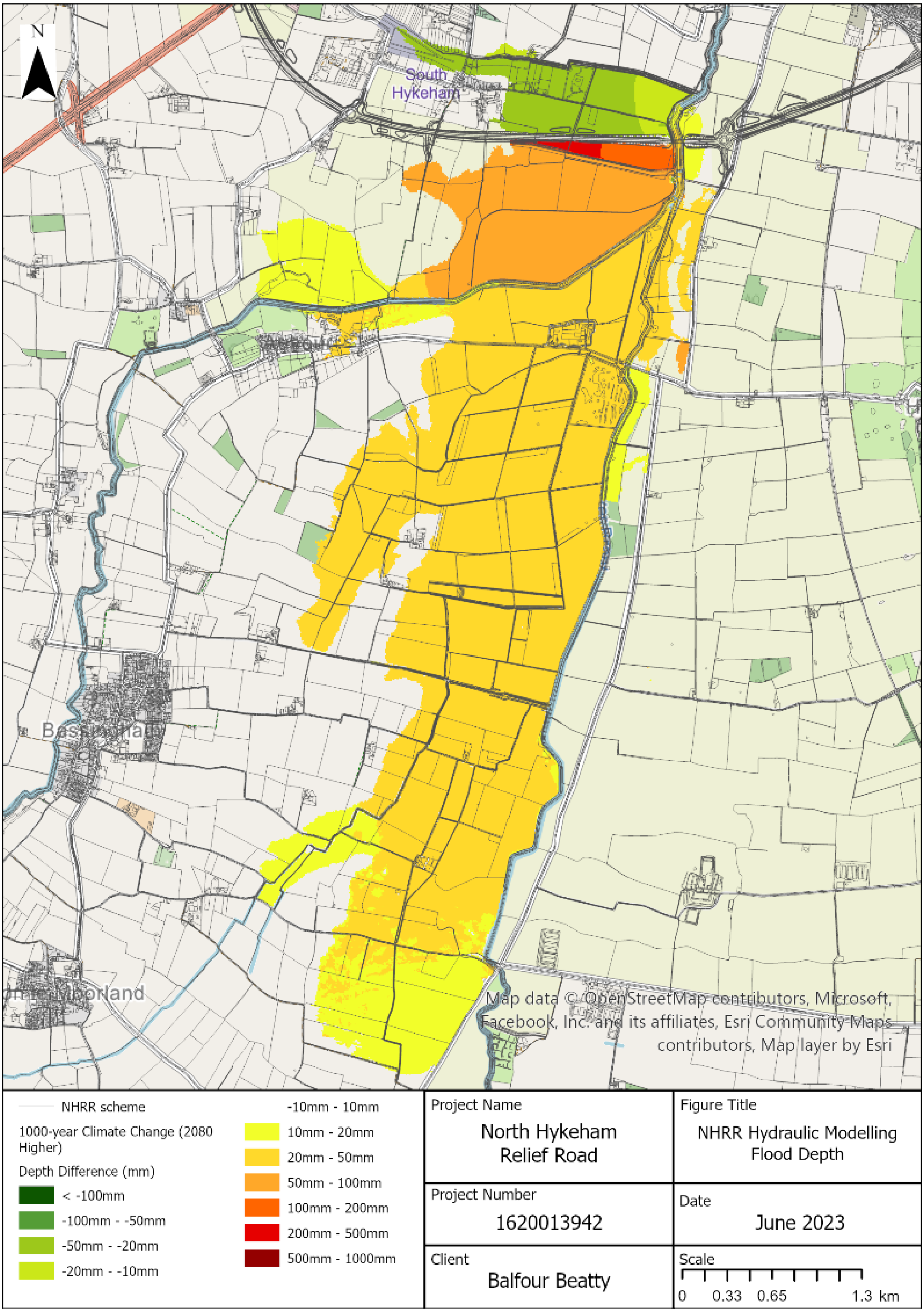

Figure 9-12: 1,000-year plus climate change (2080 Higher) flood depth difference between the Baseline and NHRR Scenario